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Digital Twin for Anti-lock Braking System in Virtual Reality

Master's thesis

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Tallinn 2021

Author's declaration of originality

I confirm that I am the sole author of this thesis. The materials of other works that are used here are referenced. The work has not been submitted elsewhere and has not been presented for examination.

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05.05.2021

Abstract

Anti-Lock Braking system is a system that monitors and controls wheels while slipping or during braking of vehicle. It helps to improve stopping distance and provide an additional control on vehicles. Digital twin is a digital copy of a desired object that behaves as a real object and it is modelled on a computer (in case of this study, in Unreal Engine software). Virtual Reality is an environment that simulates another experience on personal computers. It is supposed to be a different representation of the world and it could be used for different purposes (for example, simulations that are similar to real world conditions). This work discusses the potential use of Anti-Lock Braking system as a digital twin using virtual reality. This field of study is not well investigated and needs more attention. The possibility to interact with the virtual world and affect the real environment creates new interesting challenges that look inspiring. Anti-Lock Braking system is not an exception. This thesis will show what is done so far in the mentioned field and what steps could be made in order to create such virtual environment using digital twin of Anti-Lock Braking system, Virtual Reality, and physical Anti-Lock Braking system itself. In the end, reader will understand the main concept of digital twin of Anti-Lock Braking system in Virtual Reality application in Unreal Engine 4 environment. Overall, there are achievements. Matlab model was created and it interacts with Unreal Engine using UDP protocol. A digital copy of Anti-Lock Braking system was created in Unreal Engine 4 and it moves almost synchronously with real Anti-Lock Braking system. At last, characteristics of digital twin of ABS were applied to wheels on a virtual car.

The VR-based application is developed by a team of 2 students. However, the progress is divided into 2 parts. One of them is dealing with hardware-in-the-loop, another – simulation only in UE4. This thesis describes the second side of the project: simulation only in UE4. The project was forked, so it is not the same, but it has similarities with another one that is used by another student. The contributions in this case are a little bit different.

Thesis is completed in English and it contains 53 pages, 5 chapters, 3 tables, and 30 figures.

List of abbreviations and terms

VR	Virtual Reality
ABS	Anti-lock Braking System
UDP	User Datagram Protocol
UE4	Unreal Engine 4
ECU	Electronic Control Unit
PID	Proportional-Integral-Derivative
3D	3-Dimensional
LED	Light-Emitting Diode
IR	Infra-red
RAM	Random Access Memory
CPU	Central Processor Unit
GPU	Graphics Processing Unit
USB	Universal Serial Bus
PC	Personal Computer
RPM	Rotations Per Minute
FPS	Frame Per Second
HDMI	High Definition Multimedia Interface

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1 Introduction

Anti-lock braking system (ABS) is designed for controlling and monitoring wheel slip when a vehicle starts braking. It is an electronic vehicle safety system that helps to improve stopping distance. As brakes are applied to the car, the wheel speed begins to decrease. A decrease in vehicle speed does not necessarily lead to a decrease in wheel velocity. The non-correspondence between the speed of a wheel and the speed of the vehicle is called slip. Its magnitude is represented in formula (1).

$$\lambda = \frac{V_x - R \cdot \omega}{V_x} \cdot 100 \quad (1)$$

Where,

V_x – Vehicle Speed

R – Radius of wheel

ω – Angular speed of wheel

For the development, ABS from Inteco is used. It is not perfect in terms of hardware and calibrations, but it is considered to be a good object for the beginning. Worth to mention that it was used before by other researchers. Therefore, the obtained results from the model could be not satisfactory in terms of efficiency.

The topic of digital twin is not new, but interesting in many perspectives. It is important concept in various industries. Generally, digital twin is a digital representation of a physical object. It could simulate the same functionality as the real object. However, there are needs to display real actions of the real object or, even, control it through digital twin. Usually, sensors are used in order to have a communication between digital twin and object. Additionally, digital twin could be a separate instance with its own characteristics. However, the final goal in the current investigation to achieve is to make it similar or, ideally, the same as a real object that could work independently. In summary, digital twin can be described as a physical asset's virtual representation that could be accessed through simulators and data for real-time prediction, controlling, optimization, improved decision making, and monitoring [2].

ABS from Inteco is going to be used for creating a digital twin. At the end, it should be the same or similar to the real object in terms of characteristics and functionality.

Usually, Virtual Reality (VR) is defined in terms of technological hardware that generates the dimensions of experience in an interactive or para-reality environment that provides various degrees of vividness and interactivity. VR headset wearers use either tethered or wireless controls with built-in sensors to track hand movements in order to generate input for simulation. For HTC Vive-like devices (e.g., Sony PlayStation VR, Oculus Rift, and Oculus Touch), wearers keep two controllers and use VR simulation keys, thumbsticks, and triggers to register actions. Wearers are also able to see their hands through the headset on the show [3].

In case of this thesis, the final goal is creating a virtual environment where a user can test ABS and see how it works in basic and advanced terms. Unreal Engine, driving steering wheel Logitech G29, and Oculus VR headset are used in order to create a virtual environment. The final goal is to create a simulation in Unreal Engine with a car that have simulated ABS on its wheels. This final simulation should be controlled using Logitech G29 and/or Oculus Rift VR headset.

1.1 Literature review

In this section, the literature (mainly from IEEE Xplore and ResearchGate) is reviewed from the point of usefulness. There are many conference papers found, however they are not considered as solid sources. Some of them can be considered as ways for the further development, but they are not robust. However, some of the conference papers are listed here since they are closely related to the current topic.

When it comes to the definitions of digital twin and virtual reality domains, they are excellently described in [2] and [3] respectively. These sources are used for the explanation in Section 1. Also virtual reality domain is explained in [14] in very detailed manner. These sources could be a good starting point if there is a need to understand the essence of the topic fully.

In general, there were little researches in the study field related to digital twin of ABS. There was a good attempt to push forward a topic related to efficiency of ABS and a there was a proposal to use a simulation test and virtual reality technology in order to improve it [4]. This is closely related to the topic of the investigated research. It is not fairly new (2012), but its results could be useful for further developments. For instance, there are some interesting and useful results that could be used in the development. The connection between virtual environment and physical mode was described in a good manner including mathematical formulas. However, LabVIEW was used here as a communication channel between physical and virtual environment. This work is great to use in further development since it follows almost the same goal: creating a safe environment for learning ABS. But the “virtual reality” is presented here as 3D application which makes the reading of the article a little bit confusing from the modern point of view. Considering the usefulness of the article in the current stage, it is valuable source for developing hardware-in-the-loop applications. However, the scope of the thesis is the simulation part of ABS and the source was valuable at the beginning of the development.

It would be weird, but it is the only document that can be found regarding developing ABS on virtual reality domain. Next sources describe mathematical models of controllers which are, actually, pretty good when it comes to developing simulation of ABS in UE4.

One more research that came at the same year as previous article describes how to make a fuzzy control on Matlab which is considered as a main instrument for communication with ABS directly [5]. This document concludes that fuzzy control is worth to be further developed. It could be considered as an additional brunch for further developments in the research, but, since it is a conference paper, it is not considered as a solid source. It proposes methods that could be efficient and reduce braking distance additionally comparing to basic controllers.

When it comes to control strategy of ABS, there is an article that is worth for mentioning. It proposes to use control method for single wheel that is based on Lyapunov stability theory [6]. The method is supposed to be used for maximizing tire-road friction and minimizing yaw moment of a commercial vehicle. Comparing to the previous source, it proposes an efficient controller, and it has detailed mathematical model for it. The mathematical model in this is computed using Matlab environment. This mechatronics' article from journal could be a robust source for upgrading the current project in UE4 simulation. It is worth to emphasize that it is applicable on one wheel, but later the model could be applied on other wheels too. Since this article describes control strategy for commercial vehicles, it is absolutely gold.

However, the scope of this project is to apply ABS on all the wheels. There is a very good source related to it. It discusses the use of ABS on each wheel separately and how effective PID controller can be applied [18]. The theory is based on wheel slip control and it is explained using Matlab environment. It would be a great source for applying controllers in UE4 in the future. This is relatively fresh source from 2020 and its results are satisfactory. This source can be used in order to proceed with the current topic.

Unfortunately, there were no researches about digital twin of ABS and connection of ABS with virtual reality headsets. In addition, the attempts to implement ABS on UE4 were not found. All the developments in the thesis are based on the findings from each document in the references list and on the developments from other students.

1.2 ABS overview

This section provides an overview of ABS and its existing models that are kindly provided by Inteco. It describes the system itself and its limitations. Mathematical models are not fully described in the thesis and full reference can be found here [13].

1.2.1 Description

Usually, the ABS system is composed of subsystems:

- Wheel Speed Sensor
- Electronic Control Unit (ECU)
- Hydraulic Pressure Modulator

Other inputs such as roll angle sensor, gyroscope sensors, acceleration sensors are used in the advanced ABS system to realize advanced features such as HSA (Hill start assist), Curve traction control, cornering ABS, lateral stability control, etc [1].

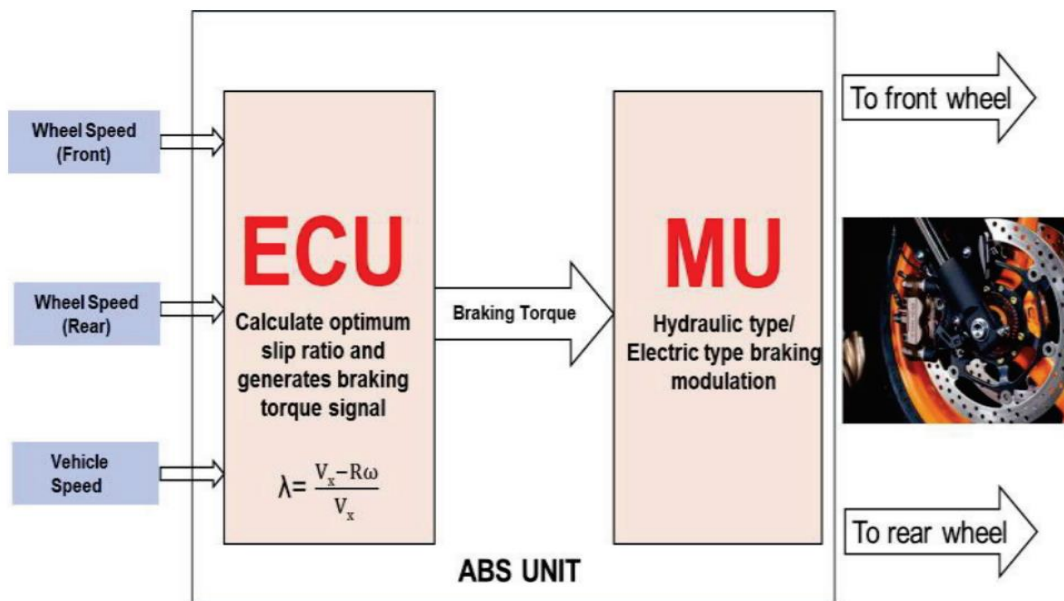


Figure 1. ABS system components

Wheel Speed Sensor: In the case of two ABS channels two wheel sensors are used, i.e. the front wheel and the rear wheel. This wheel sensor continuously tracks the speed of the wheel and senses the rapid deceleration of the vehicle. These sensors are mounted near a spinning disk or, in some situations, toothed rings are used for electromagnetic or Hall-effect pulse pickups and are mounted directly on the rotating components of the wheel hubs. In certain ABS cases, the speed of the vehicle is determined from the speed

of the wheel using an estimation algorithm such as Kaman's filtering, observer design, etc [1].

Electronic control unit (ECU): It is clear from Figure 1 that the performance of the wheel speed sensors is supplied as an input to the ECU, which then calculates the slip ratio and produces an optimum braking torque to prevent the wheel from being locked. Operations such as slip comparison and velocity estimation are carried out in ECU. The output signal produced is given to the hydraulic pressure modulator [1].

Hydraulic Pressure modulator: Hydraulic Pressure Modulator is an electrohydraulic pressure modulation system, i.e. minimizing, retaining and building pressure. It consists of electromagnetic solenoid valves, pump motor, pressure sensors and accumulators. The ECU output signal actuates the solenoid valves and the engine to achieve intended resistance while the pressure sensor measures the pressure within the calipers [1].

The above is a general description of ABS. Inteco ABS is used and the main characteristics and features listed below [13].

Key features:

- Double-wheel laboratory model of ABS equipped with powerful flat DC motor;
- Two high-resolution measuring encoders;
- Full integration with MATLAB® / Simulink®. Operation in real-time in Windows® XP/W7 32bit;
- Complete model of the car-road relations;
- Library of pre-programmed braking control algorithms familiarize the user with ABS technique in a fast way;
- Rapid prototyping of real-time control algorithms. No C-code programming;
- Ideal illustration of nonlinear control algorithms.

Key benefits:

- Enables to provide laboratory tests of the antilock braking system in the car velocity range from 0 to 50 km/h;
- Accelerates implementation of new slip control algorithms;
- Demonstrates the slip control under different road conditions.

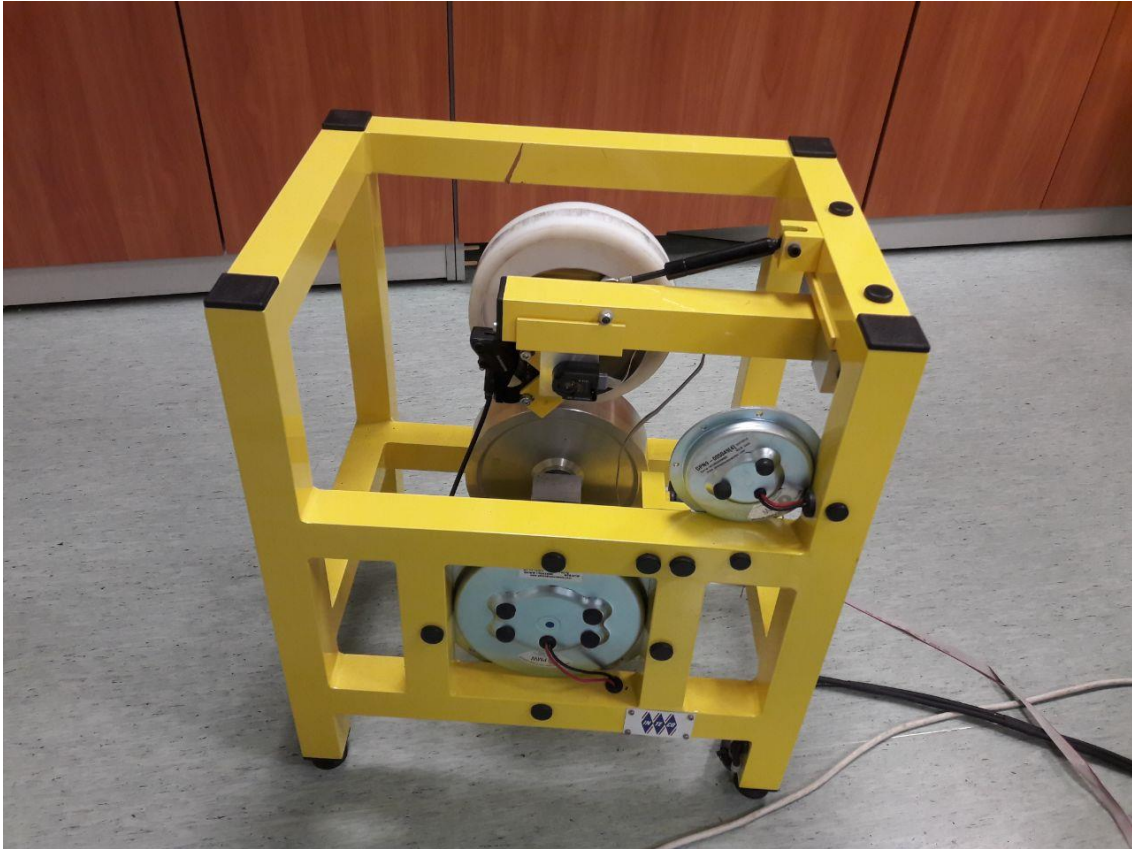


Figure 2. Inteco ABS

1.2.2 Physical model

Physical model of ABS consists of two wheels. Upper one, which is made of plastic, represents car wheel whereas lower wheel, which is made of iron, represents road wheel. Additionally, the model contains of PWM derived motor which accelerates road wheel and, by contact, car wheel. Braking is done by switching off the motor and activating braking disk that is on car wheel. Road wheel is much heavier to represent moment of inertia of road wheel.

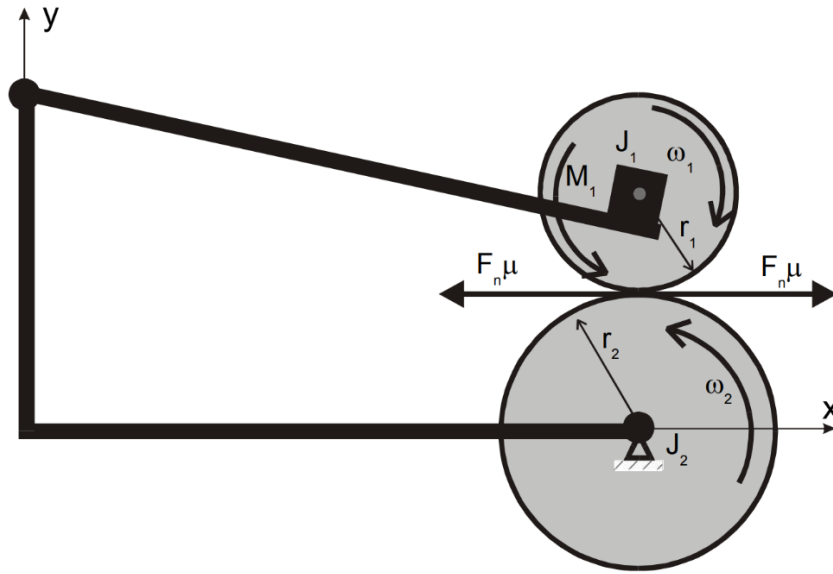


Figure 3. Schematic diagram of ABS [13]

1.2.3 Mathematical model

This section discusses the mathematical model of laboratory ABS. This mathematical model is given since it is a part of the project. For instance, slip coefficient calculations are used in the UE4 project. However, it is given for an understanding that Inteco laboratory model has its own limitations that is not applicable in UE4, but they explain why the mathematical model of this model is different from the model that is given in UE4. Additionally, it is a part of hardware-in-the-loop project part that is done by another student.

Before giving explanation about the model, it is worth to define the parameters first [13]. In addition, further explanations and discussion in this chapter are based on the following sources: [11], [13].

Table 1. Parameters of the model

Name	Description	Units
x_1	Angular velocity of the upper wheel	rad/s
x_2	Angular velocity of the lower wheel	rad/s
M_1	Braking torque	Nm
r_1	Radius of the upper wheel	m
r_2	Radius of the lower wheel	m
J_1	Moment of inertia of the upper wheel	kgm ²

J_2	Moment of inertia of the lower wheel	kgm^2
d_1	Viscous friction coefficient of the upper wheel	kgm^2/s
d_2	Viscous friction coefficient of the lower wheel	kgm^2/s
F_n	Total force generated by the upper wheel and pressing on the lower wheel	N
$\mu(l)$	Friction coefficient between the wheels	
l	Slip – the relative difference of the wheels velocities	
M_{10}	Static friction of the upper wheel	Nm
M_{20}	Static friction of the lower wheel	Nm
M_g	Gravitational and shock absorber torques acting on the balance lever	Nm
L	Distance between the contact point of the wheels and the rotational axis of the balance lever	m
φ	Angle between the normal in the contact point and the line L	°
u	Control of the brake	

Two wheels are described using Newton's second law for rotational motion (2).

$$\sum_i M_i = J\ddot{\varphi} \quad (2)$$

Using auxiliary diagram of ABS in Figure 3, the motion equation for the upper wheel can be described using equation (3).

$$J_1\dot{x}_1 = F_n r_1 s \mu - d_1 x_1 - s_1 M_{10} - s_1 M_1 \quad (3)$$

The motion equation for the lower wheel can be described using equation (4).

$$J_2\dot{x}_2 = -F_n r_2 s \mu - d_2 x_2 - s_2 M_{20} \quad (4)$$

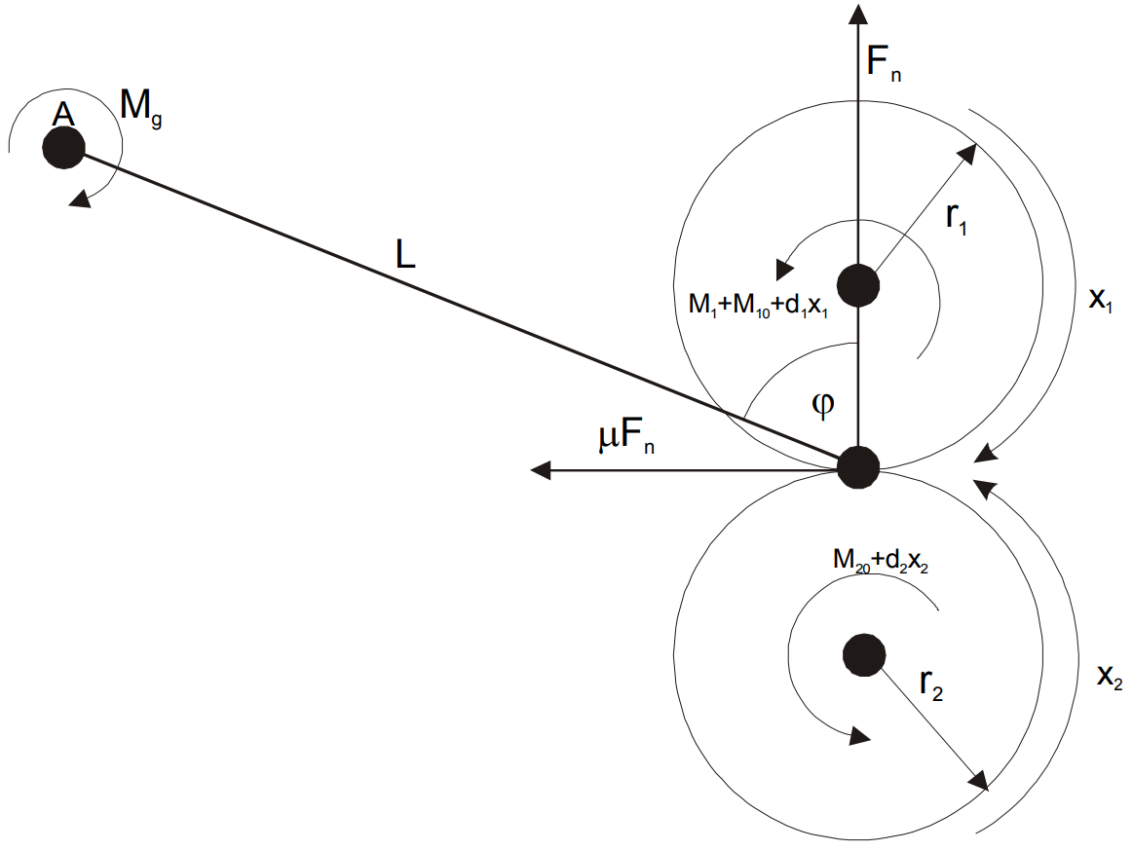


Figure 4. Auxiliary diagram of moments of forces in ABS model [13]

Auxiliary variables, introduced in formulas (5), (6), and (7), are used to distinguish the direction of rotation of wheels.

$$s = \text{sgn}(r_2 x_2 - r_1 x_1) \quad (5)$$

$$s_1 = \text{sgn}(x_1) \quad (6)$$

$$s_2 = \text{sgn}(x_2) \quad (7)$$

Slip coefficient is defined in formula (8) as relative difference of the wheels velocities.

$$\lambda = \begin{cases} \frac{r_2 x_2 - r_1 x_1}{r_2 x_2}; r_2 x_2 \geq r_1 x_1, x_1 > 0, x_2 > 0 \\ \frac{r_1 x_1 - r_2 x_2}{r_1 x_1}; r_2 x_2 < r_1 x_1, x_1 > 0, x_2 > 0 \\ \frac{r_2 x_2 - r_1 x_1}{r_2 x_2}; r_2 x_2 < r_1 x_1, x_1 < 0, x_2 < 0 \\ \frac{r_1 x_1 - r_2 x_2}{r_1 x_1}; r_2 x_2 \geq r_1 x_1, x_1 < 0, x_2 < 0 \\ 1, x_1 < 0, x_2 > 0 \\ 1, x_1 > 0, x_2 < 0 \end{cases} \quad (8)$$

Next equations in formulas (9), (10), and (11) are describing nonlinear state model. It is done to simplify the model since if the parameters above are substituted then the model becomes too complicated.

$$\dot{x}_1 = S(l)(c_{11}x_1 + c_{12}) + c_{13}x_1 + c_{14} + (c_{15}S(l) + c_{16})s_1M_1 \quad (9)$$

$$\dot{x}_2 = S(l)(c_{21}x_1 + c_{22}) + c_{23}x_2 + c_{24} + c_{25}S(l)s_1M_1 \quad (10)$$

$$\dot{M}_1 = c_{31}(b(u) - M_1) \quad (11)$$

Model coefficients that are mentioned here such as c_{11} are listed in **Error! Reference source not found.** They are used to simplify the model. They are calculated using formulas (12), (13), (14), (15), (16), (17), (18), (19), (20), (21), and (22).

$$c_{11} = \frac{r_1 d_1}{J_1} \quad (12)$$

$$c_{12} = \frac{(s_1 M_{10} + M_g)r_1}{J_1} \quad (13)$$

$$c_{13} = -\frac{d_1}{J_1} \quad (14)$$

$$c_{14} = -\frac{s_1 M_{10}}{J_1} \quad (15)$$

$$c_{15} = \frac{r_1}{J_1} \quad (16)$$

$$c_{16} = -\frac{1}{J_1} \quad (17)$$

$$c_{21} = -\frac{r_2 d_1}{J_2} \quad (18)$$

$$c_{22} = -\frac{(s_1 M_{10} + M_g) r_2}{J_1} \quad (19)$$

$$c_{23} = -\frac{d_2}{J_2} \quad (20)$$

$$c_{24} = -\frac{s_2 M_{20}}{J_2} \quad (21)$$

$$c_{25} = -\frac{r_2}{J_2} \quad (22)$$

S and μ functions are defined in formulas (23) and (24) which were obtained from formulas (9), (10), and (11).

$$S(l) = \frac{s\mu(l)}{L(\sin\varphi - s\mu(l)\cos\varphi)} \quad (23)$$

$$\mu(l) = \frac{w_4 l^P}{a + l^P} + w_3 l^3 + w_2 l^2 + w_1 l \quad (24)$$

Following coefficient values in **Error! Reference source not found.** are used in default in mathematical model following recommendations from Inteco.

Table 2. Model coefficients values

$c_{11} = 0.00158605757097$	$c_{12} = 2.593351896228796e + 002$
$c_{21} = c_{13} = 0.01594027709515$	$c_{14} = 0.39850692737875$
$c_{15} = 13.21714642472868$	$c_{16} = 132.8356424595848$
$c_{21} = 0.000464008124048$	$c_{22} = 75.86965129086435$
$c_{23} = 0.00878803265242$	$c_{24} = 3.63238682966840$
$c_{25} = 3.86673436706636$	$c_{31} = 20.37$

$w_1 = 0.04240011450454$	$w_2 = 0.00000000029375$
$w_3 = 0.03508217905067$	$w_4 = 0.40662691102315$
$a = 0.00025724985785$	$p = 2.09945271667129$

Please, take note that this mathematical model describes the behaviour of 2 wheels where, in fact, it helps to observe the behaviour of ABS on one-wheel vehicle only. So, it was suitable to use at the beginning for observation how ABS works.

1.3 Software used in the development

This section provides an overview of software that is used in the development of thesis. There are 2 main instruments listed here. Visual Studio is not listed since visual programming (Blueprint) in UE4 was used instead of coding.

1.3.1 Matlab as a supportive environment

Matlab is a programming and mathematical tool which was developed to support scientific researches. It was developed in 1984 and it is still supported until these days [14]. The main languages here are C and C++. There is also possibility here to use Simulink as a visual programming which makes life easier for researchers. On the project its usage is valuable when it comes to real-time communication with the ABS Inteco laboratory stand. The Simulink model is kindly provided by Inteco and it is a good supportive tool for understanding all the interfaces that are connected. Of course, the provided models are not ideal, but the drivers made life easier for the project participants. Worth to mention that UDP communication channel could be used here which is a great possibility to communicate with UE4 in order to create hardware-in-the-loop model. This part is done by another participant, but the author of the document participated into development of the controller and logic.

1.3.2 Unreal Engine 4 as a virtual environment

Unreal Engine is a software tool that is used for real-time 3D creativity. It is developed by Epic Games company and first time it was used for developing games since it is a game engine [8]. However, after passing some time, the tool has started to be interesting for scientific researches [9]. Since it is flexible and easy to use even for

complete beginners, it is a good software for developing projects based on VR. The main programming language here is C++, but there is a possibility to use “Blueprints” (visual scripting system). Oculus Rift VR headset is used along with Unreal Engine and it is a good and stable combination for debugging and developing [10]. For communication between UE4 and Matlab, UDP (User Datagram Protocol) is used. It makes possible to do real-time operations between digital twin and the real object. It is worth to mention that it is possible to simulate physics and mathematical calculations in UE4 for every object and achieve immediate results. This tool is the primary one in the development and all the final achievements obtained here. The progress and results will be elaborated more in Section 2.

1.4 Definition of VR

Virtual Reality is a simulated experience of reality in hardware devices that differs from the real world. However, it is more accurate to say that VR is an experience of presence in the Virtual Environment as it is described in [15]. So, in the thesis VR and Virtual Environment are simulated through software and hardware packages which make a feeling that the world is different and there is a possibility to interact with it. From the source, „Interactivity is defined as the extent to which users can participate in modifying the form and content of a mediated environment in real time.” Consequently, „Interaction is defined as the action with which users can participate in modifying the form and content of a mediated environment in real time.”.

1.5 Hardware and equipment used in the development

This section describes used equipment in the project. The equipment was kindly provided by TalTech representatives for the development. In addition, there are 2 personal computers used with following characteristics:

Table 3. Computers' characteristics

Computer number	1	2
CPU	Intel(R) Core(TM) i7-6700K CPU @ 4.00GHz 4.00 GHz	Intel(R) Core(TM) i7-7700 CPU @ 3.60GHz 3.60GHz
GPU	NVIDIA GeForce GTX 980 Ti	Intel (R) HD Graphics 630
Purpose of using	-Developing applications on UE4	-Developing applications in Matlab; -Real-time communication with ABS.
RAM, GB	32	16
HDD memory, GB	2000	-
SDD memory, GB	500	250

1.5.1 Oculus Rift VR headset

Oculus Rift is a device that is used for interacting with Virtual Environment. It is a soft and comfortable headset with custom optics inside and headphones. Optics are used to create immersive 3D environment. Touch controllers are used as trackers for hands. These controllers are tracked by IR LEDs (that looks like cameras) that should be calibrated by the user. Since it is an old version of headset that is used in this project, the IR LEDs are separate instances from VR headset and should be placed in front of the place that is going to be used [16].



Figure 5. Oculus Rift set

1.5.2 Steering wheel Logitech G29

Playseat and Steering wheel Logitech G29 is a device that is used to simulate the experience of driving at home conditions without risks if there is a wish to drive hard. For the project development, this tool is considered to be absolutely necessary since it helps the user to feel the connection with the simulated environment. The device is fairly simple. It has a set of buttons, pedals, and steering wheel that could rotate by 900 degrees. Additionally, there is a force feedback on the steering wheel. Dual-motor force feedback creates a feeling that there is a tire slip [17].



Figure 6. Steering wheel and playseat Logitech G29

1.6 Problem

As it is stated at the beginning, ABS is used widely in different vehicles such as cars, planes, or motorcycles. It is an important part since it provides an additional control to the vehicles and improves the performance overall. Of course, there are simulations that are already developed and could be useful for trainings and investigations. However, it does not provide a full experience of driving still. There is a need to develop an application that could be better than predecessors. There is no VR application still for experiencing ABS behaviour in cars or motorcycles.

1.7 Purpose

The purpose of the thesis is to suggest a different approach to the problem. Fortunately, there are many possibilities these days for the improvement. For instance, in this project Steering Wheel, pedals, and VR headset are used as equipment for experiencing dangerous scenarios. There is an obvious difference here comparing to

traditional approaches using on-screen 3D applications only. Since VR technologies grow fast these days, it is worth to try to develop such application and try a different approach which could lead to further developments in this field. In addition, it would be interesting for researches who are interested in mechanics side. So, there is additional purpose to develop such an application where it is easy to observe ABS behaviour and develop feasible controller.

1.8 Goal

The main objective of the thesis is to create a virtual environment where it is easy to observe ABS behaviour and results. Additionally, there should be a possibility to develop controllers for ABS for improving the performance of vehicles in the future. Another goal is to have a extend ABS tests on several wheels. With the Inteco ABS laboratory stand, it is possible to test the system as on one-wheel vehicle. The goal is to have a possibility to have an environment and vehicles where it is possible to apply ABS on several wheels and they should behave independently.

1.9 Motivation

There are several aspects that lead to such project. There are too few researches in the field of ABS in virtual environment. However, there is a personal interest involved here to create a digital twin of ABS in UE4 since it is relatively new experience for the author. The virtual environment could be useful for the beginners to understand why ABS exists since there are many people who are not familiar with such concept. These findings could be useful also for game and simulation developers who wish to improve the performance of their simulated vehicles in virtual environments. It will also help to have extreme driving experience without hurting anybody. It is especially important for Northern countries and lands where it is necessary to know such concept for vehicles in practice. For instance, ice road is the case where using ABS is necessary if not a must. Therefore, the application could be a good option for the people who want to get familiar with ABS not involving themselves into dangerous situations. The gained experience would help to understand the possibilities of controlling the car during slippage and see the obvious benefits instead of using simple wheel's locking.

2 System design and development

This chapter discusses about the system design and the achievements that are obtained during the development. There will be discussed different approaches and stages of the development and how the results are achieved.

2.1 Development approaches

The development of the project has been set back by some discoveries made and corresponding uncertainties during the research phase, until a clearer goal was established in the end of February 2021. Therefore, there are 2 main approaches that were agreed in the team:

1. Develop a hardware-in-the-loop system with digital twin in UE4. It basically means that there should be a VR application in UE4 that could interact with Logitech G29 and an application in Matlab (through UPD communication channel) that interacts in real-time manner with Inteco ABS laboratory stand. In that way, the user can experience the real behaviour of ABS and he could hear it himself how it works.
2. Develop a digital twin of ABS and apply characteristics of mathematical model of it on the car's wheels in UE4. It means that there is no communication with real ABS and it should work fully in UE4 only. The digital twin should have a mathematical model and this system should be possible to apply on each wheel.

This thesis is about the second approach. The second team member followed the first approach and contributed heavily in developing the physics of the car in UE4.

It is worth to mention that Matlab Simulink model has limitations. As it is mentioned earlier, the laboratory stand has been considered to be investigated as it is one-wheel vehicle with ABS on it. In the project of the second team member, it is applied on a car fully and, besides it is four-wheel vehicle, it follows the behaviour of laboratory stand. However, the author of the document participated in developing the model as well and it is mentioned in the next sections in the document.

2.2 System design

There is only one VR application (game) in UE4 that is designed for the user. There is a “main menu” scene where user chooses the right mode of the game. In case of this thesis, it should be “ABS simulator” (Figure 7).



Figure 7. Main menu of the application

Then there is a transition to the scene with car. The user should be equipped with VR headset already and sit on in front of Steering Wheel on Logitech G29 equipment. Using pedals, user can accelerate a vehicle and press the brake. The Steering Wheel of Logitech G29 rotates the Steering Wheel in the game exactly in the same way.

UE4 communicates with Logitech G29 through USB interface. With VR headset it uses USB and HDMI interfaces (Figure 8).

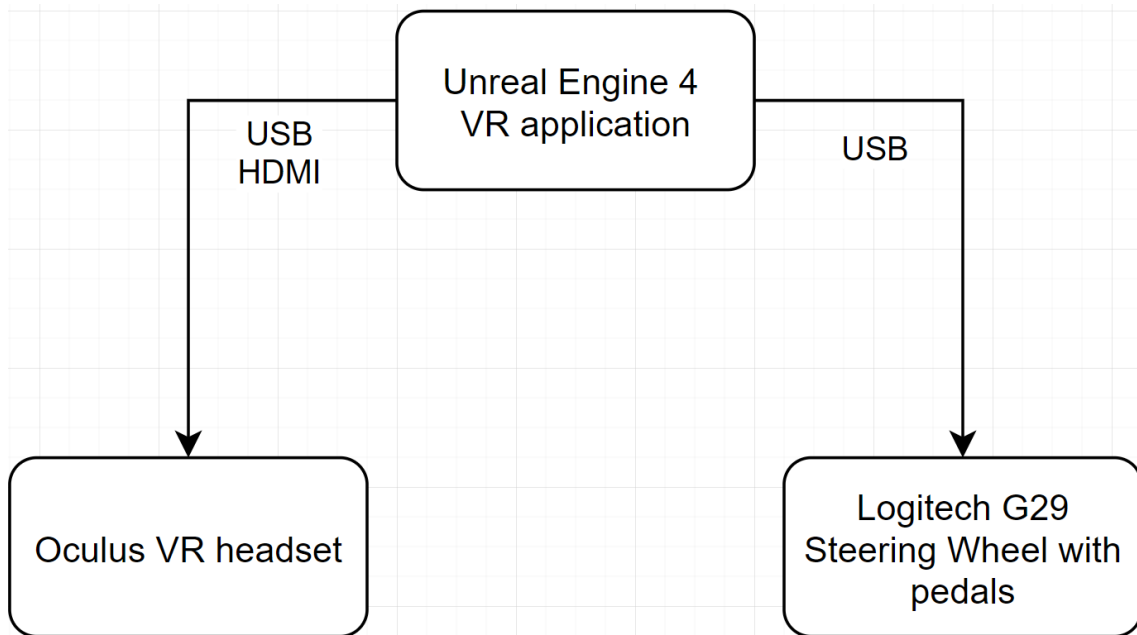


Figure 8. System diagram of connections

The used control buttons and pedals are assigned in UE4 project. Steering wheel logic is done using Blueprints (Figure 9). Input data, that comes from Logitech G29 Steering Wheel when wheel is turned, is in range from -1 to 1. If the value is 1, then the wheel is fully turned on the left. If the value is -1, then it is fully turned on the right. This number is multiplied by 500 in order to transform it into the degree range. It can be used then for rotators which can turn the wheels in the simulator in the right rotation position. UE4 tracks the position of the steering wheel in real-time manner.

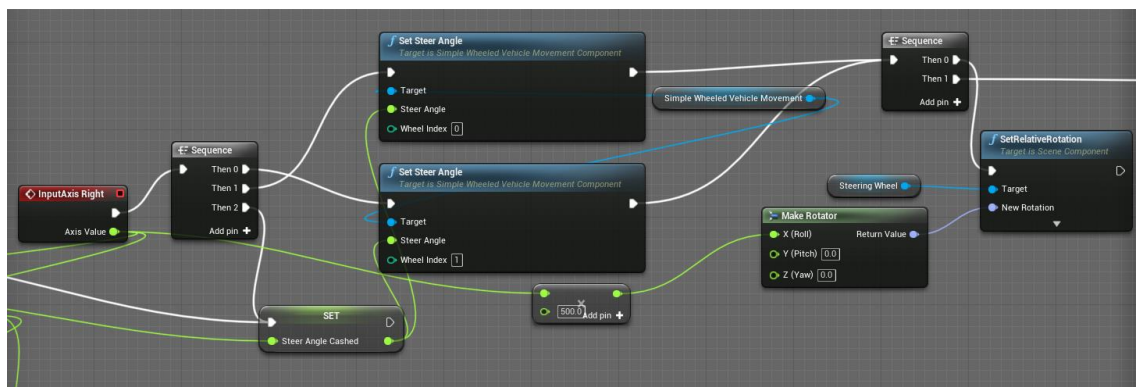


Figure 9. Steering wheel logic section in Blueprint

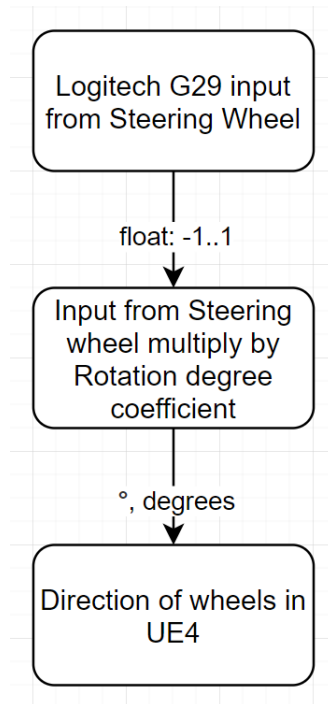


Figure 10. Decision diagram for Steering Wheel logic

2.3 Car model in Unreal Engine 4

Before proceeding with the logic, first of all the model of the car should be created. The model was borrowed from another thesis that is done in TalTech [12]. This vehicle is accelerated by four wheels at the same time. Each wheel has an ABS logic applied. When the user brakes, all 4 wheels brake at the same time.



Figure 11. The model of a car

The logic of it is done in Blueprint called “SimpleWheeledVehicleBP” and the controls are divided into different sections.

2.3.1 Acceleration of the vehicle

Acceleration of a vehicle is described in the section called “Gas input”. It takes the actual value of the pedal from 0 to 1 depending on the pressing force on the gas pedal on Logitech G29. It is multiplied by “drive torque” variable that equals 1000 in the project. Drive torque applies on each wheel on the car and the vehicle starts moving. However, there is limitation and “broken” logic here regarding engine rotation speed. For some reasons, UE4 does not count engine as an instance properly, but it could be revised and fixed by adding additional coefficients or fixing the logic.

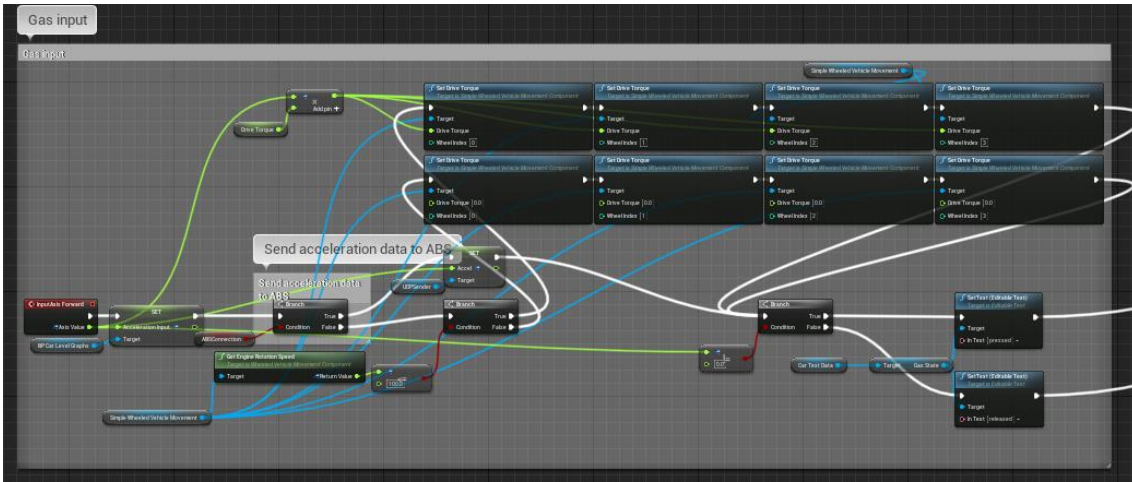


Figure 12. Whole visual logic of “Gas input” section in Blueprints

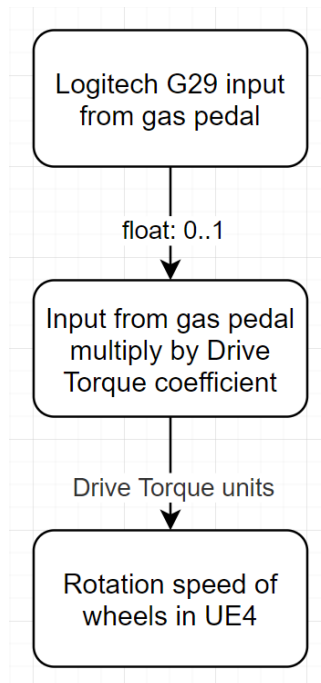


Figure 13. Decision diagram for Acceleration of the vehicle wheels

2.3.2 Brake control of the vehicle

This is the most important part of the project and, fairly, the most complicated one because of the connection with ABS logic. It is described in the block called “Brake input”. The signal comes in the same way as an acceleration input with the same range: from 0 to 1. “Brake Torque” variable controls the force of braking and it equals 1500 in the project. This force is applied on each wheel of the vehicle when the braking process begins. Since it is connected with ABS logic, it is applied when certain conditions are true depending on the controller that is described in the Section 2.4. The data from the fourth wheel is transferred to “BP_CarLevelGraphs” Blueprint for building a graph.

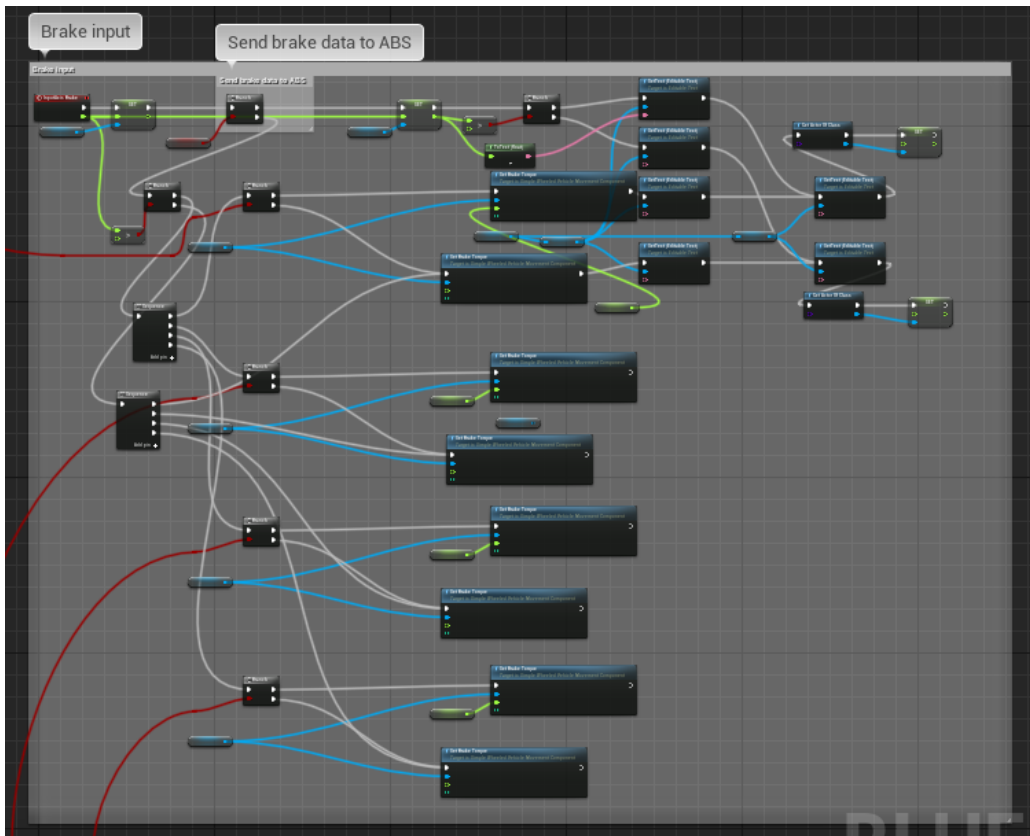


Figure 14. Whole visual logic of “Brake input” section

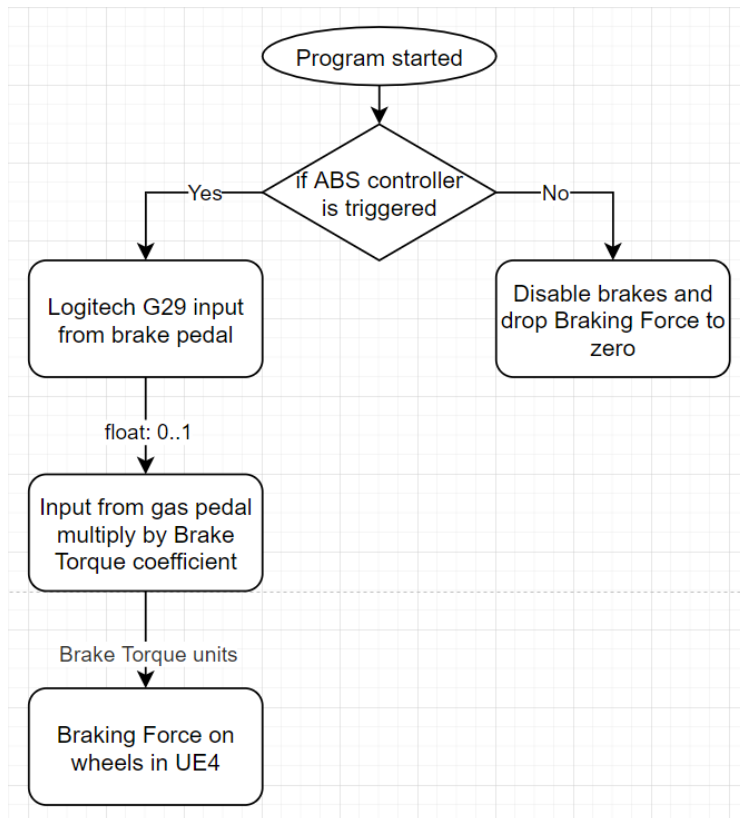


Figure 15. Decision diagram for Brake control of the vehicle

2.3.3 Reversing gear

If the user wants to change the direction of the movement of the vehicle, he can press the assigned button for this. Right now it is assigned on keyboard button R, but later it could be changed to the button or, even, the gear of Logitech equipment.

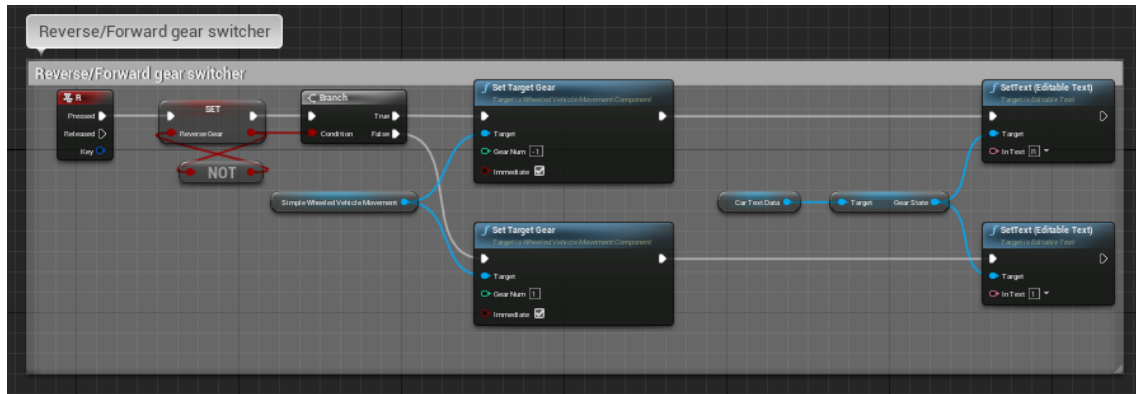


Figure 16. Logic for reserving gear of the car

2.4 Model of ABS in Unreal Engine 4

This section describes how the ABS logic is constructed and how mathematical model from Inteco is applied in UE4. There are several parts that need to work together and they will be reviewed step by step.

Time per tick, that is mentioned in the subsections, equals 0.012 seconds roughly. This value depends on the performance of PC and how many frames per second in the game.

2.4.1 Wheel distance measurement

All the four wheels have the same logic in calculating the distance that they passed, but there will be taken only one of it for reviewing the logic. The fourth wheel will be reviewed in this and next sections regarding the calculations and math modelling.

For calculating the passed distance in meters, there is a formula (25) used.

$$S = \frac{n}{360} \cdot L \cdot 1000 \quad (25)$$

Where

S – distance passed, m;

L – length of the wheel, km;

n – number of rotations.

Length of the wheel can be calculated in the following way in formula (26).

$$L = \pi \cdot r^2 \quad (26)$$

Where

r – radius of the wheel.

There are also macros used called “Alert Value Change Tracker”. It tracks if the incoming value is changed. If the new value comes and it is different from previous one, then old value is decreased by new value. Since it is used on four wheels, UE4, surprisingly, increases the time per tick and, because of that, the resulting value needs to be divided by 4.

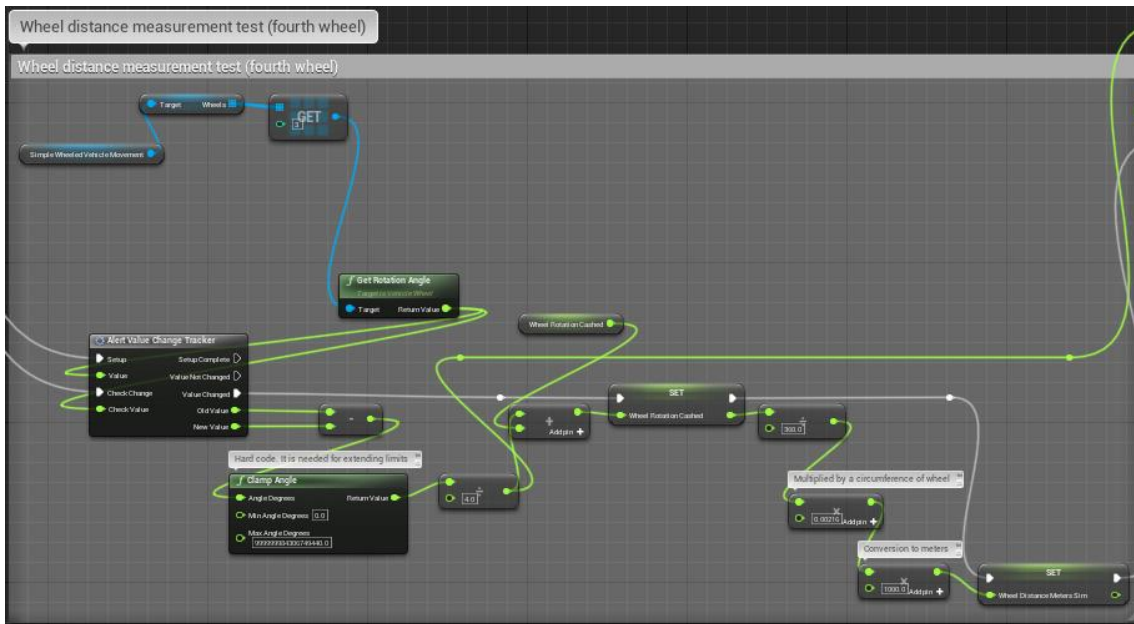


Figure 17. Whole visual logic of calculating passed distance by the fourth wheel

2.4.2 Wheel speed measurement

The speed of the wheel is calculated in the following way in formula (27).

$$v = \frac{n}{360} \cdot L \cdot \frac{1}{f_{us}} \quad (27)$$

Where

v – speed of the wheel, m/s;

n – number of rotations;

L – length of the wheel, m;

f_{us} – time per tick, s.

Please note that, for the same reason as it is described in the previous section 2.4.1, there should be used the number 4 instead of 1 in converting to seconds.

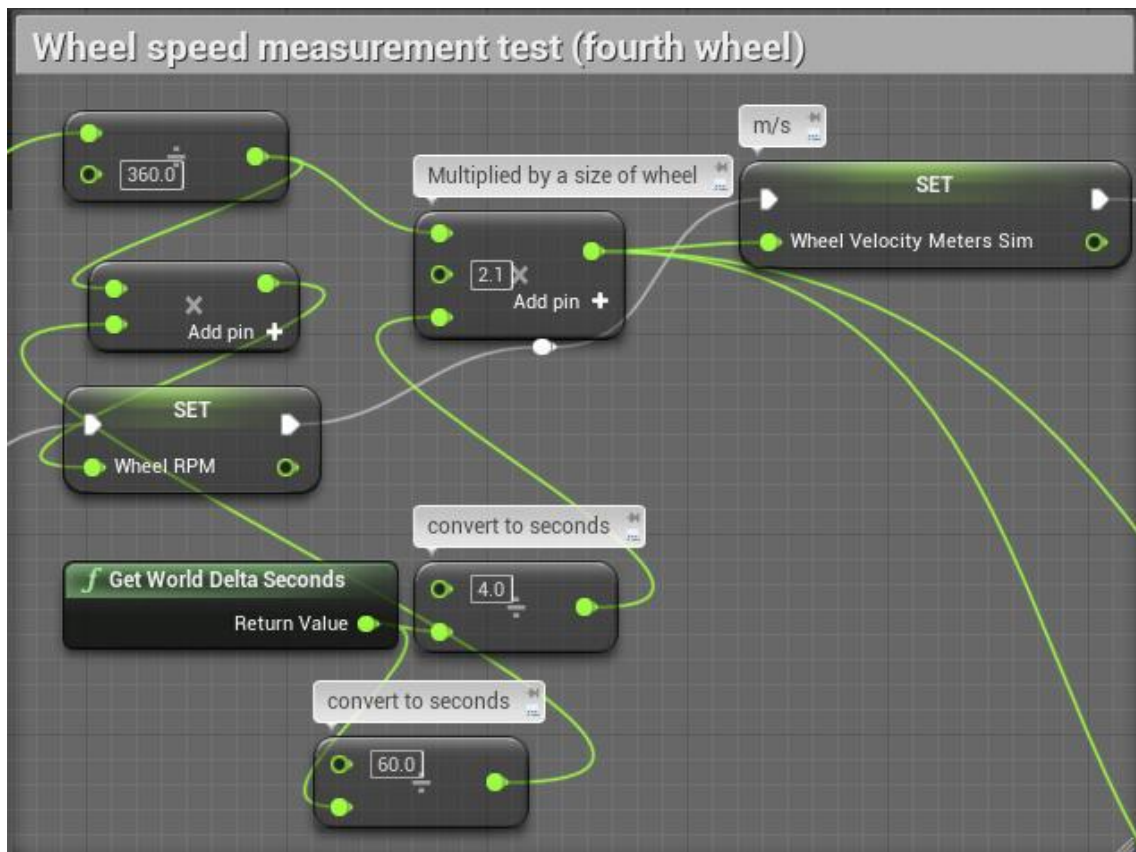


Figure 18. Whole visual logic of calculating speed of the fourth wheel

2.4.3 Travel distance measurement

Vehicle speed calculation starts with getting speed of the vehicle in Unreal Engine units. Following the documentation, 1 unit in UE4 equals 1 centimetre. The same macro is used here and it is described in 2.4.1. If the value is changed, the new value is multiplied by frame rate. Then it is converted to meters and sent to “BP_CarLevelGraphs” Blueprint for building a graph. The value will be used in the next section 2.4.4.

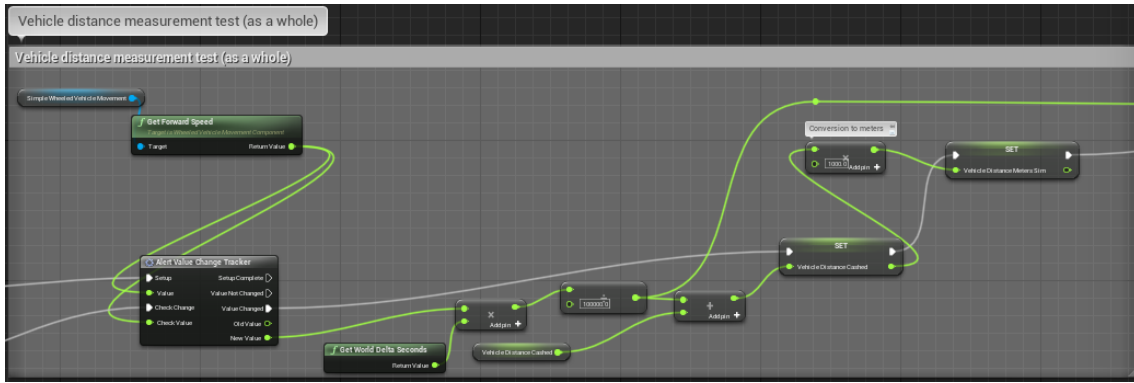


Figure 19. Whole visual logic of calculating distance of the vehicle

2.4.4 Vehicle speed measurement

The speed of the vehicle is measured in the following way. The resulting value from previous section 2.4.3 comes in centimetres/frame rate. It needs to be converted into meters/second. In order to do that, the following formula (28) needs to be used.

$$v_1 = v_2 \cdot 1000 \cdot \frac{1}{f_{us}} \quad (28)$$

Where

v_1 – vehicle speed, m/s;

v_2 – vehicle speed from the incoming value from previous section 2.4.3, centimetres per time per tick;

f_{us} – time per tick, s.

The resulting value is transferred to to “BP_CarLevelGraphs” Blueprint for building a graph.

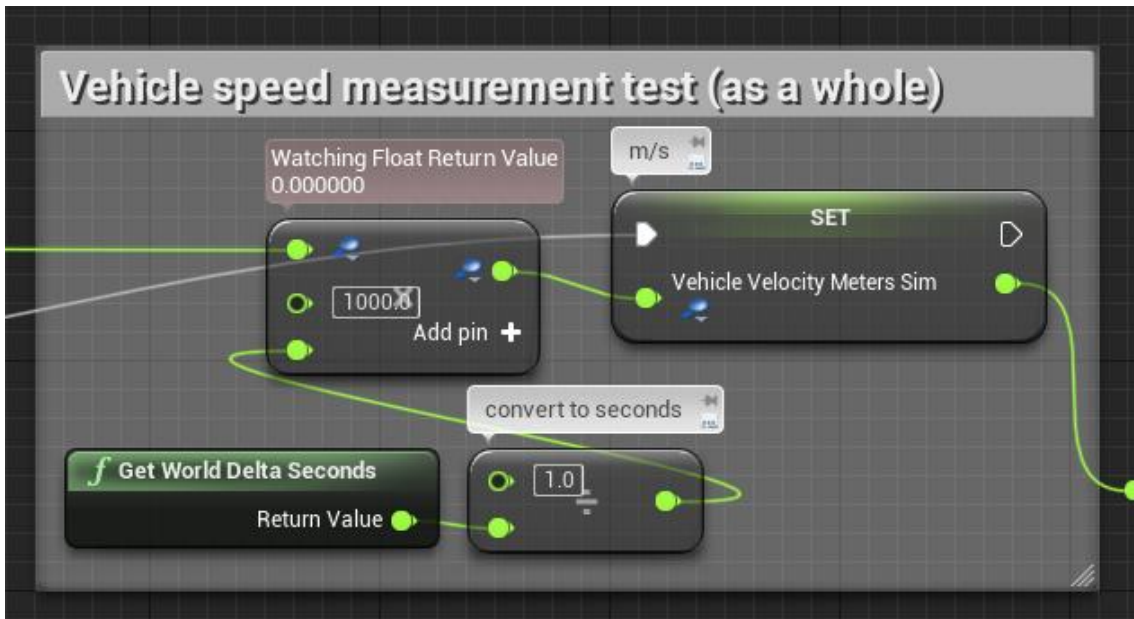


Figure 20. Whole visual logic of calculating speed of the vehicle

2.4.5 Slip coefficient calculation

Slip coefficient is calculated in the following way. Vehicle speed is decreased by wheel speed. Then the resulting value is divided by wheel speed. Please, take a note that slip coefficient is different for each wheel during the braking since it is calculated for each wheel separately.

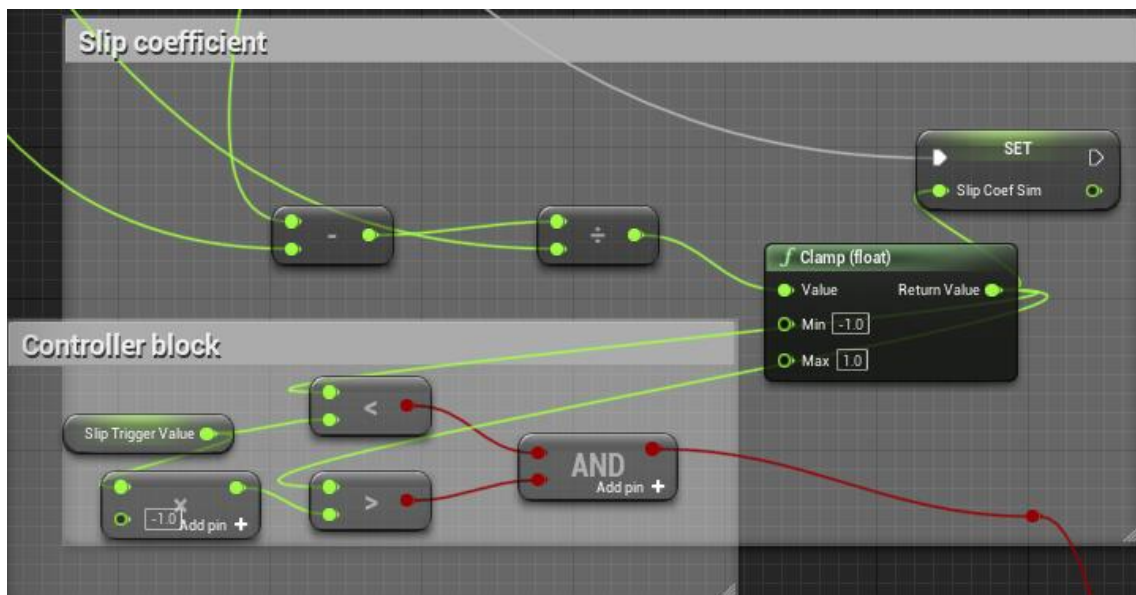


Figure 21. Whole visual logic of calculating slip coefficient

2.4.6 Controller block

The controller here is very simple and not very well developed, but it is, basically, a simple trigger that acts as a relay. If slip value is less than higher trigger value (in case of the thesis project, it is 0.3) and more than lower trigger value (it is -0.3), then it allows to lock the wheel. When the value goes beyond the limit, then it disables the possibility to lock the wheel. Each wheel behaves in a unique way depending on the road (surface) conditions.

2.5 Graphs in UE4

This section describes how the graphs is drawn in UE4 project.

All the logic regarding graphs is done in “BP_CarLevelGraphs” Blueprint. At the moment, the feature can be used with keyboard and mouse only. Later it can be improved by adding such controls to the buttons on Steering Wheel on Logitech G29. Graph selection menu can be called by pressing button “P” on keyboard and if the vehicle is fully stopped. To start drawing charts, “Start” button needs to be pressed and recording begins. When the ride on the vehicle is finished, data recording needs to be stopped by pressing “Stop” button. For observing the results, particular graph can be selected if user is interested in one of the characteristics. There are, overall, 8 graphs available for observing except ABS brake output (it is supposed to be used in case if Simulink model that is connected to real ABS laboratory stand communicates with UE4 project which is not in the scope of this thesis project part).

All the graphs are drawn in green colour in general. However, when brakes are applied, the line turns into red colour. It is done for highlighting the braking process and make it easier for the reader to understand how ABS works. Graphs in the next sections are done with the same ride except slip graph in Section 2.5.6.

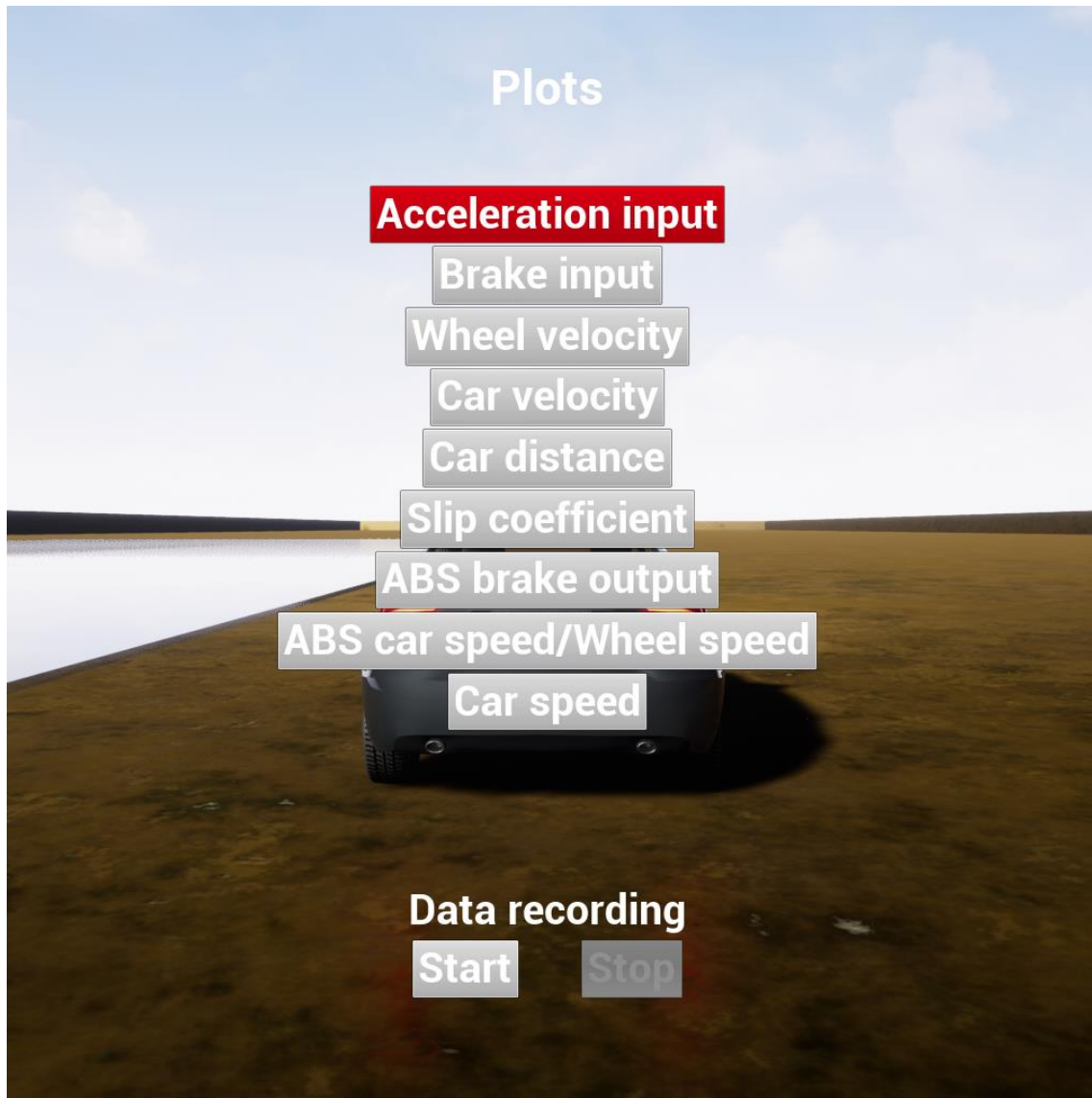


Figure 22. Graph selection menu

2.5.1 Acceleration input graph

Acceleration graph is build based on the input from the gas pedal. From the graph below, it can be clearly seen how the user pressed the gas pedal and how much force he applied on it. As it was described in Section 2.3.1, acceleration range is from 0 to 1. Time is measured on X-axis in seconds and acceleration input value on Y-axis.

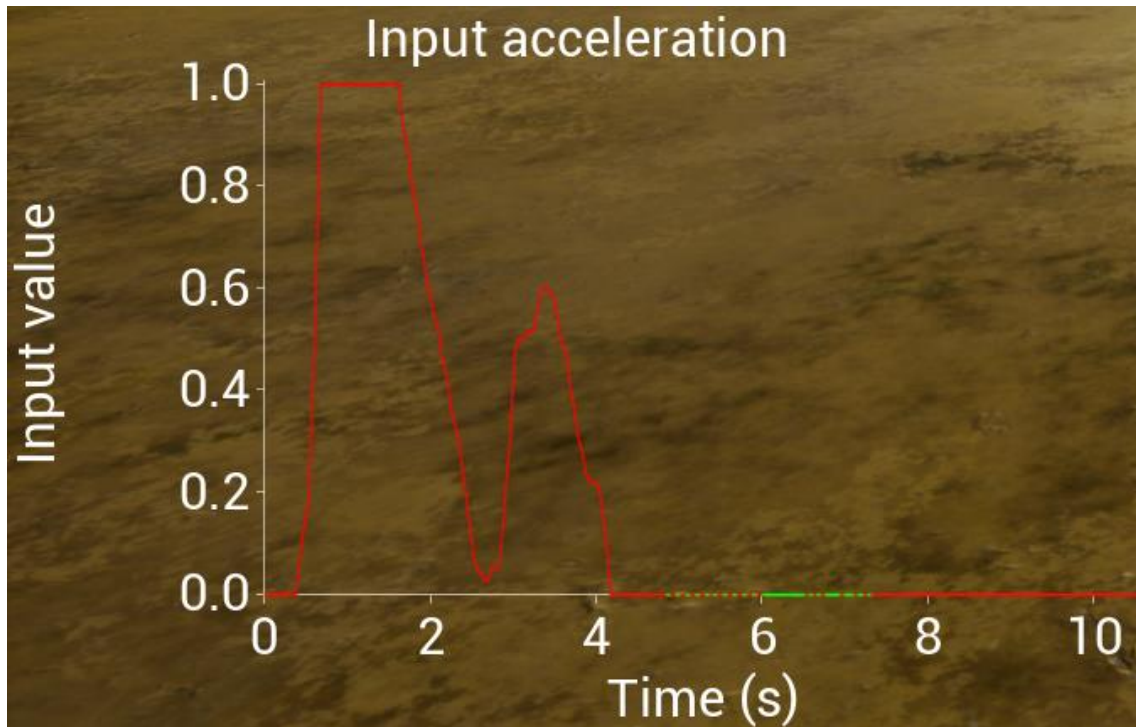


Figure 23. Acceleration input graph sample from the application

2.5.2 Brakes state graph

Brakes state graph is build based on the state from the brakes of the fourth wheel. From the graph below, it can be seen how ABS releases the brakes from time to time for giving a control on the vehicle for the user. As it was described in Section 2.3.2, brake state could be 0 or 1. Time is measured on X-axis in seconds and brakes state value on Y-axis.

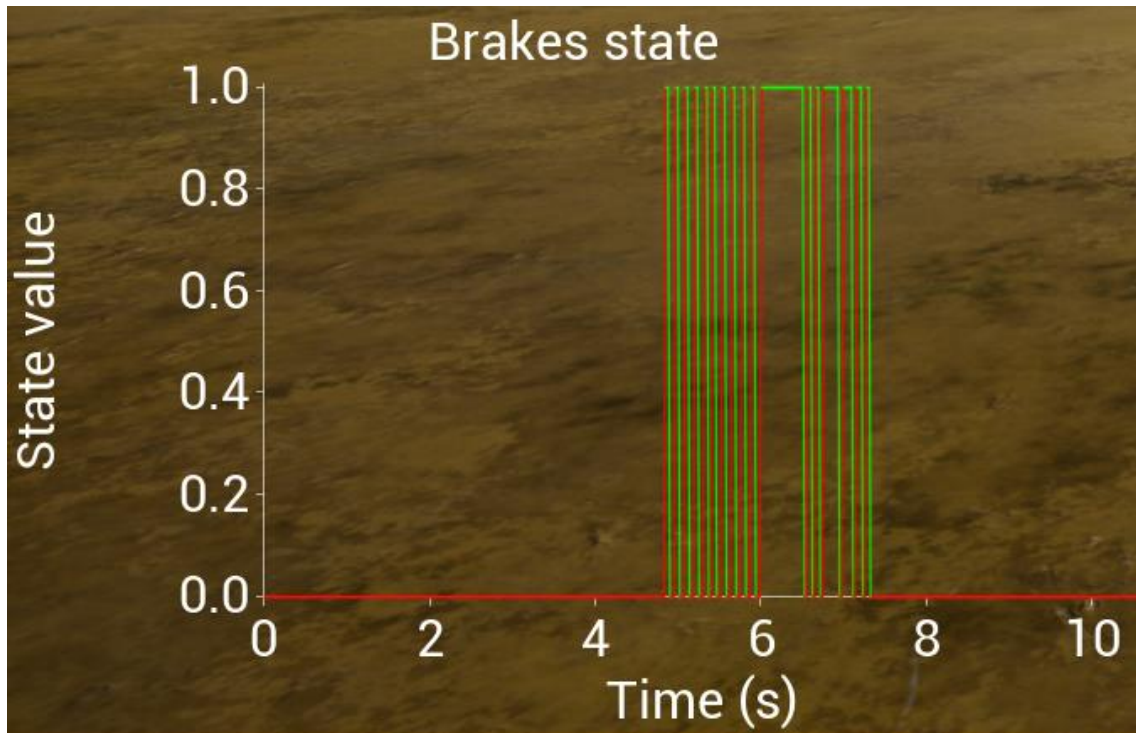


Figure 24. Brakes state graph sample from the application

2.5.3 Wheel velocity graph

The graph is built based on values from variable “Wheel RPM” that is inside the block “Wheel speed measurement test (fourth wheel)” in “SimpleWheeledVehicleBP” blueprint (check section 2.4.2 for more information). Time is measured on X-axis in seconds and wheel’s velocity value (rotations per minute) on Y-axis.

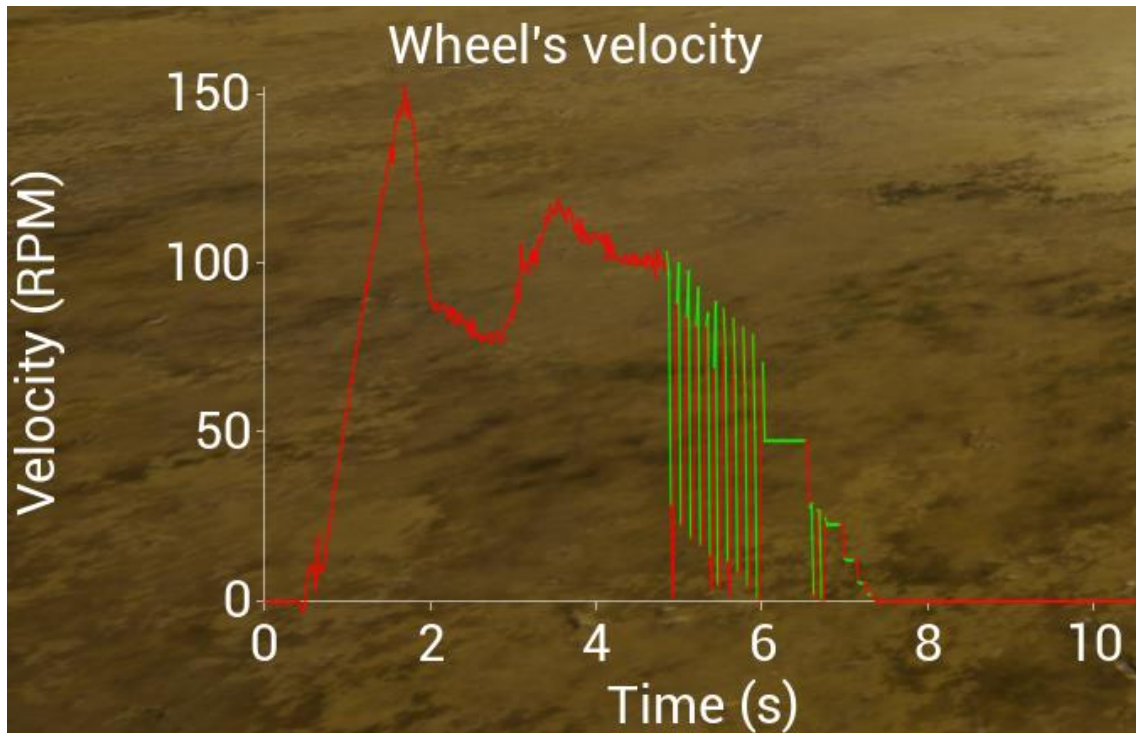


Figure 25. Wheel's velocity graph sample from the application

2.5.4 Car's engine velocity graph

The graph is built based on values from function "Get Engine Rotation Speed" from "SimpleWheeledVehicleBP" blueprint. The function is UE4 based. The data seems not quite right and the limitations are discussed in section 2.3.1. Time is measured on X-axis in seconds and car's engine velocity value (rotations per minute) on Y-axis.

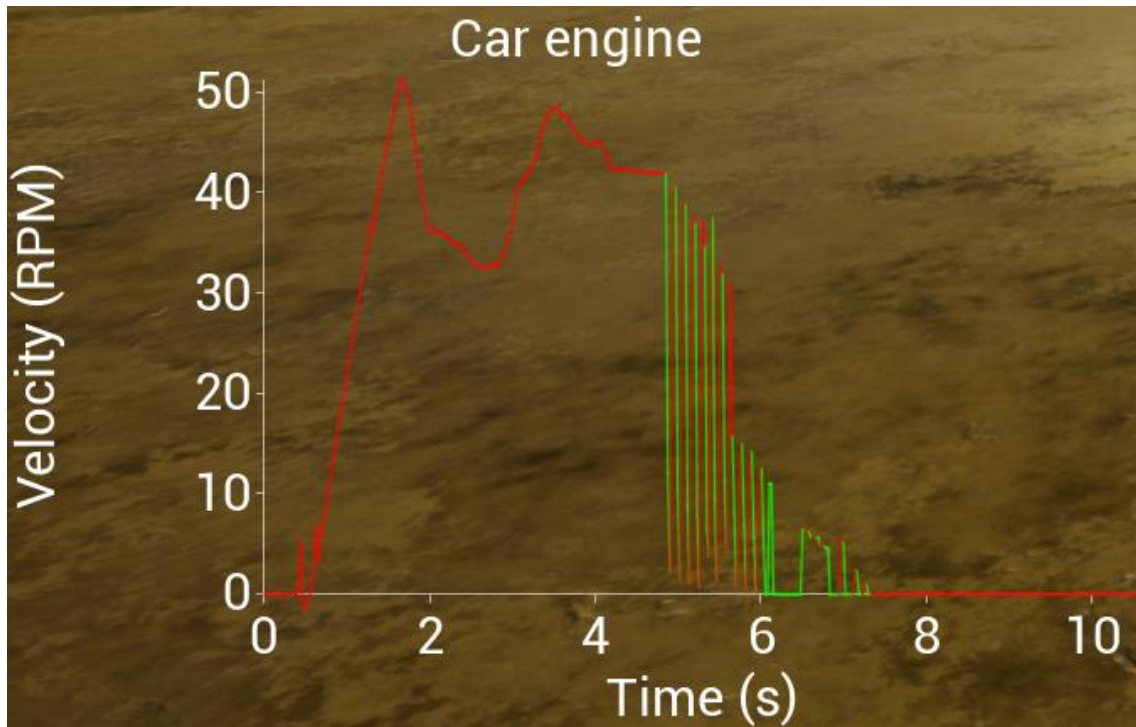


Figure 26. Car's engine velocity graph sample from the application

2.5.5 Travel distance graph

The graph is built based on values from variable "Vehicle Distance Meters Sim" that is inside the block "Vehicle distance measurement test (as a whole)" in "SimpleWheeledVehicleBP" blueprint (check section 2.4.3 for more information). Time is measured on X-axis in seconds and car distance value (meters) on Y-axis.

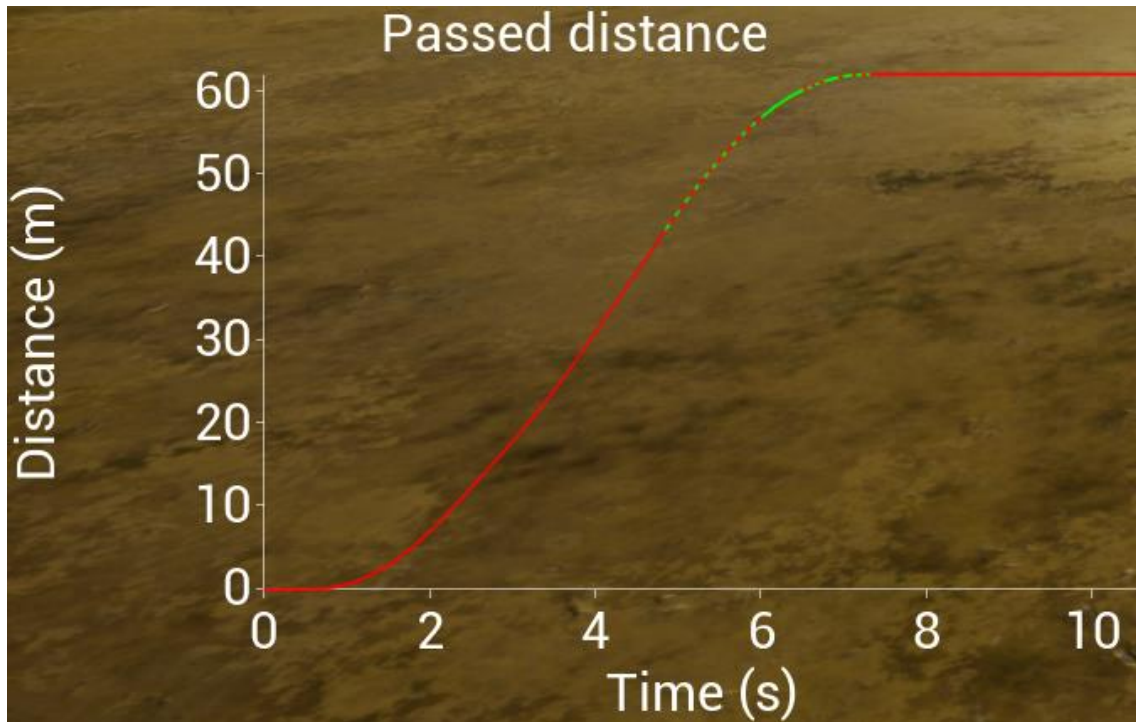


Figure 27. Car distance graph sample from the application

2.5.6 Slip coefficient graph

The graph is built based on values from variable “Slip Coef Sim” that is inside the block “Slip coefficient” in “SimpleWheeledVehicleBP” blueprint (check section 2.4.5 for more information). The range of the value is from -1 to 1. Time is measured on X-axis in seconds and coefficient value on Y-axis.

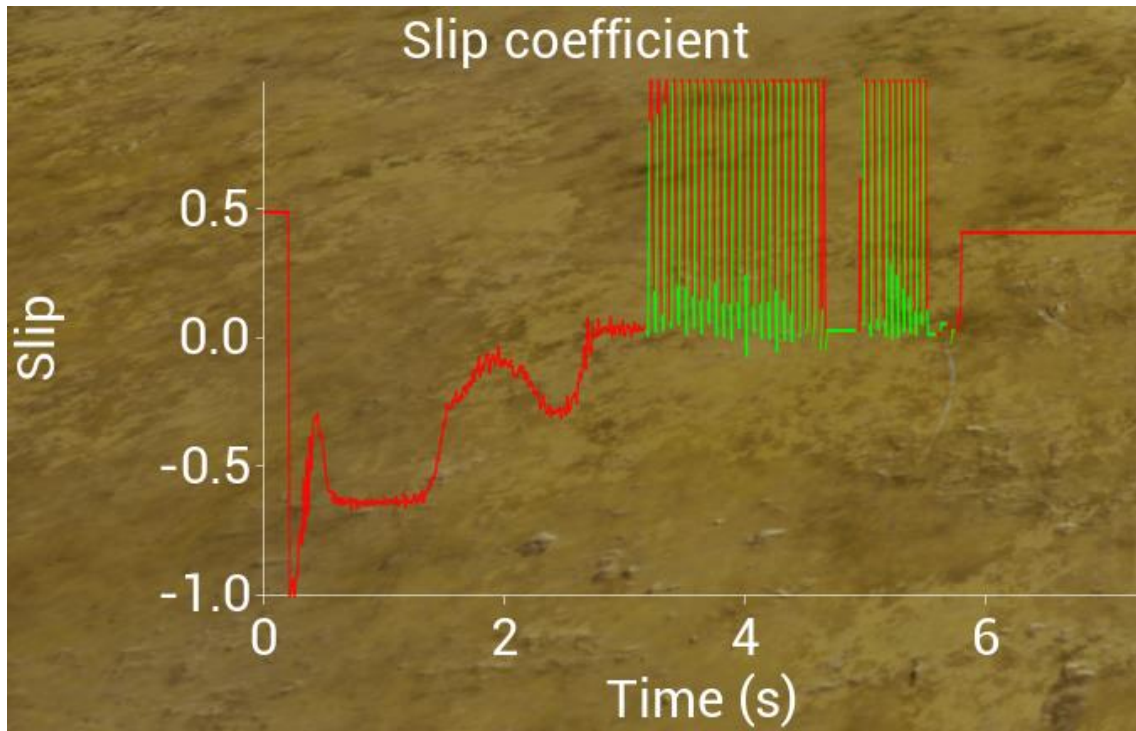


Figure 28. Slip coefficient graph sample from the application

2.5.7 Wheel speed graph

The graph is built based on values from variable “Wheel Velocity Meters Sim” that is inside the block “Wheel speed measurement test (fourth wheel)” in “SimpleWheeledVehicleBP” blueprint (check section 2.4.2 for more information). Time is measured on X-axis in seconds and wheel speed value (meters per second) on Y-axis.

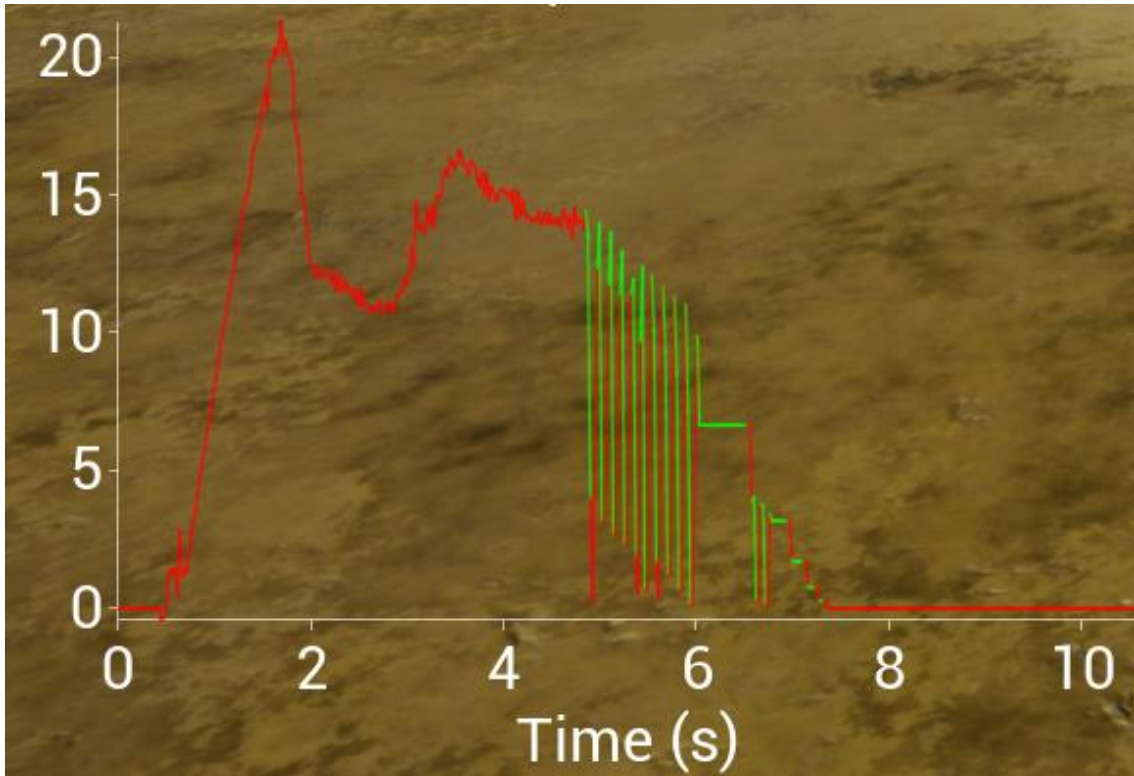


Figure 29. Wheel speed graph sample from the application

2.5.8 Car speed graph

The graph is built based on values from variable “Actual Car Speed” in “SimpleWheeledVehicleBP” blueprint. It is calculated in the following way: value from function “Get Forward Speed” is multiplied by 0.036. The resulting value is written in variable “Actual Car Speed”. Time is measured on X-axis in seconds and car speed value (kilometres per hour) on Y-axis.

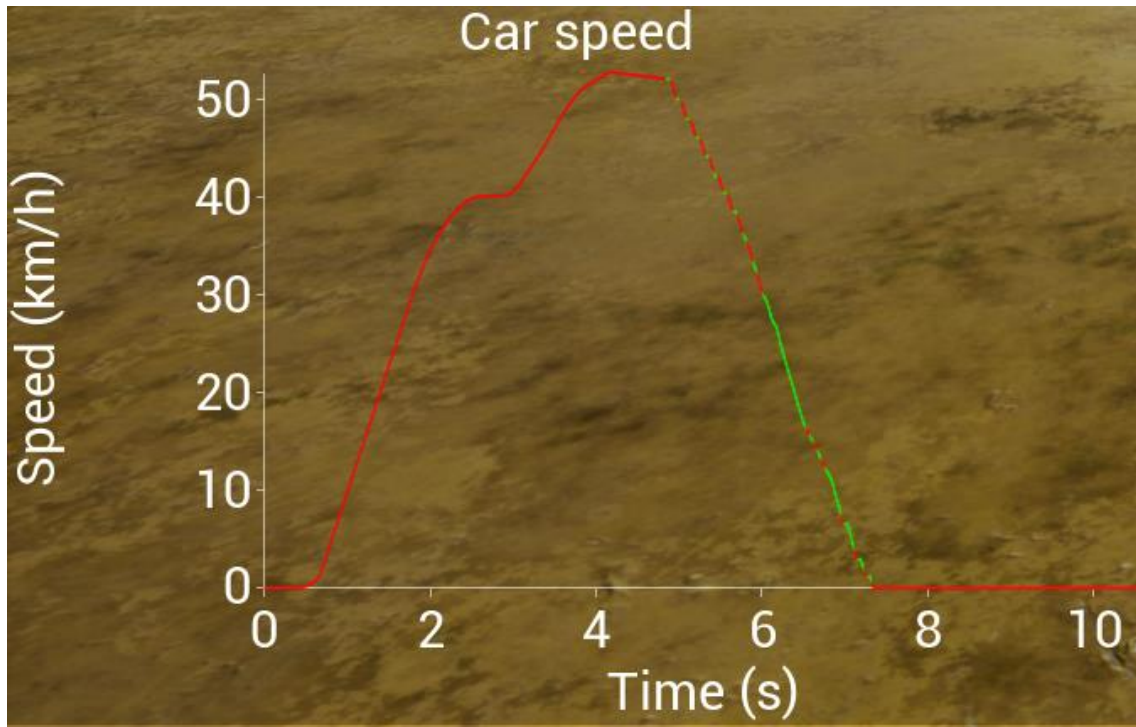


Figure 30. Car speed graph sample from the application

2.6 Analysis of the results

The application is not ideal, but the goal is reached and there is an environment and system to work with. The most important achievement is the possibility to apply ABS on any wheel and it does not matter which vehicle is going to be taken and how many wheels on it. Thanks to the developments of the vehicle that were done by another student, it was easier to focus on developing logic for controlling braking process and simulating ABS.

Event tick that is used in the project is similar to “fundamental step size” in Matlab. But Event tick time is dependent on frame rate. For instance, if there are 30 FPS, then 1 frame lasts roughly 0.03333 seconds ($1 \text{ frame} / 30 \text{ seconds} = \sim 0.03333$). The “delta time” value is based on the frame rate and reader should be aware of it while working with UE4.

3 Summary

There are two different approaches that are tried to be managed by a team: hardware-in-the-loop based and full UE4 simulation approaches. There is a trial in the thesis to do modelling in UE4 without using Matlab and there are achievements in this case. Firstly, right now it is possible to use ABS on the wheels separately instead of using the physics of one wheel only. Secondly, there is a possibility to try different road conditions and surfaces. Observing results in that way is much easier and the development of an effective ABS controller could be more efficient for the future research.

The goal of the thesis is reached, but with some limitations. Due to the time limitation, it is hard to make the project perfect. There is lack of experience in applying additional physics. The laboratory stand has some issues with sensors from time to time and, sometimes, the issues could be unsolvable and the only solution could be just waiting and restarting PC. That makes observing tougher while exhaustive tests and the team wasted a lot of time because of it.

The developed application is VR-based. User should use PC, Oculus Rift VR headset, and Steering Wheel Logitech G29 in order to receive full driving experience. ABS system is applied on each wheel separately. The vehicle is four-wheel drive car which means every wheel is accelerated.

In summary, the result of the thesis is a prototype platform that was developed for studying the effects of applying the ABS system in driving. Initial tests show that the system has a good potential for contributing to understanding in improving driving safety from the perspective of maintaining vehicle controllability when there is sufficient slip between the wheels of the vehicle and the driving surface using the ABS system. The driving experience is delivered through a realistic VR environment. This would provide a good opportunity for investigating the behaviour of drivers in difficult road conditions [12]. The information for behaviour analysis should be collected by running relevant experiments which is the next logical step for this research and development effort. For instance, different surface types or roads could be tried, and the results could be compared. The application is developed in UE4 meaning that the results are observable and it is a good possibility for future researchers to develop an ABS controller in virtual environment.

4 Discussion and Future Work

There are some issues related to measuring rotation speed of an engine of the vehicle. It does not work as intended since author has tried to find a solution to control all the wheels separately. It could be fixed easily by adding coefficients, but it needs to be investigated.

In addition, the controller block is not very well developed. Now, it is just a relay that triggers if the slip value reaches the limits. It can be replaced by proportional-derivative or proportional-integral-derivative controller in the future to improve the performance of ABS.

There is definitely the possibility to add more surfaces for the tests and develop scenes with different dangerous situations. It would add more user experience and it will increase the meaning of using ABS instead of hard locking the wheels.

Of course, four-wheel vehicle is not the limit here. ABS can be developed for other vehicles such as motorcycles, planes etc. In this thesis all the four wheels have ABS, but it can be applied on any wheel and disabling ABS on one of the wheels will lead to a different experience.

Mechanical side of the vehicle is not very well investigated and it could be calibrated through UE4 features such as Blueprints. The whole project is developed using Blueprints, but there is a possibility to improve physics or logic through coding using C++. So, developing the libraries for the project, instead of using macros or constructors in Blueprint, would be a way to go.

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