



**Title goes here**

Thesis WIP

RICHARD ODELL

Master's Thesis at ITM  
Supervisor: Lars Svensson  
Examiner: Lei Feng

TRITA xxx yyyy-nn



# Abstract

Write the abstract here.

# Referat

**Title in Swedish goes here**

Abstract in Swedish goes here.

# Acknowledgements

I would like to thank...



# Abbreviations

Abbreviation	Description
ABS	Anti-lock braking system
DC	Direct Current
ITRL	Integrated Transport Research Lab
RCV	Research concept vehicle
PID	Proportional-Integral-Derivative

# Contents

**Abbreviations**

**Introduction**

Section . . . . .	
Sub-Section . . . . .	
Background . . . . .	
Research design/Methodology . . . . .	
Delimitations . . . . .	
Ethics . . . . .	
Risk assessment . . . . .	
Requirements? . . . . .	

**Background study**

Frame of reference . . . . .	
------------------------------	--

**Results**

**Conclusion**

**Discussion**

**Future work**

**Bibliography**

**Appendices**

**First Appendix**



## List of Figures

## List of Tables

# Introduction

This is what a chapter looks like.

## Section

This is what a section looks like.

### Sub-Section

This is what a subsection looks like.

**Paragraph** This is what a paragraph looks like.

## Background

The Research concept vehicle (RCV) at KTH is a platform for research in vehicle autonomy and vehicle dynamics. For precise autonomous operation, accurate actuation of steering input and wheel torque is critical. The electrical wheel motors of the RCV can produce torque for acceleration and braking up to a limit. However, for hard braking maneuvers, regenerative braking is not sufficient and a hydraulic brake system actuated by electric linear actuators is used in addition. In the current configuration, the hydraulic brakes actuate fairly slow (41s before braking request is met). Thus, a redesign of the control software and possibly the mechanical assembly is needed. The task is challenging due to the non-linear and environment dependent dynamics of the hydraulic system.

## Research design/Methodology

The methodology used for this project will be a case study of how to implement one or more brake controllers, which works best for solving the problem stated together with a comparison of the controllers advantages and disadvantages. The case study will have its focus on qualitative research, as there's extensive work already done withing this area. The testing will also have a qualitative orientation in the end to validate the brake model as well as how the controller performs.

### Delimitations

A lot of aspects affects the behavior of the brakes, and thus not everything can be included in the scope for a thesis. The focus will lie in building a efficient and robust controller for the electrohydraulic brake as well as implementing a basic brake blending algorithm. Hence, aspects like wheel slip, ABS functions and split mu will not be taken into consideration while designing the brake system.

### Ethics

Brakes is a vital part of the safety of a vehicle. Although this project handles the brakes while in autonomous drive mode, there will still be one or two people in the car monitoring the autonomous driving, whom might be susceptible to great risks if the brakes do not work. To keep the safety of the vehicle at acceptable levels there is a manual brake pedal that overrides the autonomous drive mode, and brakes the vehicle if necessary. This brake pedal is controlled by the person in the drivers seat, who has experience with the vehicle and is much aware of the risks and behavior of the car.

The vehicle is not legal to drive in regular traffic, and thus is only driven in big closed off areas, such as a rented runway on Arlanda or in a closed off parking lot, where it is driven at low speeds of up to 45 km/h. The vehicle is also equipped with seat belts dimensioned for racing. It is an electric car so the people around wont be exposed to any harmful exhausts.

### Risk assessment

The risks that is involved with this project include the availability of the RCV as well as that ordered hardware gets here on time. Concerning the availability of the RCV is mainly concerning test. I do not know how to drive the vehicle or how the whole system works, so I will need help doing the tests. Since the testing phase and later parts of the thesis takes place during summer, I might need to change my plan to match peoples vacation.

Concerning the hardware, the actuators that are mounted on the vehicle is relatively slow, and the system will need to be upgraded to achieve a fast enough response time. The lead times in deliveries must be taken into considerations in the time plan.

### Requirements?

- Speed of the actuators, in ms before request to actual torque meet.
  - Should it be optimized for torque meet, or regeneration? that is, should the regenerative me used as torquefill or as main brake? Probably torque fill.

## REQUIREMENTS?

- Maximum negative acceleration/ deceleration.



# Background study

## Frame of reference

The literature search was done directly in the IEEE Xplore database as well as Google Scholar. The search began with broad definitions as 'braking system autonomous driving' as well as 'braking control methods in autonomous driving', which resulted in a few methods that appeared frequently. These methods were then included in the search, together with searches solely for that method.

## Hardware setup

Yu et al. [1] discusses differences in a linearly actuated system vs a hydraulic pump system. The linearly actuated system uses a linear actuator that press directly on a hydraulic cylinder, while a hydraulic pump system uses an electric pump to build up pressure and controls the pressure in the system by valves and/or solenoids. The linear actuators are simpler and more fail safe, since it doesn't have as many valves from where there can be a leakage of hydraulic fluid.

Line, Manzie and Good [2] has constructed a electro-mechanical brake-by-wire system, which utilizes an electrical motor in the calipers as actuator that controls the pressure of the brake pads. There is also a brake pedal that sense the pedal position which in turn sends the brake request to a controller. They compare two different controllers in this paper, a cascaded PI controller and a model predictive control (MPC). The cascaded PI controller has three control loops for force, motor angular velocity and motor current. The PI controller works, but due to the systems nonlinearity it is somewhat inconsistent in different situations. The MPC performs better in this case, but in order for it to work this efficiently a very good model of the system is needed as ground work, and this might be time consuming.

Xiang et al. [3] writes that a electro-mechanical system is preferable over a electro-hydraulic system, due to the simplicity, the efficiency and stability, the enhanced diagnostic capabilities, cost reduction, space and weight saving as well as the elimination of environmental concerns associated with traditional hydraulic braking systems.

Line, Manzie and Good [4] as well as in Ahn et al. [5] is articles about using a cascaded PI controller to control a electro-mechanical brake-by-wire system. Here they present requirements on a electromechanical braking system. They discuss the influence of friction, which makes the system nonlinear. The nonlinearity is discussed in the conclusion, where the nonlinear system is the explanation why the cascaded pi controller does not work as fast in the lower brake pad force spectrum as it does for the higher part of the spectrum.

Frede, Khodabakhshian and Malmquist [6] has done a state-of-the-art report on by-wire systems, with an extensive part about brake-by-wire. They present an overview of brake blending strategies as well as control strategies to regulate braking torque. Most reports discuss brake blending control, but reports where brake torque control is achieved by fuzzy logic is presented as well. Isermann [7] also describes the strengths of a fuzzy logic controller, due to its ability to handle nonlinear systems.

Milanés et al. [8] presents in an article how an autonomous braking system is implemented into a ordinary road car. The car is already fitted with a hydraulic braking system with a manually controlled braking pedal, and the autonomous braking system is added on to that, resulting in a electro-hydraulic autonomous braking system similar to that on the RCV. Although the actuator in this car is a electric pump compared to a linear actuator on the RCV, this report shows that a electro-hydraulic system is satisfactory, even though other reports state that electro-mechanical systems are preferable [9] [3].

The brake blending will be done by a simple function where the regenerative brakes brakes as much as possible, and when they have reached their maximum braking power, the friction brakes steps in to fill in the missing torque, as described by Troung [10].

## Results

The results from the literature study is that the two friction brake controllers will consist of a PID controller and a fuzzy logic controller. The brake blending algorithm will be a simple one where the regenerative brakes brake as much as possible, and the friction brakes fills in the missing torque.



# Results

This chapter presents the results of the thesis.

## Hardware

The highest needed braking torque on each wheel was calculated with respect to the maximum negative acceleration that is stated in the requirements. If the acceleration is known, as well as the mass of the vehicle the total force that needs to act on the vehicle can be calculated with Newtons second law,

$$F_{tot} = m \cdot a, \quad (1)$$

where  $F_{tot}$  is the total force needed to achieve acceptable deceleration,  $m$  is the mass of the vehicle and  $a$  is the acceleration. The vehicle has four wheels and the force is considered to be divided evenly distributed on each wheel. Hence, this gives us

$$F_{wheel} = \frac{F_{tot}}{4}, \quad (2)$$

where  $F_{wheel}$  is the force needed on each wheel. The torque needed on that wheel can then be calculated by

$$M = F_{wheel} \cdot r, \quad (3)$$

where  $M$  is the torque and  $r$  is the radius of the wheel. The required torque on each wheel was calculated to 350 Nm.



# Conclusion

This is what a chapter looks like.



# Discussion

This is what a chapter looks like.



# Future work

This is what a chapter looks like.





# Bibliography

- [1] Z. Yu, S. Xu, L. Xiong, and W. Han, “An integrated-electro-hydraulic brake system for active safety,” in *SAE Technical Paper*. SAE International, 04 2016. [Online]. Available: <http://dx.doi.org/10.4271/2016-01-1640>
- [2] C. Line, C. Manzie, and M. C. Good, “Electromechanical brake modeling and control: From pi to mpc,” *IEEE Transactions on Control Systems Technology*, vol. 16, no. 3, pp. 446–457, May 2008.
- [3] W. Xiang, P. C. Richardson, C. Zhao, and S. Mohammad, “Automobile brake-by-wire control system design and analysis,” *IEEE Transactions on Vehicular Technology*, vol. 57, no. 1, pp. 138–145, Jan 2008.
- [4] C. Line, C. Manzie, and M. Good, “Control of an electromechanical brake for automotive brake-by-wire systems with an adapted motion control architecture,” in *SAE Technical Paper*. SAE International, 05 2004. [Online]. Available: <http://dx.doi.org/10.4271/2004-01-2050>
- [5] J. Ahn, K. Jung, D. Kim, H. Jin, H. Kim, and S. Hwang, “Analysis of a regenerative braking system for hybrid electric vehicles using an electro-mechanical brake,” *International Journal of Automotive Technology*, vol. 10, no. 2, pp. 229–234, 2009.
- [6] D. Frede, M. Khodabakhshian, and D. Malmquist, “A state-of-the-art survey on vehicular mechatronics focusing on by-wire systems,” KTH, Mechatronics, Tech. Rep. 2010:10, 2010, qC 20111204.
- [7] R. Isermann, “On fuzzy logic applications for automatic control, supervision, and fault diagnosis,” *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, vol. 28, no. 2, pp. 221–235, Mar 1998.
- [8] V. Milanés, C. González, J. Naranjo, E. Onieva, and T. De Pedro, “Electro-hydraulic braking system for autonomous vehicles,” *International Journal of Automotive Technology*, vol. 11, no. 1, pp. 89–95, 2010.
- [9] R. Isermann, *Mechatronic Systems: Fundamentals*, 2nd ed. London: Springer-Verlag, 2005.

## BIBLIOGRAPHY

- [10] B. Truong, “Development of an active braking controller for brake systems on electric motor driven vehicles,” Sweden, 2014.

# First Appendix

Appendix text goes here.