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Improving braking and cornering sensation in a driving simulator by developing an active seat belt tensioner

Master's thesis in Automotive engineering

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MASTER'S THESIS 2021

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Cover: Image of Casters driving simulator with a belt tensioner device mounted at the back of the seat.

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Abstract

This report is about the research, development, manufacturing and implementation of an active seat belt tensioner in a driving simulator delivered by Cruden, located at Chalmers university of technology. The seat belt tensioner is developed to work with a six point seat belt and is capable of tightening the shoulder straps individually to improve the sensation of both braking and cornering.

A small user study was conducted to determine required tension force in the belts. Another test was made on the simulator platform, to estimate the required response time of the system. The design requirements were based on these tests. In order to maintain the budget of 4000 sek, a sponsor was required, Autoliv kindly provided two complete belt tensioner units. These units were slightly modified and the required supportive hardware was added. A mounting bracket for the tensioning devices was built and mounted on the simulator platform and the necessary software was created and implemented in Simulink.

When the system was installed and tuned, another user study was made to investigate the potential performance gain in braking performance, along with improved braking and cornering sensation. The results from the subjective evaluation showed a clear improvement in both braking and cornering sensation, however it was not possible to statistically determine if the system has any affect on braking performance. In order to determine any change in braking performance, further testing needs to be conducted with a larger set of test subjects.

Keywords: Active Seat belts, Simulator, Product development, Control system, Driver-In-the-Loop, Simulator experience.

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Abbreviations & Nomenclatures

Abbreviation	**Description**
ADAS	Advanced Driver-Assistance Systems
Arduino	An Affordable Microcontroller
CAD	Computer Aided Design
CASTER	Chalmers Automotive Simulator Technology Education Research
CoG	Center of gravity
DIL	Driver In the Loop
DOF	Degree Of Freedom
int16	16 bit integer
MF	Magic Formula
MPC	Model Predictive Control
OEM	Original Equipment Manufacturer
PWM	Pulse Width Modulation
uint8	unsigned 8 bit integer

Contents

1

Introduction

This is a master thesis project within automotive engineering with driving simulators in focus. This report will cover the master thesis project about improving the sensory feedback in CASTER's driver in the loop simulator at Chalmers. Since driving simulators are frequently used in automotive engineering, it is important to keep up with the ongoing development of such engineering tools.

1.1 Background

Vehicle simulators have been around for almost as long as airplanes, one of the first documented uses were in the early 20th century as a flight simulator for pilot training, as documented by Bouchner [2]. The benefits of having a training simulator for pilots were to minimize the costs and the risks of having an accident. Vehicle simulators in the form of car simulators has been around since the 1970s [2] when Volkswagen built the first motion based driving simulator and the simulator technology has been improving ever since.

Although driving simulators have been developed continuously since the '70s, further improvements can still be made. The most important factor for a driving simulator is the feedback given to the driver, which is limited in many ways compared to a real vehicle. Producing realistic feedback is therefore a challenge. One of the main limitations of limited motion simulators is the fixed base. Fixed base simulators cannot simulate sustained accelerations without introducing exaggerated motions. This can be overcome with simulators that can translate the entire motion base. This method requires large investments as the BMW simulation centre for example, where they have invested in a large facility that contains several different vehicle simulators with some that can translate the entire motion base, BMW [1].
Other ways of achieving acceleration feedback requires ingenious ways of tricking the driver. One method is to tilt the motion platform during sustained accelerations to utilize earth's gravity, this method gives the driver the sensation of being pressed against the seat belts when braking. The forward tilt is restricted by two factors, the physical hardware and the pitch angle calculated by the vehicle model. Tilting the motion platform more than the vehicle model gives the driver a greater sense of deceleration but induces false movement of the motion platform, this is called "false cueing". Inducing more tilt can reduce the performance of an experienced driver or give a driver false disposition of how a real version of the vehicle would behave. The platform tilt angle can be reduced by implementing an active seat belt that tightens

when braking, since the function responsible for creating the hanging sensation is moved from the motion platform tilt angle to a dedicated system. By introducing more components to the system, the level of complexity increases along with the number of cues received by the driver. If these cues are out of sync it could lead to simulator sickness, where the driver experience a strong sense of discomfort, as explained by Henriksson [9].

1.1.1 Vehicle engineering and Simulators

Driving simulators are becoming more important for exploratory automotive research in situations where the human is a critical part of the system and computer-controlled simulations are not good enough to produce applicable and trustworthy results. The feedback to the driver in the driving simulator affects the outcome of the test in the driving simulator according to Cruden [5], it is therefore critical to provide high fidelity feedback to the driver. Another important factor in vehicle development is cost, the cost can be reduced by simulations instead of physical models. A more advanced vehicle simulator available for early testing means that further savings can be made on test vehicles.

1.1.2 Existing solutions for seat belt tensioners

There are a couple of existing solutions for seat belt tensioners on the market, the first solution is a complete two axis "bolt-on" system from SimXperience called G-belt [13]. The system includes software to control the tensioning device. The downsides of this system is that the price does not fit the budget of this project and the software is limited to specific desktop applications and will therefore not be applicable on the CASTER simulator. The second product available on the market comes from a company called Evotek [6] and this product would probably handle all of the demands of this project with ease, however the price starts at € 6.100 + VAT per unit and is therefore not an option.

1.2 Goal

At Chalmers University of Technology there is a vehicle simulator that is maintained by a student organisation called CASTER. The simulator is delivered by Cruden and is a stationary driver in the loop simulator that is based on a Stewart platform, meaning a simulator on six actuators that reacts to the input from a human operator.

The investigations and products created during this project was made to suit CASTER's simulator and the hardware budget was limited to 4000 SEK. Everything required for building, installing and control the end product was covered by this budget.

The goal for this master thesis project is to develop, manufacture, implement and evaluate a seat belt tensioning system in the CASTER simulator at Chalmers. This system will be realised through a thorough engineering process, where the groundwork will be based on basic theory studies and practical tests resulting in engineering prerequisites.

The requirement sheet will contain specifications for both the physical hardware and the software controller needed to realise the tensioning function in the simulator. The implementation process will follow the development process where all requirements are fulfilled and safety is maintained.

Evaluation, tuning and verification of the whole system starts when the new tensioning system is installed in the simulator, the goal is to tune the tensioning controller and evaluate its effectiveness at improving the sense of deceleration and hard cornering. The verification process will encompass data collection of test runs using volunteer drivers that have previous experience of simulator driving.

A stretch goal is to make the control system modular and flexible in its inputs, so that it may be used as a feedback device to the driver in other scenarios. The primary idea in this area is to use the seat belt to increase the driver's attention based on data coming from ADAS systems.

Another stretch goal is the ability to tighten the seat belts individually through a two axis seat belt tensioning system and use this to increase the sensation of cornering.

The research questions this thesis aims to answer are:

- Does the addition of seat belt tension improve the drivers braking performance?
- Does the addition of seat belt tension improve the sensation of braking?

The research questions aimed to be answered for the stretch goals are:

- Can the seat belt tensioner lower the driver's reaction time
- Does the addition of a two axis seat belt tensioning system improve the sensation of cornering?
- Does the addition of a two axis seat belt tensioning system give the driver useful feedback for vehicle control?
- Does the addition of a two axis seat belt tensioning system improve the driver's cornering performance?

1.3 Deliverables

- Engineering prerequisites containing requirements for a belt tension device and its application
- Installation of tensioning hardware in the CASTER simulator
- A controller that is developed and tuned to work in harmony with existing motion cueing
- A statistical trial to investigate it's impact on driver performance
- An adaptable seat belt tension controller
- Documentation of how to use and tune the tension controller

Stretch Goals

- Ability to control belt tension individually on each side to give sensory feedback during lateral accelerations
- Demo of tension pulse to increase driver attention

1.4 Limitations and delimitations

- Parts budget limited to 4000 SEK
- The developed tensioning solution must fit in with existing seat in the CASTER simulator
- The implementation will be tailored to the CASTER simulator, other types of simulators will not be taken into consideration
- No changes to the vehicle model, audio or motion cueing will be made
- The tension of the seat belt will not exceed levels that is perceived as unpleasant for the driver
- No experimental studies on safe levels of seat belt tension for continuous use will be carried out
- User tests will only be carried out by people with previous experience of simulator driving
- Calculations of forces in the seat belt will be simplified.

1.5 Social and ethical aspects

The solution created will not be tested for every possible user, people with deviating weight and length compared to the test subjects may experience different results. Various medical conditions such as motion sickness or other problems regarding the vestibular system will not be taken into consideration. One of the key advantages with an advanced vehicle simulator is the reduced need of creating physical vehicle prototypes, by implementing an active seat belt tensioner the simulator will be further advanced and thereby taking another step towards a reduced need for physical prototypes, which is environmental friendly. It is also safer to test new vehicle configurations in a simulator compared to testing a prototype on a test track.

2

Theory

The following chapter presents the theory behind vehicle simulators, simulator sickness, statistical methods and vehicle dynamics used in this project.

2.1 Vehicle Dynamics

The physical motion of a car is explained through vehicle dynamics, a few of the basic terms used in vehicle dynamics will be presented below. The dynamics are divided into longitudinal and lateral dynamics.

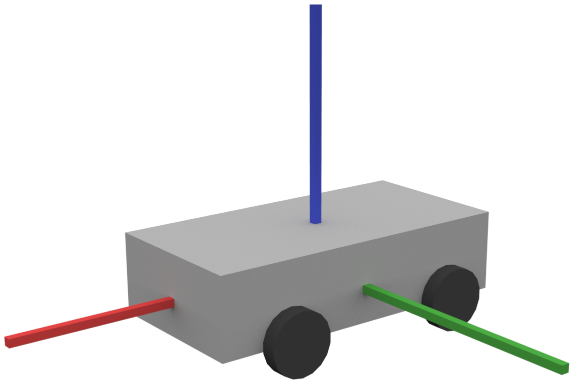


Figure 2.1: Vehicle with coordinate axis, red - x, green - y, blue - z

2.1.1 Longitudinal dynamics

In order to describe a vehicle's motions in the longitudinal direction, there are a few terms related to a specific motion or behaviour. When the car is accelerating on level ground, the car tends to "squat", Jacobson [10] this means that the rear end of the car is compressed towards the road surface and the front end is raised, this results in a negative rotation around the y-axis (green) illustrated above in figure 2.1. When the car brakes it is the other way around, the rear end lifts and the front end is closer to the ground, this is called "dive" [10] and is a positive rotation around the y-axis. This is quantified through a pitch angle which is a measurement of how many degrees the body of the car is leaning in relation to its stationary position on flat ground. The amount of squat and dive is dependent on the vehicle characteristics and properties.

2.1.2 Lateral dynamics

When a car rotates along its longitudinal axis it is called "roll" and is quantified as the roll angle [10] which is a rotation around the x-axis (red) in figure 2.1. Roll is something that occurs during cornering and the roll angle depends on the speed of the vehicle and the sharpness of the corner. Like the pitch angle, the roll angle is a measure of the cars angle with respect to its stationary position on flat ground and is dependent on the vehicle characteristics and properties.

2.2 Vehicle simulators

Vehicles simulator comes in many forms, each with its own set of limitations and weaknesses to manage. Two interlinked areas to manage is the motion cueing risk of simulator sickness. Motion cueing is the process of taking vehicle motions and translating that to movement in the simulator. Simulator sickness is a form of motion sickness that can occur in a motion simulator.

2.2.1 Motion cueing

MPC or Model Predictive Control is a control method that can maximize the usable range of motion of the simulator, as the name suggests, it uses a prediction of what will happen in the future. At the moment these models are not used in interactive simulations with a human driver in the loop. MPC motion cueing has a known vehicle motion path that it will try to recreate to its best ability by preparing the motion platform for a future cue Cleij et al. [4]. For example, consider a vehicle is driving through a roundabout, to maximize the utilization of the available range of motion, the platform would slowly windup in the opposite direction of the upcoming motion cue. This allows the platform to move more than if it is unaware of what a future cue would be. Due to its nature, MPC is very useful in simulators where the perceived motion is most important or where the subject in question is a passenger.

DIL simulators are inherently unpredictable and cannot utilize the windup techniques from MPC theory, instead they must be ready for an unpredicted input to its best ability. The motion platform has therefore a "resting point", where all cues are originated from. Windup becomes a problem in this situation instead of being a desirable effect. Washout filters are used to combat windup and are a constant cue to move back to the resting point. High frequency moves are undesirable as they constantly tells the platform to move, giving no opportunity to move towards the resting point. Filters are therefore applied to all signals going to the cueing algorithm, this reduces the platforms dynamic range and must therefore be of consideration when designing a test in a simulator. Studies has been performed to bring some of the benefits of MPC cueing to the DIL simulator, Hanson and Stenbeck [8] proposes the use of a prediction of future cues based on vehicle speed and upcoming road curvature.

2.2.2 Simulator sickness

Simulator sickness is a state of motion sickness that is induced by a simulator rather than a moving vehicle or a roller coaster for example. This type of illness is often derived from a mismatch between sensory signals Henriksson [9]. A typical mismatch would be a difference between an expected motion of the simulator in relation to a displayed scenario. In order to minimize the risk of simulator sickness, these mismatches needs to be prevented. Simulator sickness can also occur due to false cueing, that the platform rotates more than what is visualized on the screens of the simulator. Another theory mentioned in the VTI-report [9] of why simulator sickness occurs, is a change in the relationship between force vectors acting on the body and the supportive surface or posture instability. The posture stability could be increased by tightening the seat belts. However, if the tightening sequences occurs too frequently, the driver would instead be put out of balance and simulator sickness could be induced.

2.3 Statistical method

Statistical methods have been in use and developed for a long time, the ANOVA method is a well known and recognised method used throughout the field of clinical studies. The ANOVA method returns a p-value, which is the probability that the two groups of data have the same mean. This means that a small p-value, usually in the range of 0.01 to 0.1, indicates that the two data sets have a different mean. Depending on a predetermined statistical significance, i.e the desired p-value, a rejection of the null hypotheses can be made based on the p-value calculated from the ANOVA method Chow and Liu [3].

2.3.1 Hypotheses

Each statistical endpoint will have two hypotheses associated with it, called the null hypotheses, H_0 and the alternative hypotheses, H_1. The alternative hypotheses is usually constructed as the statement to be confirmed with the study, the null hypotheses is then the opposite to the alternative hypotheses. This method allows for developing a statistical test that can reject the null hypotheses and thereby accepting the alternative hypotheses.

$$\begin{cases} H_0 : \mu_C \leq \mu_T \\ H_1 : \mu_C > \mu_T \end{cases}$$

With the hypotheses construction above, the target is to confirm that the mean in the testing/treatment group is lower than the control group. The alternative hypotheses in this example is that the mean is higher in the control group than the test/treatment group, which is good if the target is to have a lower mean in the test/treatment group.

The alpha value is used to control the risk for false positives, that the test has good efficacy while in reality it does not. Typical alpha values are by convention 95% or

99%, meaning that the risk of having a false positive result is 1% or 5% respectively. False negative results are usually not as critical, and are therefore given less influence on the sample size. Typical beta values are in the range 80%-90%.

2.3.2 Sample size

For the trial to have enough statistical power of 80 %, i.e. $1-\beta$ of 0.80, to reject the null hypotheses the sample size needs to be large enough. The study will reject the hypotheses with a significance level α of 0.05. Guogen and Changxing [7] presents the following formula to calculate an appropriate sample size:

$$n = 2\sigma^2 \frac{(Z_{1-\alpha/2} + Z_{1-\beta})^2}{(\mu_C - \mu_T)^2} \tag{2.1}$$

Where n is the sample size of one arm, σ^2 is the expected variance in the sampled data, $Z_{1-\alpha/2}$ and $Z_{1-\beta}$ is the z-score to adjust the statistical power, $(\mu_C - \mu_T)^2$ is the mean change between the control group and test group.

The sample size is usually compensated to allow for drop outs, bad measurements and other events that results in data from one subject to be unusable.

3

Methods

The following chapter presents the methods used in this master thesis and contains information on how the development process of the tension system was performed, this includes the physical prototype, control system and evaluation procedure.

The idea of an active seat belt tensioner is to increase the sensation of driving in the simulator during braking and cornering. By tightening the shoulder straps of the seat belt it would be possible to offload the simulator platform during roll and dive scenarios. For example in a braking scenario, the platform could maintain the same pitch angle as the car model and the sense of deceleration could be generated by the seat belts being tightened and not by the platform executing a false cue. This could also result in less simulator sickness originated from false cueing.

3.1 Requirements studies

The concept generation process started with requirement studies to establish design prerequisites. The main objective was to find the required tensioning force and how quickly the set force had to be reached.

3.1.1 Seat belt tension test

In order to determine the desired tensioning force on the seat belt in the simulator, a user test was conducted. All of the participants in the test had previous experience of the simulator used in the test. The purpose of using experienced drivers was due to their knowledge on how it is to use the simulator, thereby being able to judge whether the tension level of the belt is acceptable for a continuous use without resulting in discomfort. Since the test subjects have previous experience of the simulator with the current belt configuration, they could easily tell a difference and identify how much tension force in the belt that is required in order to feel the tension from the belt, compared to the normal tension from the belt after it has been fastened and tightened properly.
The test subjects were briefed on how the test would be performed, that a lower and upper value would be recorded. The lower limit was supposed to give an indication of how much tension force that is required for the subject to feel the belt is being tightened. The force recorded for the upper value was supposed to give an indication of how much force required to simulate a hard braking scenario. A maximum value of what was regarded as endurable was also a target for this study.

Unfortunately this could not be obtained due to the measurement range of the test equipment, instead a tightening level that corresponded to a hard braking scenario was the objective.

After being briefed, the subjects were seated and fastened the lap belt to a normal level. The test supervisor then tightened the belt shoulder straps with a force measuring device until the test subject called out a noticeable change in tension that could be equivalent to low deceleration. The force was then increased until the test subject called out that the tightening level for a hard braking scenario was reached. The test results can be viewed in table 3.1 and the average results in table 3.2.

This procedure was repeated three times per test subjects to reduce the uncertainty in the measured force levels. The tensioning distance for the seat belt was also noted to be around 5 cm.

An issue not considered beforehand is the fact that the four-point seat belt moved noticeably upwards when the tension was increased on the shoulder straps. This gave a reason to believe that a change to a five or six point seat belt might be necessary to create a good experience, since having the seat belt moving upwards could both create discomfort distract the user. This will of course affect the tensioning distance due to the increased rigidity of a belt with more fixation points.

Table 3.1: User study on seat belt tension

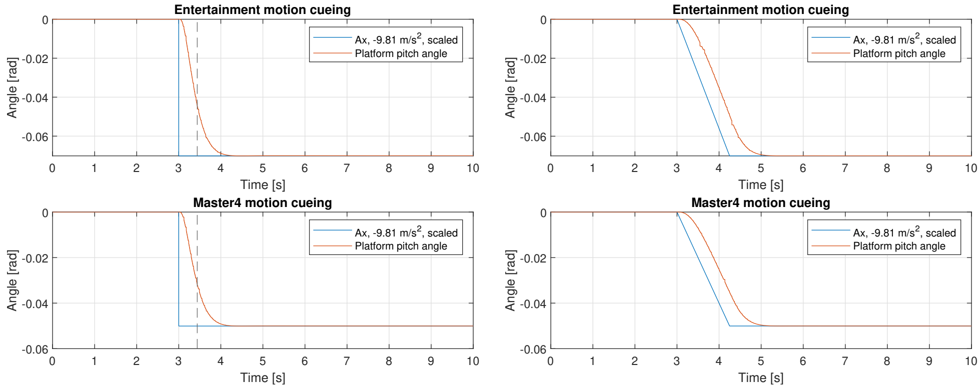
Subject No	**Lower limit [N]**	**Upper Limit [N]**
1	80	160
1	88	180
1	84	200
2	48	120
2	56	96
2	72	112
3	52	96
3	60	132
3	52	120
4	56	120
4	64	100
4	56	116

Table 3.2: Averages of tension forces

Subject No	**Lower limit [N]**	**Upper Limit [N]**
1	84	180
2	59	109
3	55	116
4	59	112

3.1.2 Motion platform response

To understand the responsiveness of the motion platform, a quick simulation was run where a longitudinal acceleration command was sent to the motion platform. The response time of the platform was monitored in get a measured response time. This information formed the basis for how responsive the seat belt tension system need to be to provide feedback with similar characteristics as the platform. The data from the simulation is presented in figure 3.1, the dashed line is the point where 63.2% of the final value is observed. The Master4 cueing has a more direct vehicle feel compared to Entertainment.



(a) Platform response, step input **(b)** Platform response, ramp input

Figure 3.1: Platform response to different types of input

The perceived acceleration by the driver was calculated with the following equation, where θ is the rotation around the y axis in the global XZ plane.

$$\begin{bmatrix} A_{x,d} \\ A_{z,d} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} A_{x,g} \\ A_{z,g} - 9.81 \end{bmatrix} \tag{3.1}$$

Figure 3.2 show how the car acceleration, platform movements and driver acceleration evolves during a braking maneuver. The driver's perceived longitudinal direction were calculated using equation (3.1) and only taking the $A_{x,d}$ component.

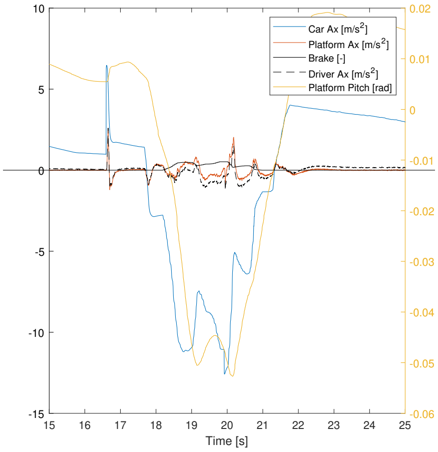


Figure 3.2: Telemetry from driving simulator, braking maneuver, Master4 cueing

3.2 Hardware and software specifications

The specifications for the seat belt tensioner are divided into hardware and software, the specifications are described below.

3.2.1 Hardware

The seat belt tensioning test revealed an issue with the four point seat belt in the simulator, after discussion with the CASTER board, a new six point seat belt was ordered and installed by the board. Further the requirement studies gave the prerequisites of how hard the belt needed to be tightened and thereby set the base requirement of the tensioning device. The requirement was set to 200 N to get some headroom, the upcoming changes to the belt configuration in the simulator, going from 4 points to 6 points will also increase this headroom. The motor was required to have a sufficient acceleration in order to comply with the requested rise time of the system, the motion platform response investigation combined with the requirement study, it was determined that the belt had to be tightened 5 cm within 0.5 s as in figure 3.1. Further the power supply had to deliver enough power to the system and an emergency stop was required for safety precautions.

3.2.2 Software/Controller

The software must provide an interface to Simulink where the vehicle model runs, the model must also ensure that the rise time requirement is fulfilled. The developed controller must also be understandable and available to the CASTER board to provide for upcoming projects and further development.

3.3 Solution concepts

To find possible solutions that satisfies the set prerequisites during the limited time period available, a concept generation session was carried out where possible solutions to tighten the belt according to the requirement specification was identified. The solutions are presented below as a complete concept. All concepts have a configuration that allows for individual tightening of the seat belts to achieve the set stretch goals. A bill of materials for all concepts can be viewed below in table 3.3

Concept 1 - Pneumatic

A solution with a pneumatic pressure cylinder pulling the belt, this is feasible due to the availability of compressed air within the facility where the simulator is located. To control the pressure in the cylinder accurately and swiftly, an Electro-Pneumatic Pressure Regulator is required. The tension force acting on the belt could be determined by measuring the air pressure or by using a load cell.

Concept 2 - Linear actuator

This solution features a linear actuator that tensions the seat belt upon activation. The combination of a fast actuator with enough force to tighten the belt sufficiently might become an obstacle with this solution. To measure the force acting on the seat belt an external load sensor would be required.

Concept 3 - DC-motor

This concept involves a DC-motor and a gearbox to deliver sufficient power and speed to the belt. To control the force acting on the belt, the current input to the motor could be monitored. A simplified belt force measurement can be made since the motor current has an almost proportional relationship to torque output of the motor. This provides good feedback to the controller and enables precise tension control.

Eliminated concepts

An electromagnetic concept was created, but was rejected because of the high power demand and higher cost. Another solution with a step actuator was also investigated, but due to the low actuation speed, the rise time requirement would not be fulfilled.

Table 3.3: Bill of Material for all Concepts

Concept	Part	Cost [SEK]	Qty	Total cost
Pneumatic	Pneumatic cylinder	515	2	9661
	Pressure regulator	3505	2	
	4-20 mA current loop	235	2	
	Micro controller	352	1	
	Power supply	799	1	
Linear actuator	Linear actuator	2890	2	10575
	Motor controller	933	2	
	Force gauge	789	2	
	Load cell amplifier	100	2	
	Micro controller	352	1	
	Power supply	799	1	
DC-motor	Electric motor	1900	2	9837
	Motor controller	569	1	
	Gearbox	2195	2	
	Micro controller	279	1	
	Power supply	799	1	

3.4 Final concept

After all the suitable parts for the different concepts had been identified, it was obvious that the budget of 4000 SEK was insufficient. A sponsorship was required for the project to succeed without compromises.

A successful contact turned out to be Autoliv that showed interest in the project and were willing to sponsor the project with two seat belt tension modules, complete with belts, motors and gearboxes. This made the concept selection procedure straightforward and the DC-motor concept was chosen, but with the motor and gearbox changed to the components provided by Autoliv instead.

3.5 Controller specification

With the hardware identified, the controller specification could be developed. It consists of two parts, the Arduino/tensioner side and Simulink/vehicle model side. Table 3.4 lists all identified requirements.

Table 3.4: Tension controller specification

	Function	**Solution**	**Value/Dimension**
Arduino	Set motor power	Arduino Library	-400 to 400 [1x2]
	Receive motor request from Simulink	Serial.read	-400 to 400 [1x2]
	Read motor current	Arduino Library	(A) [1x2]
	Read fault status	Arduino Library	true/false
	Send motor current	Serial.write	(A) [1x2]
	Send fault status	Serial.write	true/false
Simulink	Read motor current	Serial input block	(A) [1x2]
	Read motor fault	Serial input block	true/false
	Input vehicle rotation matrix	Read from Simulink	(rad) [3x3]
	Input platform rotation angles	ePhyse input block	(rad) [1x3]
	Input platform acceleration	ePhyse input block	(m/s^2) [1x3]
	Transform platform acc to driver FOR	Simulink calculation	(m/s^2)
	Find acc delta of vehicle and platform	Simulink calculation	(m/s^2) [1x3]
	Calculate requested seat belt force	Simulink calculation	(N) [1x2]
	Regulator for motor power	Simulink calculation	
	Send motor power	Serial output block	-400 to 400 [1x2]

3.6 System design

Once the final concept had been established, a detailed system design was created. The design overview is located below in figure 3.3. As the image describes, Simulink is connected to the motion platform and the vehicle model is run within Simulink. A seat belt tension controller added in Simulink would then communicate with an Arduino along with a motor driver shield attached to it. The two motors in the belt tensioners are then connected to the driver shield, the motors and the shield are powered by a 12 V power supply mounted on the motion platform.

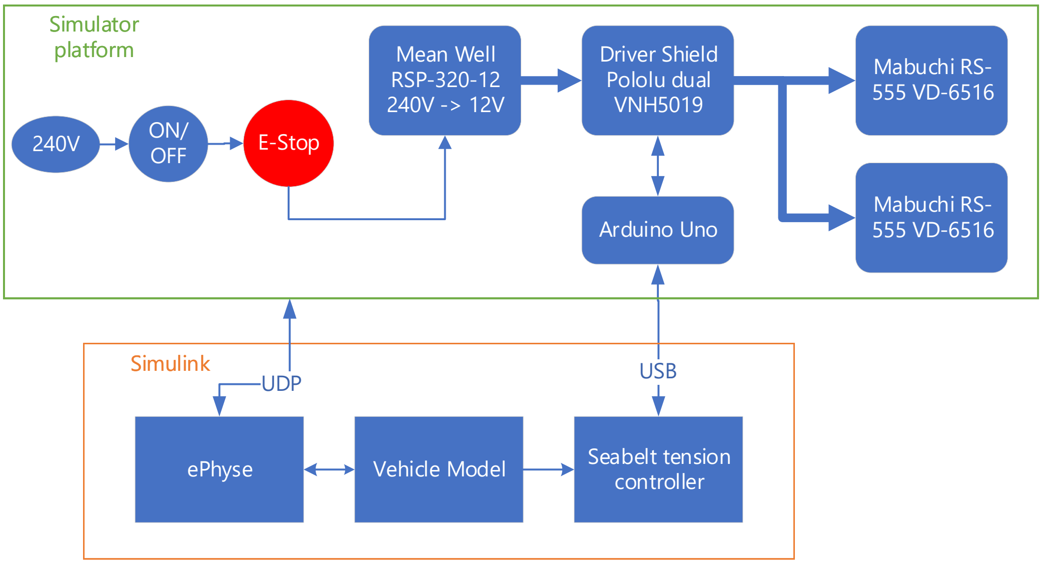


Figure 3.3: General overview of system design

3.6.1 Bill of material

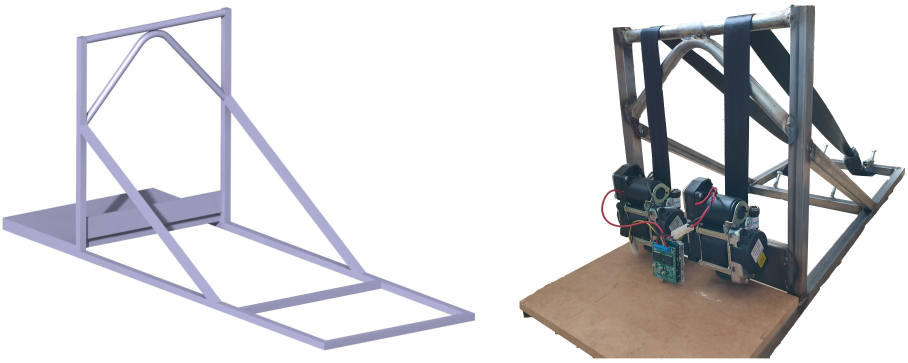
A final bill of material was created for the final concept in combination with the system design and can be viewed below in table 3.5. Once all the components in the system had been established, it was clear that the budget limitations were met and the parts were ordered.

Table 3.5: Bill of Material

POS	Item	Qty	Cost [SEK]
1	Arduino Uno	1x	279
2	Polulu Dual VNH5019	1x	638
3	Mean Well RSP-320-12	1x	750
4	Power switch	1x	258
5	Emergency power switch	1x	379
6	Heat glue	1x	60
7	Engine power cable	4 m	25
8	USB-cable	1x	399
9	Belt tension module	2x	-
10	Motor driver heat sinks	2x	-
11	Motor mounting bracket	2x	-
12	Power cable for power supply	1x	-
13	3D printed Arduino housing	1x	-
Total			**2863**

3.6.2 Test bench

In order to not occupy the CASTER simulator during for early stage testing, a test bench was designed using CATIA V5. The initial bench design is shown in figure 3.4a. The test bench was built using mainly 25x25 mm steel profiles, cut to dimensions using a metal cutting band saw and put together using a MIG welder. An image of the test bench is displayed in figure 3.4b. The test bench also made it easier to test the belt tension modules, since there was no need for a human operator to be seated. Instead a small scale was used to measure forces generated by the belt tensioner.



(a) Rendered image of test bench **(b)** Image of test bench

Figure 3.4: Test bench CAD model and prototype

3.6.3 Manufacturing

Mounting bracket

The final design was made in CATIA V5, a render of the mounting bracket is shown below in figure 3.5. Drawings of the mounting components were also made in CATIA. The final solution was manufactured in the mechanical engineering prototype workshop at Chalmers using a metal cutting band saw, a mill and a TIG welder. The product was then painted to resist corrosion and to give a nice finish, since it would be visible in the simulator. Images of the final product can be viewed below in figure 3.6a and 3.6b before and after being mounted on the simulator.

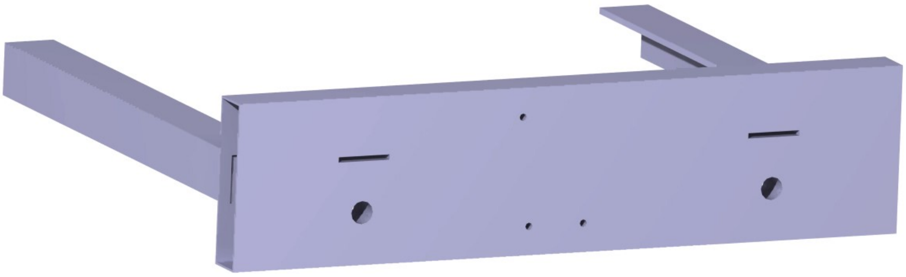
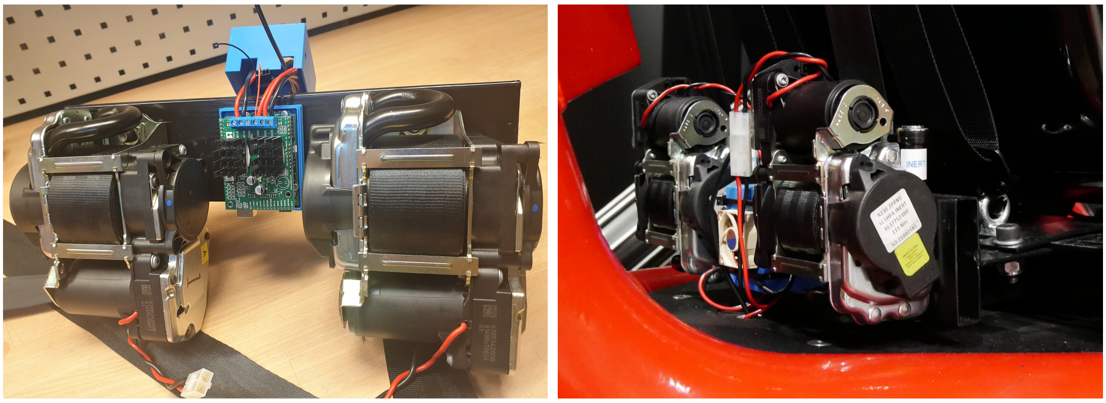


Figure 3.5: Render of mounting bracket



(a) Tensioner sub assembly (b) Tensioner assembly mounted

Figure 3.6: Tensioner assemly in progress and mounted in the simulator

Side panel

A new side panel was made for the gear lever housing on the simulator, this was done in order to be able to mount power switches to the belt tensioner that was easy to access, While it was still possible to revert to previous state since the original side panel was retained. An image of the side panel with the switches installed in the simulator can be viewed in figure 3.7.

Figure 3.7: Side panel with power switch and emergency stop

Arduino Casing

An encapsulation with a fan mount was created to mount the Arduino securely and protected while providing cooling for the motor driver MOSFETs. The case is based on a design by jimmyvargas [11], CC-BY 4.0 where some modifications has been done. The height was increased to accommodate the heat sinks on the shield, the hole on the side of the case was enlarged and stretched to allow the motor and power cables to connect to the driver shield. In figure 3.8 both designs can be seen, where the left case is the altered model with the necessary modifications.

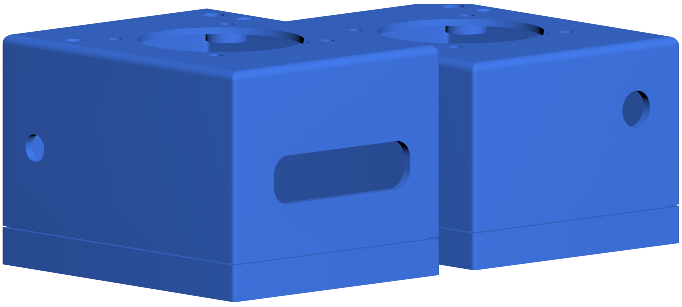


Figure 3.8: Housing design, modified on the left, original on the right

Power supply
To install the power supply, a custom piece of aluminum sheet metal was cut out and the edges were folded for increased stability. The sheet metal with the power supply was mounted inside the simulator platform according to figure 3.9.

Figure 3.9: Mounting of power supply

3.6.4 Installation procedure

To install the hardware into the simulator, some light modifications were made. A few holes were drilled to enable cable management and avoid exposed cables. The incoming power to the system was taken from a previously installed socket in the front of the simulator through a regular Schuko plug. The power was then connected through the switch and the emergency stop in the new side panel and then routed to the power supply in the rear of the platform. Cables from the power supply to the motor controller were routed through a hole in the back of the simulator that was located between the motor controller and the power supply. The cables were twisted to reduce electromagnetic radiation. A 15 m USB-cable were routed from the server rack containing the simulator computers through the simulator to the Arduino in the back of the platform. The mounting bracket along with the Arduino, motor controller and the belt tensioners were mounted behind the seat in the simulator using metal brackets and screws to clamp the piece to the seat fixation.

3.6.5 Programming

Careful consideration is key when developing a cueing system, the tension cue needs to be correctly timed and have an appropriate magnitude to avoid inducing simulator sickness as discussed by Cruden [5]. Minimizing the delay between the vehicle model reacting to brake input and the tension provided by the seat belts is crucial to ensure a good experience, but it also needs to match the cues from the motion platform.

The strategy employed here was to minimize code complexity on the Arduino side, since its computational capability and data bandwidth is limited, only information needed to control the motors are sent to the Arduino.

Arduino

The Arduino side of the project was straightforward, the requirements specified in table 3.4 needed to be implemented. Utilizing the code library by Pololu [12] made interfacing with the motor driver shield easy. However, the library can only handle integers for the speed request function, meaning that the precision is limited. The main task of the Arduino code were to read the requested motor speed from Simulink using a serial connection and sending back the sensed motor currents. Some considerations were needed to handle Simulink simulation termination, so that the motors are switched off and any processing loops that waits for Simulink data are exited and returned to the main program loop.

Simulink

With minimal data processing on the Arduino comes flexibility in Simulink, where rapid changes can be made and multiple models can be used with different goals. Which was beneficial in creating a method to characterize the motors, where the ability to use one Arduino program loop for everything gives Simulink full control over the motors.

Tension cueing algorithm

Panthera's Simulink interface provides information about the motion platform, such as position and rotation and its time derivatives. Combining this with data from the vehicle model allows for cancellation of the platforms movement cues from the cues calculated for the seat belt tensioners. This strategy can produce bad cues if there are large delays between vehicle model and motion platform, where the vehicle model responds quickly to input but the motion platform is slow to move. One plausible scenario is during braking where the vehicle model quickly achieves a quasi steady state, while the motion platform is still rotating to its steady state tilt angle. This behaviour can produce tension cues where the tension in the seat belt is immediately increased to a correct level. When the motion platform continues to rotate, a mismatch between the reduction of tension and the rotation causes the experienced seat belt tension to fluctuate.

Motor characterisation

Since the torque produced by an electric motor is closely linked with the current flowing through the motor, a lookup table to use feed forward control of the motor is a sound approach. Feed forward control in this fashion allows for a responsive and accurate control if the system is well known. The desired target value is used as an input to the lookup table and from there an appropriate driving signal is generated, a lookup table in this fashion is flexible and can use multiple inputs to generate one output. The motor characteristics were identified using the test bench described in section 3.6.2 and a stepped motor request with 10 second pulse followed by 10 seconds of rest. Stepping in this fashion allowed a reading to be done and the motor driver to cool down. 10 second high power pulses are not expected in normal usage, and should therefore not be a limiting factor. The request sent to the motor is a value between 0 and 400, where 0 is no power output and 400 is maximum power output.

Table 3.6: Belt tension vs motor request for motor 1 (M1) and motor 2 (M2)

Request [-]	M1 [kg]	M2 [kg]	**Request** [-]	M1 [kg]	M2 [kg]
10	0	0	90	3	3
20	0	0	100	3.75	3.5
30	0	0	110	4	4
40	0	0	120	4.5	4.5
50	1	1	130	5	5
60	1.5	1.5	140	5.5	5
70	2	2	150	6	5.5
80	2.5	2.5	160	6	-

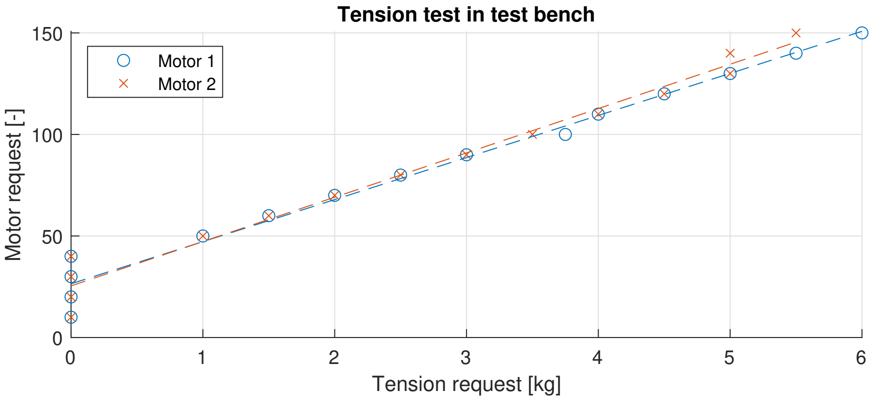


Figure 3.10: Test data and line fit of data points

The data recorded from the test in table 3.6 is plotted in figure 3.10, a linear behaviour is observed. An opportunity to save computational power is revealed. The regulator was simplified to use a line fit instead of a lookup table, removing the need for a search algorithm to find the correct parameters for linear interpolation. A loss in precision at low tension requests are expected since the line fit is poor in the range 0-1 kg as seen in figure 3.10.

The linear model used $u = P_1 * y + P_2$, where u is the motor request, y is the desired belt force and P_1, P_2 is the model parameters in table 3.7.

Table 3.7: Line fit constants

	P_1	P_2	R^2 Value
Motor 1	20.72	26.48	0.980
Motor 2	21.83	25.43	0.978

The parameters in table 3.7 were calculated using MATLAB 2019Bs polyfit function, the R^2 value is a measure of how well the model approximates the data set. An R^2 of 1 is optimal while a value of 0 indicates poor correlation between data and model.

3.6.6 Implementation

The Simulink implementation interfaces with the Arduino through a serial connection, where the Simulink sends two PWM values and the Arduino applies them to the motor controller. If no data is received from Simulink for 300 ms all tension is released until new data is received. This ensures that the motors are not stuck in an activated state in case of a software error or Simulink model termination.

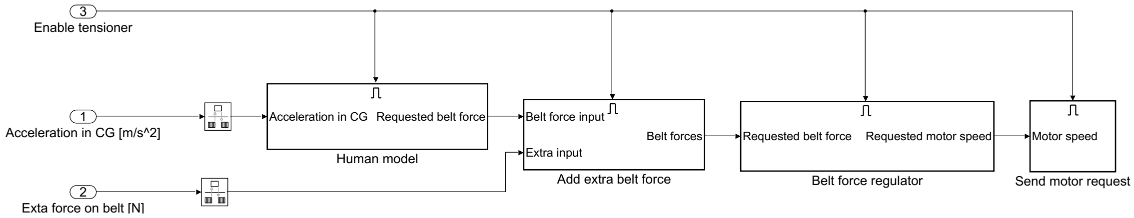


Figure 3.11: Tensioner Simulink model

Dimension reduction

The tensioning algorithm must reduce the dimension to two axis since the tensioner has two DOF, the final solution uses the vehicle body acceleration in a frame without gravity. This meant that a three axis input must be reduced to two axis, the model separates each axis to make calculations on them individually and sums up the contributions from each axis at a final step. The tuning process is described in section 3.7

The longitudinal acceleration was split in half and scaled with a constant value of 0.3125. Additionally a tension release algorithm is acting with longitudinal acceleration, which reduces the tension if there is a negative acceleration while the rate of deceleration is decreasing.

Lateral acceleration was scaled with a dead-zone at low lateral accelerations. This reduced the time to release of tension after cornering and getting out on a straight. Low lateral accelerations kept a low tension request which in turn kept the tensioners active. The dead-zone ends at a lateral acceleration of 1.8 m/s^2, the scale constant is 0 in the dead-zone and increases linearly to 0.1275 at 3.6 m/s^2

Vertical accelerations was scaled with a constant value of 0.1.

Tension controller

The tension controller takes two values as an input, these are forces in newtons per belt. The tension controller has a simple model of the belt tension module. An input of belt tension is calculated to a torque that the motor must produce. Three strategies were tested here, a linear model as presented in table 3.7, a lookup table as in table 3.6 and a PD controller. The linear model presents an issue at zero request, where it has a residual output, the lookup table removed that issue at the cost of performance. The PD controller acts on the proportional value of the request (P) and its rate of change (D), the PD controller was a bit nervous which might have been possible to alleviate with more tuning of the gain values.

Arduino communication

Communication with the Arduino was done using a serial connection, the two requested PWM values are reformatted and converted to int16 values and then converted to a packet of series uint8 values, or bytes. These are sent using an arbitrary header, the header denotes the start of a packet. The data is sent with Simulink's Serial Send block from the instrument control toolbox.

3.7 Controller tuning

A controller that provides a good experience has been carefully tuned with rigorous testing. The controller developed has been briefly described in sections 3.6.5 and 3.6.6.

Tuning the linear and nonlinear scale constants was done by subjective testing in the simulator. This provides direct feedback on changes made, which made it uncomplicated to find a good balance between feedback and strain on the motors. High tension request pushed high currents through the motors, causing heat build up in the motor windings due to the electrical resistance. The design of the motor housing has emphasis on durability and reliability with short duty-cycles, cooling was therefore not of a great concern. This application has higher duty-cycle which needs to be considered to protect the motors and their longevity. Higher tension levels was tested and thought to provide good feedback at the cost of excessive heat buildup. Lower tension levels was consequently settled on to prevent damage.

An issue identified during the tuning process was a tendency to hold the tension in situations that did not specify the high tension level. Testing identified that this occurred when the tension had been pulled high and then requested to be lowered. For example when braking and locking the brakes or cornering and then slightly weaving on the straight afterwards. The remedy of this has been discussed in section 3.6.6 under headline *Dimension reduction*, the requested tension is reduced to a small fraction of the original value. This reduction is triggered by a negative acceleration that is reducing i.e, negative acceleration and positive jerk. Reducing the tension with this strategy provided a better experience where the tension is released when the braking rate reduces, tests with zeroing the tension request instead of reducing it was performed. Zeroing instead of reducing produced a very jarring experience with the tension jumping from high to low to high quickly.

Residual tension after cornering was dealt with by employing a dead-zone in the lateral plane. Low lateral acceleration was filtered out and not sent as a request to the motor controller. This reduced the effect on straights when weaving from side to side, however this was not a scenario envisioned for the tensioner to provide useful feedback.

3.8 Method of verification

To test and verify the tensioning feedback from the belt, two tests were created and a test group of eight people conducted the tests. The first test was a braking scenario where the driver should accelerate to 160 km/h and then stop the car as quickly as possible by only using the brakes of the car. The test was performed three times with the tensioning device switched off and three times switched on. During the test procedure relevant data was recorded and stored for evaluation. The time it took to decelerate from 150 km/h to 20 km/h were calculated and used for comparison. The reason for not looking at 160 km/h to 0 km/h is to avoid disturbances in the data. Variations such as driver reaction time and how quickly the driver can achieve peak deceleration is thereby with this method. The test was performed on a simulated test track with a flat surface. After the drivers had performed the test a questionnaire was answered.

The second test was performed on a simulated race track where the drivers drove two laps around the circuit without the belt tensioner activated, followed by two laps with the belt tensioner activated. After a total of four laps were completed, a subjective assessment was done through a questionnaire. The purpose of this test was to evaluate the cornering sensation and overall driving experience with the belt tensioner.

3.8.1 Questionnaire for subjective assessment

For the braking test scenario, the questions in table 3.8 were answered using the rating guidelines in table 3.9. The assessment of the questions are subjective and the purpose of the questions were to find out how the drivers perceived their own change in behaviour when driving with or without the belt tensioner. Another question aimed to be answered was if the belt tensioner affected the braking performance of the drivers. This was done through a statistical analysis of the braking test data collected during the tests, where two groups were randomly divided into two subgroups, one control group and one tension group. The tension group had the tensioning system switched on for the second measurement while the control group had it switched off as in the baseline measurement for the second measurement. The test scenario used was a straight line braking maneuver with a vehicle model based on a BMW 320i from the E90 generation. Section 3.9 goes into more detail on the statistical method used.

Table 3.8: Questionnaire on driver brake maneuvers

Questions
1. Did the the tensioning device improve your confidence when braking
2. Did the the tensioning device give you more feedback from the vehicle
3. Did the the tensioning device let you be closer to max braking force
4. Did the tensioning device give a realistic experience
5. Did the tensioning device give an enjoyable experience
6. How much did the the tensioning device improve the simulator experience
7. How much did the the tensioning device worsen the simulator experience
8. Which braking scenario provided the best braking sensation

Table 3.9: Rating guidelines on driver brake maneuvers

Question	**Rating scale**	**Rating guidelines**
1.	1-10	1 - no, 2 - yes a little 6 - quite a lot, 10 - yes a lot
2.	1-10	1 - no, 2 - yes a little 6 - quite a lot, 10 - yes a lot
3.	1-10	1 - no, 2 - yes a little 6 - quite a lot, 10 - yes a lot
4.	1-10	1 - not at all, 2 - a bit realistic 6 - quite realistic, 10 - very realistic
5.	1-10	1 - not at all, 2 - a bit enjoyable 6 - quite enjoyable, 10 - very enjoyable
6.	1-10	1 - no, 2 - yes a little 6 - quite a lot, 10 - yes a lot
7.	1-10	1 - no, 2 - yes a little 6 - quite a lot, 10 - yes a lot
8.	with/without	with - scenario with tensioner without - scenario without tensioner

The project intends to answer the following questions, if applicable stretch goals are achieved

Applicable stretch goals were achieved, two tension modules was obtained and a two axis tension controller was developed and tuned. A track driving experience was thought out, with the aim to answer the questions raised as stretch goals. The track driving focused on the experience of lateral acceleration, the questionnaire in table 3.10 was answered by all drivers after the driving session. A rating guideline to help the drivers understand the rating scale is presented in table 3.11. The specific track driving setup is detailed in section 3.9.3.

Table 3.10: Questionnaire on lateral maneuvers and general simulator experience

Questions
1. Did the the tensioning device improve your confidence when cornering
2. Did the the tensioning device give you useful feedback from the vehicle
3. Did the tensioning device give a realistic experience
4. Did the the tensioning device give an enjoyable experience
5. How much did the the tensioning device improve the simulator experience
6. How much did the the tensioning device worsen the simulator experience
7. Which track driving scenario provided the best cornering sensation

Table 3.11: Rating guidelines on lateral maneuvers and general simulator experience

Question	**Rating scale**	**Rating guidelines**
1.	1-10	1 - no, 2 - yes a little 6 - quite a lot, 10 - yes a lot
2.	1-10	1 - no, 2 - yes a little 6 - quite a lot, 10 - yes a lot
3.	1-10	1 - not at all, 2 - a bit realistic 6 - quite realistic, 10 - very realistic
4.	1-10	1 - not at all, 2 - a bit enjoyable 6 - quite enjoyable, 10 - very enjoyable
5.	1-10	1 - no, 2 - yes a little 6 - quite a lot, 10 - yes a lot
6.	1-10	1 - no, 2 - yes a little 6 - quite a lot, 10 - yes a lot
7.	with/without	with - scenario with tensioner without - scenario without tensioner

3.9 Statistical method

The trial was open with no blinding, meaning that the drivers knew which group they belonged to. No blinding was chosen since the drivers could feel the effect of the tensioning system. Therefore the drivers were told if the tensioning system would be switched on for the second measurement.

Eligibility criteria to participate in the study ensure the validity and relevancy of the results, the study focused on high performance simulator driving. The test sample group consisted of drivers that had previous experience in driving the CASTER simulator. This had the benefit of making a more precise conclusion on if an experienced driver would benefit of the system. As a consequence it is not possible to say if the developed tensioning system benefit an inexperienced driver in the same way it affects an experienced simulator driver.

3.9.1 Endpoint selection and hypotheses

The following hypothesis are of interest and will be used to verify our question regarding the drivers braking performance:

$$\begin{cases} H_0 : \mu_C \leq \mu_T \\ H_1 : \mu_C * 0.9 > \mu_T \end{cases}$$

where μ_C, μ_T is each drivers mean change in braking time from the baseline measurement for the control and tension group respectively. The study procedure is described in detail in section 3.9.3.

This study uses an alpha value of 0.05, beta value of 0.2 to achieve statistical relevance in the study. Which means that a p-value of 0.05 or less is needed to reject the null hypotheses.

3.9.2 Sample size selection

Equation (2.1), used to estimate the required sample size, presented in the theory chapter requires prior knowledge since the desired change and estimated variance is unknown. Estimations based on earlier studies and desired effect can be used to approximate the unknowns. The desired change from baseline was given as a direct consequence of the set goal, a 10 % reduction in braking time. Variance was more difficult to estimate since it is dependent on driver skill and the vehicle capability.

Variance and mean estimation
A small pre-trial was held with the authors driving the vehicle to enable an accurate estimation of the variance expected to be seen. The pre-trial was preformed in accordance to the procedure in the main trial, the variance will therefore be relevant to the final test, the data recorded is shown in table 3.12. As seen here, a change from baseline of -0.287 seconds can be expected in the control group.

Table 3.12: Variance estimation prior to trial

Test	Change from baseline [s]
1	0.10
2	-0.19
3	-0.80
4	-0.26
5	0.18
6	-0.06
7	-0.26
8	-0.84

Estimated mean	-0.287 s
Estimated variance	0.141 [s^2]

Sample size estimation

The method of estimation presented in equation (2.1) was used to calculate the sample size needed to reject or accept the hypotheses that the braking time decreases with the tensioning system activated. The desired effect was set to 5% according to the hypotheses, the Z values were set to provide the trial with enough statistical power, $Z_\alpha = 1.96$, $Z_\beta = 0.8416$. The variance was estimated to 0.141 as shown in table 3.12, where $\mu_C - \mu_T$ is the desired effect of 1000 basis points in the primary objective.

Using the expected standard deviation of $\sigma = 0.3755$ in change from baseline as estimated from limited quantity pre-trial data, desired effect $\mu_C - \mu_T = 0.2603$ and the significance level and power discussed above:

$$n = 2 * (0.3755^2 \frac{(1.96 + 1.282)^2}{0.2603^2}) = 33 \tag{3.2}$$

When correcting for 15 % bad data in both arms the total sample size is calculated as follows:

$$n_{corrected} = (\frac{n * 2}{0.85}) = 76 \tag{3.3}$$

This implies that the study would need to use a sample size of around 80 test drivers while allowing for 15 % bad data points. Due to the scope of this project, restrictions and limitations such as time constraints, it was not possible to include 80 drivers in the study. The time frame available was not long enough to admit that amount of test subjects to the study due to the pandemic restrictions in place during the study period. Due to the low number of drivers included in the study, no statistically significant conclusions could therefore be drawn, and any results must be considered as incomplete. The test was still carried out with a small sample size to obtain the subjective assessments and find some tendencies that could improve the method for future work.

3.9.3 Study procedure

Each driver was subject to the same study procedure, visualized in figure 3.13, where the baseline measurements were done without the seat belt tensioners. One brake maneuver is performed as follows;

- Accelerate up to 160 Km/h
- Come to a complete stop as quickly as possible by only applying the brakes
- Measure time to brake from 150 Km/h to 20 Km/h

This measurement method minimizes influencing factors such as driver reaction time and the vehicle transient behaviour. This subsequently isolates the measured variance to the drivers ability to maintain peak deceleration.

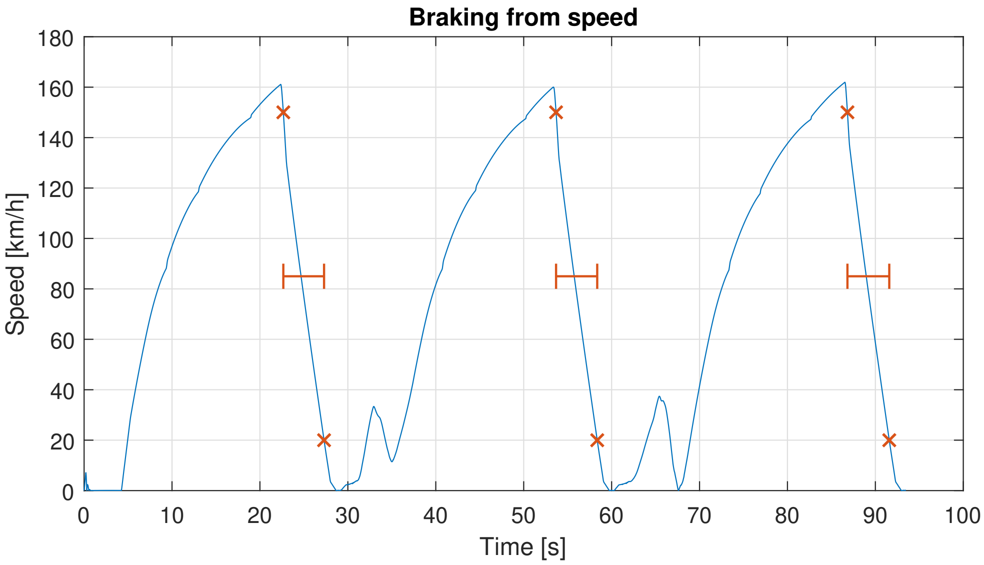


Figure 3.12: Velocity trace of one driver in the braking test

Figure 3.12 visualizes a speed trace for one test run, the crosses marks the start and end of one braking event and the bar marks the time span between that was measured.
After driving the baseline setup successfully 3 times, the tensioning system is enabled for the test group and left switched off for the control group. The same braking maneuvers are performed again upon which the drivers are to make a subjective evaluation according to the questionnaire described in section 3.8.1.

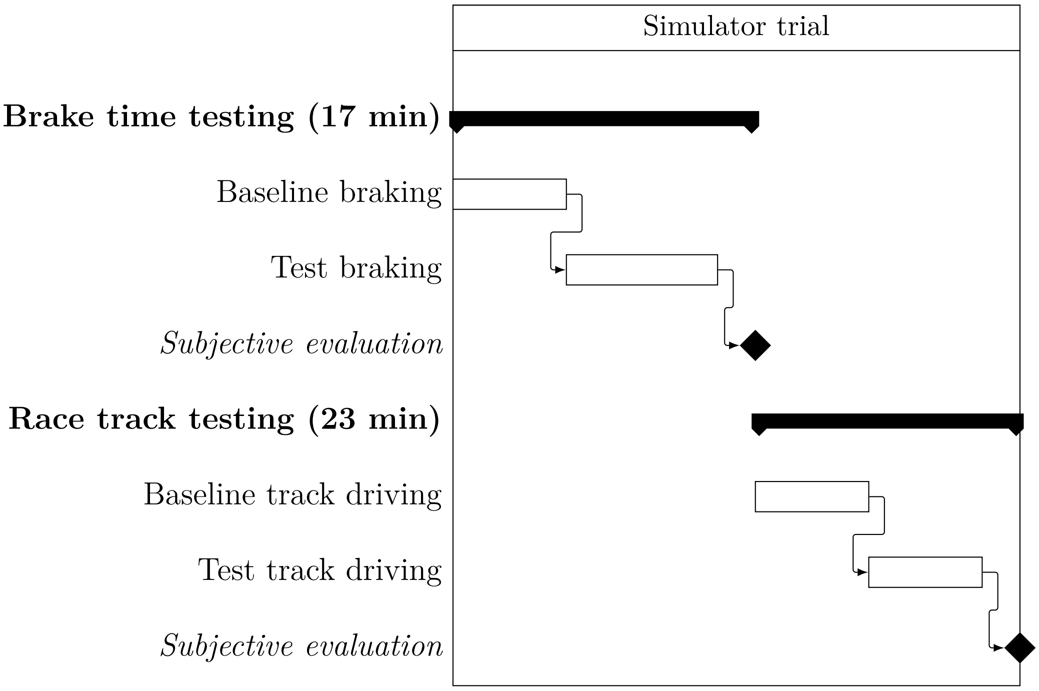


Figure 3.13: Simulator study procedure

The lateral part of the test was performed immediately after the subjective questionnaire had been answered. The track is well known to the drivers, where the driver first drives the vehicle without the tensioning device for two laps, and then enabling it and letting them drive another two laps. All drivers had the tensioners active during the track driving, in contrast to the braking maneuvers where half of the drivers had the tensioner disabled. No statistical test has been developed for the track driving since the variability is very high with many confounding variables. No test have been identified that can isolate the variability in lap times and provide good statistical power with a reasonable sample size. All drivers instead answered the second part of the questionnaire after driving baseline and test runs.

4

Results

4.1 Tensioner hardware

All hardware installed and mounted have a finished look and feel and is perceived as an integrated solution. The mounting is solid and no movement or otherwise unwanted behaviours have been identified. Issues observed in the test bench related to high peak load disappeared when mounting heat sinks on the driver chips. The extra thermal capacity and cooling eliminated issues with the driver entering thermal protection mode.

4.2 System performance

The overall system performance is stable and feels responsive, with the exception of some visual stutters during cornering when the tensioning device is active. Stutters appear when the rendered view moves between an approximated position and the vehicle model's actual position. The reason for this performance issue is Simulink's way of sending data through a serial port in combination with the graphics engine way of handling a vehicle model running slower than real time. Apart from that, no other system performance issues has been identified. The electric motors in the belt tensioners got quite warm during extensive testing, this has not resulted in any change of performance of the system and is therefore not regarded as a problem. The heating of the motors was not a performance issue in our testing and has not affected the results obtained during the tests.

4.3 Driver performance evaluation

The drivers objective performance is analysed and presented, acceleration traces of a driver's braking performance can be seen in figure 4.1, where the two colors represent braking with and without the tensioner activated.
Keep in mind that the reliability and significance of the study has its limitations due to the low sample size of 8 in relation to the required one of around 80, according to section 3.9.

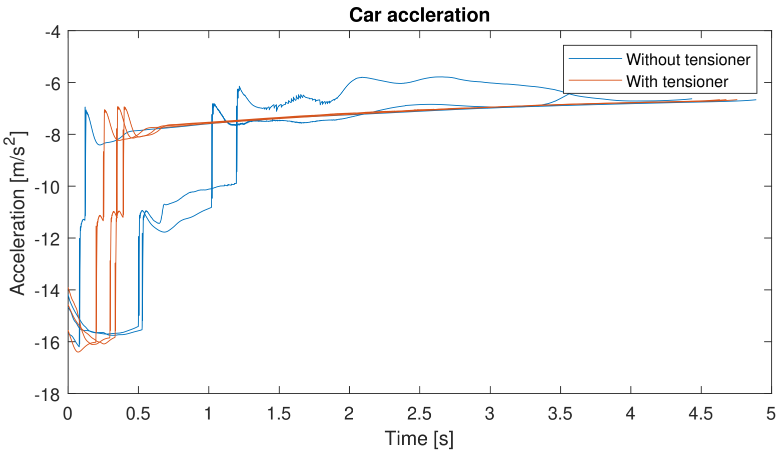


Figure 4.1: Acceleration trace of one driver in the braking test

4.3.1 Test data

The test data recorded is presented in table 4.1, where the group column tells which arm of the study that the subject is part of. Where C indicates that the subject is part of the control group while a T indicates the test group as constructed in section 3.9.3.

Table 4.1: Braking performance per subject

Subject	Group	Baseline [s]	Test [s]	Change from baseline [s]
A	T	3.8447	3.8557	0.0110
B	T	6.6058	5.9333	-0.6723
C	T	3.5020	5.1403	1.6383
D	T	4.9023	4.9900	0.0877
E	C	4.8227	3.2080	-1.6147
F	C	4.9813	4.9327	-0.0487
G	C	3.2533	3.7873	0.5340
H	C	4.9463	4.9487	0.0023

Table 4.2: Metrics for each subject group

Average change from baseline control group	-0.2817 [s]
Average change from baseline tension group	0.2662 [s]
Variance in control group	0.8590 [s^2]
Variance in tension group	0.9535 [s^2]
ANOVA p-value	0.4468 [-]

The probability that these two have the same mean is 0.4468 by comparison using a one way ANOVA test. This means that the null hypotheses cannot be rejected since the trial had a rejection level of 0.05 as stated in section 3.9. The study can therefore not say that the mean value of the two groups are statistically different from each other. Figure 4.2 visualizes the small quantity of sampled data.

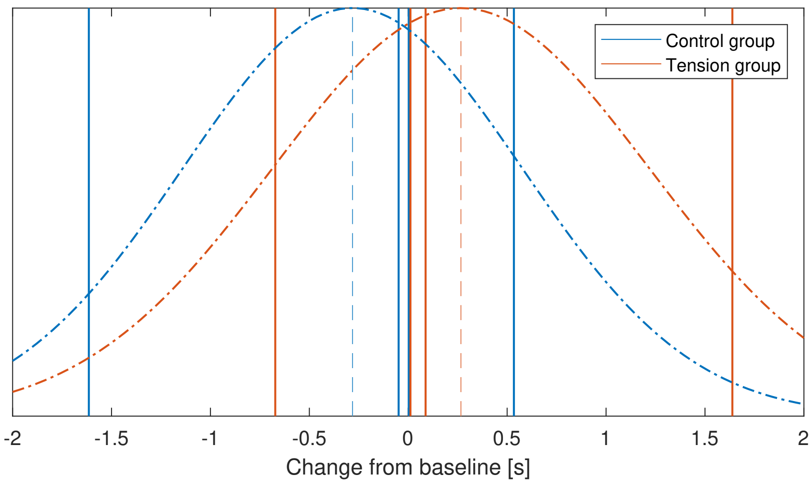


Figure 4.2: Change from baseline visualised based on the small sample size

4.4 Driver experience and subjective assessment

The results from the subjective assessment were very positive, all of the test subjects preferred to drive the simulator with the belt tensioner active rather than deactivated, this was true for both the braking test scenario and the track driving. The mean values from the braking test forms can be viewed below in figure 4.3 and the mean values from the track driving forms can be viewed in figure 4.4, All of the individual answers can be viewed in appendix A. There were no comments on the belt tensioner being jerky during the tests, as opposed to what was identified during the initial testing and tuning process.

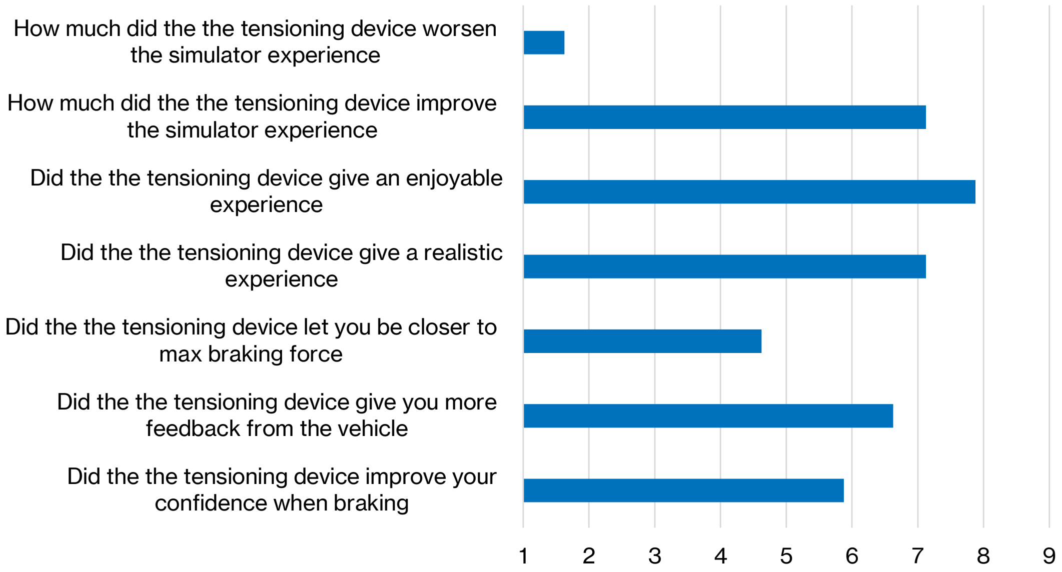


Figure 4.3: Mean results from braking test forms

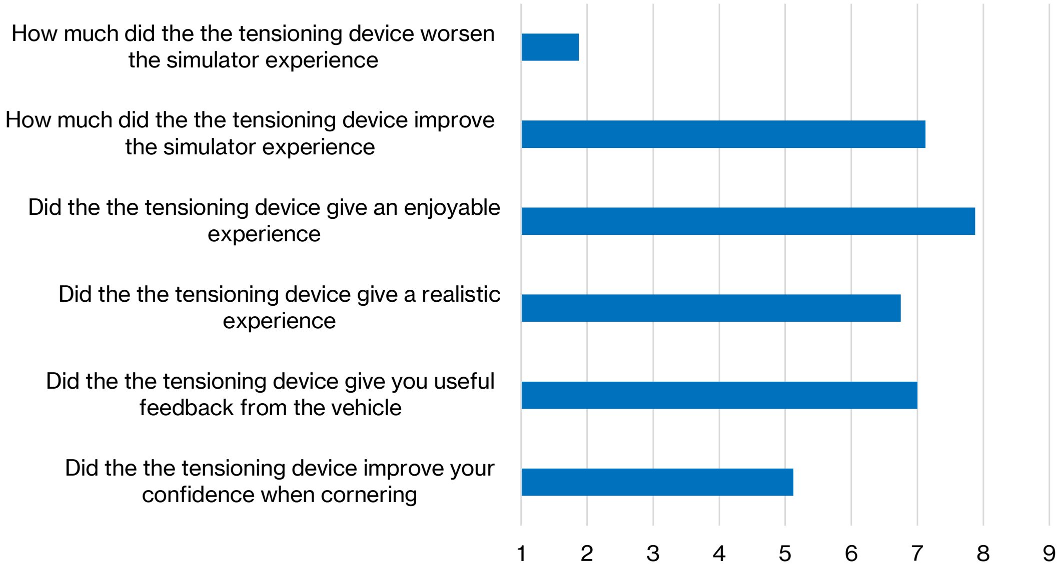


Figure 4.4: Mean results from track driving test forms

5

Discussion

5.1 Assessment and verification

This section summarises the results from the initial tension test with the four point seat belt, results from the objective braking performance test and the subjective questionnaire.

5.1.1 Initial belt tension test

The user test conducted to determine the required tension force of the belt was performed using several dynamometers in parallel, due to the limited range of the dynamometers. This affected the precision of the tests since the dynamometers had to be pulled simultaneously and read individually.

5.1.2 Braking test

One of the test subject did not feel much effect from the belt tensioning device during the braking test, compared to when the tensioning device was off. This might have been due to over-tightening of the shoulder belts so that the required tightening force to increase the pressure on the shoulders was larger than the tensioning device could deliver. Since all of the other participants felt a clear and distinct difference between driving with or without the tensioner, this deviation was not further investigated.

As seen in table 4.2 and figure 4.2, drivers found it difficult to improve their braking performance. The same trend can be seen in both the control and tension group, which tells us that the braking task by it self is so difficult that the benefit of a belt tensioner is negligible to the test subjects in this study. There is a potential to improve the braking performance, which can be seen in figure 4.1, where there is a clear difference between the run with and without the tensioner activated.

All but one participant stated that they could be closer to maximum braking force when the belt tensioner was active, compared to when it was inactive. The results are interesting since the measured stop times did not correlate to the drivers perceived improvement due to the belt tensioner. This further emphasizes the complexity of a driving simulator, that the driver experience things differently based on additional input, when there in fact is no obvious difference in braking performance.

5.1.3 Track driving

A comment that came up during the circuit driving from one of the test subjects, was that the wrong belt was being tightened during cornering. The test subject meant that the inner belt was supposed to be tightened, instead of the belt on the outside of the turn. This method would simulate the belt force on the torso when pushed outwards during high speed cornering. The reason why the belt is tightening the opposite side is to increase the sensation of being dragged to the outside of the corner, since the simulator platform is limited in its movements. Whether this approach is correct or not is hard to determine, but it should also be taken into consideration that only one of the test subjects had this type of comment.

During the cornering tests, some performance issues of the Simulink model was experienced. This resulted in stutters during cornering when the tensioning device was activated in the Simulink model, the simulation ran smoothly when it was disabled. This might have had an impact on the general experience when comparing the two test scenarios with each other.

As mentioned in the results, no comment on jerky behaviour from the seat belt tensioner was given. This might be something that only is discovered after driving a certain amount of time with the belt tensioner activated, since there is a lot of new sensory cues from the tensioner to take in.

5.1.4 Statistical method

The change from baseline in the control group was believed to be small since one admission criteria for being a participant is to be an experienced simulator driver, therefore the training from braking in the baseline measurement is minimal. This turned out to not be as expected, drivers found it difficult to achieve and maintain peak acceleration as seen in figure 4.1, and some completely locked the front wheels throughout the test as in figure 6.1. Low statistical power comes as a consequence of the low participant number, all conclusions drawn must have this in mind. Though the alternative hypotheses cannot be rejected, figure 4.2 clearly shows that the two groups behaved differently. More testing is therefore required to establish with statistical significance whether or not there is a difference in the average braking time.

In hindsight, the study procedure could have been changed to lower the variability in the data. This might have been possible to do by increasing the number of practice runs and also increasing the number of samples each driver makes for their average. The driver would practice until their variability in braking time is stable, upon which the tensioner is switched on to see if a change can be observed.

5.2 Tensioner hardware implementation

Physical implementation

The shoulder straps were put through the dedicated holes on the seat to route the belts to the back and down to the tensioners, where they were connected. A potential issue regarding friction was spotted where the shoulder straps had a lot of surface contact towards the belt guides in the seat. This was never further investigated and it is possible that the friction had negative influence on the tensioning performance. It was also discovered that the contact surface of the belt varied depending on the drivers length, a taller driver resulted in less contact surface between the belt and the seat, this might have benefit the tensioners when it comes to maximizing the tensioning force. Mounting a metal cylinder of some sort with less friction for the belt to slide on instead of the seat might have been a viable solution to this potential issue.

The electric motors in the belt tensioner became quite warm during the testing procedures, this might become a problem for future applications if they are more demanding compared to the current application and should be taken into consideration.

Communication

Switching to Ethernet based communication could improve system performance if the Simulink implementation is better. However, pin remapping would be required to accommodate both an Ethernet shield and the Polulu motor controller.

5.3 Tension controller software

Tuning

During the tuning process it was also tested to run the simulator without motion enabled on the platform, to isolate the influence of the belt tensioner without any disturbances. It was discovered that the belt tensioner gave a good simulator experience even without the motion platform. This creates an opportunity to improve stationary vehicle simulators without any large investment.

6

Conclusion

6.1 Design and development

The design phase, which was based on the established prerequisites resulted in a successful hardware solution. This hardware was accompanied by software developed in accordance with the established requirements for integration with the simulator's software.

6.1.1 Hardware

The hardware mounted in the simulator performed as expected, the belt tensioners satisfied the rise time prerequisites and are also suitable for further use and development. Upgrades are required if increased tightening capacity is desired for applications outside of this project's scope. Both the power supply and motor controller needs to be upgraded to provide an increased tightening force. A protective shield to cover the belt tensioners could increase the lifespan as it would be harder to damage the components by mistake. The mounting rigidity of the belt tensioners are sturdy and does not flex during use.

6.1.2 Software

Tuning the controller proved more difficult than expected, two main factors contributed to the troubles faced. First one was the unanticipated difficulty to release tension, the control strategy would have been different from the outset if this had been identified at an earlier stage. The second factor was the lack of current feedback from the motor controller. System control options are limited without feedback from the system, no closed loop design is possible without it.

The performance hit from the feedback was not identified since the early testing was done on a more modern PC than the one running the vehicle model and tension controller in the simulator.

If the issues faced had been anticipated, an alternative PD controller would have been pursued. The PD controller might have mitigated the tension release issue more gracefully than the solution found in the final controller. A PD controller does not explicitly need feedback in contrast with an PI controller which was the intended solution from the start of the controller development.

6.2 System performance and evaluation

With limited the time for testing, objective conclusions must consider the low number of data points. The subjective assessment was generally positive.

6.2.1 Statistical study

Due to constraints and availability of the simulator our statistical study have low statistical power and fails to reject the alternative hypotheses. The required sample size of at least 80 participants is several times greater than the eight that participated. This is unfortunate, as the driver learning factor cannot be differentiated from the effect of the tensioner. How large effect each factor has on the braking time remain uncertain.

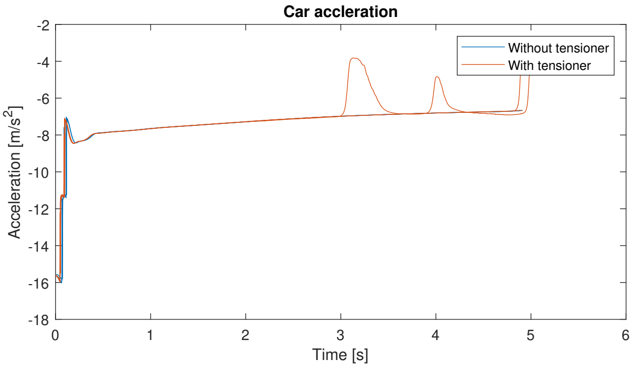


Figure 6.1: Example of driver without any improvement between the tests

The study performed in this report can be seen as what an average driver can expect to experience when having the tensioner switched on. The driver cannot reliably perform at peak performance and the tensioner is therefore unable to contribute to a better braking performance individually. As seen in figure 6.1, the acceleration curve is identical whether or not the tensioner is active. The two traces follows the same trajectory which we suspect is what is produced when fully locking the wheels and skidding to a complete stop.

6.2.2 Subjective assessment

By looking at the results from the braking test forms and the track driving test forms it can be concluded that the tensioning device provides a positive experience and is appreciated by the test subjects. Since every single test subject answered that they preferred to drive with the belt tensioner than without, it is safe to say that it is an improvement to the driving simulator and improves the sensation of braking and cornering.
The tensioner and its controller installed might not enhance the performance of an average driver, but it might be able to increase immersion and enjoyment. Lowering simulator sickness by reducing the false cues generated by the motion platform might be possible if the motion cueing is altered to account for the fact that there is a belt tensioner installed.

7

Future Work

In order to statistically verify the effect of the seat belt tensioner during braking scenarios, more tests with more test subjects needs to be conducted. Alternative test designs should be considered to better analyze braking performance. An idea would be to look at the wheel slip, for example by defining braking performance as a function of wheel slip.

It would be interesting to conduct a study in order to evaluate which side the tensioning during cornering should apply, perhaps a user study on this could be done. A user study on driver length would also be interesting to perform, in order to determine if a modification to the seats belt loops would be necessary to maintain a constant behaviour of the tensioners, regardless the length of the drivers.

A protective encapsulation to cover the tensioners on the back of the simulator might be of interest to increase lifespan and the aesthetics of the tensioner unit. Reducing the number of exposed parts and tying all together to a well developed and finished product concept.

7.1 Hardware improvements

An improvement that could be quite beneficial would be to add a roller behind the seat upon which the belt can run. The roller would be placed at a height not too far off the height of the holes in the seat. This addition would change how the force is perceived by the driver as the belt tensions to the rear instead of downwards. The changed belt path could reduce the friction between the belt and the seat and thereby increase the belt tension with the same power usage.

7.2 Tension controller

An alternative strategy not evaluated in this project would be to use a PD controller to control the tension in the seat belt. This strategy would have the advantage of being a bit more responsive and might eventually solve the problems observed when releasing the tension in the belt. Principally you could think of having the P term handling the holding torque, while the D term makes sure the tension achieves the desired level of tension. There is also room for improvement in the current tension controller, however to start over with a more advanced controller would potentially provide a higher performance cap and is therefore recommended.

An interesting area to explore is the possibility to reduce the false cues of the platform and instead use the seat belt tensioner to simulate forces occurring during braking and cornering. It would be interesting to see if a more realistic experience could be created and if it also could lead to a decrease in simulator sickness.
The stretch goal formulation states that an attention grabbing pulse should be developed, this was partially omitted from the project as focus was placed on the controller tuning and analysis process. The groundwork for integrating a pulse has been developed, the pulse generator can be connected to the *Extra force on belt [N]* port in the Simulink model, figure 3.11. This attention pulse can be used to evaluate ADAS systems and driver alertness active safety applications.

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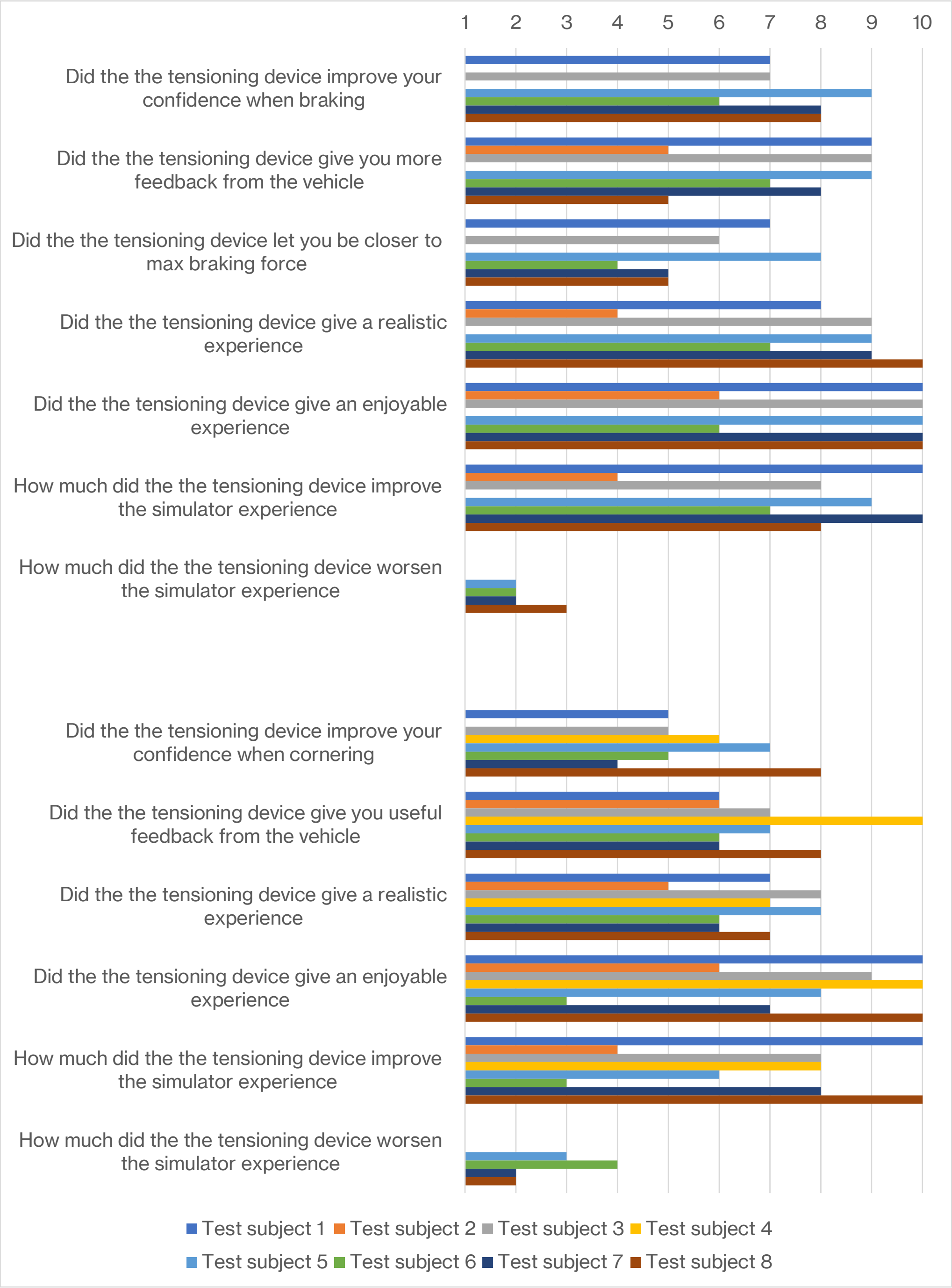
A

Subjective assessment results



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