Implementation and Analysis of Platoon Catch-Up Scenarios for Heavy Duty Vehicles

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KTH Electrical Engineering

Master's Degree Project

Stockholm, Sweden 2013

XR-EE-RT 2013:008

Implementação e análise de cenários de estabelecimento de pelotões de veículos pesados

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Dissertação para a obtenção de Grau de Mestre em

Engenharia Eletrotécnica e de Computadores

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Junho 2013

To my parents.

Acknowledgments

There are many people I would like to thank for supporting me during my academic career.

I would like to start acknowledging my examiner Karl Henrik Johansson who has given me the opportunity to work in the Automatic Control department and in the Smart Mobility Lab with all the best conditions possible. Your advices and detailed comments are irreplaceable.

Then, I would like to show my gratitude to the amazing support of my supervisor Jonas Mårtensson. Your advices, availability, good mood, enthusiasm and dedication made everything a lot easier and rewarding for me. Furthermore, this project would not be possible without the research made by Kuo-Yun Liang who has helped me with all the technical and mathematical details.

I have to reserve a special thanks for José Araújo that introduced me to the lab and presented me to my examiner. Your constant compliments, advices, the inspiring discussions and the football afternoons were a fantastic motivation to continue the good work!

Thanks to Matteo Vanin and Mani Amoozadeh for the inspiring days spent in the Smart Mobility Lab. We finally got the good chairs and the window sills were not cleaned!

A sincere thanks to Lígia Fernandes, Inês do Ó, Inês Felix, João Feio, João Carriço, Tiago Rodrigues and Joana Vieira for your support during my academic career. Even though you are not here with me right now, I owe you my gratitude for what you have done.

Another sincere thanks to Elísio Quintino and Julius Adorf, the best corridor mates that one can have!

I have to acknowledge Instituto Superior Técnico in Portugal and The Royal Institute of Technology in Sweden for giving me the possibility of studying in two of the best universities in the world and learn from the best.

A heartfelt thanks goes to João Pedro Alvito not only for the partnership in this thesis but for the last 5 years that culminated with it. You have been my partner in almost all projects and our results have been fantastic. Thanks for your unlimited friendship and all the patience for my countless idiosyncrasies! This project would not have been possible without our FIFA matches, football watching marathons and long nights awaken doing brainstorming. No thanks thank you enough for your support!

I would specially like to thank my girlfriend Madalena. Your love, care, dedication and patience were key to overcome the great difficulty of being away from my beloved. Thanks to you, the few last years have been the best years of my life.

Last but definitely not the least, there are no words to express my gratitude to my parents and my grandparents. Mom and dad, thanks for encouraging me to study engineering. Thanks for everything that you gave me and that enabled me to study abroad. Grandparents, thanks for all the love and care you have bestowed. Without you I could never get to where I am. I hope to make you all proud.

Resumo

O estabelecimento de pelotões de veículos pesados é, hoje em dia, um tema muito actual, tanto no mundo académico como na indústria. A formação de pelotões é uma forma inteligente de resolver os problemas como a segurança, o congestionamento do tráfego, consumo de combustível e as emissões de gases nocivos, dado que sua concepção permite que vários veículos conduzam perto uns dos outros, permitindo ainda assim a manutenção de todos os requisitos de segurança. Dessa forma, cada veículo irá usar o chamado efeito de *slipstream*, uma redução da resistência do ar que ocorre atrás de veículos, consumindo assim menos combustível e reduzindo, consequentemente, as emissões de combustível. Além disso, aumenta o fluxo de tráfego visto que a distância entre os veículos é significativamente reduzida. O conceito e a ideia de pelotões não é particularmente nova, mas só nas últimas décadas é que tecnologia necessária emergiu e os tornou possíveis.

Foram desenvolvidos cenários de formação de pelotões de camiões no completamente renovado *Smart Mobility Lab* na KTH em Estocolmo. Um programa em LabVIEW foi desenvolvido permitindo um controlo robusto e estável dos camiões, permitindo-lhes andar numa rede de estradas totalmente nova que foi projectada e construída de raiz. Os camiões são capazes de andar sobre uma trajetória pré-definida, mudar de faixa e estrada, formar pelotões uns com os outros com diferentes distâncias entre eles, ultrapassar quando outro mestre de pelotão é definido a fim de assumir a sua liderança e mudar a velocidade para apanhar outro camião e assim formar pelotões, entre outros.

A última parte desta tese é composta pela análise dos cenários desenvolvidos no laboratório. Estes cenários representam diversas situações de formação de pelotões com camiões, focando o caso em que um camião é obrigado a acelerar para apanhar outro. Os objectos de estudo foram o combustível poupado devido ao facto de ser formado um pelotão e o momento em que se dá ponto de equilibro, ou seja, o rácio de distâncias em que nem continuando sozinho nem formando um pelotão é melhor. Usando modelos de camiões reais e modelos de consumo de combustível, foram realizadas simulações a fim de verificar os benefícios da formação de pelotões e os dados adquiridos foram posteriormente analisados. Finalmente, foram também tiradas conclusões a partir de experiências em que os parâmetros tais como o aumento da velocidade para que o camião que vai atrás apanhe o camião à frente e a distância entre camiões quando o pelotão é formado eram diferentes em cada tentativa. Concluiu-se que um único camião tem de viajar 8 a 15 vezes mais do que a distância que inicialmente o separa do camião à frente para poder economizar 5 a 13% de combustível, dependendo de se tratar de um camião ou um pelotão já existente. Além disso, é menos benéfico para um pelotão já formado decidir capturar outro camião.

Palavras-chave: Estabelecimento de pelotões, veículos pesados, consumo de combustível, redução da resistência do ar.

Abstract

Heavy duty vehicle (HDV) platooning is currently a big topic both in the academic world and in industry. Platooning is a smart way to solve problems such as safety, traffic congestion, fuel consumption and hazardous exhaust emissions since its concept enables several vehicles to drive close to each other while maintaining all the security requisites. This way, each vehicle will use the so called slipstream effect, an atmospheric drag reduction that occurs behind a traveling vehicle, consuming less fuel and consequently reducing the exhausted gases. Furthermore, it increases the traffic flow since the distance between vehicles is significantly reduced. The concept and idea of platooning is not particularly new, but only in the last few decades new technology made it possible.

HDV platooning scenarios for scale model trucks were developed in the completely renovated Smart Mobility Lab, in KTH, Stockholm. A LabVIEW application was developed giving a robust and stable control of the trucks while following and driving on a newly designed and built road network. The trucks are able to follow a predefined trajectory, change lane and road, platoon with each other with different platooning distances, overtake when the platoon master is changed in order to take the lead of the platoon and change speed to catch up, among other features.

The last part of this thesis covers the analysis of the scenarios developed in the testbed. These scenarios represent several situations of HDV platooning, particularly the platoon catch-up case. The main object of this study was the saved fuel due to platooning, and the break-even point, i.e. the distance ratio when neither driving alone nor catching up a platoon ahead would be more feasible. Using real HDV models and their fuel consumption models, simulations were performed in order to check the benefits of platooning and the data got from the scenarios was analyzed. Finally, conclusions were drawn from the experiments where the parameters such as HDV weight, speed increment when catching up and intermediate distance when platooning were different in each trial. It was concluded that a single HDV has to travel 8 to 15 times more than the initial distance that separates it from the HDV(s) ahead and it can save 5 to 13% of fuel depending if catching up a single HDV or a platoon an already existing platoon. Furthermore, it is less beneficial for a platoon already formed to decide to catch up another HDV.

Keywords: Heavy duty vehicle, platooning, fuel consumption, air drag reduction.

Sammanfattning

Fordonståg är för närvarande ett stort ämne både i den akademiska världen och inom industrin. Platooning är ett smart sätt att lösa problem såsom säkerhet, trafikstockningar, bränsleförbrukning och skadliga avgaser då konceptet möjliggör att flera fordon kan köra nära varandra samtidigt som alla säkerhetsaspekter bibehålls. På så sätt kommer varje fordon nyttja de så kallade fartvindseffekterna som är en reduktion av luftmotståndet som inträffar bakom ett fordon i rörelse vilket då leder till mindre förbrukat bränsle och därmed reducerade avgaser. Dessutom flödar trafiken bättre eftersom avståndet mellan fordonen minskas avsevärt. Konceptet och idén om Fordonståg är inte särskilt nytt men det har inte varit implementerbart förrän de senaste decennierna då ny teknik har gjort detta möjligt.

Fordonstågsscenarierna i detta projekt var framtagna i det nya Smart Mobility Lab på KTH i Stockholm. En LabVIEW-applikation har utvecklats som ger en robust och stabil reglering av model lastbilar som kan följa och köra på ett nydesignat vägnät. Lastbilarna har möjlighet att följa en fördefinierad bana, byta körfält och väg, köra i fordonståg med varandra med olika relativa avstånd, byta ordning på fordonen i fordonståget samt många andra funktioner.

Den sista delen av denna avhandling omfattar analys av de scenarier som utvecklats i testmiljön. Dessa scenarier representerar flera situationer som kan ske för fordonståg, särskilt fallet för ett fordon att köra ikapp en fordonståg. Det huvudsakliga syftet med studien var att analysera bränslebesparingen, som fŒs genom att kšra i fordonståg, samt den brytpunkt som definieras som det avstånd mellan fordonståget och det ensamma fordonet då, mer bränsle sparas om fordonet kör ensam än om den skulle åka ikapp fordonståget. Genom att använda riktiga modeller för tunga fordon och deras bränsleförbrukning kunde simuleringar för att kontrollera fördelarna med fordonståg utföras och de data som kom från dessa scenarier analyserades. Slutsatser drogs från experimenten där parametrar såsom hastighetsökning när fordonet ska komma ikapp fordonståget samt det mellanliggande avståndet mellan fordonen i fordonståget ändrades. Slutsatsen var att ett enda tungt fordon måste färdas 8 till 15 gånger längre än det initiala avståndet till fordonståget men detta kan spara 5 till 13% av bränslet beroende på antalet fordon i fordonståget. Dessutom är det mindre fördelaktigt för en fordonståg som redan bildats att åka ikapp ett annat fordon eller en annan fordonståg.

Keywords: Tunga fordon, platooning, bränsleförbrukning, luftmotstånd minskning.

Contents

Acknowledgments v

Resumo vii

Abstract ix

Sammanfattning xi

Nomenclature xvii

Acronyms and Abbreviations xix

1 Introduction **1**

1.1 Motivation 1

1.2 Background 3

1.2.1 Vehicle Platooning 3

1.2.2 Cruise Control and Adaptive Cruise Control 3

1.2.3 V2X Communication 4

1.2.4 Platoon Catch Up 4

1.3 Problem Definition 5

1.4 Related Work 5

1.4.1 Main Related Work 5

1.4.2 Other Related Work 6

1.5 Thesis Objectives 7

1.6 Thesis Contributions 8

1.7 Thesis Outline 9

2 Experimental Setup **11**

2.1 Motion Capture System 13

2.1.1 Working Principle 13

2.1.2 Positioning of the Cameras 14

2.1.3 Markers Configuration and Placement 14

2.2 Communications 15

2.2.1 Communication Between Mocap and PC 15

2.2.2 Communication Between PC and Trucks 15

2.2.3 Communication Between PC and Visualization Tool 16

2.3 Road Network Design and Creation 16
2.3.1 Concept and Ideia 16
2.3.2 States Division and Trajectories 17

3 Control of the Trucks **19**
3.1 Truck Kinematics Model 19
3.2 Truck Controllers 20
3.2.1 Speed Controller 21
3.2.2 Steering Controller 21
3.2.3 Platoon Controller 22
3.3 Control Algorithms Details 24
3.3.1 Controlling the Speed 24
3.3.2 Controlling the Steering 26
3.3.3 Driving on the road network 27
3.3.4 Platooning 28
3.3.5 Overtaking 31

4 HDV Modeling **33**
4.1 HDV Model 33
4.2 Fuel Consumption Model 34
4.3 Fuel Ratio 35
4.4 Break-Even Ratio 36
4.5 Scaling from Trucks to HDVs 36

5 Experimental Scenarios and Results **37**
5.1 Scenario 1 - One HDV catching up one HDV 38
5.2 Scenario 2 - One HDV catching up two HDVs 41
5.3 Scenario 3 - One HDV catching up two HDVs and the middle one has another destination 44
5.4 Scenario 4 - Two HDVs catching up one HDV 46
5.5 Scenario 5 - One HDV catching up one HDV from another road 48
5.6 Scenario 6 - One HDV catching up one HDV with another destination 49

6 Conclusions and Future Work **51**

References **56**

A User's Manual **57**
A.1 System Overview 57
A.1.1 Key Features 59
A.1.2 Who are we? 60
A.2 Getting Started with the Tamiya Trucks 61
A.2.1 T-Motes set up 62

A.2.2 Trucks Set Up . . . 64
A.3 Getting Started with QTM . . . 65
A.3.1 How to Define a truck as a 6DOF Body . . . 66
A.4 Trajectory Creation With Matlab . . . 71
A.4.1 Prerequisites . . . 71
A.4.2 Matlab Qualysis Client . . . 71
A.4.3 Configuration File . . . 72
A.4.4 Trajectory Creation . . . 74
A.5 Getting Started with the LabVIEW Program . . . 77
A.5.1 Prerequisites . . . 78
A.5.2 Program Structure . . . 79
A.5.3 Running the LabVIEW program . . . 82
A.6 Getting Started With The Visualization Tool . . . 85
A.6.1 Prerequisites . . . 85
A.6.2 Running The Visualization Tool . . . 87
A.6.3 Visualization Tool . . . 89
A.7 Troubleshooting . . . 93
A.7.1 Trucks . . . 93
A.7.2 Trajectory Creation . . . 94
A.7.3 Visualization Tool . . . 94

Nomenclature

α	Slope of the road.
$\bar{\eta}_{eng}$	Mean combustion efficiency in the engine.
δ	Indicates whether fuel is injected into the engine or not.
κ	Platooning incentive factor.
λ	Fuel consumed ratio.
ϕ	Air drag parameter.
ρ_a	Air density.
ρ_d	Energy density of diesel fuel.
A_a	Frontal area of the vehicle.
c_D	Air drag coefficient.
c_r	Roll resistance coefficient.
F_b	Braking force.
f_c	Instantaneous fuel consumption.
F_g	Gravity force.
F_r	Roll resistance force.
F_{ad}	Air drag force.
F_{eng}	Engine force.
g	Acceleration of gravity.
m	Accelerated vehicle mass.
T	Total time.
v	Vehicle speed.

Acronyms and Abbreviations

ADR	Air Drag Reduction.
DOF	Degrees Of Freedom.
GPS	Global Positioning System.
HDV	Heavy Duty Vehicle.
IR	Infra-Red.
LUT	Look-Up Table.
MoCap	Motion Capture System.
PID	Proportional-Integral-Derivative.
QTM	Qualisys Track Manager.
RT	Real-Time.
SML	Smart Mobility Lab.
V2I	Vehicle-to-Infrastracture.
V2V	Vehicle-to-Vehicle.

Chapter 1

Introduction

1.1 Motivation

The world financial crisis, especially the European financial crisis, triggered the emergence of the need for more sustainable and efficient economies. The world population will exceed more than 8 billion people in less than 15 years meaning that the need of goods will grow at least at the same rate [12]. In rapid growing economies, like in some developing countries, the need of good growth rate could be even bigger. Consequently, the traffic intensity will continue increasing making traffic congestions a major concern for decision makers. Furthermore, predictions indicate that the classification of road traffic injuries will jump from the 9th place in 1990 to the 3rd place in 2020 in the ranking of causes of the global burden of disease [24].

Studies done by the European Commission, described in [11], show that traffic congestions cost Europe about 1% of the European Union's (EU) gross domestic product (GDP) every year. The transport industry is heavily dependent on imported oil and this is another major problem since the oil price is expected to double its price in less than 20 years. In the EU, the transport industry depends on oil for more than 96% of its energy needs. The transport industry is responsible for about a quarter of the EU's greenhouse gas emissions where 71.3% was the share of road transport in 2008 and this industry is the main contributor of the increase in oil consumption in the last decades. The transport industry is the backbone of today's modern economy, directly employing more than 10 million people in the EU, accounting for 4.5% of total employment, and represents 4.6% of EU's GDP. The increasing emissions CO_2 and the greenhouse effect problems are part of a very actual discussion and while most sectors have been reducing CO_2 emissions, transport's quota continues increasing.

Naturally, a lot of research and work has been done during the last few decades to reduce these greenhouse gas emissions. Consequently, the long haulage vehicles have been reducing the fuel consumption every year which, naturally, yields to less pollution. The vast majority of the approaches taken in the last decades to the above problems has been purely technical in the sense of optimizing the efficiency of engines or to produce lighter vehicles, electric cars or hybrid cars. However, stricter requirements about the vehicle emissions in Europe mean that other ways of reducing the fuel consumption must be found. Hence, in parallel with these approaches, research about intelligent transport systems is being developed. In the 1960's and 1970's emerged the idea of driving in formations, as platoons. In a platoon all vehicles drive close to each other taking advantage of the air drag reduction due to the proximity to the vehicle ahead. Driving too close to a vehicle ahead at high speeds is not comfortable for a human driver and sometimes not possible. However, it is feasible using automated navigation systems. It was studied that in an ordinary life cycle of an European long haulage heavy duty vehicle (HDV), the fuel costs represent almost one third of the total life cycle costs [4]. Since the air drag constitutes almost one fourth of the total force that acts against an HDV it is very important to find ways to reduce it as much as possible. Aerodynamics improvements were made on the HDVs but platooning is being in the last years studied as a major solution for this problem. Research presented in [6] shows that it is possible to reduce the fuel consumption up to 7.7% when platooning. Studies under the Safe Road Trains for the Environment (SARTRE) project [25] conclude that this fuel reduction can potentially reach 20%, the road fatalities will be reduced by 10% and a smoother traffic flow with potential increase in traffic flow. Well known researchers, such as Levine and Athans [17], Melzer and Kuo [23] studied the problem control of vehicular platoons. However, it was only in the last decade that platooning-enabling technology saw the light and made the implementation of such concepts feasible. Countless examples are given in [6]: advanced driver assistance systems (ADAS), downhill speed control (DHSC), cruise control (CC), adaptive cruise control (ACC) [15], information about the road grade [26] and communication technology such as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I).

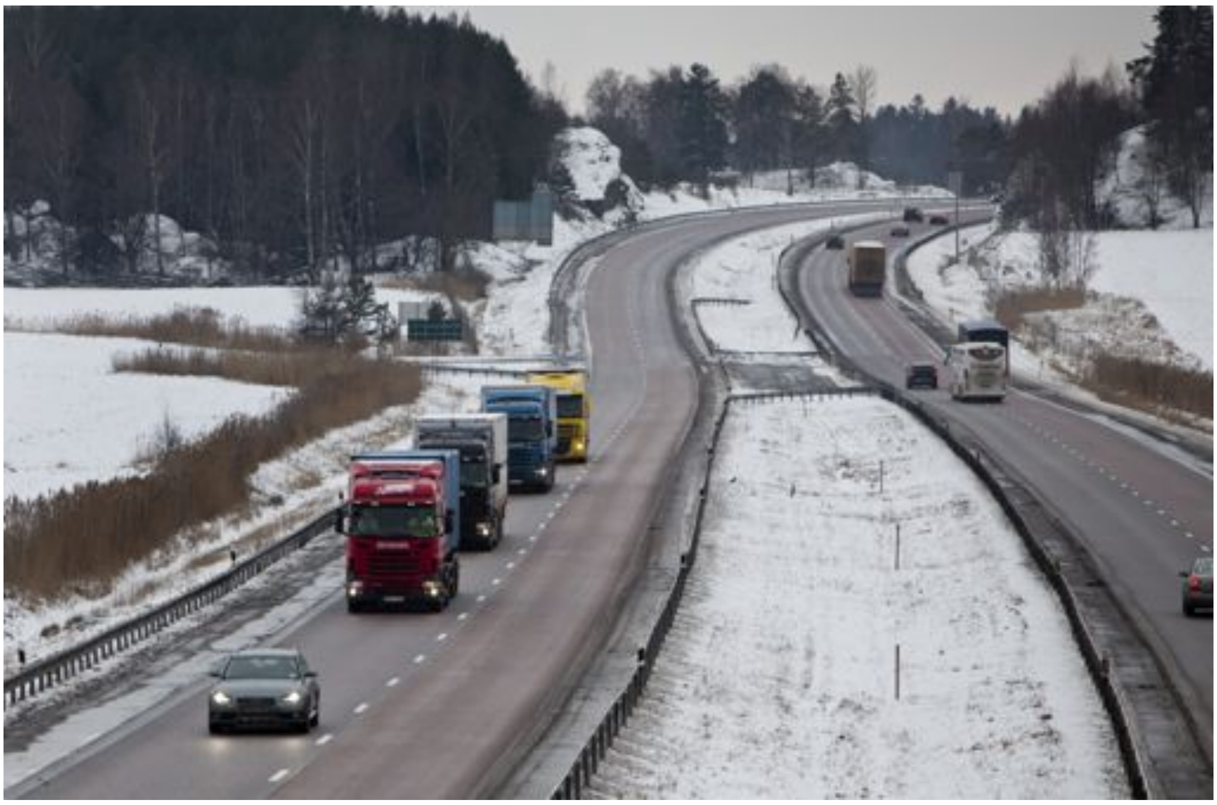


Figure 1.1: HDV platoon demonstration (courtesy of Scania).

1.2 Background

The idea of driving vehicles in formations, as platooning, is not new. However only a few decades ago the technology that made it possible became available. The so called electronic control units (ECUs) are now faster, cheaper and smaller because they are widely used, not necessarily only in the vehicle industry. Innumerable examples can be given such as wireless networks, the Global Positioning System (GPS), temperature sensors, the Anti-lock Braking System (ABS), the Electronic Stability Program (ESP), airbag, etc.

1.2.1 Vehicle Platooning

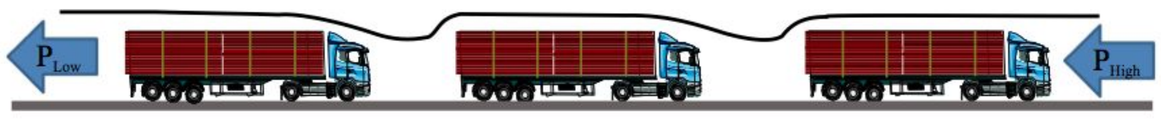


Figure 1.2: HDV platoon formation and air drag reduction (reprinted from [6]).

Platooning (Figure 1.2) is a smart way to solve the problems such as safety, traffic congestion, fuel consumption and harmful exhaust emissions since its concept enables several vehicles to drive close to each other maintaining all the security requisites. This way, each vehicle will use the so called slipstream effect, an atmospheric drag reduction that occurs behind a traveling vehicle, consuming less fuel and consequently reducing the emissions. Furthermore, it increases the traffic flow since the distance between vehicles is significantly reduced.

1.2.2 Cruise Control and Adaptive Cruise Control

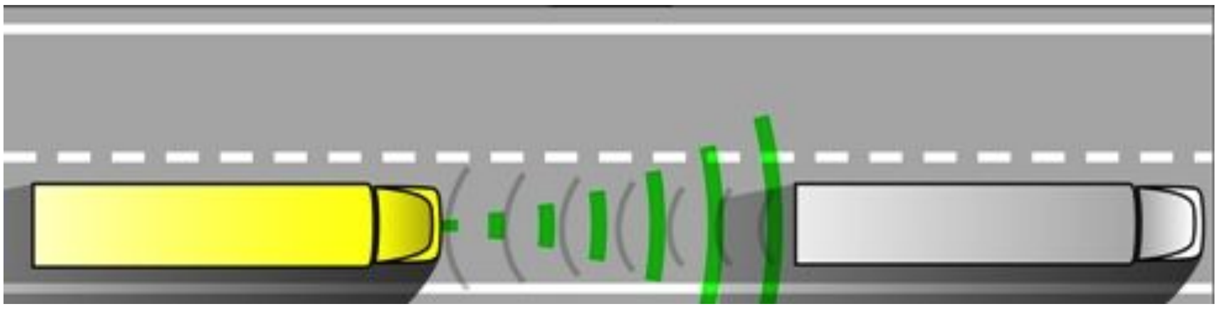


Figure 1.3: ACC is a cruise control system with enhanced functionality that helps the driver to keep a safe distance to other traffic ahead and alerts the driver if manual intervention is required (courtesy of DAF trucks).

Cruise Control (CC) is present in almost all commercial vehicles. It is a system that automatically controls the speed of the vehicle to a predefined speed reference set by the driver.

Some new vehicles have an extension of the CC called Adaptive Cruise Control (ACC) (Figure 1.3). ACC uses the idea of CC but takes into account the vehicle ahead, if there is any. In that case, it lowers the vehicle's speed so it can maintain a reference distance to the vehicle ahead. In short, ACC is activated if an ahead vehicle in front exists and its speed is lower than the one predefined by the driver. Otherwise it behaves as the original CC.

When platooning, the ACC is inherently present in the sense that the platooning HDVs maintain the same speed as the HDV in front of them.

1.2.3 V2X Communication

Figure 1.4: V2X Communication (courtesy of US Department of Transportation).

V2X is the combination of two types of vehicle communication: Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastracture (V2I) (Figure 1.4).

V2V communication enables a vehicle to a 360 degree awareness of the position and speed of other vehicles. It sends the driver warnings or advices in order to avoid crashes. This type of communication makes the platooning possible, since every vehicle has the information of what is the status and intentions of the surrounding vehicles in order to make driving adjustments accordingly.

V2I communication allows the vehicle to gather important information such as the traffic flow, traffic accidents, road work ahead and information about the road grade. This can lead to fuel and time savings since the paths are planned using more information.

As a result, V2X communication allows cooperative driving and automated platooning systems.

1.2.4 Platoon Catch Up

Today, HDVs are scattered on the road network and there are several ways to coordinate them in order to platoon to reduce the fuel consumption. For example, rerouting the HDVs to align when the road merges ahead or if the HDVs are on the same road then the leading HDV can slow down or the following HDV can catch up. In this thesis, the catch up concept is studied in detail.

Even reducing the fuel consumption when platooning, it is not trivial to decide when should a truck catch up another in order to platoon or not. One has to consider the fuel consumed during the catch up phase and the fuel saved during the platoon phase. This is where the concept of break-even ratio is applied (explained in Section 4.4).

1.3 Problem Definition

The purpose of this thesis is to answer the question ”when is it fuel efficient for a heavy duty vehicle to catch up with a platoon?” in a practical point of view. This question was studied and answered in [19]. The models that will be used are a longitudinal HDV model based on Newton’s second law of motion and the real-time fuel consumption model studied in [21] and used in [19]. One will make use of the the break-even ratio defined in [19] to evaluate quantitatively the benefits of catching up, thus answering the above question.

In this thesis project, an integrated system where HDV platooning scenarios can be developed, focusing the catch up situation. This integrated system includes the usage of a Motion Capture System in order to track scale model trucks in real time that are controlled throughout a road network using a LabVIEW program. Using a system like this, the data acquired in the scenarios developed is converted into real-world values thereby representing in scale, real world problems and situations.

The scenarios should address a wide range of situations within the scope of the catch up topic. The influence of parameters such as the platooning distance and the number of trucks involved in the catch up phase and posterior platooning phase should be studied. This thesis also proposes answers to the following questions:

1. Do the assumptions made in [19] such as flat road, no traffic and that accelerations will not influence the catch up decision, influence the break-even point and the total fuel saved?

2. What is the impact on the benefits of catching up if one of the HDVs leaves the platoon in the middle of the trip?

1.4 Related Work

The literature on vehicle platooning is quite substantial so only those works more directly related to this thesis will be covered here. Among those one should point out a licentiate thesis on Automatic Control by Assad Alam presented in [6] and a recent paper submitted to the 7^{th} International Federation of Automatic Control (IFAC) Symposium on Advances in Automotive Control by Kuo-Yun Liang, Jonas Mårtensson and Karl Henrik Johansson [19].

Since most of the work will be done in the SML in KTH, Stockholm, the work done by Alejandro Marzinotto [22] and the project course work for Automatic Control reported in [13] will be used as a starting point, especially the work using Scania’s scale trucks.

1.4.1 Main Related Work

The focus of Alam’s research [6] is to establish and validate real constraints of fuel optimal control for platooning vehicles. The fuel reduction potential was investigated throughout simulation models and experimental results that were derived from standard vehicles traveling on a Swedish highway. Fuel reduction of $4.7 - 7.7\%$ was proven to be dependent on the inter-vehicle time gap and does not compromise safety. Furthermore, a systematic design methodology for inter-vehicle distance control based on linear quadratic regulators (LQRs) is presented and it is shown that a decentralized controller provides a good tracking performance: it is robust, it lowers the control effort downstream in the platoon and it is string stable for an arbitrary number of vehicles in the platoon.

In [19] it was studied whether it is beneficial or not for a HDV to drive faster in order to catch up and join a platoon ahead. Using a longitudinal HDV model and a standard Scania fuel consumption model, a formula is derived to calculate the break-even ratio. This ratio is defined as the distance ratio when neither driving alone nor catching up a platoon ahead would be more feasible. Furthermore, simulations were made in order to forecast fuel savings. It was proven that, comparing to continuing driving alone, a fuel saving of 7% is possible if the follower vehicle decides to increase the speed from 80km/h to 90km/h in order to catch up and form a platoon with the vehicle ahead when the distance to the vehicle ahead is 10km and the trip length is 350 km. These conclusions are derived assuming flat road, no traffic and that accelerations will not influence the catch up decision break-even ratio.

1.4.2 Other Related Work

In Marzinotto's master thesis [22] an experimental testbed was developed to demonstrate several scenarios of multi-agent systems such as platooning and surveillance using scale models of Scania trucks and quadrocopters. Vehicle dynamics were studied and simulations and experiments were performed in the testbed. Both the hardware and the software used is thoroughly explained. Besides the trucks and the quadrocopters, several T-Motes for communication were used as well as infra-red (IR) sensors, Pololu boards to control the servos. In the thesis the problem of creating a controller capable of forming a platoon of an arbitrary number of vehicles was approached and, in order to do that, the implementation of a speed and a steering controller for each vehicle in a platoon and a framework where it is possible to share information between them were described. Furthermore, an implementation of a controller capable of removing any vehicle from the platoon except for the leader or inserting a vehicle into an existing platoon rearranging the remaining vehicles in the same platoon was proposed.

Using the same testbed, the project group in the Automatic Control project course designed and built an integrated scenario which consisted in controlling wirelessly several scale models of Scania trucks, a quadrocopter and a stationary tower crane. They designed and implemented Proportional-Integral-Derivative (PID) controllers for the scale trucks and the quadrocopters and a Model Predictive Controller (MPC) for the crane. Additionally, they were also responsible for designing a messaging scheme such that all the agents could communicate with each other. Finally, the MoCap from Qualisys AB was used to retrieve the location information in each moment. The MoCap offers an easy way to obtain accurate 3D and six degrees of freedom (DOF) position in real time. It consisted of four cameras strategically placed in the lab and several passive IR markers. In the final scenario the trucks were able to follow a certain path, navigate on the road network, arrive at a given destination and communicate with the crane and the quadrocopters. The trucks were also able to drive in platooning formation and avoid collision with other trucks while on the road network that was also developed during the project.

Important work done in this area was also done by Macias in his master thesis [21]. Here, it is deeply studied the requirements of a fuel consumption model for HDVs. Two methods were proposed: the look-up tables and real time calculations with a fuel consumption model. The goal of this study was to find eco-routes for HDVs, i.e the route between two points that minimize the fuel consumption of the truck which is not necessarily the shortest in time or distance. It was concluded that the Real-Time model (RT-Model) and the Oguchi Model were the best ones. In fact, they are used in [19] as well as in this thesis.

Other research made by Alam [5] is worth mentioning since it is focused on the control methods that optimize the fuel efficiency of a HDV due to the several road constraints like curvature speed limitations, road grade and posted road speed. A non-linear model for the HDV was derived and Pontryagin's Principle and LQR methods were discussed. It was concluded that a switching controller based on optimal control and engineering experience minimizes the fuel consumption $5-15\%$, and the brake wear by $5-15\%$ while the traveling time is only increased by $1-2\%$.

Liang in [18] considers the advantages of forming vehicle platoons, a LQR and a Linear Quadratic Tracking (LQT) controller, with respect to a given information structure for a three-vehicle platoon. This resulted in an energy reduction between 8.4% and 13.1% in the vehicles on a highway between Södertälje and Norrköping with a time headway of 0.25 seconds. The energy consumption was assumed to be proportional to the fuel consumption and it was used as cost value.

1.5 Thesis Objectives

The main goal of this master thesis is to show in practice, using scaled models of Scania HDVs[1], the implementation of solutions for the problem "when is it fuel efficient for a heavy duty vehicle to catch up with a platoon?" described in [19]. The scenario for the experiments is the Smart Mobility Lab (SML) located at KTH, Stockholm. There, a Motion Capture System (MoCap) from Qualisys AB composed of 12 cameras is installed. A lab environment is specially interesting for developing these experiments since one is able to try a huge range of scenarios and possibilities without having to drive real trucks. It is a lot easier to experiment the feasibility of the control algorithms and situations proposed on a controlled environment than on a real highway with real trucks.

Most of the available literature assumes that the vehicles are already in a platoon. However, that assumption is not very realistic. Thus, when an HDV or a platoon of HDVs is on the road, the system must be able to autonomously decide if it should catch up or not with other vehicle(s) or platoon(s), in known position, velocity and trip destination, considering the pros and cons of doing so.

The work was divided in three phases:

1. designing, in partnership with another master student [9], a completely new testbed where it is possible to simulate several different scenarios. This included:
    (a) renovating the Smart Mobility Lab, which included increasing the working space and installing the complete MoCap system with twelve cameras;
    (b) designing a scaled road network on which the trucks are able to drive;
    (c) building the entire road network on the lab's floor;

[1]For now one, the designation trucks will be used when referring to the scaled trucks and the designation HDV when referring to the real trucks. The meaning should be obvious from the context.

   (d) developing a program that creates the trajectories which the trucks are able to follow;
   (e) developing a program that is able to control the trucks through the road network. The trucks should be able to follow the trajectories created, do platooning with each other, overtake each other, change from one road to another and stop due to virtual traffic lights;
   (f) developing a visualization tool that can be used in demonstrations. It should be a real-time tool where the position, speed and some other important informations appear in a form of plot, numbers or text allowing the audience to understand what is happening in each moment.

2. developing and implementing demonstration scenarios where the HDV platoon catch up problem is clearly stated and visualized. Different scenarios and theoretical improvements were proposed such as the catch up of several trucks at the same time, the benefits of catching up for the entire platoon and possible fuel losses due to the decision of leaving the platoon from one of the trucks. The data collected in the experiments using the scale trucks is converted in real-time during the experiments in order to apply the real HDV and fuel consumption models;
3. concluding about the testbed overall performance, the feasibility of all different scenarios and the possible benefits of catching up.

The outcome of the thesis does not intend to be a new solution for the problem studied in [19] but to design, implement and integrate such a simulation environment that complements the constraints of the Smart Mobility Lab and make a realistic down-scaled demos of several different scenarios on this topic.

1.6 Thesis Contributions

- Development of HDV platooning scenarios, focusing the catch up situation, in the completely renovated Smart Mobility Lab, in KTH, Stockholm;
- installation of the full complete MoCap system with twelve cameras strategically positioned;
- design and built a newly road network;
- development of a LabVIEW application giving a robust and stable control of the trucks while following and driving on the road network. The trucks are able to:
  - follow a predefined trajectory;
  - change lane and road;
  - platoon with each other with different platooning distances, i.e distance between two consecutive vehicles;
  - overtake when the platoon master is changed in order to take the lead of the platoon;
  - change speed to catch up;
  - stop due to virtual traffic lights.

- development of a visualization tool in MATLAB that allows audience-targeted demos. This visualization tool includes all the relevant data of the running demo such as real speed, distance between trucks and fuel consumption values;
- perform real-time demos with both the visualization tool and the trucks running simultaneously. Translation of the scaled trucks data retrieved in the experiments to real trucks data in order to simulate fuel consumption.

The HDV platooning scenarios are used to demonstrate the feasibility and the phases involved in catching up and platooning situation. Using real HDV models and their fuel consumption models, simulations were performed in order to check the benefits of platooning and the data taken from the scenarios was analyzed. These simulations were performed at the same time as the scale trucks drove on the road network. The real models were applied scaling the trucks to real HDVs with all the assumptions that it implies.

Conclusions were drawn from the experiments where the parameters such as HDV, speed increment when catching up and intermediate distance when platooning were different in each trial. It was concluded that:

- a single HDV has to travel to travel 8 to 15 times more than the initial distance that separates it from the platoon, driving at constant speed of 80km/h, and it can save 5 to 13% of fuel depending if catching a single HDV or a platoon already existent and if increasing the speed $12,5\%$ or 25%;
- it is less beneficial for a platoon already formed to decide to catch up another HDV;
- when one of the HDVs leaves the platoon the others either stay alone, if there was only one more HDV in the platoon, or they continue platooning with the remaining HDVs of the previous platoon. The fuel benefits, comparing to the situation when there is no HDV leaving the platoon, decrease for the HDVs that are behind the HDV that leaves the platoon.

1.7 Thesis Outline

The outline of the thesis is as follows. In Chapter 1 the project developed in this thesis is clearly motivated. The concept and the idea of platooning are explained together with the most important technologies that made it possible. Furthermore, the problem dealt throughout this thesis is defined and the most important literature about HDV platooning is reviewed in detail. The methods used and their conclusions are explained and an overview about the influence of those works on this thesis is made. Finally, the objectives and contributions are enumerated.

In Chapter 2 the experimental setup in carefully presented and detailedly explained. The working principle of the Motion Capture System, the camera positioning as well as the marker placement idea are explained. Then, the communication between all the elements is overviewed. Finally, the design of the road network is then presented as well as its usefulness.

In Chapter 3 the models used to control the trucks in the lab are introduced. The trucks' kinematics are considered to be the same as car-like kinematics. The trucks' PID controllers are then explained. In the end of the chapter, the problem approached in this thesis is presented. Finally, the implementation of the speed, steering, platooning and overtaking controllers is detailedly justified together with its performance and the calibration procedures.

In Chapter 4 a longitudinal HDV model based on Newton's second law of motion is considered and a simplified fuel consumption model is introduced together with the model parameters typical values. Furthermore, from the definition of fuel model, both fuel ratio and break-even ratio formulas are presented. Finally, the reasoning used for scaling the results obtained with the scale trucks to the real HDVs is explained.

Chapter 5 addresses the development of six HDV platooning scenarios on the testbed. These scenarios are supposed to represent HDV platooning situations, particularly the influence of the catching up decision. The models previously described are applied in real time experiments and the parameters such as HDV and platooning distance are changed and their influence evaluated. The scenarios cover a wide range of HDV platooning situations. It is studied when it is good for a HDV to decide to catch up another and which are the more and less beneficial cases. The results obtained are usually compared with theoretical results.

Finally, Chapter 6 provides the concluding remarks and future work ideas are provided.

Chapter 2

Experimental Setup

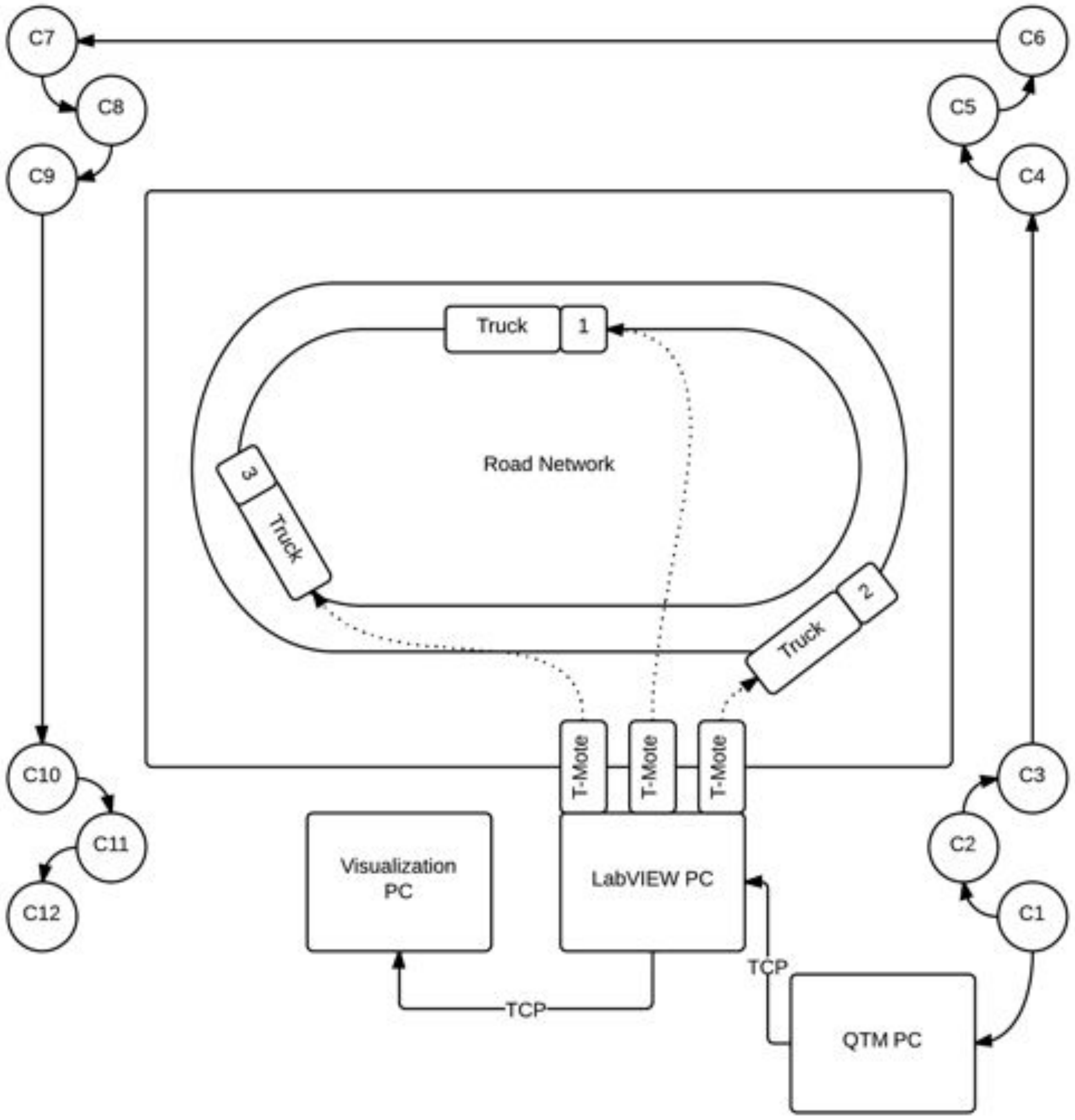


Figure 2.1: Experimental setup block diagram (reprinted from the appendix).

As can be seen in Figure A.1 the developed testbed has several different elements. The system has up to three PCs running at the same time, together with up to five trucks and the MoCap with twelve cameras. This chapter is fully dedicated to all the technical details of the testbed development such as how the communication between modules is accomplished and how are certain aspects implemented as well as their performance.

For a less technical description and to learn how to use and start the system please refer to the User's Manual in appendix. Here, it is not intended to detail material specifications, to understand that refer to [22] and [10].

This experimental setup was developed in partnership with other master student and his thesis also makes use of the testbed [9].

2.1 Motion Capture System

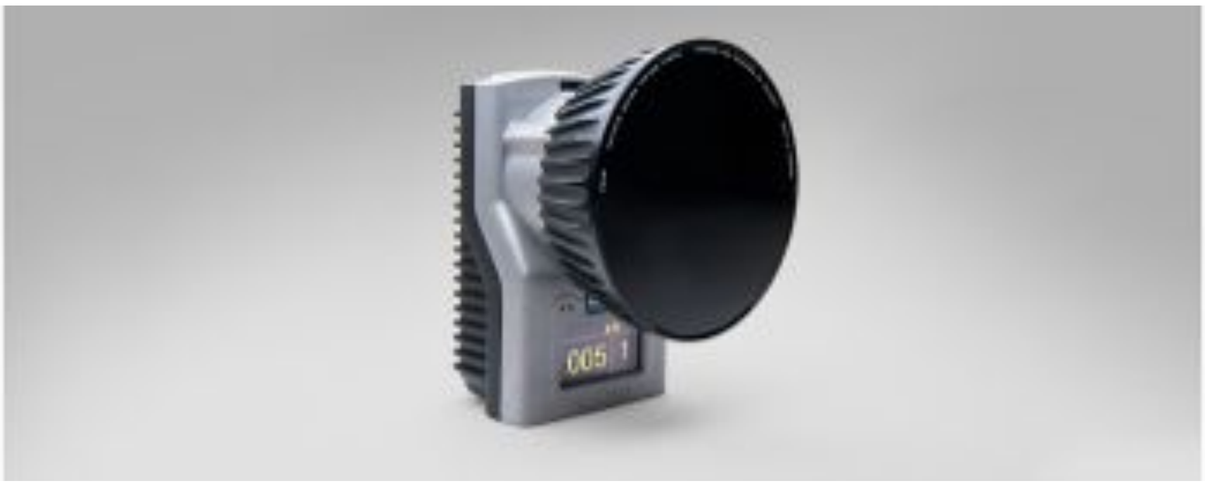


Figure 2.2: MoCap camera (courtesy of Qualisys AB).

The MoCap is constituted, in this testbed, by twelve cameras provided by Qualisys AB strategically positioned in the SML. It is used as an indoor global positioning system (GPS) and it is used for 6DOF real-time tracking of the trucks. The cameras are connected to a central computer running the Qualisys Track Manager (QTM) that provides the cameras' information to the other PCs.

2.1.1 Working Principle

The working principle of MoCap is similar, in fact, with GPS. It uses the principle of triangulation. In general, only two cameras are sufficient to know a 3D position of a point in space if both see that point and if the cameras position is known. Consequently, twelve cameras is more than enough to determine 3D coordinates of points in space. The cameras are infrared sensitive and the objects to be tracked are equipped with markers placed in strategic positions. These markers are small IR-reflective spheres.

2.1.2 Positioning of the Cameras

The twelve cameras are divided in four groups of three cameras. Each group of cameras is placed on the corners of the SML since it is cuboid-shaped. In all groups each camera is pointing to strategic locations as represented in Figure 2.3.

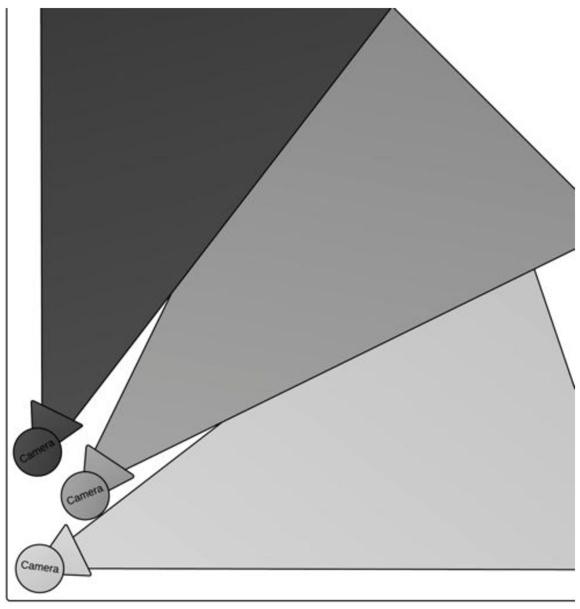


Figure 2.3: Smart Mobility Lab top-view. Cameras positioning setup on a corner.

The idea is to cover the whole space. In each group, two of the cameras cover the space using the orthogonal walls of the SML as guidance and the third one covers the spot that is left empty by the other two.

The whole system must be calibrated once in a while since, even with twelve cameras, the noise inherent to the utilization of the lab miscalibrates the system. The calibration is explained in detail onin [3].

2.1.3 Markers Configuration and Placement

To define a 6DOF Rigid Body in QTM at least three markers are required. The utilization of four markers is recommended since if one marker is hidden, the system still has the other three to perform the 6DOF tracking. This idea was used when designing the marker configurations for each truck. Each marker configuration must be unique and the markers used for representing the X and Y axis must not form an equilateral triangle. The definition of a 6DOF Rigid Body in QTM is explained detailedly in the appendix. The procedure for designing a marker configuration is explained in Figure 2.4.

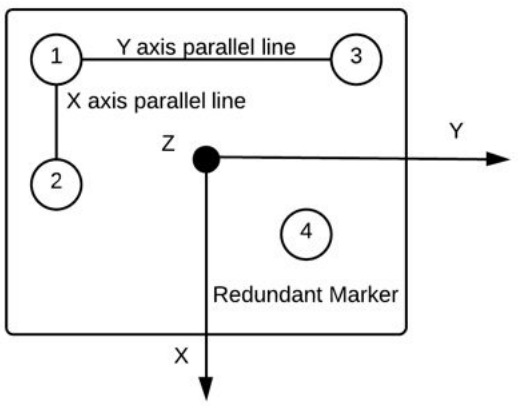


Figure 2.4: Truck's cabin top-view. Markers configuration example and consequent axes of the body.

The local coordinate system of the rigid body is set at the center of mass of all markers. Specific markers are used to represent the X and Y axis and the Z axis is a consequence of the right-hand rule. In Figure 2.4, the X axis is defined as being a parallel line to the line that crosses the markers 1 to 2 and the Y axis is defined as being a parallel line to the line that crosses the markers 1 to 3. Marker 4 is just a redundant marker used for more robust tracking in case of some other marker is hidden, as explained before. The definition of a 6DOF rigid body in the QTM is thoroughly explained in the appendix for marker configurations such as this one.

2.2 Communications

The overall system is constantly interchanging information between each one of the constituents. The information must be up-to-date possible and the update frequency should be as high as possible.

2.2.1 Communication Between Mocap and PC

The twelve cameras are connected to a central computer by an Ethernet cable. On that computer a program called QTM is running. It is responsible for collecting all the data from the cameras, identifying the 6DOF Rigid Bodies and track them in real-time. Also, it provides the measured data over an proprietary protocol via TCP/IP or UDP/IP. For fetching that data, the LabVIEW PC runs a client, which is integrated in the main program.

2.2.2 Communication Between PC and Trucks

For each truck one pair of T-Motes is used. The T-Motes are commercial wireless sensor nodes that run on an operative system called Tiny OS. Using one pair for each truck makes the control easier since the frequency of data sending is maximized. The frequency used is 10Hz, i.e, once each 100ms.

One T-Mote of each pair is USB-connected to the LabVIEW PC. There, the LabVIEW program sends the data to the T-Mote using a serial forward. Then, the T-Mote sends the data wirelessly to its pair in a specific radio channel and ID. The other T-Mote of the pair is connected into a serial adapter board in the truck. Hence, the serial board converts the signals from the T-Mote to serial signals. Finally, the Pololu board receives the serial signal and outputs two pulse-width modulated servo signals that are sent to control the servos. In this case, only two out of eight outputs of the Pololu board are used since only the speed and the steering are controlled.

2.2.3 Communication Between PC and Visualization Tool

The visualization tool is a graphical user interface (GUI) application created in MATLAB in order to do demonstrations and to present real-time results and visualize the scenarios. In the LabVIEW PC a TCP/IP server is created and initialized every time the program starts. Furthermore, a TCP/IP client was created in MATLAB. It can run in every computer inside the KTH internet network. The message protocol is present on the User's Manual in appendix.

2.3 Road Network Design and Creation

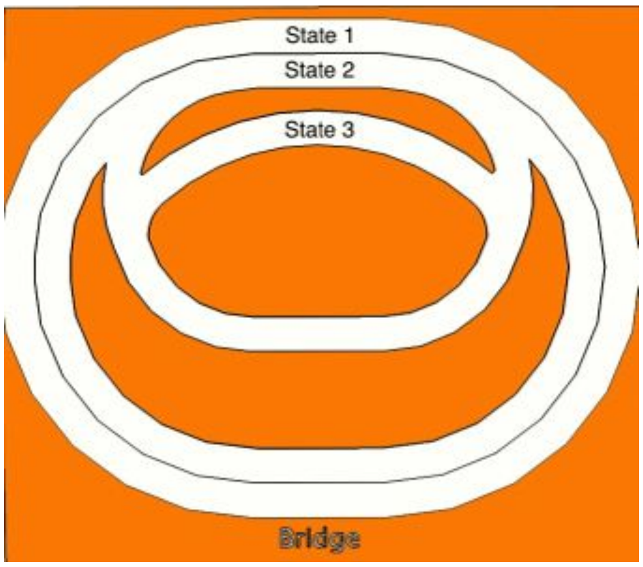


Figure 2.5: Road network design.

The road network that can be seen in Figure 2.5 was designed from scratch. It was designed in Google Sketch Up and both real dimensions of the SML and the trucks were used in order to design a feasible road network.

2.3.1 Concept and Ideia

When picturing the road network the idea was to create something scalable into the real world. To do so, all available space in the SML was used. The main and outer dual lane road are supposed to represent either a road with two lanes used in opposite directions or a highway with two lanes both in the same direction. The inner road, the smaller one and single laned, is used to simulate a merging of two highways, for example. It connects itself to the outer road using two connection roads.

2.3.2 States Division and Trajectories

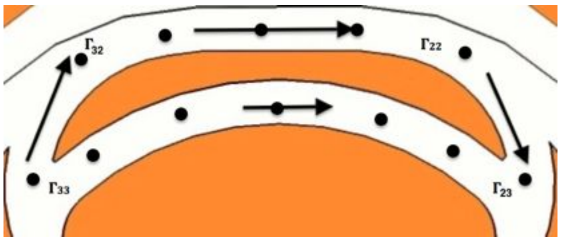


Figure 2.6: Transitions programming idea.

The designed road network has three states. The outer lane and the inner lane of the main road, and the single lane of the inner road are state 1, 2 and 3 correspondently. There are allowed transitions between states 2 and 3 and vice-versa. Those transitions are made through the connection segments between the states. Those segments are not described as being additional states though which the truck must pass. A matrix Γ was created in order to describe the transitions between states. The idea behind the construction of the matrix is sketched in Figure 2.6. The matrix diagonal contains the exit waypoint number of each state if there exists one, otherwise it contains -1. The index ij of the matrix contains the waypoint of the state j that the truck should head to if it actually is in state i, otherwise contains -1. For example, if the truck is driving on the inner lane, i.e state 2 and wants to go to the inner road, i.e state 3, the truck must be driving towards the waypoint 5 of the state 2 ($\Gamma(2,2)$) and then the truck drives towards the waypoint 1 of the state 3 ($\Gamma(2,3)$).

The final form of Γ is

$$\Gamma = \begin{bmatrix} -1 & -1 & -1 \\ -1 & 5 & 1 \\ -1 & 50 & 25 \end{bmatrix} \tag{2.1}$$

Chapter 3

Control of the Trucks

3.1 Truck Kinematics Model

The trucks used in the project are $1/14$ scale models of the Scania V8 HDV. In order to be able to control those trucks it is necessary to describe their kinematics. They can be approximated, without lost of generality, to car-like vehicles. The back wheels are assumed to be used for traction and both front wheels behave as an equivalent single steering wheel in between them. It is also assumed that there is no wheel slip. The control variables are the angular speed of the back wheels and the steering wheel angle.

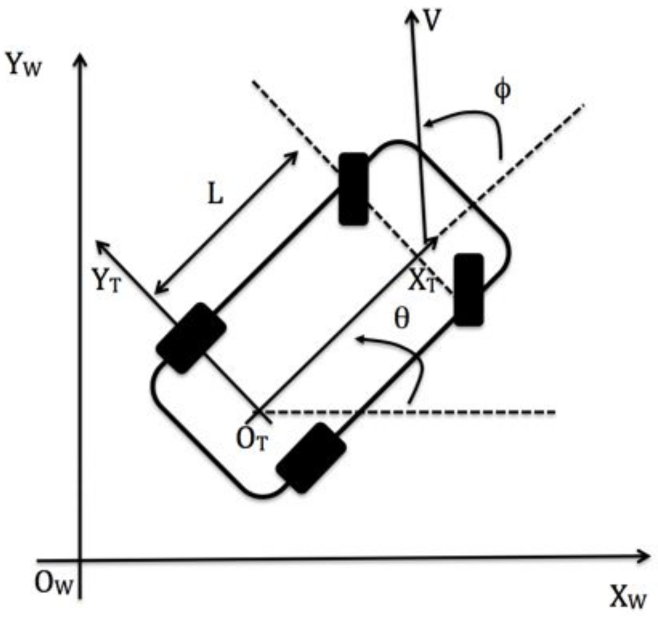


Figure 3.1: The notation used in the truck kinematics model.

Notation	Description
V	Linear velocity of the steering wheel in the robot coordinate system
ϕ	Steering angle
θ	Orientation of the vehicle (yaw)
L	Length between the rear and front wheels axes
X_W, Y_W and O_W	World coordinate system
X_T, Y_T and O_T	Truck local coordinate system

Table 3.1: Truck kinematics model notation description.

From Figure 3.1 the differential truck kinematics are given by

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} \sin(\theta) & 0 \\ \cos(\theta) & 0 \\ \tan(\phi)/L & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V \\ \omega_s \end{bmatrix} \tag{3.1}$$

3.2 Truck Controllers

Since there are two control variables two different controllers were developed, one for the speed and other for the steering of the truck. The system model, including the truck models, the transmission delays and possible nonlinearities, was not deeply studied and a PID controller was used. Both the speed and the steering controller are in the form

$$u(t) = K_P e(t) + K_I \int_0^t e(\tau) d\tau + K_D \frac{d}{dt} e(t) \tag{3.2}$$

where $u(t)$ is the control signal, K_P, K_D and K_I are the proportional, differential and integral gains respectively and $e(t)$ is the error between the reference value and the actual value.

3.2.1 Speed Controller

The block diagram representing the PID speed controller can be seen in Figure 3.2.

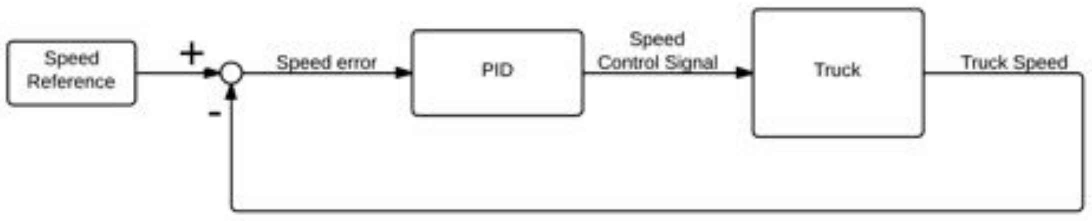


Figure 3.2: Block diagram representing the PID speed controller.

The proportional control is adjusted so that the controller responds immediately to the error. The error is never reduced to zero, i.e, there will be inherently present an offset error. This offset is removed using an integral term. The integral term is essential since $e(t)$ is zero when the truck speed reaches the reference speed meaning that neither the proportional nor the derivative terms will influence the static error controller output. This way, the integral part is responsible for maintaining the speed equal to the reference. In order to easily achieve stability, the derivative control is introduced reducing the need of the proportional gain being large and to dampen out the response oscillations.

3.2.2 Steering Controller

The block diagram representing the PD speed controller can be seen in Figure 3.3. It is a PD controller since it is only controlled the position of the steering wheel and consequently K_I is zero.

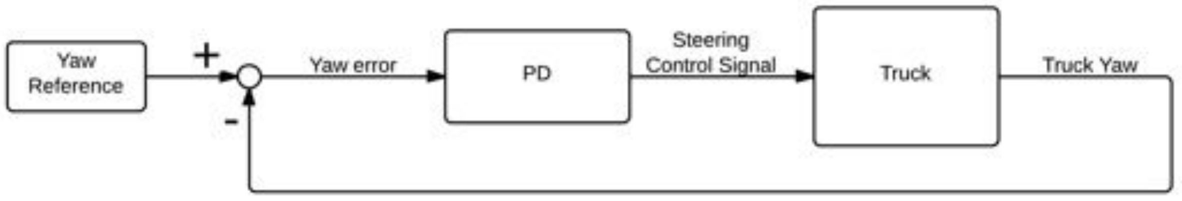


Figure 3.3: Block diagram representing the PD steering controller.

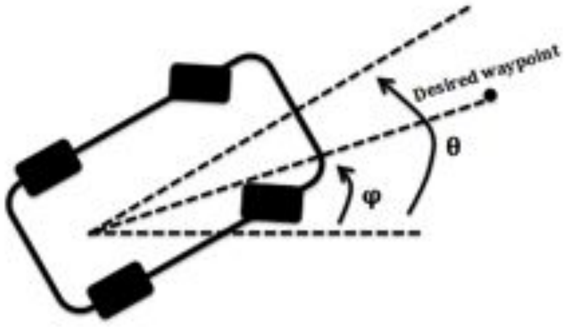


Figure 3.4: Determination of the reference steering angle.

Here it is introduced the reference yaw angle, φ. The reference yaw angle is calculated using

$$\varphi = \arctan(\frac{y_d - y_t}{x_d - x_t}) \tag{3.3}$$

where (x_d,y_d) and (x_t,y_t) are the desired waypoint and truck actual coordinates respectively. Since the trucks drive at constant speed when steering it is assumed that controlling the steering is equivalent as controlling the yaw rate directly itself then the steering angle is calculated using

$$\phi = \theta - \varphi \tag{3.4}$$

3.2.3 Platoon Controller

The block diagram representing the controller used when platooning can be seen in Figure 3.3.

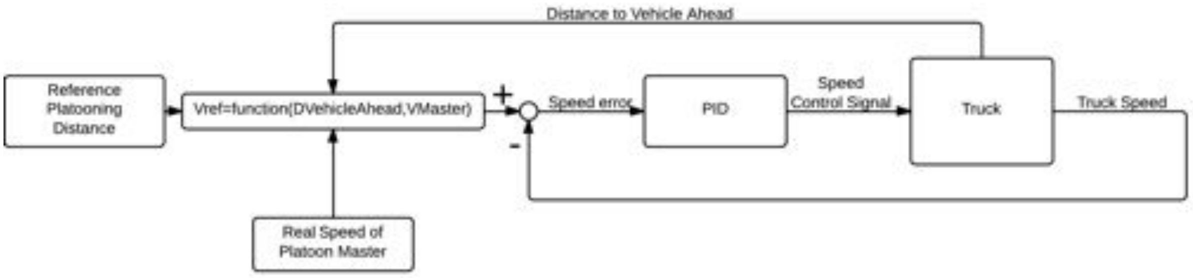

Distance to Vehicle Ahead
Reference Platooning Distance
Vref=function(DVehicleAhead,VMaster)
+
-
Speed error
PID
Speed Control Signal
Truck
Truck Speed
Real Speed of Platoon Master

Figure 3.5: Block diagram representing the PID speed controller when platooning.

When a platoon master is defined all the other trucks on the same lane are supposed to maintain a user-defined reference platooning distance between each other. To achieve that goal, a reference speed must be computed for each truck. The reference speed depends on the reference platooning distance d_{ref}, on the real speed of the master V_{Master} and on the distance to the master (or to the truck immediately ahead) of each truck $D_{VehicleAhead}$. Equations (3.5) and (3.6) are proposed. In these equations the reference speed sent to the pursuing trucks is higher than the master's speed when the distance to the vehicle ahead is bigger than the reference distance and vice versa.

The reason for trying out these two functions is its different slope around the ”equilibrium point”. The ”equilibrium point” corresponds to the reference platooning distance and master real speed used to compute the reference speed for the pursuing trucks. In Figures 3.6 and 3.7 some examples of functions used to compute the reference speed of the trucks in a platoon are represented. In Section 3.3.4 the choice of the equation used is justified.

$$V_{ref} = \frac{V_{Master}}{d_{ref}} D_{VehicleAhead}; \tag{3.5}$$

$$V_{ref} = V_{Master} + (D_{VehicleAhead} - d_{ref})^3; \tag{3.6}$$

where $V_{ref} \in [0.2; r_v V_{Master}] ms^{-1}$ where r_v corresponds to how much faster the truck will drive comparing to the master's speed.

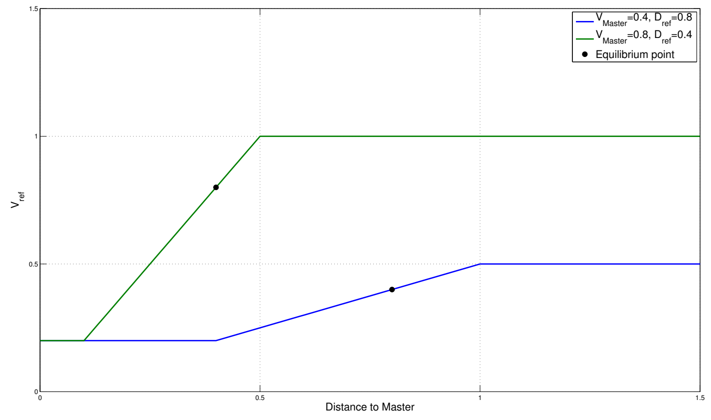


Figure 3.6: Some examples of the function (3.5) used to compute the reference speed of the trucks in a platoon.

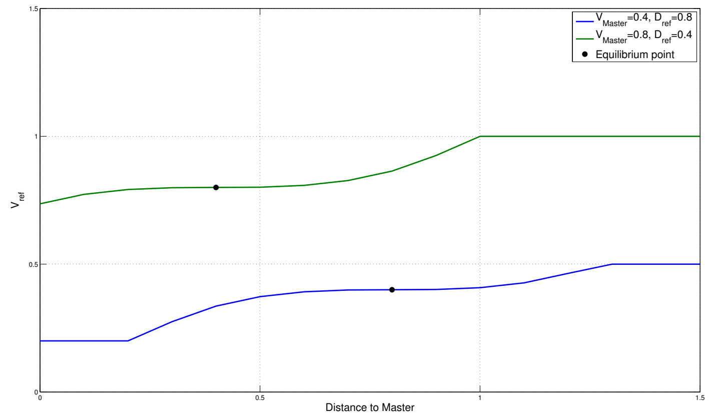


Figure 3.7: Some examples of the function (3.6) used to compute the reference speed of the trucks in a platoon.

3.3 Control Algorithms Details

The LabVIEW PC is responsible for controlling and for the decision making of the trucks on the road network. The control of the trucks is, consequently, centralized in one single PC. It is assumed that the communications V2V and V2I are instantaneous and that each truck knows all the time the exact position and speed of all other trucks. The MoCap provides all the information needed for the trucks to be controlled. The implementation details are explained in this section.

3.3.1 Controlling the Speed

Calibration

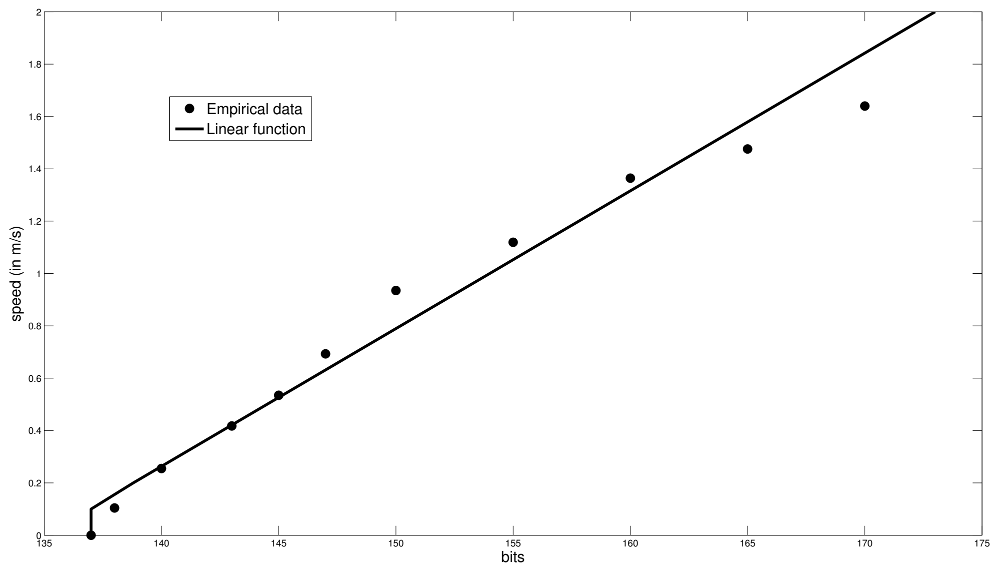


Figure 3.8: Truck speed calibration function and empirical data.

The units used in the speed controller presented in Figure 3.2 are in m/s. However, the values sent to the truck must be in the $[0, 255]$ interval. With the purpose of converting the output of the controller from m/s to bits, a calibration procedure was developed. Using a simple program, several values from 127 to 175[1] were sent to the truck and its real speed recorded in MATLAB. Then, using the curve fitting tool (`cftool`) of MATLAB, a linear regression that better fitted the data was chosen (Figure 3.8). The function 3.7 was found.

$$Speed_{bits} = 19Speed_{m/s} + 135; \tag{3.7}$$

The assumption that the midrange value 127 was correctly set is made[2]. One may ask why does the speed $0m/s$ does not correspond to the value 127. There is a deadzone in the interval $[127, 135]$ that corresponds to

[1]Below 127 the truck move backwards. Above 175 the speed saturates.
[2]How to set the midrange value is explained in the appendix.

speed $0m/s$. For that reason, when the controller output is within the interval $[129, 135]$, the value sent is 135. Bellow 129 it is sent 127. Only positive velocities, i.e. that make the truck move forward, are considered.

Controller Implementation

The MoCap only provides the coordinates of the position of the trucks. Therefore, to calculate the speed of the truck one needs at least the current and the previous position of the truck as well as the time elapsed between each measurement. So, the calculation of the actual speed of the truck is not directly given from the system but computed simultaneously when computing the control values.

Performance

For the analysis of the speed controller (Figure 3.2) performance it is presented in Figure 3.9 the real speed of a truck for two different reference speed values.

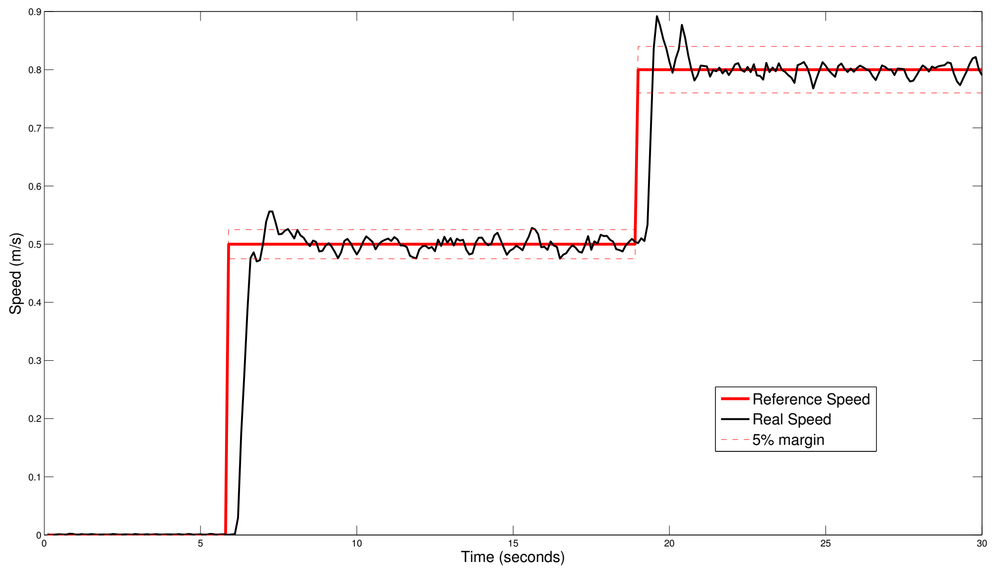


Figure 3.9: Speed response of a truck.

In Table 3.2 some relevant performance indicators are summarized.

Overshoot	10%
Settling time (5%)	$1.6s$
Time constant, τ	$0.6s$

Table 3.2: Performance indicators for the speed controller.

The controller seems to behave very well. The real speed is maintained inside the limit $\pm 5\%$ every time except the first one or two peaks. The overshoot is quite high but on the other hand the settling time is very fast.

3.3.2 Controlling the Steering

Calibration

As for the speed, the units used in the steering controller presented in Figure 3.3 are in degrees, but the values sent to the truck must be in the $[0, 255]$ interval. With the purpose of converting the output of the controller from degrees to bits, a calibration procedure was developed. Using a simple program, several values from 75 to 175[3] were sent to the truck and the relative angle of the roads with the truck was recorded in MATLAB. Then, using the curve fitting tool (`cftool`) of MATLAB, a linear regression that better fitted the data was chosen (Figure (3.10)). The function 3.8 was found.

$$Steering_{bits} = -1.637 Steering_{degrees} + 127; \tag{3.8}$$

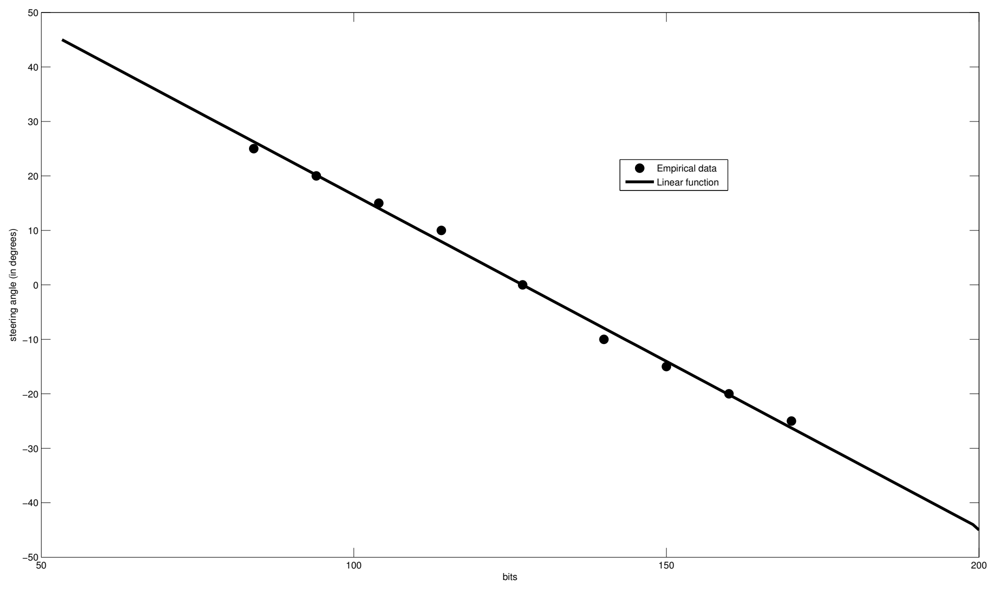


Figure 3.10: Truck steering calibration function and empirical data.

Once again, the assumption that the midrange value 127 was correctly set is made.

Controller Implementation

The MoCap automatically provides the yaw angle of the trucks. The reference yaw is directly calculated with (3.3) and the steering controller model (Figure 3.3) is directly applied.

Performance

For the analysis of the steering controller (Figure 3.3) performance it is presented in Figure 3.11 the reference yaw of a truck and its real yaw values when driving in one of the lanes of the road network.

[3]Below 75 and above 175 the steering saturates.

A small offset between the reference yaw angle and the real angles can be seen almost every time. This happens in consequence of the controller design due to the absence of an integral part on the steering controller. This is not a problem since the error is very small and has almost no influence in the road following.

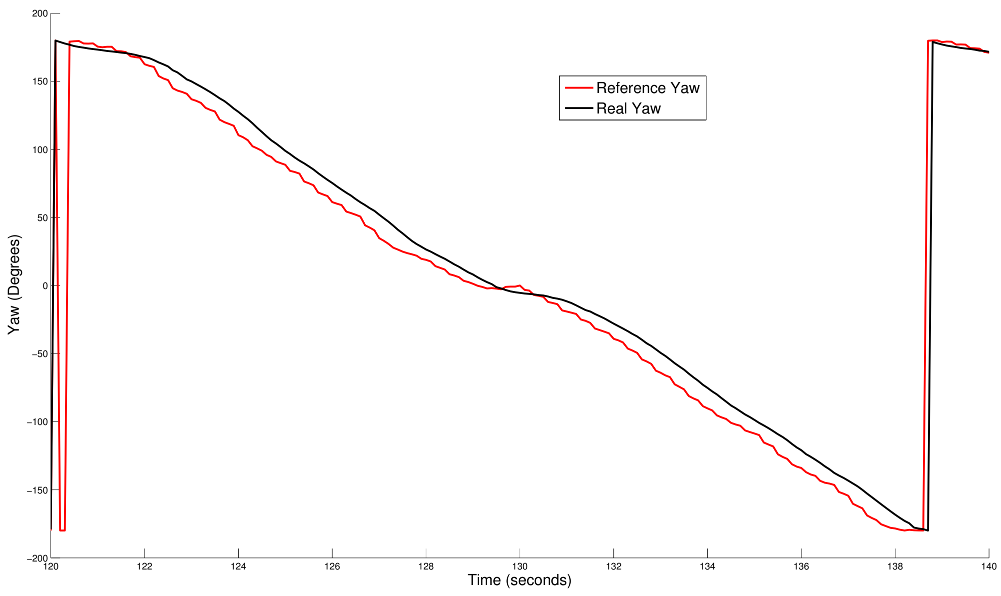


Figure 3.11: Steering response of a truck.

3.3.3 Driving on the road network

The trajectories on the road network are not fully described, i.e, the linear and angular speed are not defined in each point. The trajectories are only described by waypoints. The waypoints are spaced approximately $30cm$ from each other. The speed controller receives a reference constant speed. The steering controller receives the heading of the next waypoint. Meanwhile, the waypoint for which the truck is heading to is computed. The truck should head itself to the next waypoint when it is inside of a circle with $40cm$ of radius with the actual waypoint as center (Figures 3.12 and Figures 3.13).

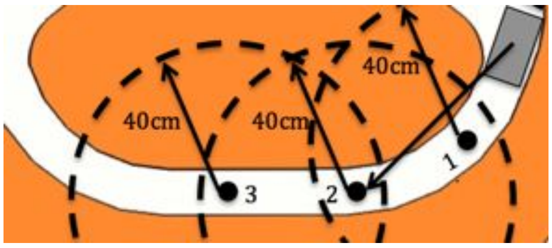


Figure 3.12: Heading to a waypoint.

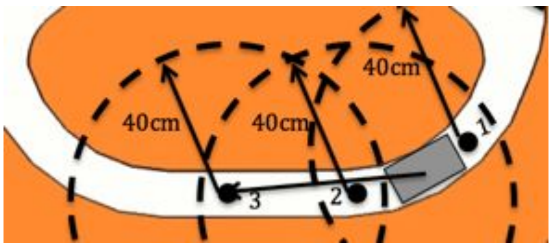


Figure 3.13: Heading to another waypoint.

A simulation in MATLAB using the truck model and the control algorithms described in the Section 1.2 was developed in order to find the approximate gains values for the controllers. After tuning the controllers in the real trucks and road network, the gains values found are summarized in the Table 3.3.

Gain	Steering Controller	Speed Controller
K_P	1	1
K_D	0.05	0.2
K_I	0	3

Table 3.3: Reference controller gains values.

The values presented are reference values, since each truck is slightly different from each other and some tuning around these values must be done.

3.3.4 Platooning

When a platoon master is chosen, all the trucks in the same state, i.e. lane, as well as the master are supposed to maintain a user-defined reference distance to the truck ahead. One of the main aspects of this controller is the distance between trucks calculation. The distance between trucks is measured along the trajectory of the lane. This is achieved by measuring the Euclidean distance between waypoints in between each truck (Figure 3.14).

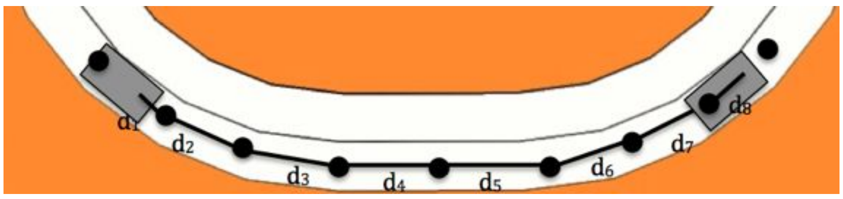


Figure 3.14: Method for calculating the distance between each truck.

The distance between trucks D is calculated according to (3.9).

$$D = d_1 sign(\cos(\varphi_b)) + \sum_{n=2}^{N-1} d_n - d_N sign(\cos(\varphi_a)) \tag{3.9}$$

where d_n with $n \in [2, N-1]$ are the distances between waypoints in between each truck, d_1 and d_N are the distance from the truck behind to its closest waypoint and the distance from the truck ahead to its closest waypoint respectively. They are multiplied by $sign(\cos(\varphi_b))$ and $sign(\cos(\varphi_a))$ respectively in order to guarantee that it is the total distance between trucks. φ_b and φ_a are the angle to the closest waypoint for the truck behind and the truck ahead respectively. For instance, when the closest waypoint to the truck ahead is in front of it, the distance from that waypoint to the truck must be subtracted from the total distance. The computation of the distance between trucks is done very often, but the distances between waypoints are fixed from the moment the trajectories are created. When the trajectories are created, a look-up table (LUT) with the distances between each waypoint is created. This way computation time and effort is significantly reduced. So instead of calculating the second term of (3.9), the LUT is accessed and only the first and the third are calculated.

When there are more than two trucks in a platoon the distances between the trucks are calculated as well. First the distance to the platoon master is calculated, then if there are any trucks in between, the distance of the truck ahead to the master is subtracted to its own distance to the master so the remaining is distance to the truck ahead.

In Figure 3.15 represents an example of platooning with three trucks with the master truck. In that figure, each truck has a fixed ID number just to be able to manipulate each one of the trucks in terms of programming language. Each time a platoon is formed, an array is created with all the trucks' ID in the platoon appearing in order. In this case, the so called platoon array is $\begin{array}{|c|c|c|c|c|}\hline 2 & 5 & 3 & - & - \\ \hline\end{array}$. Another array is created where the distance of each truck to the truck ahead is placed in the index that corresponds to the truck's ID. The distance to master array is in this case: $\begin{array}{|c|c|c|c|c|}\hline - & - & D_3 & - & D_5 \\ \hline\end{array}$.

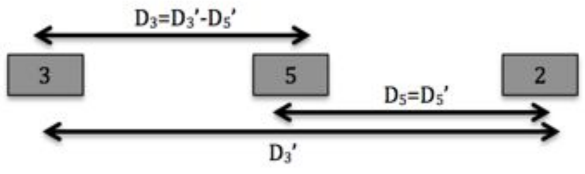


Figure 3.15: Distances between trucks.

Equations (3.5) and (3.6) were already referred as being alternative control functions to calculate the reference speed for the trucks that are pursuing the master. That reference speed depends on the distance to the truck ahead and on the master's speed. The control function with better performance was the linear function (3.5). The explanation is that the cubic function is approximately linear around the "equilibrium point", i.e the point where the reference distance and the master's speed is achieved. However, this linear approximation has a very low slope comparatively with the linear function proposed. As a consequence, the lower the slope the lower the control reactivity and it is harder for the system to maintain the reference distance.

Performance

The performance of the platoon formation can be commented analyzing the plots in Figures 3.16 to 3.18.

In Figure 3.16 the truck is first trying to maintain a distance of 3 meters to the master and then 0.3 meters. One can see the approximation to the reference value with a constant slope due to the limitation of $1.25V_{Master}$ imposed to the pursuing truck. Then, the distance is maintained quite well with a mean absolute error (MAE) of $0.02m$ and a mean squared error (MSE) of $5 \cdot 10^{-4}m$.

In Figure 3.17 shows how the reference speed for the platooning truck is calculated. Using a function as (3.5) the reference speed is calculated depending on the master speed and distance to it.

Figure 3.18 shows the performance of a case where three trucks are platooning (Scenario 3, Section 5.3). The second truck, i.e. the middle one, leaves the platoon for some reason. The third and last truck must maintain the predefined distance to the truck ahead and it has to fill the gap left empty by the truck that left the platoon. In this case, the middle truck leaves the platoon around the 52^{nd} second of the simulation and it is quite noticeable the peak in the distance to the truck ahead. Then, it speeds up in order to maintain the reference platooning distance to the first truck.

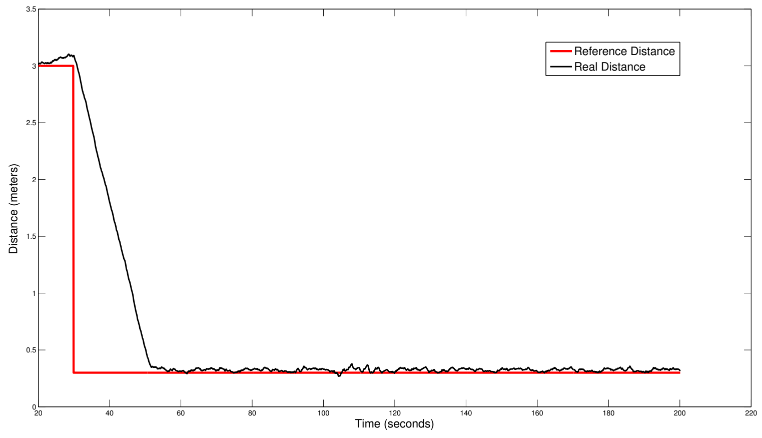


Figure 3.16: Platooning distance response.

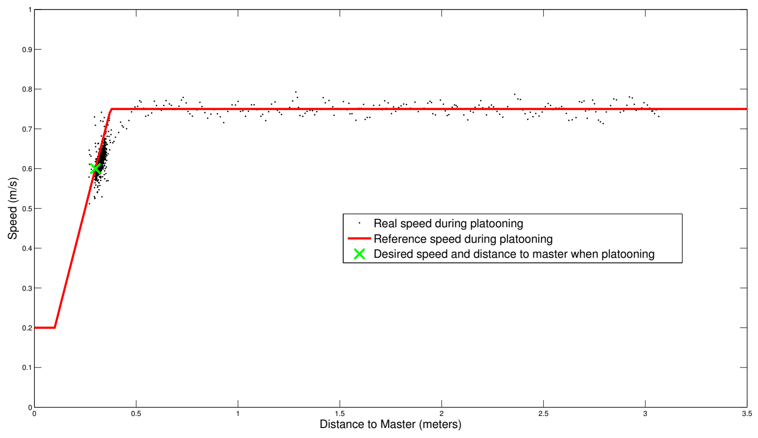


Figure 3.17: Reference speed when platooning using a linear function with $d_{ref} = 0.3$ and $V_{Master} = 0.6$.

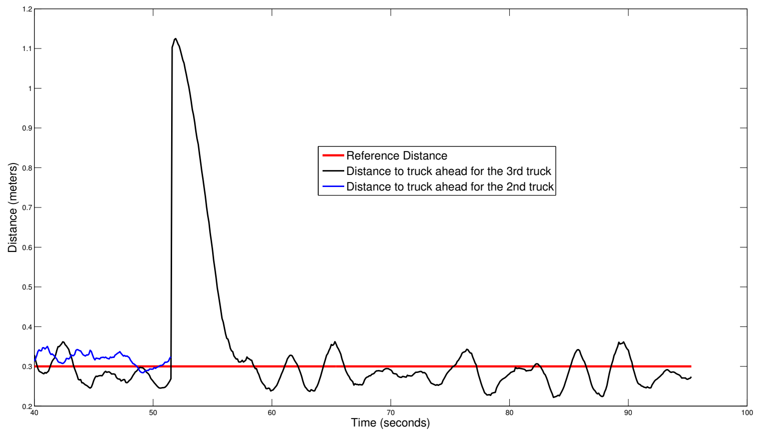


Figure 3.18: The 2^{nd} truck leaves the platoon. The 3^{rd} has to maintain the distance to the truck ahead.

3.3.5 Overtaking

One of the most fancy features of the system developed is the trucks' ability to overtake. Figure 3.19 depicts the three steps needed for overtaking.

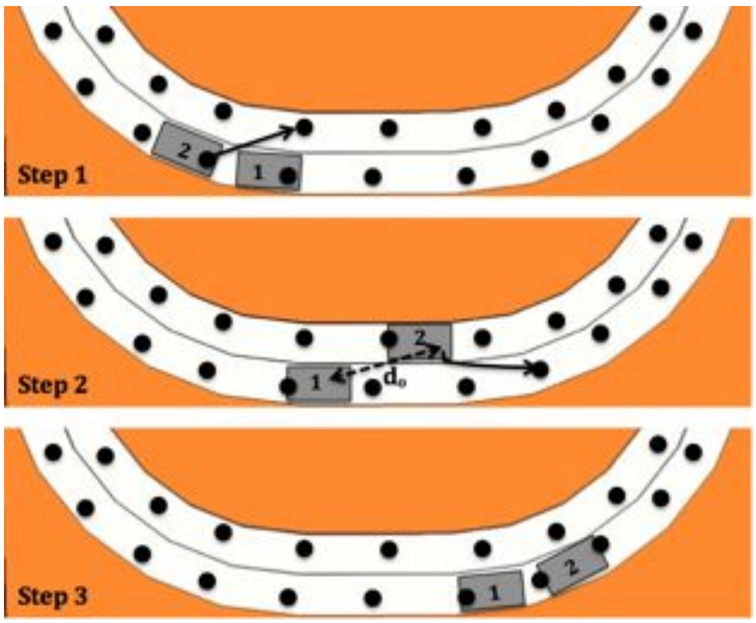


Figure 3.19: The 3 steps for overtaking.

The system decides that a truck should overtake when there is already a platoon and a new platoon master is chosen. The new platoon master had to be already in the previous platoon. Then, three steps are made. Assume that, as the example of Figure 3.19, truck 2 is platooning truck 1. At some point, truck 2 is set as platoon master.

- **Step 1.** The truck 2 must change to the other lane in order to overtake. For that, it is chosen the closest waypoint of the opposite lane that is in front of the new master;
- **Step 2.** While overtaking, the truck speeds up and the Euclidean distance between the new master and the previous master d_o is constantly being evaluated. When that distance is $d_o > d_{ref} + margin$ the new master chooses again the closest waypoint of the opposite lane to re-enter as the platoon master.
- **Step 3.** The new master is now the actual platoon master and the other truck will follow it.

This works for more than two trucks. The new master, already in the platoon, will overtake all the trucks in front of it until the previous master has been overtaken. Moreover, if the new master exits the middle of the platoon for overtaking, the platoon would rearrange itself in order to maintain the reference distance between trucks.

Chapter 4

HDV Modeling

4.1 HDV Model

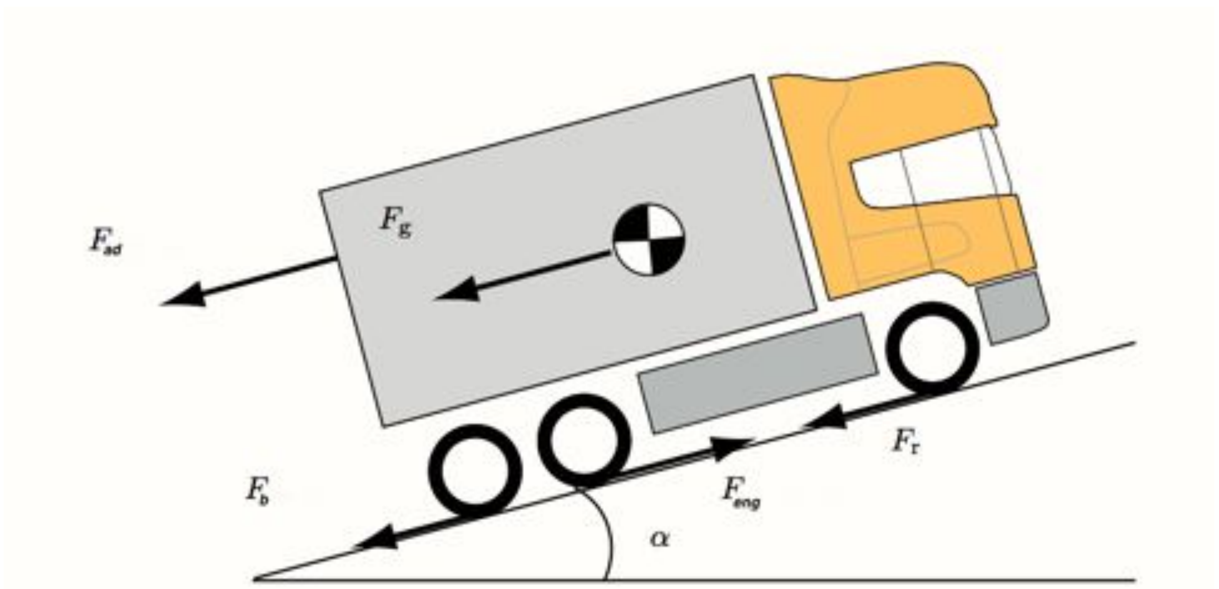


Figure 4.1: HDV model based on Newton's second law of motion (reprinted from [6]).

The model used in [19] and [21] is the HDV model used in this thesis. This model is described in detail in [6]. Therefore, a longitudinal HDV model based on Newton's second law of motion is considered:

$$m\frac{dv}{dt} = F_{eng} - F_b - F_{ad}(v) - F_r(\alpha) - F_g(\alpha) = F_{eng} - F_b - \frac{1}{2}\rho_a A_a c_D v^2 - mgc_r\cos(\alpha) - mg\sin(\alpha) \quad (4.1)$$

where F_{eng}, F_b, F_{ad}, F_r and F_g are the engine force, the braking force, the air drag force, the roll resistance force and the gravity force respectively. For the sake of simplicity and since all the scenarios do not include braking it is considered $F_b = 0$. Additionally, m denotes the accelerated vehicle mass, v the vehicle speed, α the slope of the road, ρ_a the air density, A_a the frontal area of the vehicle, c_D the air drag coefficient, g the gravitational force and c_r the roll resistance coefficient. In all scenarios considered the road is assumed flat, therefore $\alpha = 0$.

The model can also be described as a distance based model

$$m\frac{dv}{ds}\frac{ds}{dt} = F_{eng} - F_b - F_{ad}(v) - F_r(\alpha) - F_g(\alpha) \tag{4.2}$$

where $\frac{ds}{dt} = v$. Furthermore, we can derive the expression for F_{eng}

$$F_{eng} = m\frac{dv}{ds}v + F_b + F_{ad}(v) + F_r(\alpha) + F_g(\alpha) \tag{4.3}$$

4.2 Fuel Consumption Model

The fuel consumption model studied in [21] and used in [19] is the model used in this thesis to evaluate the fuel consumption behavior:

$$f_c = \frac{\delta}{\bar{\eta}_{eng}\rho_d} v F_{eng} \tag{4.4}$$

where f_c [ml/s] denotes the instantaneous fuel consumption, $\bar{\eta}_{eng}$ the mean combustion efficiency of the engine, ρ_d the energy density of diesel fuel and δ indicates whether fuel is injected into the engine or not with

$$\delta = \begin{cases} 1 & \text{if } F_{eng} > 0 \\ 0 & \text{otherwise} \end{cases} \tag{4.5}$$

The total fuel consumption over time T is also derived as:

$$f_c = \int_0^T \frac{\delta}{\bar{\eta}_{eng}\rho_d} v(t)(m\frac{dv}{ds}v + \frac{1}{2}\rho_a A_a c_D v^2 + mgc_r\cos(\alpha) + mg\sin(\alpha))\,\mathrm{d}t. \tag{4.6}$$

Using the knowledge that $\frac{ds}{dt} = v$ we can rewrite the total fuel consumption so it is distance based where D is the total distance traveled.

$$f_c = \int_0^D \frac{\delta}{\bar{\eta}_{eng}\rho_d} (m\frac{dv}{ds}v + \frac{1}{2}\rho_a A_a c_D v^2 + mgc_r\cos(\alpha) + mg\sin(\alpha))\,\mathrm{d}s. \tag{4.7}$$

Considering no acceleration or deceleration, that the initial and final velocities are equal, that the road is flat and introducing the air drag parameter $\phi \in [0, 1]$ where $\phi = 0$ means 100% air drag reduction and $\phi = 1$ means no air reduction we get:

$$f_c = \int_0^D \frac{\delta}{\bar{\eta}_{eng}\rho_d} (\frac{1}{2}\rho_a A_a c_D v^2\phi + mgc_r)\,\mathrm{d}s. \tag{4.8}$$

The values of the parameters used for a typical HDV are presented on Table 4.1. With these values, the fuel consumption that is induced by the air drag is 42% while the remaining part is induce by roll resistance.

Parameter	Symbol	Value	Unit
Vehicle Mass	m	40000	kg
Rolling resistance coefficient	c_r	$7 \cdot 10^{-3}$	-
Air drag coefficient	c_D	0.6	-
Front area	A_a	10.26	m^2
Air density	ρ_a	1.29	kg·m^{-3}

Table 4.1: Nominal vehicle model parameter values used for simulations [26].

Using the study presented in [6] about the relation between the air drag coefficient c_D and distance, d, between the vehicles a function that maps the parameter ϕ as a function of the distance was created. That function is plotted in Figure 4.2.

The parameter ϕ was calculated using the formula $\phi(d) = 1 - 0.8\frac{c_D(d)}{100}$. In the study presented in [6] it is only considered frontal wind, therefore it is reasonable that platooning only influences 80% of the air drag reduction. Other consideration made is that $\phi = 1$ when $d > 60$ meters.

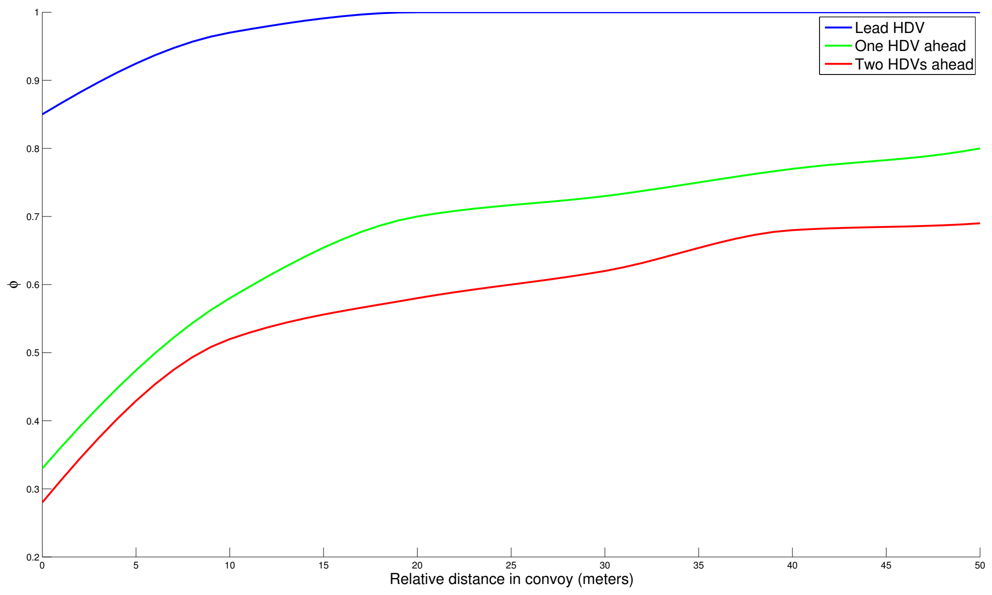


Figure 4.2: Air drag parameter ϕ and distance d between the vehicles (reconstructed from [6]).

4.3 Fuel Ratio

The fuel ratio λ is the normalized ratio between the fuel consumed from the moment in which the decision of catching up the truck ahead is made and the fuel consumed if the trucks had opted to continue alone.

$$\lambda(s) = 1 - \frac{\frac{1}{2}\rho_a A_a c_D v_{cp}(s)^2 \phi(d_r) + mgc_r}{\frac{1}{2}\rho_a A_a c_D v_a(s)^2 + mgc_r} \tag{4.9}$$

where $v_a(s)$ is the velocity that the truck would maintain if it continued alone, $v_{cp}(s)$ is the velocity it assumed after the decision was taken and d_r is the distance between HDVs. The subscript a stands for alone whilst cp stands for the two moments: catching up + platooning.

4.4 Break-Even Ratio

The break-even ratio for the HDV platooning catch up problem is defined in [19] as the distance ratio when neither driving alone nor catching up a platoon ahead would be more feasible. There, a mathematical definition of this ratio for one HDV in a platoon catching up is derived.

$$\frac{d_d}{d_p} = \frac{r_v}{r_v - 1} \frac{r_v^2 - \phi}{1 - \phi} \tag{4.10}$$

where $r_v = \frac{v_c}{v_p} > 1$ and v_c stands for the speed of the HDV when catching up and v_p stand for the speed of the HDV when platooning. The distance to the destination for the following HDV $d_d = T_a v_a$ and the distance between both platoons at the moment the decision is made $d_p = T_c(v_c - v_p)$ is also introduced. Basically, r_v corresponds to how much faster the driver or the system is willing to drive. The derivation of this break-even ratio assumes that the speed is constant both in the catch up and in the platooning phase, that the leading and pursuing HDV(s) are driving at the same speed when the decision to catch up is made and that $v_a = v_p$.

4.5 Scaling from Trucks to HDVs

In order to convert the values used in the scenario to real-world values some assumptions are made.

- The platoon master is assumed to be always traveling at constant speed of $80km/h$ and the speed of the other trucks is always calculated comparing to this value.

  Example: In the lab, if the platoon master is traveling at $0.6m/s$ and some other truck is traveling at $0.75m/s$ it means that in real-world scale the master is traveling at $80km/h$ and the other HDV is traveling at $100km/h$.

- In simulation, the reference platooning distance is 30 times bigger than the one used in the lab.

  Example: A platooning distance of 0.3 meters is simulated as being 9 meters.

- The ADR is assumed to be null for platooning distances bigger than $60m$, otherwise the values of the model in Figure 4.2 are used.

The fuel model (4.8) and the consequent fuel ratio (4.9) and break-even ratio (4.10) only make sense using these converted values.

Chapter 5

Experimental Scenarios and Results

In this chapter HDV platooning scenarios focusing on the catch up problem are presented. Those scenarios were implemented within the laboratory space constraints and the data is converted to real-world scale and used in simulations related to the fuel models and the air drag reduction (ADR) to be made.

A scenario is a predefined set of actions using the experimental setup described in Chapter 2. The trucks are autonomously controlled, the only things that are predefined are the reference speed, the reference platooning distance and the lane where the truck should be.

The fuel consumption analysis can also be performed with only a simulation-based approach instead of converting the values from the trucks to real-world values. However, the focus in this thesis is to be able to use the data retrieved from the experiments with the scale trucks as if they were real HDVs. So, the conclusions taken about the fuel consumed and the comparisons with theoretical results give an insight of the system's performance and of the conversions made.

On the X axis of the plots represented for each scenario, is represented the ratio dd/dp in order to make the plots comparable with the plots in [19]. This ratio represents the total distance traveled by the truck comparing to the initial gap between the HDVs. For example, $dd/dp = 25$ means that the HDVs have traveled 25 times more than the initial distance that separated them. The results related to the fuel ratio λ are presented in terms of the ratio dd/dp.

5.1 Scenario 1 - One HDV catching up one HDV

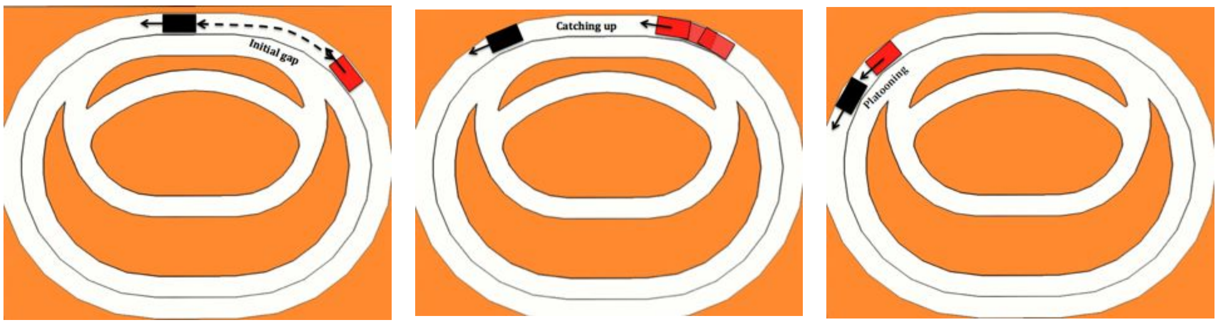


Figure 5.1: Scenario 1 explanation.

The first scenario exemplifies a situation of a single catch up (Figure 5.1). Two HDVs are traveling on the same road and have the same destination. At some point, the HDV that is far away from its destination decides to catch up with the HDV ahead speeding up until a reference platooning distance is achieved. The purpose of this scenario is to analyze the benefit of catching up on an individual perspective, either for the leading HDV as for the catching HDV.

The plots in Figures 5.2, 5.3 and 5.4 represent the fuel ratio λ for both HDVs, the total fuel consumption for the catching HDV and the ADR for both HDVs respectively. These plots result from simulating the case on which both HDVs have 40 tons, the catch up speed is 12.5% higher than the leading HDV and the reference platooning distance is $0.15m$ corresponding to $4.5m$ in real-world scale.

In Figure 5.2, two different types of lines are represented: a solid and dashed line. The solid lines represent the data acquired and processed while running the scenario in real time. The dashed lines represent the theoretical results proposed in [19].

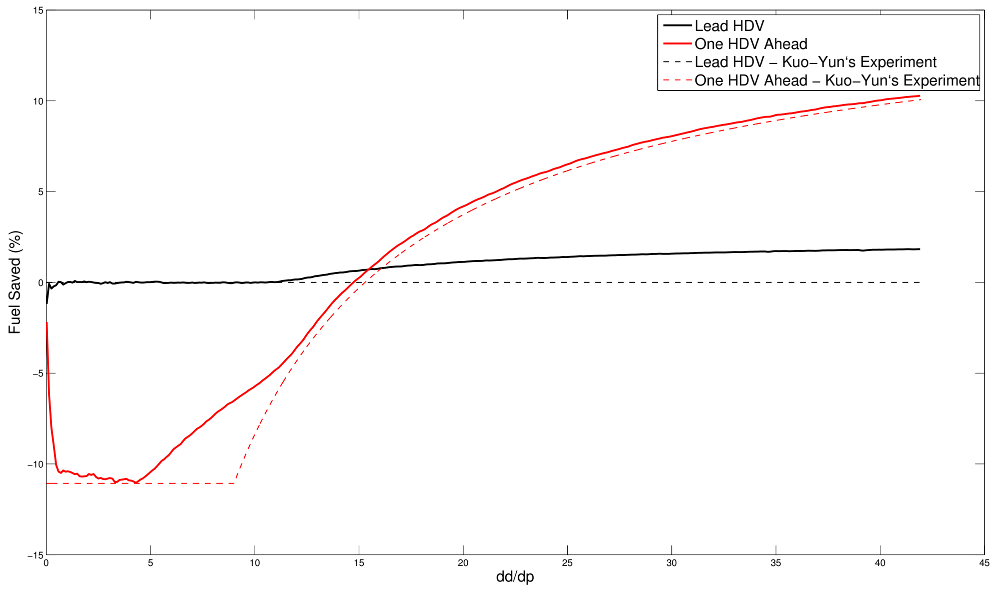


Figure 5.2: Fuel ratio of both HDVs.

The main differences between the data acquired from the scenarios (solid lines) and the result obtained using the model in [19] (dashed lines) are that for the leading HDV it is considered that it benefits as well for being in a platoon; the break-even point occurs slightly earlier than in [19]'s experiment; if the scenario continued for longer time and distance the saved fuel calculated would be smaller than the expected since the slope of the calculated ratio is smaller than the one in [19]. These differences happen for several reasons:

1. the scenario starts with the truck speeding up until it reaches the catching up speed, which means that, unlike the experience in [19], the catching up speed is not considered constant during the catch up phase;

2. during the catch up phase the HDV starts benefiting from the ADR, which is not considered in [19]'s experience;

3. for demo purposes and due to space constraints, the initial gap cannot be too big and consequently the catching up phase is not very large when compared with the total distance traveled;

4. during the platoon, the speed of the HDV behind in the platoon is not constant and equal to the leading HDV;

5. the ADR assumed to represent the theoretical plot is the mean of the total ADR during the experiment and the ADR of the following truck is not constant as assumed in the theoretical model.

The fourth and fifth reasons explain why the scenario ratio slope is, in the end, slightly smaller than the one expected.

In Figure 5.3 the total fuel consumption of the pursuing HDV is represented. Two different moments can be distinguished when analyzing the plot. First, the instant fuel consumed if it had decided to catch up is higher than if it had decided to continue traveling alone, resulting in a faster increment of the total fuel consumed in the catching up phase. However, after a while, the benefits of platooning start to be noticed due to the ADR (Figure 5.4) making the instant fuel consumption to decrease resulting in less total fuel consumption if catching up.

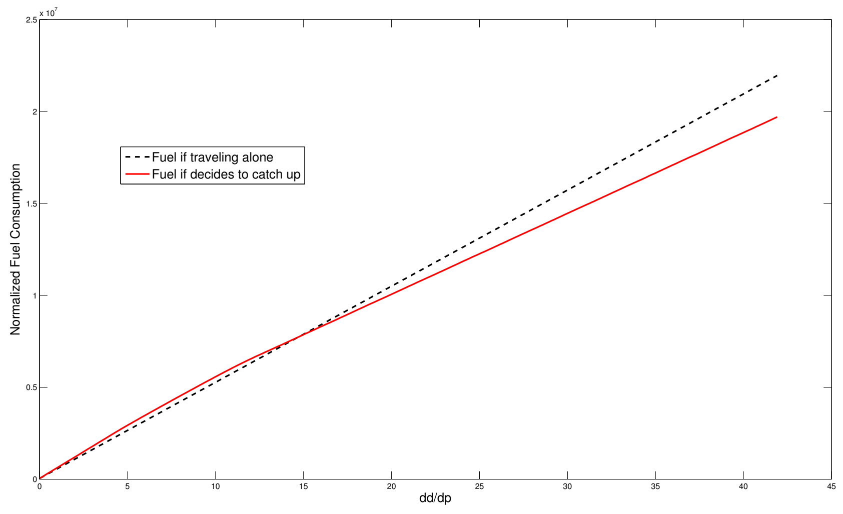


Figure 5.3: Total fuel consumed for the catching HDV.

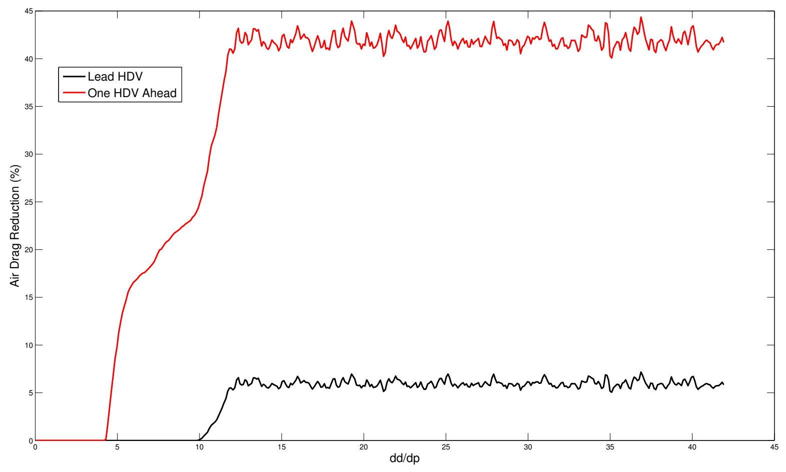


Figure 5.4: Air drag reduction of both HDVs.

m	r_v	d_{ref}	dd/dp	Expected dd/dp	$\lambda(25)$	Expected $\lambda(25)$	Platoon mean $\lambda(25)$	Catching HDV ADR
$40t$	1.125	$0.15m$	14.7	15.3	6.5%	6.2%	4.4%	38%
$40t$	1.125	$0.3m$	14.5	16.6	5.3%	4.4%	3%	31.5%
$60t$	1.125	$0.3m$	15.6	16.7	3.6%	3.3%	2.1%	31.1%
$40t$	1.25	$0.15m$	10.4	12.2	9.3%	8.2%	5.8%	39.3%
$40t$	1.25	$0.3m$	11.6	13.6	6.7%	6.2%	3.9%	32.7%
$60t$	1.25	$0.3m$	12.1	13.6	4.9%	4.8%	2.8%	32.8%

Table 5.1: Scenario 1 results.

Table 5.1 summarizes the results of six different combinations of the scenario parameters. In Figure 5.5 the fuel ratio for the whole platoon can be compared for those 6 combinations.

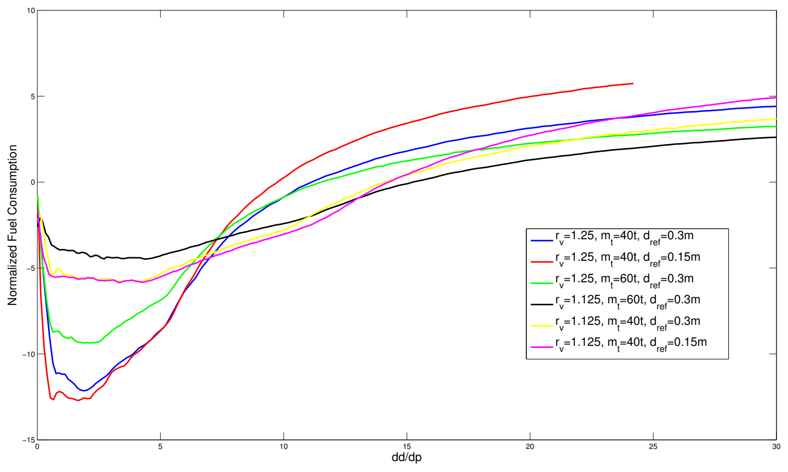


Figure 5.5: Fuel ratio of both HDVs.

The analysis of Figure 5.5 and Table 5.1 is quite similar. The experimental results are very close to the theoretical previsions. With the experiments one may be tempted to conclude that the benefits of catching up are higher in practice than those expected theoretically. This is correct, but only partially. The results, obtained in practice, are achieved using very small distances when compared with real situations where hundreds of kilometers are involved. However, these experiments can be analyzed as being a zoom analysis of what happens around 1 or 2 kilometers where both HDVs meet. This means that for very large scale the differences in fuel saving during this period result in almost insignificant savings, even if they exist.

General conclusions can be also taken. The ADR for smaller platooning distances is higher due to the proximity between HDVs. The heavier the HDV the less benefits it has in catching up. The faster the driver is willing to drive in order to catch up, the sooner the benefits of platooning start to be noticed.

5.2 Scenario 2 - One HDV catching up two HDVs

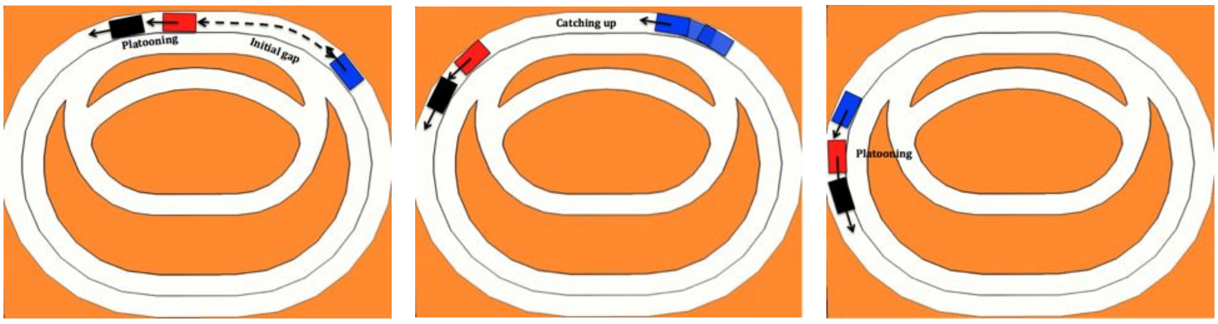


Figure 5.6: Scenario 2 explanation.

The second scenario exemplifies a situation of a platoon single catch up (Figure 5.6). Three HDVs are traveling on the same road and have the same destination. At some point, the HDV that is far away from its destination decides to catch up with the two HDVs ahead speeding up until a reference platooning distance is achieved. The purpose of this scenario is to analyze the benefits of catching up, especially comparing to the first scenario where there was no platoon already formed.

The plots in Figures 5.7 and 5.8 represent the fuel ratio λ and the ADR for the three HDVs respectively. The total fuel consumption is very similar with the one represented in Figure 5.3. These plots result from simulating the case on which the three HDVs have 40 tons, the catch up speed is 12.5% higher than the leading HDV and the reference platooning distance is 0.3 meters corresponding to 9 meters in real-world scale.

As in the previous scenario and for the same reason, in Figure 5.7 two different types of lines are represented: a solid and dashed line. One more color is represented in the plot since this scenario includes one more truck.

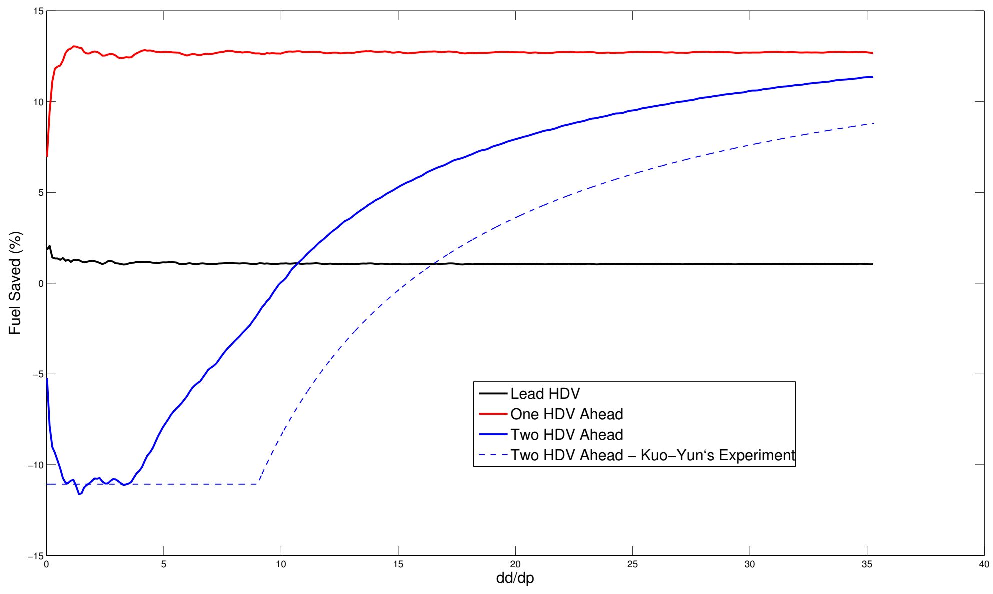


Figure 5.7: Fuel ratio of the three HDVs.

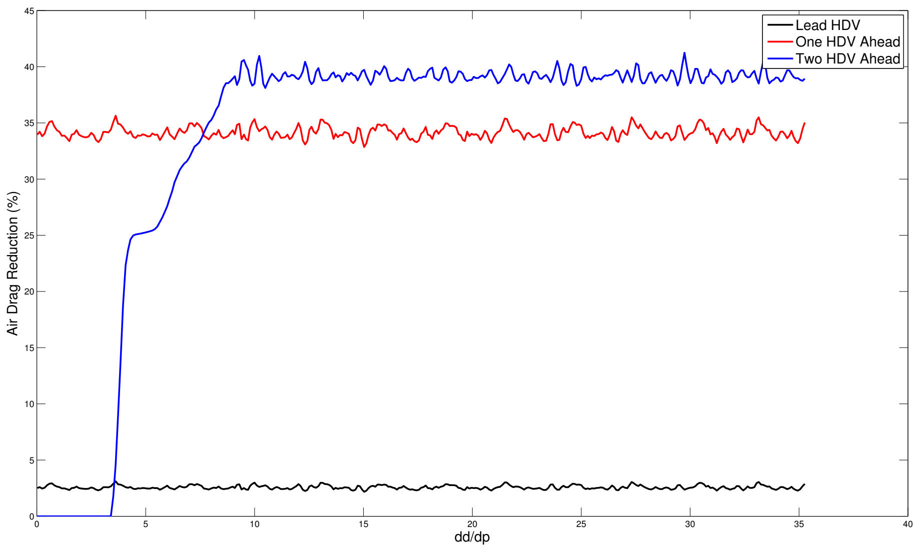


Figure 5.8: Air drag reduction of the three HDVs.

The main conclusions that can be drawn from the analysis of Figure 5.7 are very similar with the first scenario. However, the break-even point for the HDV that decided to catch up occurs, in this case, considerably earlier than expected. Apart from the explanations already given in the first scenario, the fact that now the ADR is slightly bigger (Figure 5.8) since it is the third HDV in the platoon makes the benefit of catching up being higher than in the first scenario case. This means that, the initial slope of ϕ for the third HDV is bigger that the one for the second HDV resulting in an even earlier break-even ratio (compare with Scenario 1, Section 5.1). From the same figure, it can be also concluded that the HDV that was already platooning has a benefit of almost 13% of doing so and the leading HDV has a benefit of 1% assuming that they were platooning for a long time when the third HDV decided to catch up.

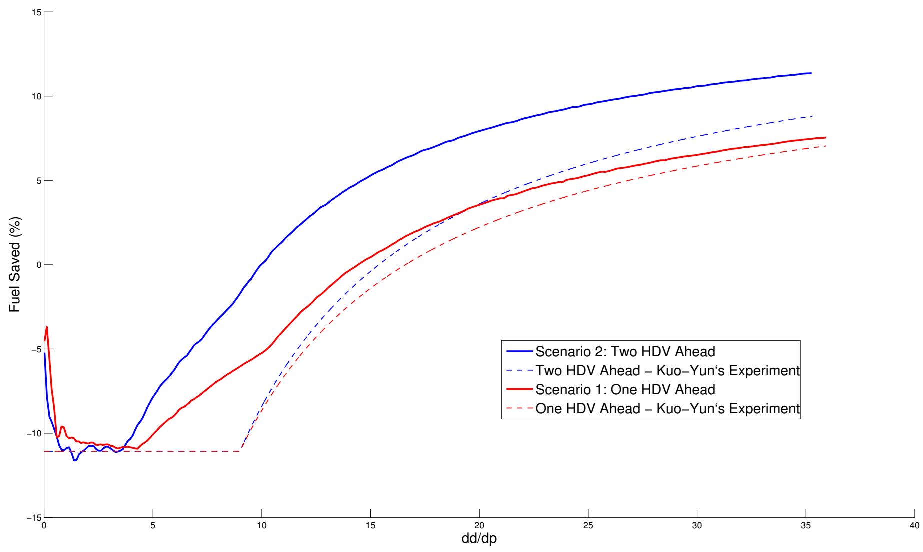


Figure 5.9: Fuel ratio of the HDV that decided to catch up in scenario 1 and 2.

For better understanding of the catching up benefits for the second and third HDV of a platoon, Figure 5.9 represents the fuel ratio for both cases. It is clear from the plots that the third truck benefits more from catching up, as expected.

In Table 5.2 the results of four different combinations of the scenario parameters are summarized. The analysis of the results expressed on the table are similar to those made in the first scenario.

m	r_v	d_{ref}	dd/dp	Expected dd/dp	$\lambda(25)$	Expected $\lambda(25)$	Platoon mean $\lambda(25)$	Catching HDV ADR
$40t$	1.125	$0.3m$	10.0	15.4	9.5%	6.0%	7.8%	38%
$40t$	1.25	$0.15m$	7.7	11.4	12.6%	9.6%	10.5%	44%
$40t$	1.25	$0.3m$	8.7	12.4	10.4%	8.0%	8.1%	38%
$60t$	1.25	$0.3m$	8.1	12.3	8.3%	6.3%	6.4%	39%

Table 5.2: Scenario 2 results.

5.3 Scenario 3 - One HDV catching up two HDVs and the middle one has another destination

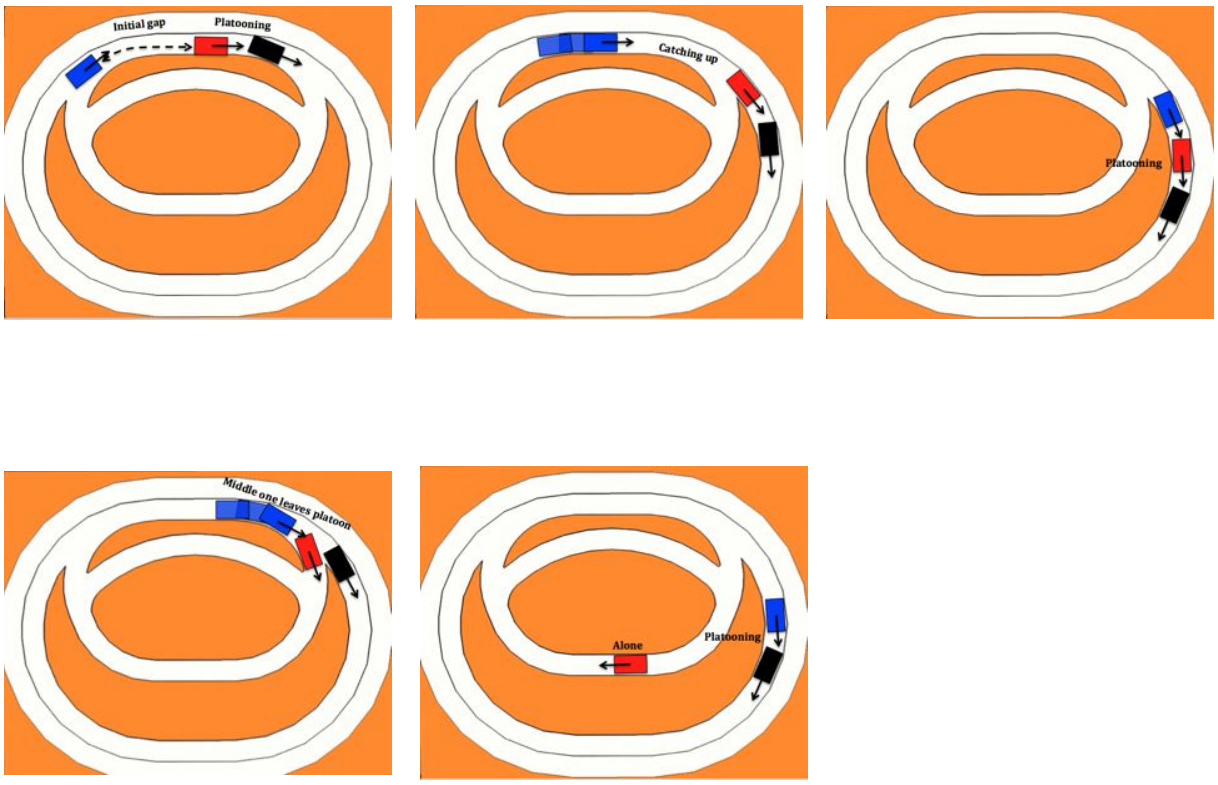


Figure 5.10: Scenario 3 explanation.

The third scenario exemplifies a situation of a platoon single catch up (Figure 5.10) similar to the second scenario. The main difference here is that, in this scenario, the HDV that is traveling in the middle of the platoon just behind the leading HDV has a different destination than the other two HDVs. The purpose of this scenario is to analyze the influence of this detail on the HDV that had to catch the platoon before.

In Figure 5.11 is represented the fuel ratio λ of the HDV that decided to catch up in this scenario comparing to the second scenario. Figure 5.12 represents the ADR for the three HDVs in this scenario. These plots result from simulating the case on which the three HDVs have 40 tons, the catch up speed is 25% higher than the leading HDV and the reference platooning distance is 0.3 meters corresponding to 9 meters in real-world scale.

From Figures 5.11 and 5.12 it is clear when does the HDV that was traveling in the middle leaves the platoon. On that moment, that HDV stops benefiting from the ADR and the HDV behind is forced to speed up to keep the reference to the distance of the leading HDV. For that reason, the third HDV spends extra fuel on that moment and the ADR is smaller than before. As expected, the benefit of catching the platoon is slightly smaller in this case than if the whole platoon had the same destination. The benefit for the third HDV will tend to be the same as if the platoon was only formed by two HDVs.

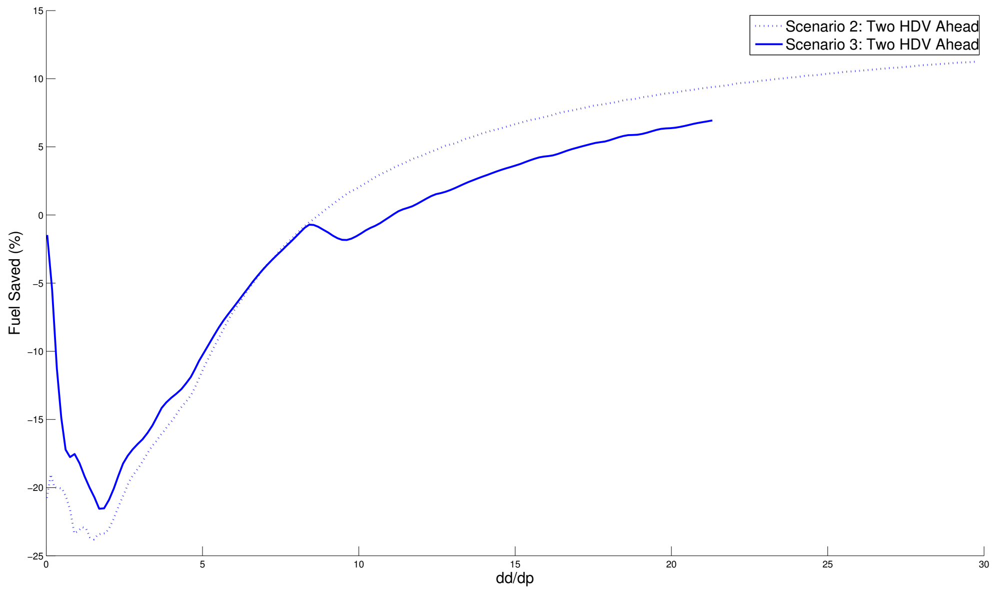


Figure 5.11: Fuel ratio of the HDV that decided to catch up in scenarios 2 and 3.

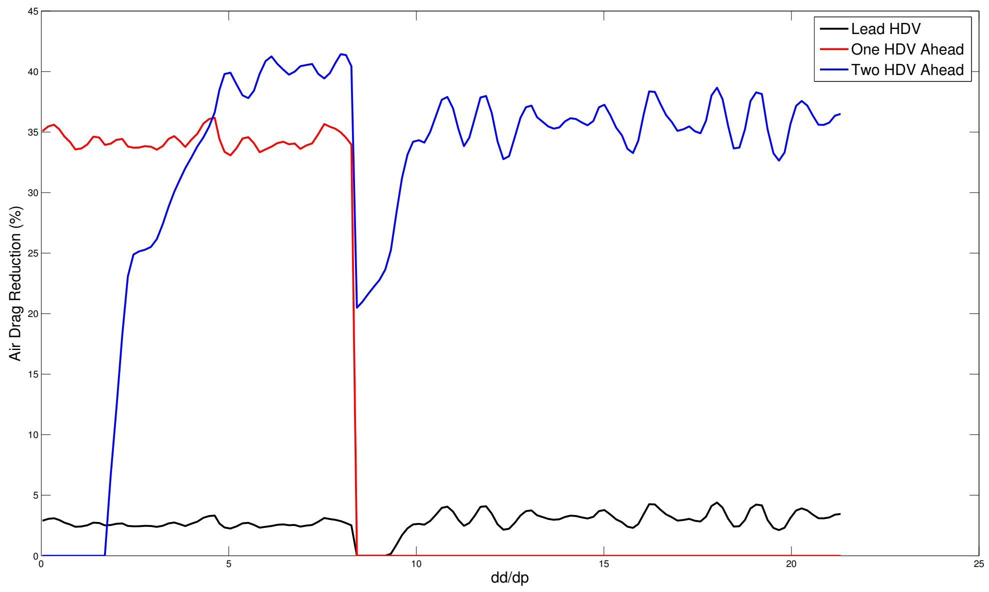


Figure 5.12: Air drag reduction of the three HDVs.

5.4 Scenario 4 - Two HDVs catching up one HDV

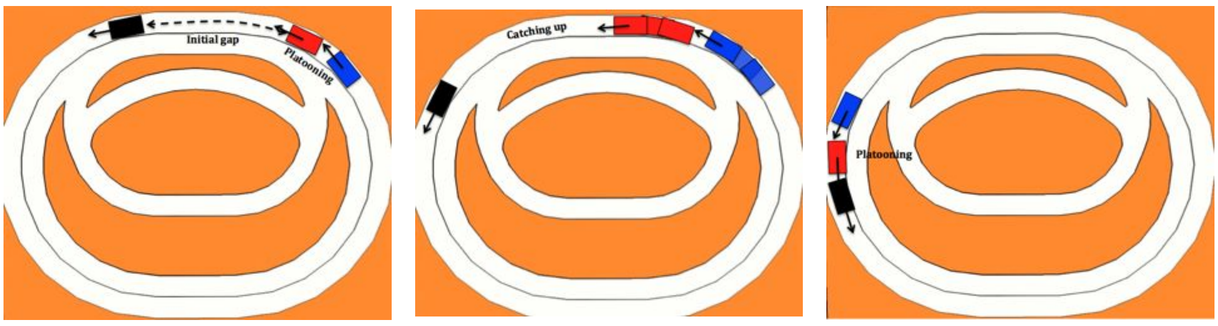


Figure 5.13: Scenario 4 explanation.

The fourth scenario exemplifies a situation in which two HDVs catch up one other HDV (Figure 5.13). Three HDVs are traveling on the same road and have the same destination. At some point, the platoon consisted of two HDVs decides to catch up with the HDV ahead, speeding up until a reference platooning distance is achieved. The purpose of this scenario is to analyze the benefits of catching up for the trucks in the platoon since they were already benefiting from being platooning with each other.

In Figure 5.14 is represented the fuel ratio λ of the three HDVs present in the scenario. This plot results of simulating the case in which the three HDVs have 40 tons, the catch up speed is 12.5% higher than the leading HDV and the reference platooning distance is 0.3 meters corresponding to 9 meters in real-world scale.

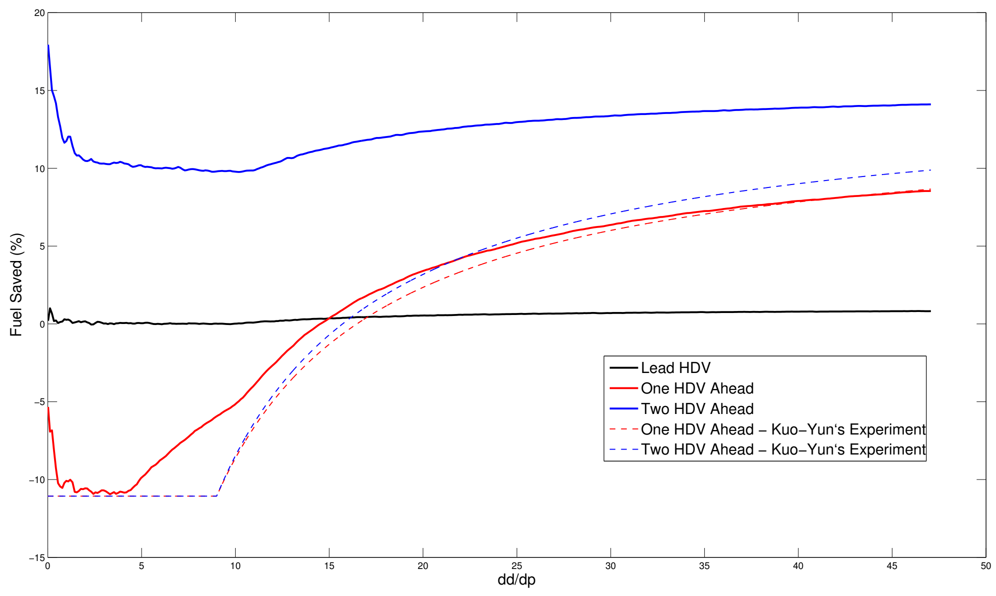


Figure 5.14: Fuel ratio of the three HDVs.

Some conclusions can be drawn from Figure 5.14. It is interesting to look only for the second and third HDVs, since they are already in a platoon and they decided to catch up. The fuel ratio of the leading HDV of the platoon that decides to catch up has the same behavior as in the other scenarios and consequently the same justifications given before apply here. On the other had, the fuel ratio of the second HDV of the platoon that decides to catch up has different behavior than if it was catching up alone, naturally. During the catch up phase, this HDV still benefits from being platooning and the benefit increases even more when the platoon become formed with three HDVs.

Figures 5.15 and 5.16 compare the fuel ratio of the HDVs in the platoon in the situation where they decided to catch up and if they would have continued alone. The fuel ratio is presented for each HDV individually and for the whole platoon. These plots result from simulating the case on which the three HDVs have 40 tons, the catch up speed is 12.5% and 25% higher than the leading HDV and the reference platooning distance is 0.3 meters corresponding to 9 meters in real-world scale. In Table 5.3 the break-even points for these two cases are presented. The break-even point here is the moment where individually each HDV or the whole platoon benefit more from the catching up decision than continue platooning just two vehicles.

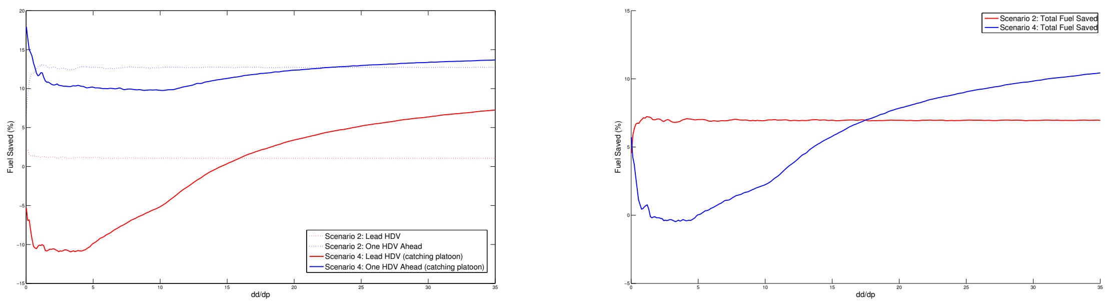


Figure 5.15: Fuel ratio of HDVs in platoon (of two vehicles) in scenario 2 and 4. Individual fuel ratio on the left. Whole platoon (2 HDVs) fuel ratio on the right.

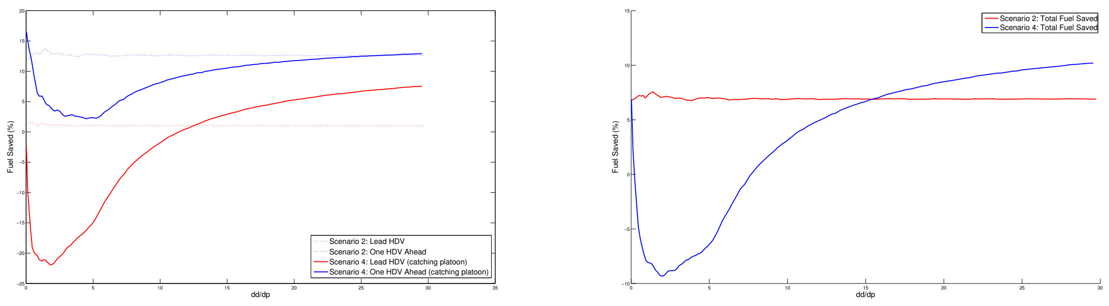


Figure 5.16: Fuel ratio of HDVs in platoon (of two vehicles) in scenario 2 and 4. Individual fuel ratio on the left. Whole platoon (2 HDVs) fuel ratio on the right.

r_v	dd/dp leading HDV	dd/dp One HDV ahead	dd/dp Platoon
1.125	16	22	17.5
1.25	12.5	26.5	15.5

Table 5.3: Scenario 4 results.

From the values in Table 5.3 and in Figures 5.15 and 5.16 it is clear that catching up is beneficial in these particular cases. However, two cases must be distinguished and some comments must be made. For the leading

HDV of the platoon that decides to catch up, the benefits are similar if caught up being alone and the break-even ratio occurs at the same distance traveled. Furthermore, the second HDV of the platoon does not benefit that much from the catch up decision. The whole platoon must travel considerably longer so that this HDV becomes rewarded, otherwise it does not get any benefit from catching up when comparing with platooning with just one HDV ahead. If the perspective is the whole platoon that decides to catch up it can be seen that the break-even occurs in between the break-evens of the two HDVs individually. When taking this decision, the decision maker must take into account that benefitting the leading HDV may not mean that the whole platoon benefits and this may not mean that the second HDV benefits as well. The catch up speed also influences the break-even points. The higher the speed increment the earlier the leading HDV benefits from catching up as seen in the other scenarios. The novelty is that the higher the speed increment the later the second HDV benefits from catching up. The speed increment has to respect a trade-off between which HDV one want to benefit more.

5.5 Scenario 5 - One HDV catching up one HDV from another road

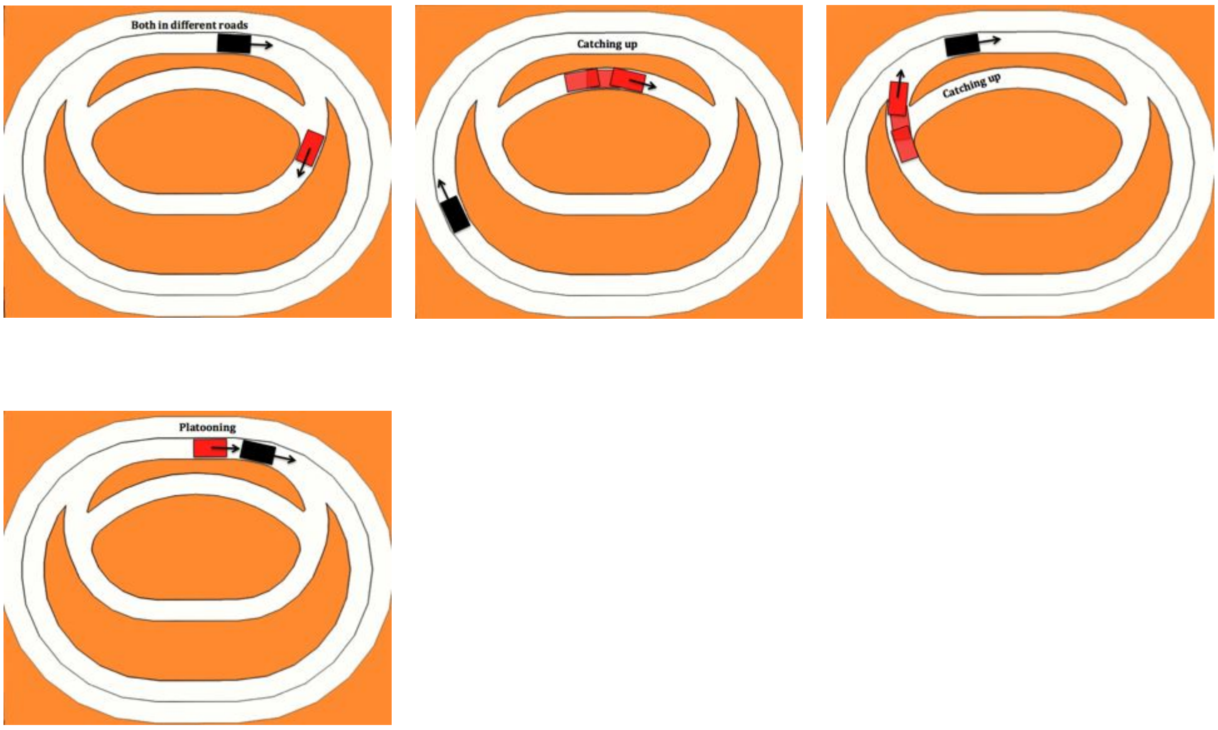


Figure 5.17: Scenario 5 explanation.

The fifth scenario exemplifies a situation of a single catch up (Figure 5.17) very similar with the first scenario. The main difference here is that, in this scenario, the HDVs start on different roads and the platoon formation occurs on the road where the platoon master is driving. The purpose of this scenario is to simulate the different alternatives of platoon formation, showing that the platoons do not occur only when HDVs are driving on the same roads. Also, this scenario shows the coordination ability of the trucks in the testbed.

The analysis and the conclusions are the same as the ones in the first scenario.

5.6 Scenario 6 - One HDV catching up one HDV with another destination

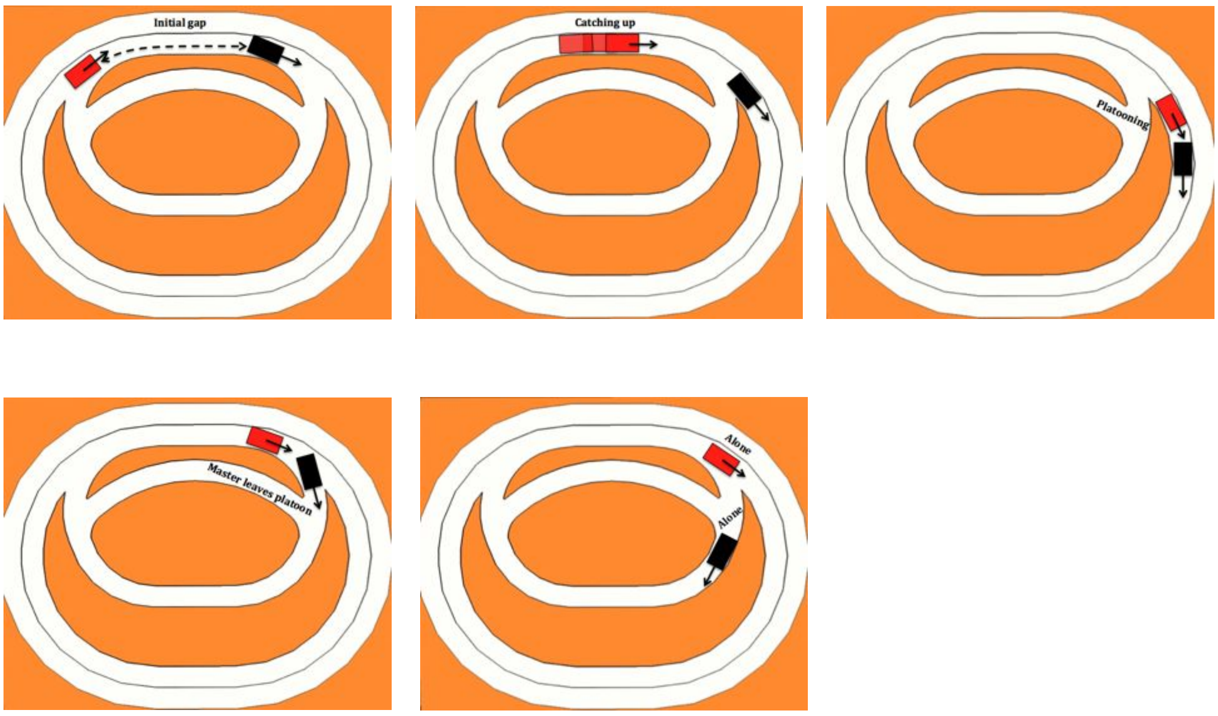


Figure 5.18: Scenario 6 explanation.

The sixth scenario exemplifies a situation of a single catch up (Figure 5.18) similar with the first scenario. The main difference here is that, in this scenario, the leading HDV has a different destination than the pursuing HDV. The purpose of this scenario is to analyze the influence of this detail on the HDV that decides to catch up.

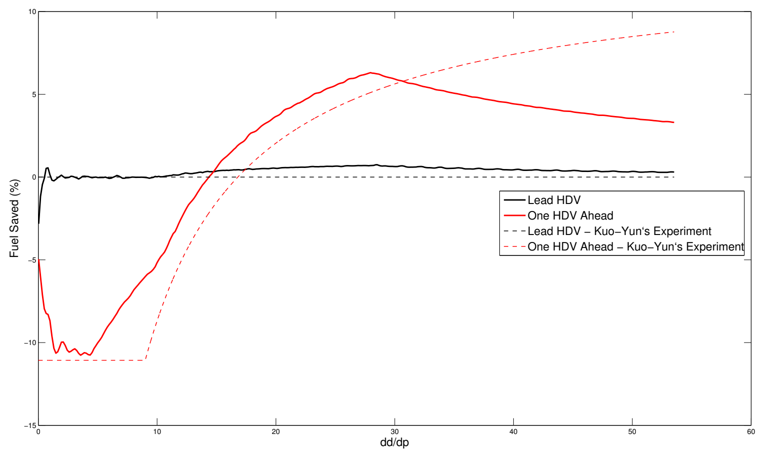


Figure 5.19: Fuel ratio of the HDV that decided to catch up in scenario 1 and 6 with $r_v = 1.125$. The Kuo-Yun's experiment plot was made without the platoon master leaving.

In Figures 5.19 and 5.20 it is represented the fuel ratio λ of the HDVs. These plots result from simulating the cases on which the HDVs have 40 tons, the catch up speed is 12.5% and 25% higher than the leading HDV and the reference platooning distance is 0.3 meters corresponding to 9 meters in real-world scale. In these plots it is clear the moment where the master leaves the platoon and consequently both trucks continue alone.

The fuel ratio of the HDV that has decided to catch up is similar to the one plotted for the first scenario (Figure 5.2). Naturally, when the master leaves the platoon the ADR is 0% for both HDVs since they carry on alone. For that reason, the farther the HDVs continue driving the less they benefit from the catch up decision.

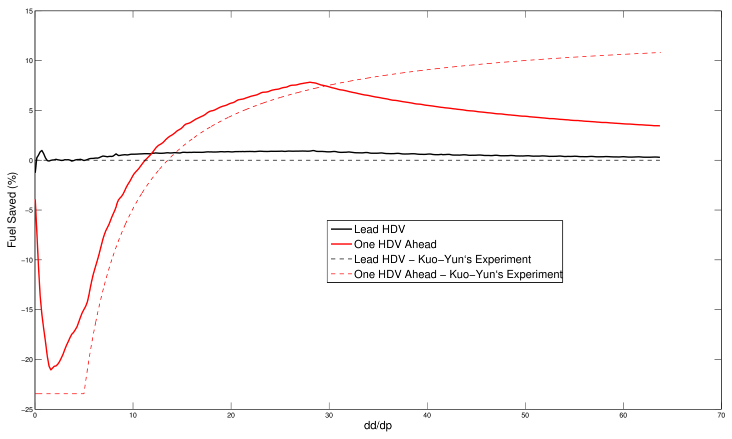


Figure 5.20: Fuel ratio of the HDV that decided to catch up in scenario 1 and 6 with $r_v = 1.25$. The Kuo-Yun's experiment plot was made without the platoon master leaving.

Chapter 6

Conclusions and Future Work

With the purpose of designing, evaluating and showing HDV platooning situations and a testbed was developed. The complete implementation of the testbed was described as well as the experiments and results obtained using it. The system includes up to three PCs running at the same time, together with up to five scale trucks and an indoor GPS (MoCap) composed of twelve cameras. The scale trucks drive themselves on a road network design and built from scratch composed of two roads and three lanes.

In this thesis, the particular case of platoon catch up is studied. To form an HDV platoon the HDVs scattered on the road network should merge in order to save fuel. There are several merging options but the one used in this thesis is to catch up the HDV ahead. This means that the following HDV(s) need to speed up in order to catch up some other HDV or platoon. The problem is to decide in which situations the fuel is actually saved since the catch up part imply an extra-spending of fuel from some of the HDVs.

In order to design HDV platooning situations, several theoretical models and mathematical definitions were introduced and explained: the HDV model, the fuel consumption model, the fuel ratio and the break-even ratio. These models were used when translating from the simulated environment to the real-world dimensions, velocities and ADR values. In the implementation part, the truck kinematics model and controllers were explained and their performance evaluated.

The last part of this thesis is composed by the analysis of the scenarios developed in the testbed. These scenarios represent several situations of HDV platooning, particularly the platoon catch up case. In this part, everything is integrated in one big system in order to apply the models earlier introduced. The object of study was the saved fuel due to platooning and the break-even point, i.e. the moment when neither driving alone nor catching up a platoon ahead would be more feasible.

Some conclusions were drawn from the experiments where the parameters such as HDV, speed increment when catching up and intermediate distance when platooning were being changed for each trial. When a single HDV catches up other HDV the break-even point occurs 10 to 15 times the initial distance that separates them. Then, the HDV that decides to catch up, can save 5 to 10% of fuel comparing to continue driving alone with an ADR around 35%. If a single HDV decides to catch up a platoon with two HDVs ahead, it only needs to travel 8 to 10 times more than the initial distance that separates them and it can save 8 to 13% of fuel.

Finally, another study about if a platoon with two HDVs should catch another HDV or not was performed.

Comparing to the previous cases it is less beneficial to catch up since the platoon that decided to catch up has to travel more than 15 times more than the initial distance that separates it from the other HDV to start benefitting. Additionally, the HDV that leads that platoon benefits a lot more than the HDV that was already platooning. For the latter, it has to travel more than 20 times more than the initial distance that separates the platoon where it is driving from the other HDV so that the catch up decision is beneficial.

It is inherent to every big project the feeling that a lot more can be done in the future. The evolution of the SML was tremendous in the last few months. To continue this evolution some of these ideas can be followed:

1. The existing road network is static. An idea is to make the road network dynamic and dependent on the scenario localization wanted. First, that road would be projected on the floor of the lab. That road network would be different according to the scenario localization. For example, the road topology and form used in a trip from Gothenburg to Stockholm is pretty different than one from Munich to Amsterdam.

2. The road network is assumed flat. Another idea could be simulate the road different grade during a travel. The HDVs have different behaviors in different topologies. It could be also interesting to simulate platooning strategies in extreme situations, like uphill or downhill.

3. No traffic is assumed during the scenarios developed. It would be good to integrate simulated traffic on the road network. Either on the static road network or in the future dynamic one. A big challenge would be to develop strategies to catch up and to overtake in situations were traffic is a problem.

4. The strategy of platooning used in this thesis is to select one HDV as the platoon master. From that moment a platoon is formed behind the master. There is no possibility in manually reordering the trucks without setting one as master, i.e, there is no way of switching the positions of the second and the third trucks, for example. A nice implementation to developed would be a graphical way to, manually, sort the trucks in real time while driving on the road network.

5. There is no remote control integrated in the system. Another idea is to add a remote control to the system in order to control the trucks. The idea is, even if the user sent an acceleration command, the ACC would be activated if another truck was dangerously close.

6. The speed and steering controllers are independent. It would be very interesting to develop a controller for trajectory tracking instead of waypoint following. This may influence the trajectory generation procedure.

7. Integrate the system with other vehicles, such as quadcopters. The quadcopters could work as traffic announcers to the trucks so they could make decisions based on the existing traffic.

8. Develop a path planning algorithm such that the trucks could be able to drive autonomously between two distinct points in the road network.

Figure 6.1: HDV platoon demonstration (courtesy of Scania).

References

[1] Qualysis AB. *QTM Getting Started*, 2011.

[2] Qualysis AB. *QUALISYS MATLAB CLIENT v1.8*, 2011.

[3] Qualysis AB. *QTM User Manual*, 2011.

[4] Scania CV AB. Annual report, 2001.

[5] A. Alam. Optimally fuel efficient speed adaptation. Master's thesis, KTH Royal Institute of Technology, March 2008.

[6] A. Alam. Fuel-efficient distributed control for heavy duty vehicle platooning, 2011. Licentiate Thesis in Automatic Control, KTH Royal Institute of Technology.

[7] A. Alam, A. Gattami, and K. H. Johansson. An experimental study on the fuel reduction potential of heavy duty vehicle platooning. In *13th International IEEE Conference on Intelligent Transportation Systems*, 2011. Madeira, Portugal.

[8] A. Alam, A. Gattami, K. H. Johansson, and C. J. Tomlin. Establishing safety for heavy duty vehicle platooning: A game theoretical approach. In *18th IFAC World Congress*, September 2011. Milan, Italy.

[9] J. P. Alvito. Implementation of traffic control with heavy duty vehicle anti-platooning. Master's thesis, KTH The Royal Institute of Technology, 2013.

[10] M. Amoozadeh. *Smart Mobility Lab Manual*, 2013.

[11] European Commission. Roadmap to a single european transport area, 2011. URL `http://ec.europa.eu/transport/strategies/facts-and-figures/index_en.htm`.

[12] United Nations Population Division. World population prospects: The 2010 revision, 2010. URL `http://esa.un.org/unpd/wpp/Excel-Data/population.htm`. Department of Economic and Social Affairs.

[13] A. Hauksson, B. Mengana, C. Westermark, F. Svensson, J. Lycke, J. Sundberg, K. Imhäuser, and S. van de Hoef. Final report in automatic control project course. Technical report, KTH The Royal Institute of Technology, December 2012.

[14] A. Hernandéz and D. Huertas Péres. Communication between pc and motes is tiny os. Technical report, KTH The Royal Institute of Technology, may 2012.

[15] P. Ioannou and C. Chien. Autonomous intelligent cruise control. *IEEE Transactions on Vehicular Technology*, 42(4):657 – 672, 1993.

[16] Y. Kanayama and B. Hartman. Smooth local path planning for autonomous vehicles. In *IEEE International Conference on Robotics and Automation, 1989. Proceedings., 1989*, may 1989.

[17] W. Levine and M. Athans. On the optimal error regulation of a string of moving vehicles. In *IEEE Transactions on Automatic Control*, July 1966. Volume AC-11, no. 3.

[18] K-Y. Liang. Linear quadratic control for heavy duty vehicle platooning. Master's thesis, KTH Royal Institute of Technology, April 2011.

[19] K.-Y. Liang, J. Mårtensson, and K. H. Johansson. When is it fuel efficient for a heavy duty vehicle to catch up with a platoon? Submitted to the 7^{th} International Federation of Automatic Control (IFAC) Symposium on Advances in Automotive Control, 2013.

[20] P. Lima. Implementation and analysis of platoon catch up scenarios for heavy duty vehicles. Master's thesis, KTH The Royal Institute of Technology, 2013.

[21] D. Macias. Estimation of fuel consumption for real time implementation. Master's thesis, KTH Royal Institute of Technology, 2012.

[22] A. Marzinotto. Cooperative control of ground and aerial vehicles. Master's thesis, KTH Royal Institute of Technology, 2012.

[23] S. M. Melzer and B. C. Kuo. Optimal regulation of systems described by a countably infinite number of objects. In *Journal Automatica*, volume 7, pages 359 – 366, May 1971.

[24] World Health Organization. Global status report on road safety: Time for action, 2009. URL `www.who.int/violence_injury_prevention/road_safety_status/2009`. Geneva.

[25] T. Robinson, E. Chan, and E. Coelingh. Operating platoons on public motorways: An introduction to the sartre platooning programme. In *In 17th World Congress on Intelligent Transport Systems*, 2010. Busan, Korea.

[26] P. Sahlholm. *Distributed Road Grade Estimation for Heavy Duty Vehicles*. PhD thesis, KTH Royal Institute of Technology, 2011.

Appendix A

User's Manual

A.1 System Overview

A block diagram of the system structure can be seen in Figure A.1.

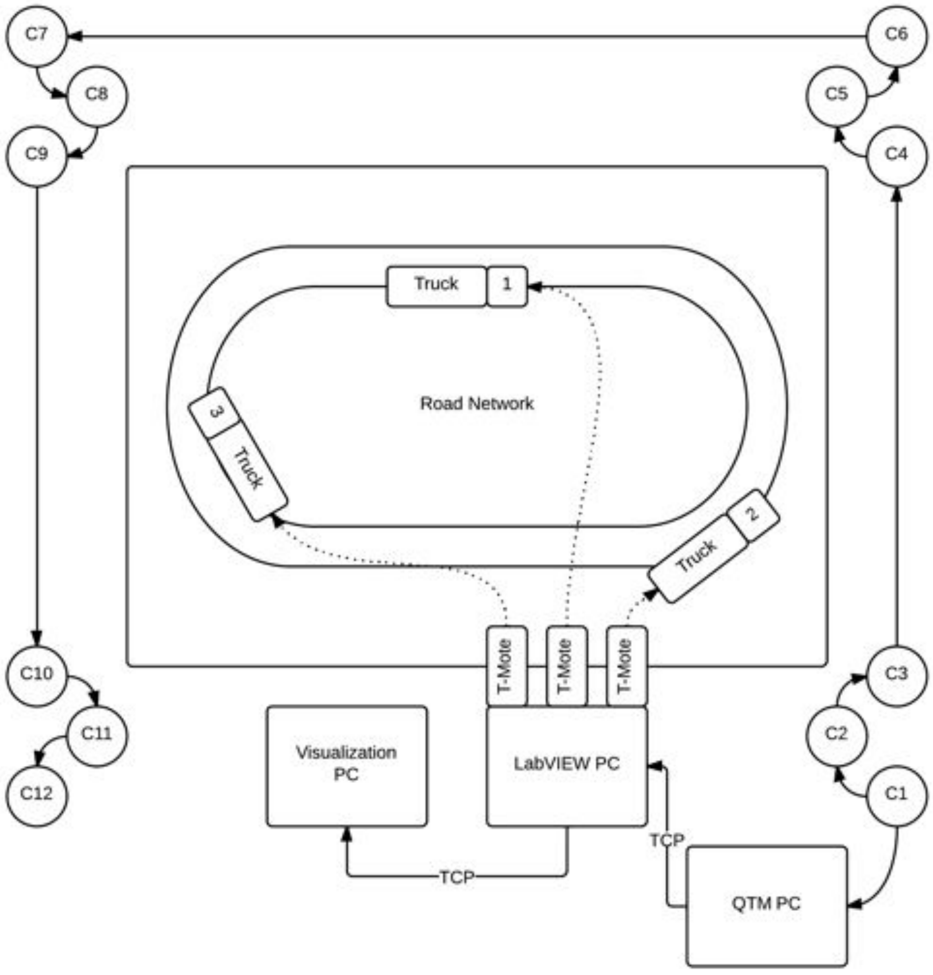


Figure A.1: Program structure block diagram.

The overall system is supposed to represent a **real-world system** in **small scale** in which the **cameras** (C1,C2,...,C12) simulate the **GPS system**, the **LabVIEW PC** simulates an **onboard computer** responsible for the **decision making** of the truck and, naturally, the **scale trucks** represent the **real trucks**. The **T-Motes** exist in order to make possible the communication between the PC and the trucks. Moreover, the QTM PC is the server that provides the **trucks' localization** retrieved by the cameras. Finally, the **Visualization PC** is used for **demonstration** purposes.

This system was developed in the first semester of 2013 in the **Smart Mobility Lab of the Automatic Control Department in KTH** in Stockholm under the supervision of **Jonas Mårtensson** and **Karl Henrik Johansson**. It is the **kernel** of two master's thesis, since it is the **test bed** for the experiments reported on them (see [20] and [9]).

A.1.1 Key Features

With the set of programs developed the user is able to:

- Use the IR markers to **create a set of waypoints** that possibly represents a trajectory, then **acquires** those points and the correspondent **interpolated trajectory** with more waypoints (see Chapter A.4);
- Define the trucks as being **6DOF bodies** using the Qualysis' QTM software. This way it is possible to **track** them in **real time** with 6DOF (see Chapter A.3);
- **Use the trucks** and do a wide range of operations from **platooning**, **platoon catch up** and **overtaking** to **traffic control with traffic lights** (see Chapter A.5);
- Run a **visualization tool** that allows the user and the target audience to easily understand what is happening (see Chapter A.6).

A.1.2 Who are we?

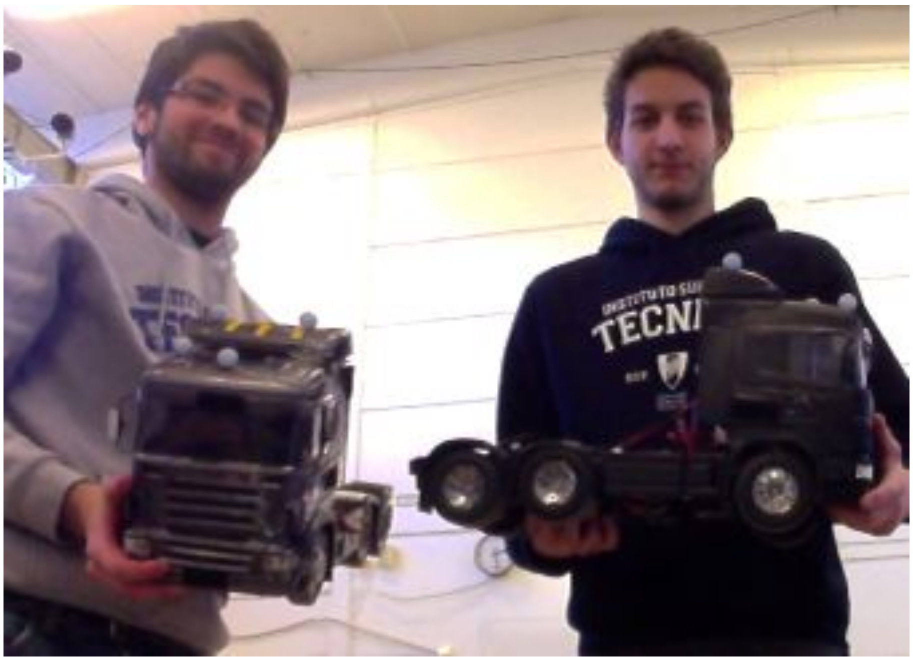


Figure A.2: The authors: Pedro Lima on the left side and João Pedro Alvito on the right side.

We are two portuguese **master students** in **Electrical and Computers Engineering** from **Instituto Superior Técnico**, Lisbon, Portugal. We both came to KTH under an agreement between IST an KTH to take the **Master Program in Systems, Control and Robotics** (TSCRM) at KTH as part of a **Dual Degree**. This agreement includes doing our master thesis in KTH.

If you want to **know more** about this project or if you have any **doubts** don't hesitate to **contact us** (`pfrdal@kth.se` and `jpfa@kth.se`).

A.2 Getting Started with the Tamiya Trucks

The **Tamiya Scania trucks** are 1/14 **scale trucks** of the real Scania V8. They are naturally one of the most important parts of the overall system.

This chapter provides a **basic tutorial of how to connect and start the trucks** and some **troubleshooting**. For a more detailed description of the material involved please refer to [10].

A.2.1 T-Motes set up

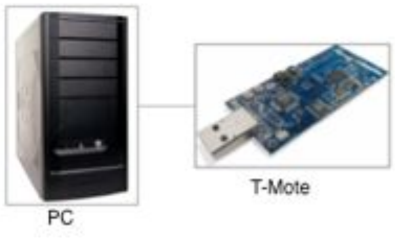


Figure A.3: Connection between a PC and a T-Mote (courtesy of [10]).

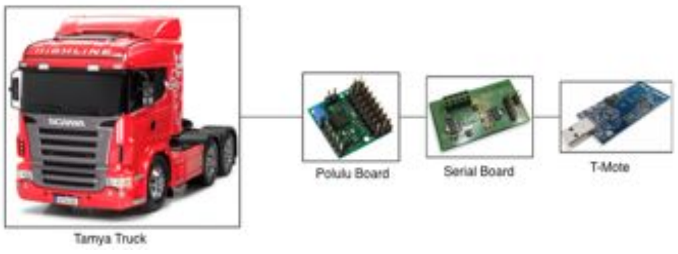
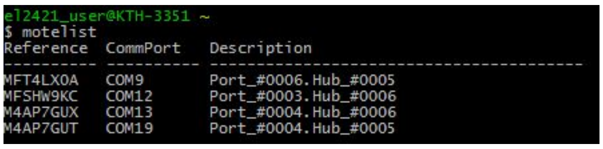


Figure A.4: Connection between a truck and a T-Mote (courtesy of [10]).

In order to communicate with the trucks from a PC you need to know how to use the T-Motes. In the project we use the **serial-forward tool** to send data from LabVIEW to the mote attached to the PC, and the **Tiny OS** to program them. In order to learn how to install the Tiny OS and serial-forward tool please refer to [14].

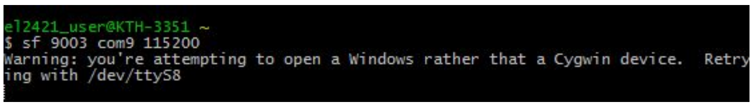
In **Windows**, after having the **Cygwin** and the **serial-forward tool** installed, you should be able to see the T-Motes connected to the PC (like in Figure A.5) using the `motelist` command.



```
el2421_user@KTH-3351 ~
$ motelist
Reference  CommPort   Description
---------- ---------- ----------------------------------------
MFT4LX0A   COM9       Port_#0006.Hub_#0005
MFSHW9KC   COM12      Port_#0003.Hub_#0006
M4AP7GUX   COM13      Port_#0004.Hub_#0006
M4AP7GUT   COM19      Port_#0004.Hub_#0005
```

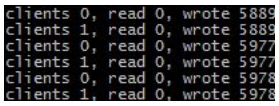
Figure A.5: `motelist` command result on a Cygwin terminal.

The T-Motes usually have its **reference number** (for example: MTF4LX0A) printed on it. If they don't, please connect **one by one** to know which COM port corresponds to each them. Then, it is possible to start a serial forward of a specific T-Mote in a specific **TCP/IP Port** like in Figure A.6. The port chosen has to be a suitable port that is not being used by any other device. The most common ports used when serial forwarding are 9002, 9003, 9004... When trying to communicate, if everything is **okay**, you should start seeing something similar with Figure A.7.



```
el2421_user@KTH-3351 ~
$ sf 9003 com9 115200
Warning: you're attempting to open a Windows rather that a Cygwin device.  Retry
ing with /dev/ttyS8
```

Figure A.6: `sf` command result on a Cygwin terminal.

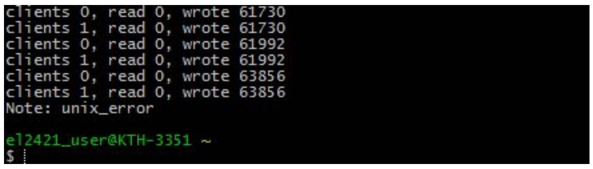


```
clients 0, read 0, wrote 5889
clients 1, read 0, wrote 5889
clients 0, read 0, wrote 5977
clients 1, read 0, wrote 5977
clients 0, read 0, wrote 5978
clients 1, read 0, wrote 5978
```

Figure A.7: `sf` normal execution on a Cygwin terminal.

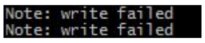
It is very important that you pay a lot of attention when doing serial-forward of a T-Mote in order to be able to communicate correctly with a truck. A T-Mote connected to the PC has a unique pair connected to a truck. The T-Motes used so far for that purpose are all labeled with ”<COLOR> PC <ID>” and ”TRUCK <COLOR> <ID>”, where <COLOR> is the **color of the truck** and the <ID> is the **communication ID**[1] of the truck. The **communication ID has to be inputed in the LabVIEW program** (see Chapter A.5).

If you receive messages like ”Note: write failed” (see Figure A.9) or ”unix_error” (see Figure A.8), try to kill the serial forward with CTRL+C inside of the Cygwin terminal and restart the serial forward again. If it still doesn’t work, try to disconnect and connect the corresponding T-Mote and restart the serial forward. Restart the PC if nothing else works. **Always check if the IDs and COM ports you inserted in the LabVIEW program correspond to the T-Motes you are using.**



```
clients 0, read 0, wrote 61730
clients 1, read 0, wrote 61730
clients 0, read 0, wrote 61992
clients 1, read 0, wrote 61992
clients 0, read 0, wrote 63856
clients 1, read 0, wrote 63856
Note: unix_error

el2421_user@KTH-3351 ~
$
```

Figure A.8: `sf` ”unix_error” example.



```
Note: write failed
Note: write failed
```

Figure A.9: `sf` ”Note: write failed” example.

If everything is okay you should see the **T-Motes’ leds blinking stressfully** when you try to transmit something through them.

[1]It is not the same thing as the radio channel number!

A.2.2 Trucks Set Up

The **truck connections** are exemplified in figure A.10 and A.11.

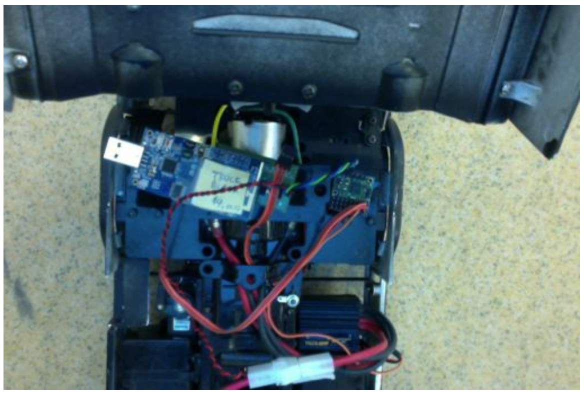


Figure A.10: Connections between each component in a truck.

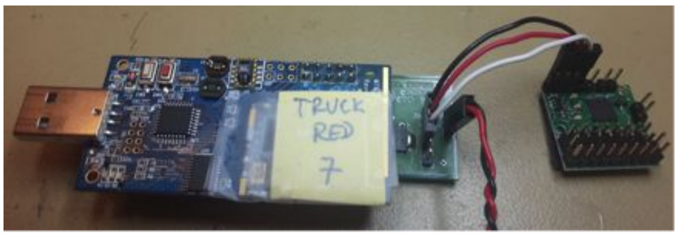


Figure A.11: Detailed connections between a T-Mote and a Polulu board (courtesy of [10]).

The following connections have to be made on the truck:

- Connect the **2-pin female jumper wire** of the **power cable** to the **serial board**. **Pay attention to the polarity of the board**;
- Connect the **2-pin female-female jumper** between the **serial board** and the **Polulu board**. **Pay attention to the polarity of the board**;
- Connect the **3 wire cable** of the **speed servo** to the **Polulu board**. **Pay attention to the cable order**;
- Connect the **3 wire cable** of the **steering servo** to the **Polulu board**. **Pay attention to the cable order**;
- Connect the **T-Mote** to the **serial board** so that the **rightmost 10 pins** of the T-Mote are connected;
- Set the **motor switch** to **"On"**;
- Connect the **battery female connection plug** to the **male connection plug of the power cable**.
- Connect the **power cable female connection plug** to the **speed servo male connection plug**.

When everything is connected the **yellow LED** should turn on on the **Polulu board**. If you see a **red LED** this can mean that the **batteries are low**, that you **misconnected some of the cables** or the **T-Mote is misconnected to the serial board**.

When you try to communicate with the T-Mote that is on the truck you should see a **blinking blue LED on the T-Mote** and a **blinking green LED on the Polulu board**. If you don't see anything happening, **check if the IDs and COM ports you inserted in the LabVIEW program correspond to the T-Motes you are using.**

To charge the batteries you should connect the battery to a battery charger.[2] The charging rate must be $0.5A$ and it takes about 10 hours for the battery to be fully charged. For safety reasons, **it is important to never forget a charging battery while no one is around**.

[2]The one used in the Smart Mobility Lab is the Vector AC/DC NX85 Variable Output Charger.

A.3 Getting Started with QTM

Qualisys Track Manager (QTM) is a Windows-based data acquisition software with an interface that allows the user to perform 2D and 3D motion capture.

This chapter provides a **basic tutoria**l of how to use QTM in order to **define a truck as a 6DOF rigid body**. For a more detailed description of the software please refer to [1] and [3][3].

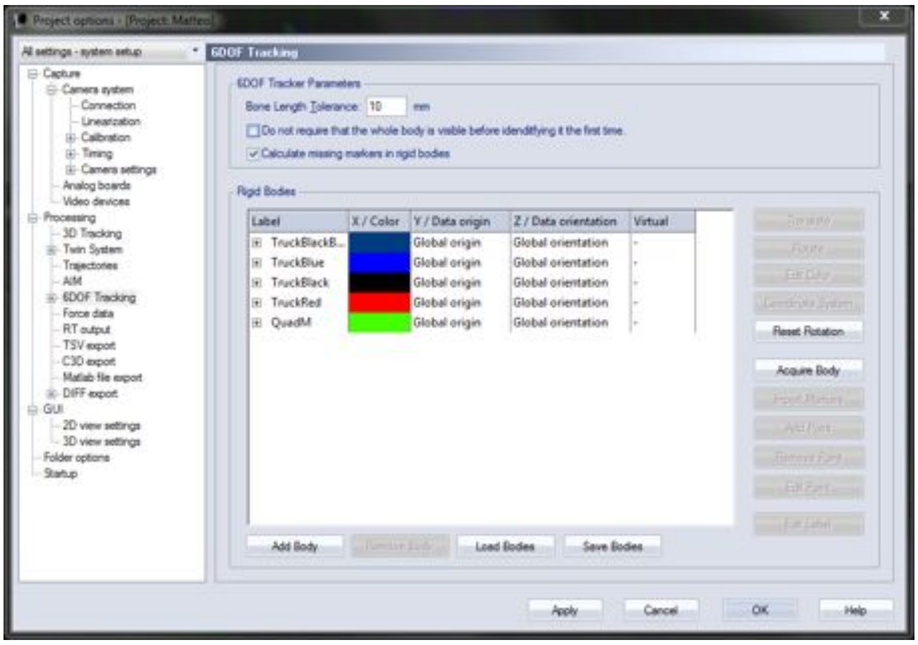
[3]Available on the Qualysis website: `http://www.qualisys.com`. It requires log in credentials.

A.3.1 How to Define a truck as a 6DOF Body

The trucks to be tracked are equipped with **markers**. These are small IR-reflective spheres placed on the top of the truck. A **minimum of 3 markers** is required in order to define a **6DOF Rigid Body**. We placed 4 markers per truck so that the trucks are more robustly tracked. Each truck has its unique marker configuration in order to be unequivocally recognized.

In order to define a 6DOF body you can follow the **next steps**.

- **Step 1**: Open the **"6DOF Tracking" page** that can be found in the **"Project Options" dialog**. There you will see the already defined 6DOF Rigid Bodies, define new ones or load old ones. To acquire a new body, **right-click "Acquire Body"** on the right side of the dialog.



6DOF Tracking

6DOF Tracker Parameters

Bone Length Tolerance: 10 mm

☐ Do not require that the whole body is visible before idendifying it the first time.

☑ Calculate missing markers in rigid bodies

Rigid Bodies

Label	X / Color	Y / Data origin	Z / Data orientation	Virtual
TruckBlackB...	🟦	Global origin	Global orientation	-
TruckBlue	🟦	Global origin	Global orientation	-
TruckBlack	⬛	Global origin	Global orientation	-
TruckRed	🟥	Global origin	Global orientation	-
QuadM	🟩	Global origin	Global orientation	-

Figure A.12: "6DOF Tracking" page in the "Project Options" dialog.

- **Step 2**: Another dialog should appear. Then click **"Start"**.

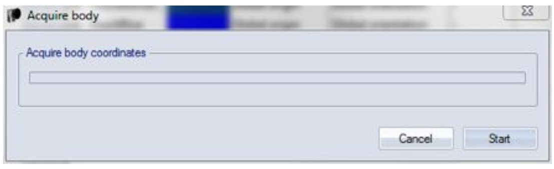
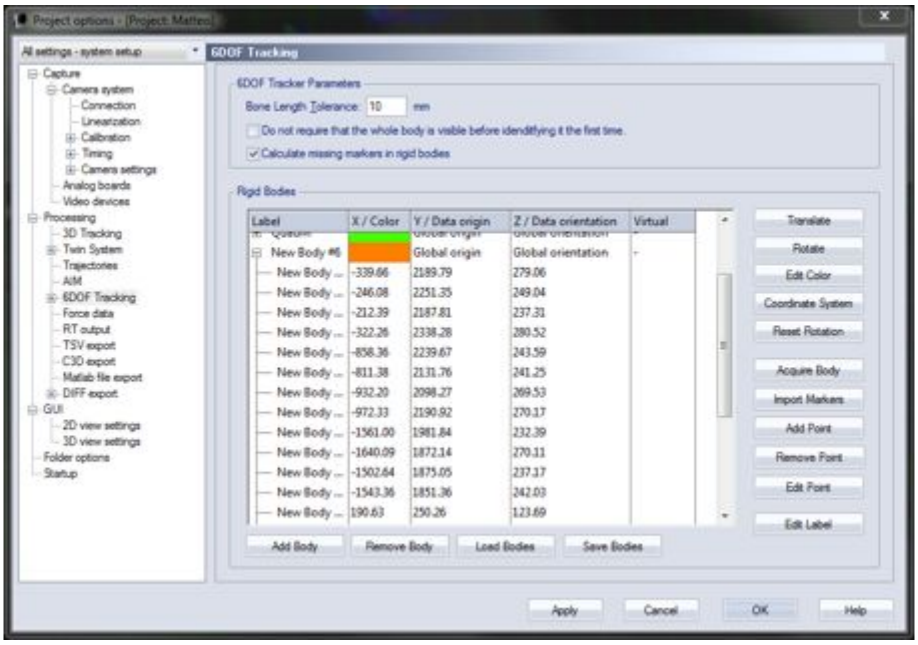


Figure A.13: "Acquire Body" dialog.

- **Step 3**: All the markers that can be seen by the cameras will appear under the "New Body" markers list. You should **delete from the list all the acquired markers that do not make part of the body you want to define**. The best way to do this is either by only putting the body you are defining on the visible are or knowing more or less the coordinates of the markers which make part of the new body and you deleting all the others.



6DOF Tracker Parameters

Bone Length Tolerance: 10 mm

☐ Do not require that the whole body is visible before idendifying it the first time.

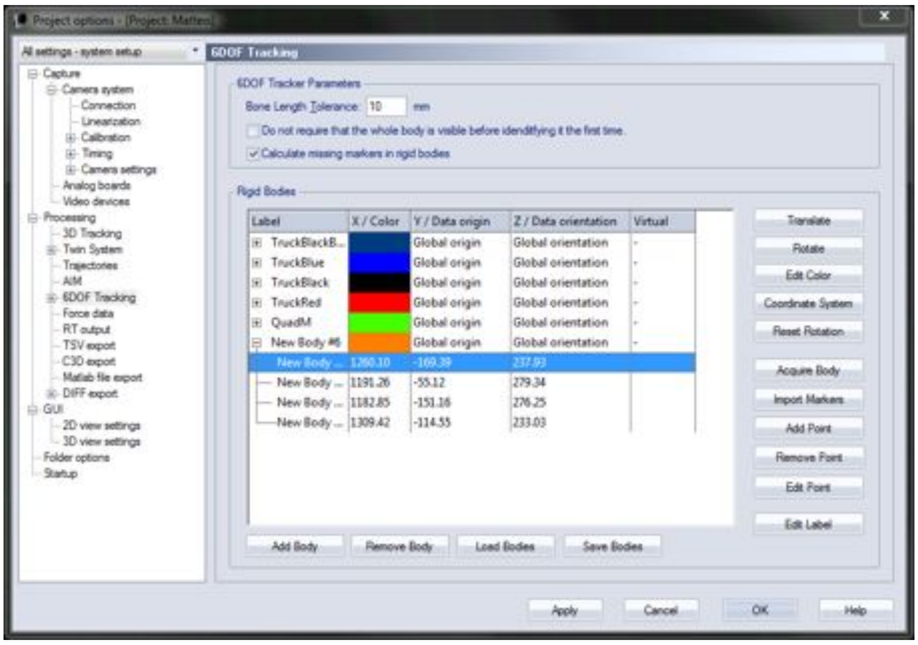
☑ Calculate missing markers in rigid bodies

Rigid Bodies

Label	X / Color	Y / Data origin	Z / Data orientation	Virtual
QuadM	🟩	Global origin	Global orientation	-
New Body #6	🟧	Global origin	Global orientation	-
New Body ...	-339.66	2189.79	279.06	
New Body ...	-246.08	2251.35	249.04	
New Body ...	-212.39	2187.81	237.31	
New Body ...	-322.26	2338.28	280.52	
New Body ...	-858.36	2239.67	243.59	
New Body ...	-811.38	2131.76	241.25	
New Body ...	-932.20	2098.27	269.53	
New Body ...	-972.33	2190.92	270.17	
New Body ...	-1561.00	1981.84	232.39	
New Body ...	-1640.09	1872.14	270.11	
New Body ...	-1502.64	1875.05	237.17	
New Body ...	-1543.36	1851.36	242.03	
New Body ...	190.63	250.26	123.69	

Figure A.14: The ”New Body #6” appeared on the page.

- **Step 4**: After deleting all the markers from the list, **you should have just 4 markers** in order to define a truck as a 6DOF Rigid Body. Now, you should **rename** the ”New Body” to a logical name like ”Truck Grey” and you **must renumber** all the markers acquired from 1 to N where N is the number of markers of the new Rigid Body you want to define. If you want you can also **change the color** that the Rigid Body will assume when recognized.



6DOF Tracker Parameters

Bone Length Tolerance: 10 mm

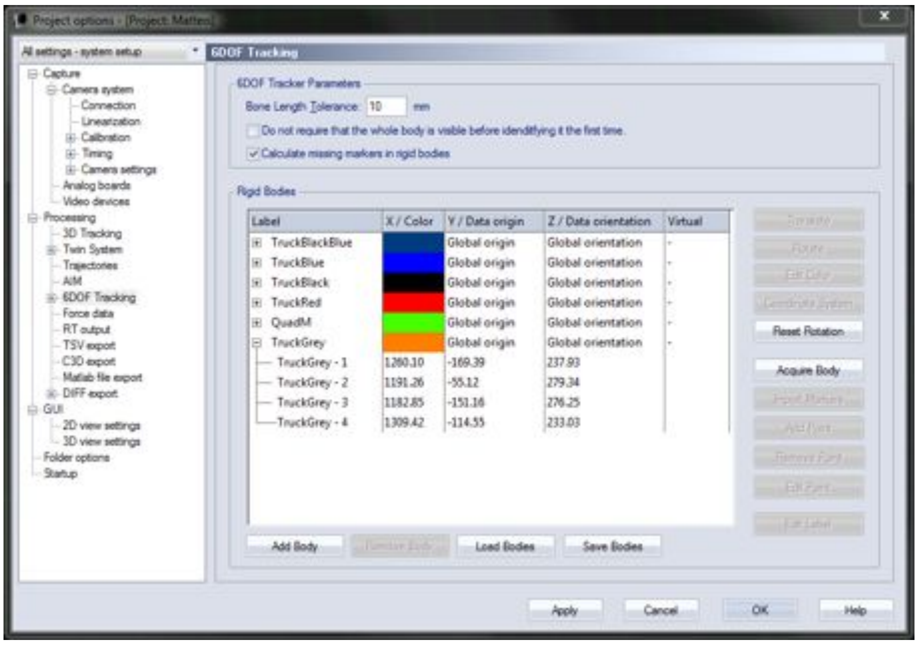
☐ Do not require that the whole body is visible before idendifying it the first time.

☑ Calculate missing markers in rigid bodies

Rigid Bodies

Label	X / Color	Y / Data origin	Z / Data orientation	Virtual
TruckBlackB...	🟦	Global origin	Global orientation	-
TruckBlue	🟦	Global origin	Global orientation	-
TruckBlack	⬛	Global origin	Global orientation	-
TruckRed	🟥	Global origin	Global orientation	-
QuadM	🟩	Global origin	Global orientation	-
New Body #6	🟧	Global origin	Global orientation	-
New Body ...	1260.10	-169.39	237.93	
New Body ...	1191.26	-55.12	279.34	
New Body ...	1182.85	-151.16	276.25	
New Body ...	1309.42	-114.55	233.03	

Figure A.15: The ”New Body #6” with just 4 markers associated.



6DOF Tracking

6DOF Tracker Parameters

Bone Length Tolerance: 10 mm

☐ Do not require that the whole body is visible before idendifying it the first time.

☑ Calculate missing markers in rigid bodies

Rigid Bodies

Label	X / Color	Y / Data origin	Z / Data orientation	Virtual
TruckBlackBlue	🟦	Global origin	Global orientation	-
TruckBlue	🟦	Global origin	Global orientation	-
TruckBlack	⬛	Global origin	Global orientation	-
TruckRed	🟥	Global origin	Global orientation	-
QuadM	🟩	Global origin	Global orientation	-
TruckGrey	🟧	Global origin	Global orientation	-
TruckGrey - 1	1260.10	-169.39	237.93	
TruckGrey - 2	1191.26	-55.12	279.34	
TruckGrey - 3	1182.85	-151.16	276.25	
TruckGrey - 4	1309.42	-114.55	233.03	

Figure A.16: The body was now renamed to "Truck Grey". Also the makers were renumbered.

- **Step 5**: You should now see the new body **recognized** with the color you have chosen. In Figure A.17, this corresponds to the 4 grey points next to the X axis. The next step is to **associate a local coordinate system to the Rigid Body**.

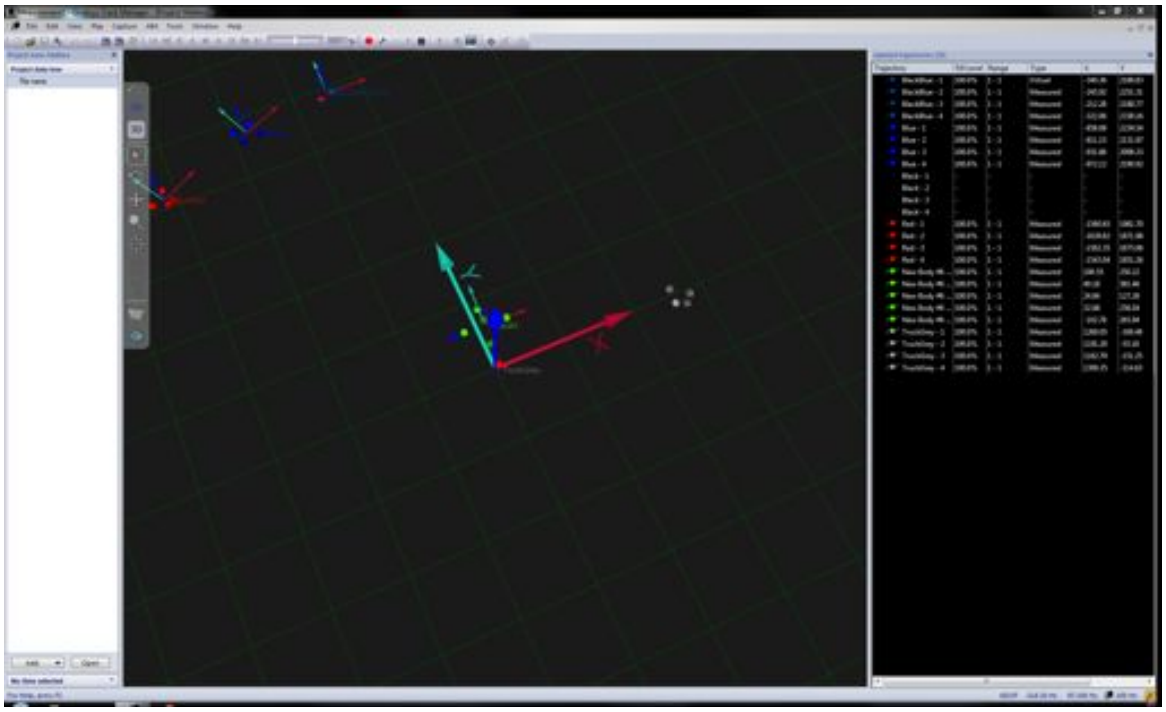
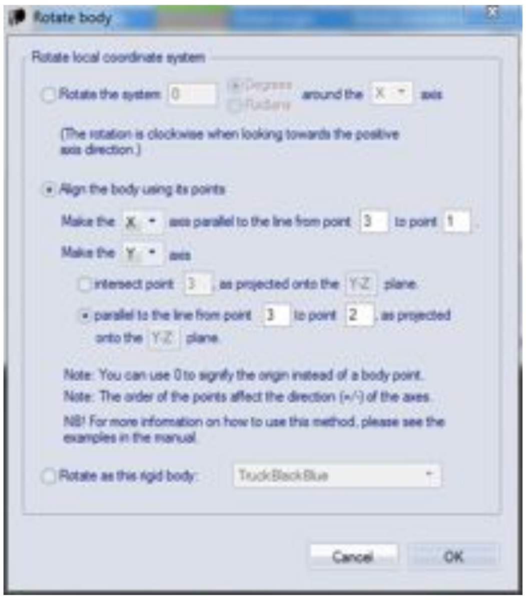


Figure A.17: 3D reconstruction to the space views by the cameras. The new body acquired appears with a new color.

- **Step 6**: To **associate the X and Y axis of local coordinate system to certain markers**, right-click **"Trans-**

late" on the right side of the "6DOF Tracking" page in the "Project Options" dialog. A new dialog box should appear. Then select **"Align the body using its points"** and **input the numbers** of the markers you want to be recognized as the X axis and the Y axis of the body.



Rotate body

Rotate local coordinate system

( ) Rotate the system [0] (•) Degrees ( ) Radians around the [X] axis

(The rotation is clockwise when looking towards the positive axis direction.)

(•) Align the body using its points

Make the [X] axis parallel to the line from point [3] to point [1].

Make the [Y] axis

( ) intersect point [3], as projected onto the [Y-Z] plane.

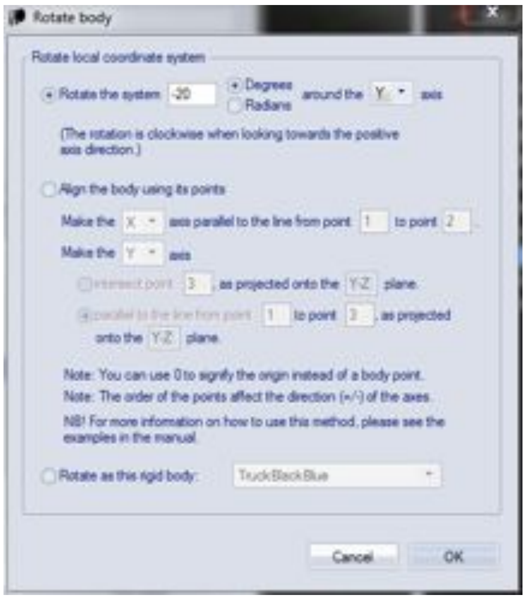
(•) parallel to the line from point [3] to point [2], as projected onto the [Y-Z] plane.

Note: You can use 0 to signify the origin instead of a body point.
Note: The order of the points affect the direction (+/-) of the axes.
NB! For more information on how to use this method, please see the examples in the manual.

( ) Rotate as this rigid body: [TruckBlackBlue]

Figure A.18: "Rotate body" dialog - aligning using its own points.

- **Step 7**: Some final adjustments like **rotating the coordinate system around a certain axis** can be done. On the same **"Rotate"** dialog, **if acquiring one of our marker configurations**, you should rotate more or less -20^o degrees around the Y axis in order to align the local coordinate system with the world coordinate system.



Rotate body

Rotate local coordinate system

(•) Rotate the system [-20] (•) Degrees ( ) Radians around the [Y] axis

(The rotation is clockwise when looking towards the positive axis direction.)

( ) Align the body using its points

Make the [X] axis parallel to the line from point [1] to point [2].

Make the [Y] axis

( ) intersect point [3], as projected onto the [Y-Z] plane.

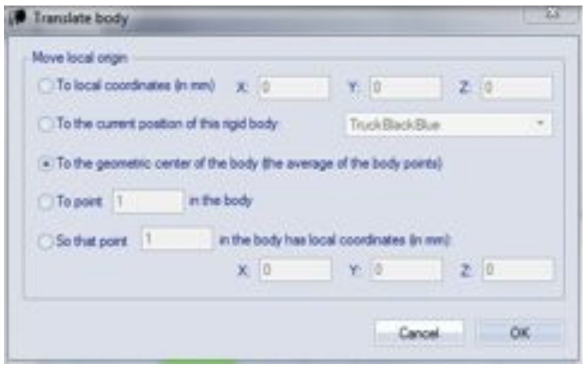
(•) parallel to the line from point [1] to point [3], as projected onto the [Y-Z] plane.

Note: You can use 0 to signify the origin instead of a body point.
Note: The order of the points affect the direction (+/-) of the axes.
NB! For more information on how to use this method, please see the examples in the manual.

( ) Rotate as this rigid body: [TruckBlackBlue]

Figure A.19: "Rotate body" dialog - rotating the local coordinate system.

- **Step 8**: To **translate the coordinate system to the geometric center of the body**, right-click **"Translate"** on the right side of the dialog. A new dialog box should appear. Then select **”To the geometric center of the body (the average of the body points)”**.


Translate body

Move local origin

( ) To local coordinates (in mm) X: 0 Y: 0 Z: 0

( ) To the current position of this rigid body TruckBlackBlue

[✓ To the geometric center of the body (the average of the body points)]

( ) To point 1 in the body

( ) So that point 1 in the body has local coordinates (in mm): X: 0 Y: 0 Z: 0

Cancel OK

Figure A.20: ”Translate body” dialog.

- **Step 9**: The new body should now appear with the **correct label and color and with the local coordinate system**.

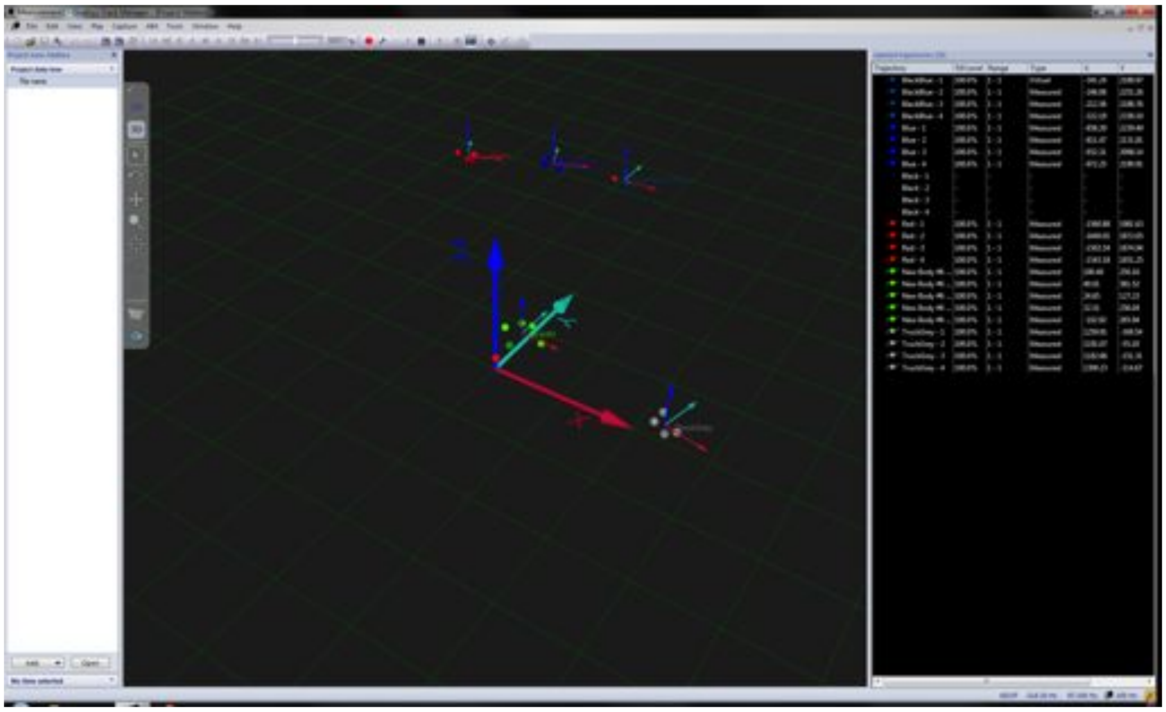


Figure A.21: The new body is now visible with correct label and color and with the local system.

If you are not getting the desired result please make sure you followed correctly all the steps and refer to [1] and [3] for more detailed information.

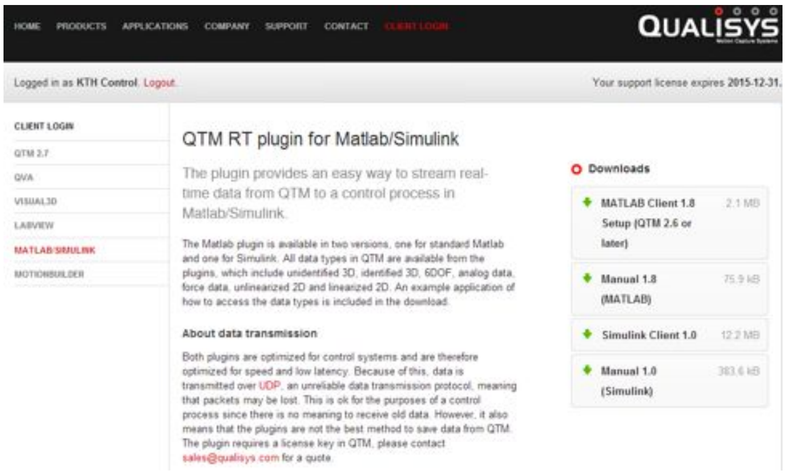
A.4 Trajectory Creation With Matlab

In order to move the trucks along the road network we have to create the trajectories. They are composed of a sequence of points that will be followed by the trucks. There are several possible ways to create the trajectory. Here we are going to present the method that we used and all the steps you should take if you want to replicate it in some way.

A.4.1 Prerequisites

A.4.2 Matlab Qualysis Client

To communicate with the **Qualysis** system you need the **MATLAB Client**(which you can download in the Qualysis website[4]). It will require login credentials, but if you use a computer in the **Smart Mobility Lab** you will have the client already installed. Naturally, to use the **MATLAB Client** you need to have installed in your computer a valid **MATLAB** license.



Logged in as KTH Control. Logout.

Your support license expires 2015-12-31.

QTM RT plugin for Matlab/Simulink

The plugin provides an easy way to stream real-time data from QTM to a control process in Matlab/Simulink.

The Matlab plugin is available in two versions, one for standard Matlab and one for Simulink. All data types in QTM are available from the plugins, which include unidentified 3D, identified 3D, 6DOF, analog data, force data, unlinearized 2D and linearized 2D. An example application of how to access the data types is included in the download.

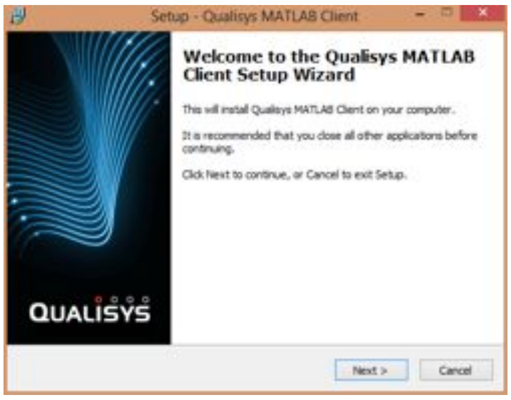
About data transmission

Both plugins are optimized for control systems and are therefore optimized for speed and low latency. Because of this, data is transmitted over UDP, an unreliable data transmission protocol, meaning that packets may be lost. This is ok for the purposes of a control process since there is no meaning to receive old data. However, it also means that the plugins are not the best method to save data from QTM. The plugin requires a license key in QTM, please contact sales@qualisys.com for a quote.

Downloads

MATLAB Client 1.8 Setup (QTM 2.6 or later)	2.1 MB
Manual 1.8 (MATLAB)	75.9 kB
Simulink Client 1.0	12.2 MB
Manual 1.0 (Simulink)	383.6 kB

Figure A.22: Downloading the qualisys MATLAB Client.



Welcome to the Qualisys MATLAB Client Setup Wizard

This will install Qualisys MATLAB Client on your computer.

It is recommended that you close all other applications before continuing.

Click Next to continue, or Cancel to exit Setup.

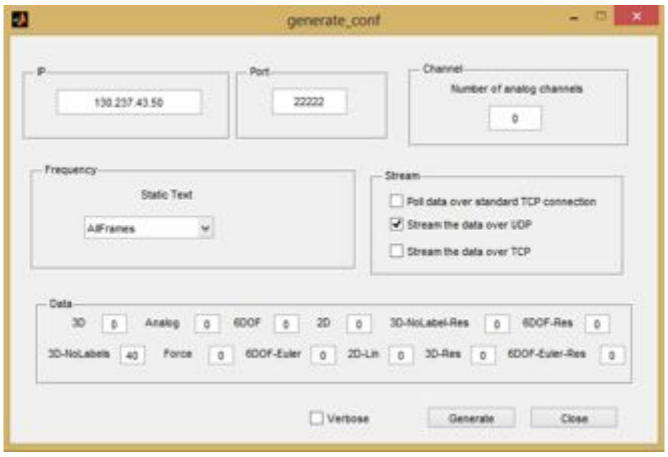
Figure A.23: Qualisys MATLAB Client installation.

[4]www.qualysis.com

If you need to use it in a different computer just download the installation file and follow the normal procedures to have the client installed. Note that a computer with Microsoft Windows installed is required.

A.4.3 Configuration File

When communicating with the Qualysis system, the MATLAB Client uses a configuration file where all the settings are defined. With the purpose of creating a more dynamical experience, we created a MATLAB application that generates the configuration file according to the settings chosen by the user.


generate_conf

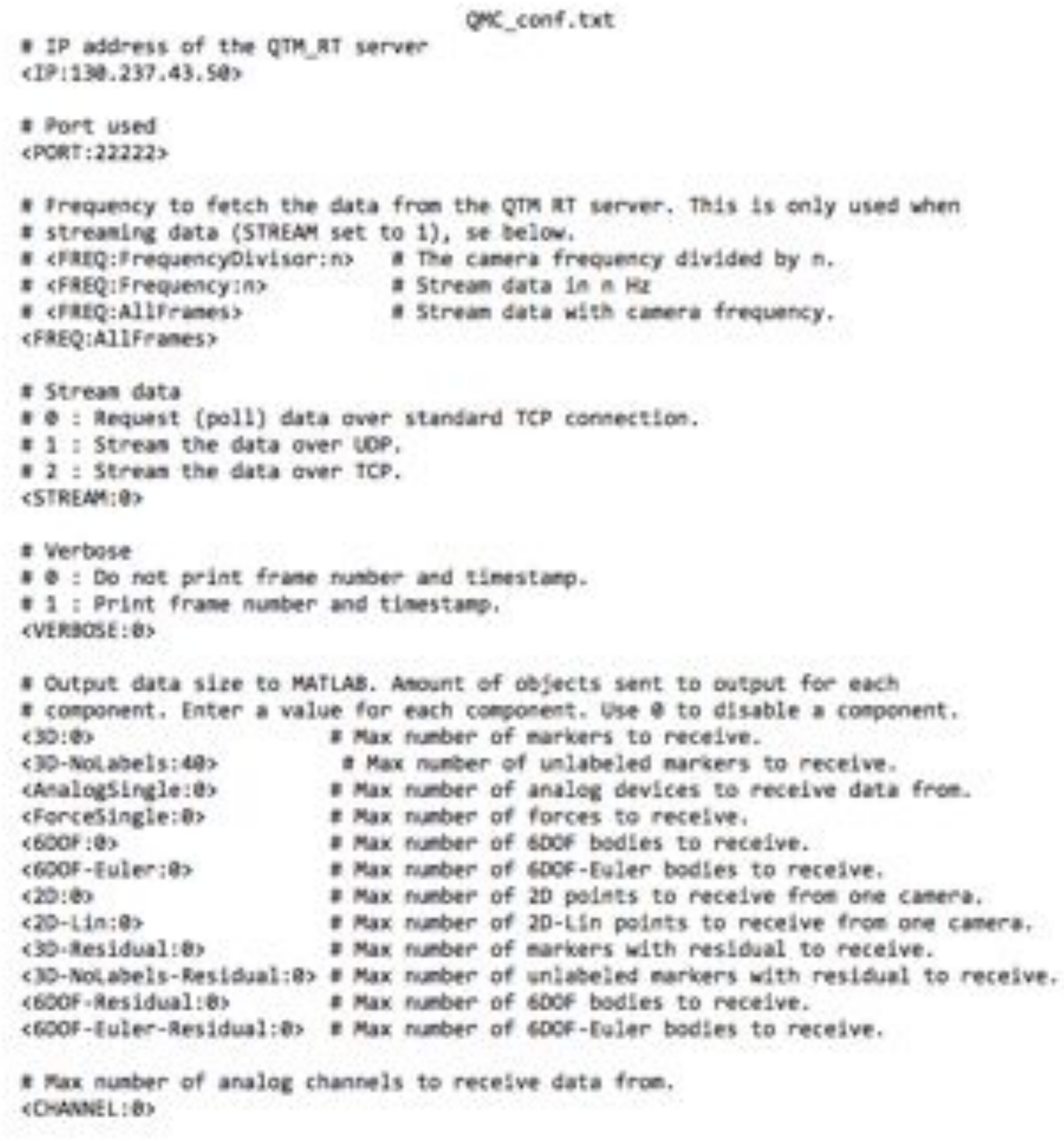
IP: 130.237.43.50
Port: 22222
Channel — Number of analog channels: 0
Frequency — Static Text: AllFrames
Stream:
[ ] Poll data over standard TCP connection
[✓] Stream the data over UDP
[ ] Stream the data over TCP

Data:
3D 0 | Analog 0 | 6DOF 0 | 2D 0 | 3D-NoLabel-Res 0 | 6DOF-Res 0
3D-NoLabels 40 | Force 0 | 6DOF-Euler 0 | 2D-Lin 0 | 3D-Res 0 | 6DOF-Euler-Res 0

[ ] Verbose

Figure A.24: Configuration file generator software.

To know more about each parameter of the configuration file we recommend you to refer to [2]. In Figure A.25, as an example, we present a sample of a generated configuration file with the settings shown in Figure A.24.



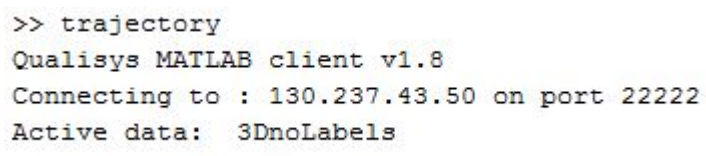
```
                                        QMC_conf.txt
# IP address of the QTM_RT server
<IP:130.237.43.50>

# Port used
<PORT:22222>

# Frequency to fetch the data from the QTM RT server. This is only used when
# streaming data (STREAM set to 1), se below.
# <FREQ:FrequencyDivisor:n>   # The camera frequency divided by n.
# <FREQ:Frequency:n>          # Stream data in n Hz
# <FREQ:AllFrames>            # Stream data with camera frequency.
<FREQ:AllFrames>

# Stream data
# 0 : Request (poll) data over standard TCP connection.
# 1 : Stream the data over UDP.
# 2 : Stream the data over TCP.
<STREAM:0>

# Verbose
# 0 : Do not print frame number and timestamp.
# 1 : Print frame number and timestamp.
<VERBOSE:0>

# Output data size to MATLAB. Amount of objects sent to output for each
# component. Enter a value for each component. Use 0 to disable a component.
<3D:0>                     # Max number of markers to receive.
<3D-NoLabels:40>            # Max number of unlabeled markers to receive.
<AnalogSingle:0>           # Max number of analog devices to receive data from.
<ForceSingle:0>            # Max number of forces to receive.
<6DOF:0>                   # Max number of 6DOF bodies to receive.
<6DOF-Euler:0>             # Max number of 6DOF-Euler bodies to receive.
<2D:0>                     # Max number of 2D points to receive from one camera.
<2D-Lin:0>                 # Max number of 2D-Lin points to receive from one camera.
<3D-Residual:0>            # Max number of markers with residual to receive.
<3D-NoLabels-Residual:0>   # Max number of unlabeled markers with residual to receive.
<6DOF-Residual:0>          # Max number of 6DOF bodies to receive.
<6DOF-Euler-Residual:0>    # Max number of 6DOF-Euler bodies to receive.

# Max number of analog channels to receive data from.
<CHANNEL:0>
```

Figure A.25: Example of a configuration file.

A.4.4 Trajectory Creation

Now that you have everything needed to acquire a trajectory, start by running the file *trajectory.m* that will start the acquisition process.

In case you already have a configuration file in the same folder you are running the *trajectory.m* file, the program will use that file; otherwise, the configuration file generator will start and allow you to create a new one. This file will be used as the configuration file to the acquisition process. If the communication is started successfully, it should appear something similar to Figure A.26.



```
>> trajectory
Qualisys MATLAB client v1.8
Connecting to : 130.237.43.50 on port 22222
Active data:  3DnoLabels
```

Figure A.26: Example of a MATLAB Client communication.

After that, something similar to Figure A.27 should appear.

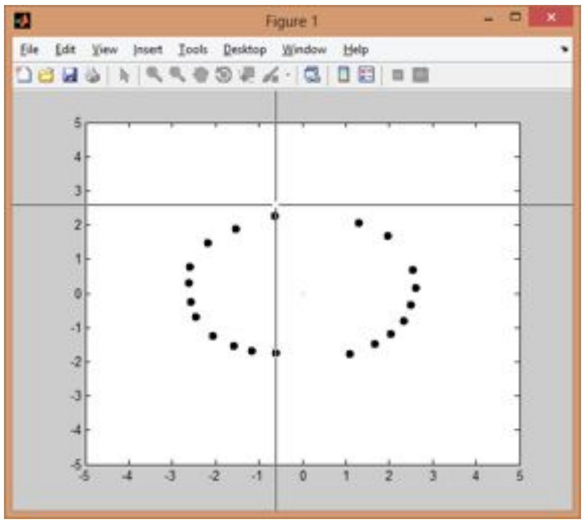


Figure A.27: Example of points acquired for one lane.

Here you are asked to choose the first two points of the trajectory. This is done with the function `ginput` of **MATLAB**, so to choose the points you just nee to click twice (once for each point) somewhere close to the desired points. We need to choose **two points** because at this point we are stipulating the direction of the lane. Since the **LabVIEW** program makes the truck follow the trajectory sequentially, it is important to choose beforehand the direction of the trajectory.

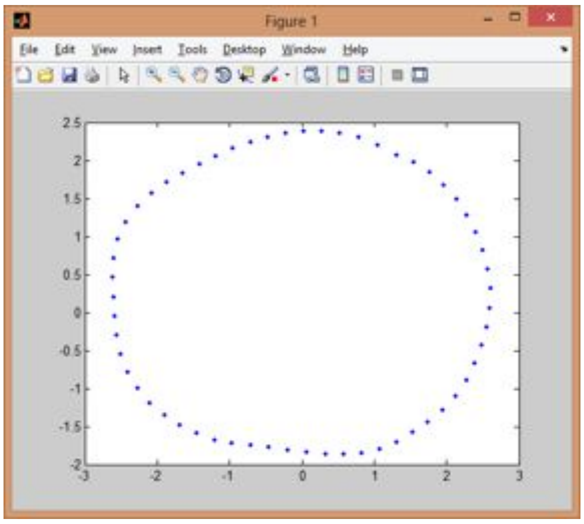


Figure A.28: Final trajectory generated.

We use an **interpolation** process to create more waypoints because this creates a **smoother trajectory** which will create a more realistic trajectory following of the trucks. After that, the result is similar to Figure A.28.

In the end, two files are created. One is *"WPList.txt"*, a file with a list of the coordinates in meters of all the trajectory waypoints. Note that it is relevant to choose if you want numbers' floating points to be **'.'** or **','**. Unfortunately, different versions of **LabVIEW** require different nomenclatures.

Version	Nomenclature
LabVIEW 2011	,
LabVIEW 2012	.

Table A.1: **LabVIEW** version floating point nomenclature.

It will also be created another file named *"TrajectoryLUT.txt"*. This is a lookup table with the distances between every waypoint to every other waypoints in meters. Once again, pay attention to the **nomenclature** that you choose. We opted to calculate the distances between every point of the trajectory in the trajectory creation stage, mainly because it only needs to be done once and since it is somewhat computational costly, it is beneficial to do it in **MATLAB** and not in **LabVIEW**.

Now that you have the trajectory files, the last step is to copy them to the correct folders in the computer that is running the **LabVIEW** program.

When creating a road network, you may need to create several roads or lanes. For that you need to do the process previously explained for every road you want to create. After that you get two files for every road, one containing the waypoints and the other one with the distances between the waypoints. If you need to create connected roads, i.e. roads that have transition waypoints between them, you just create the roads normally and then in the **LabVIEW** program you need to specify the number of those waypoints.

A.5 Getting Started with the LabVIEW Program

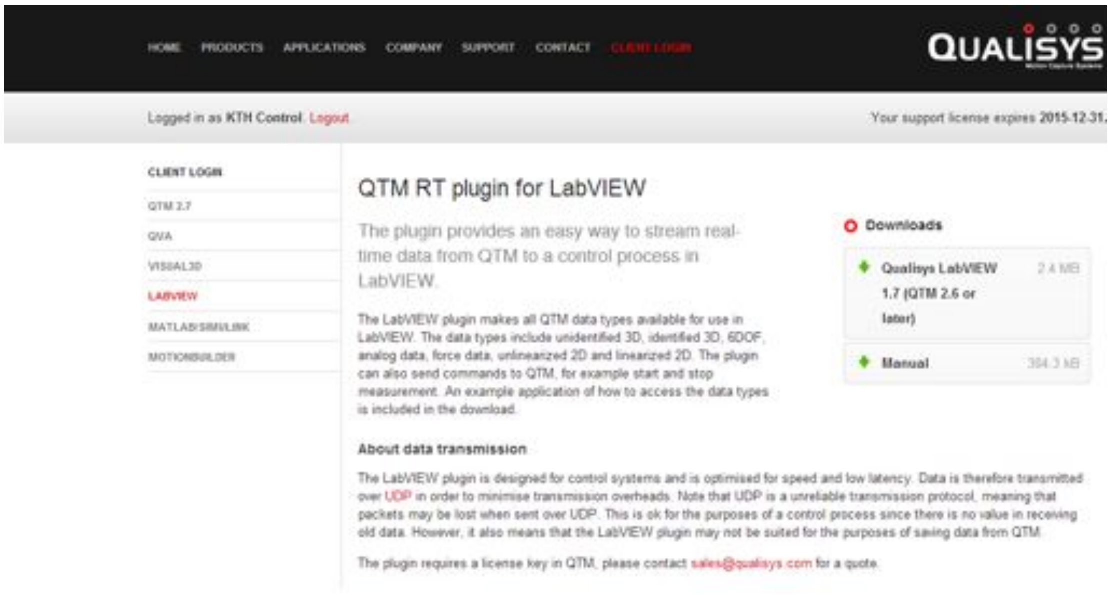
LabVIEW is a powerful **National Instruments** software that allows the user to program using a graphical interface like blocks and connecting wires. The developed LabVIEW program achieves the following objectives:

- Creates the **connection** between the **PC** and the **trucks** using the serial forwarded T-Motes;
- Creates the **TCP connection** between the PC and another PC running the **Visualization Tool**;
- Fetches the **MoCap** data;
- **Controls** the trucks behavior.

A.5.1 Prerequisites

We recommend that the program is used in a PC running **Windows 7 or higher** with **LabVIEW 2011 or higher**. Note that only the **LabVIEW 2012** is compatible with **Windows 8**. Although there are compatible versions of LabVIEW for other platforms like Linux and Mac OSX it is not guaranteed that everything works like in Windows. Problems like doing the T-Motes serial forwarding and fetching the MoCap data can arise. LabVIEW can be **downloaded** from the National Instruments website[5] and, for instance, a **student license** can be downloaded from **KTH Prodgist** website[6] and then activated. In order to do the serial forward of the T-Motes you have to install Cygwin and TinyOS (see Chapter A.2). To be able to fetch the data from the **MoCap** it is essential to download the **LabVIEW QTM Plugin** from **Qualysis** website[7]-for that it is needed a client **username** and **password**. The installation is pretty straightforward and the steps are pretty common among all the Windows installations and is explained next.

In order to find the **LabVIEW QTM Plugin** you just need to go to the **Qualysis** website and you will see its download link on the **right side** of the page.



Logged in as KTH Control. Logout

Your support license expires 2015-12-31.

QTM RT plugin for LabVIEW

The plugin provides an easy way to stream real-time data from QTM to a control process in LabVIEW.

The LabVIEW plugin makes all QTM data types available for use in LabVIEW. The data types include unidentified 3D, identified 3D, 6DOF, analog data, force data, unlinearized 2D and linearized 2D. The plugin can also send commands to QTM, for example start and stop measurement. An example application of how to access the data types is included in the download.

About data transmission

The LabVIEW plugin is designed for control systems and is optimised for speed and low latency. Data is therefore transmitted over UDP in order to minimise transmission overheads. Note that UDP is a unreliable transmission protocol, meaning that packets may be lost when sent over UDP. This is ok for the purposes of a control process since there is no value in receiving old data. However, it also means that the LabVIEW plugin may not be suited for the purposes of saving data from QTM.

The plugin requires a license key in QTM, please contact sales@qualisys.com for a quote.

Figure A.29: LabVIEW QTM Plugin download in the Qualisys webpage.

In the folder where the LabVIEW project is in, there should be as well a folder with the name *RoadNetwork2011* and *RoadNetwork2012*, which are used inside of LabVIEW 2011 and LabVIEW 2012 respectively. Inside of those there should appear several *.txt* files that describe the **road network**. Their creation is explained in Chapter A.4.

[5] www.ni.com
[6] www.kth.se/student/support/itsc/progdist/software-for-windows/labview-2012-spring-1.337984
[7] www.qualysis.com

A.5.2 Program Structure

A **block diagram** representing the LabVIEW **program structure** is shown on figure A.30.

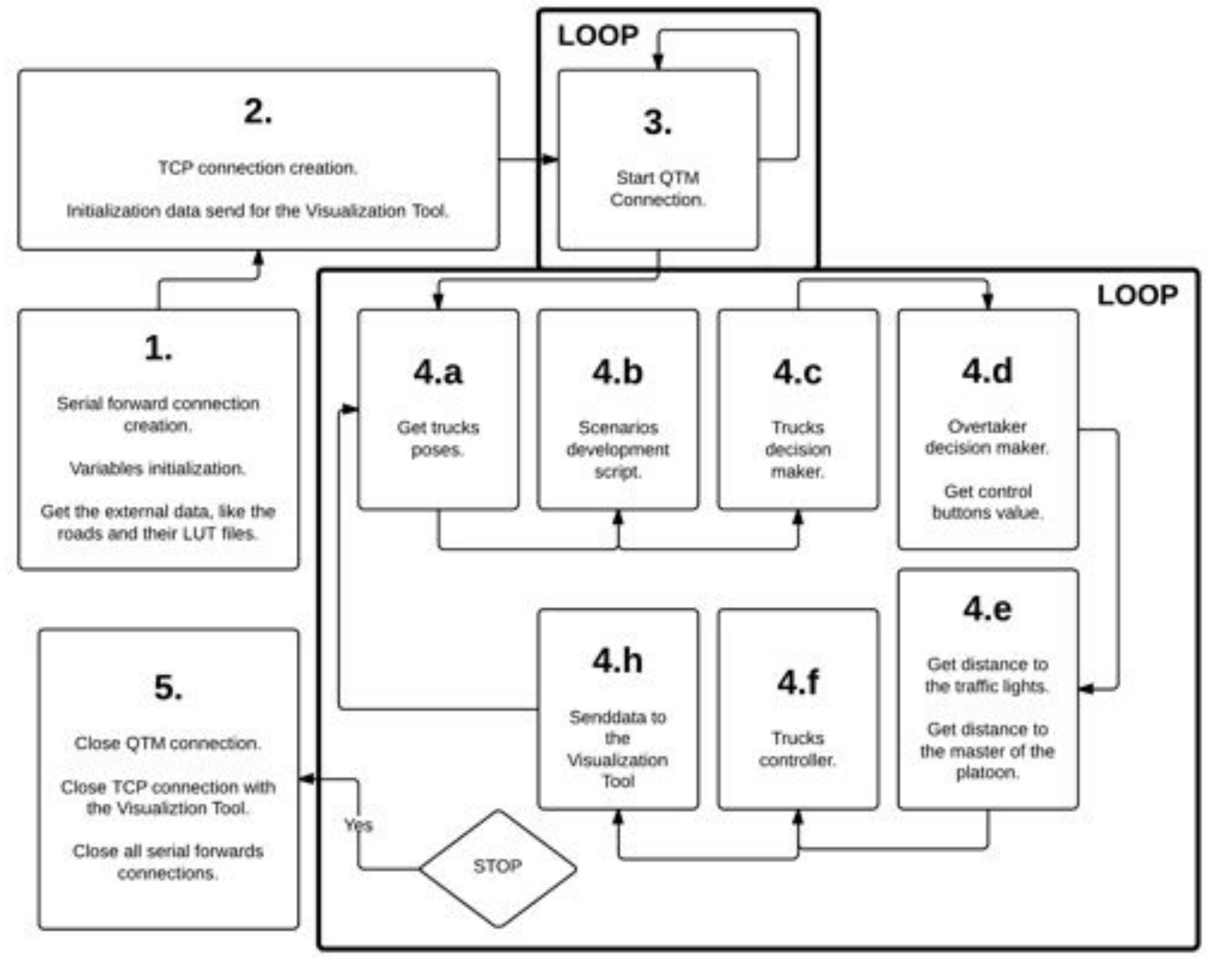

LOOP
2.
TCP connection creation.
Initialization data send for the Visualization Tool.
3.
Start QTM Connection.
1.
Serial forward connection creation.
Variables initialization.
Get the external data, like the roads and their LUT files.
LOOP
4.a
Get trucks poses.
4.b
Scenarios development script.
4.c
Trucks decision maker.
4.d
Overtaker decision maker.
Get control buttons value.
4.e
Get distance to the traffic lights.
Get distance to the master of the platoon.
4.f
Trucks controller.
4.h
Senddata to the Visualization Tool
5.
Close QTM connection.
Close TCP connection with the Visualiztion Tool.
Close all serial forwards connections.
Yes
STOP

Figure A.30: LabVIEW program structure block diagram.

- **1.** This is where the program execution **starts**. At this point you should have created the **serial forward** for each mote in the right **COM ports**. You should have checked as well if the **Road Network files** exist or not. One of the main hidden aspects about this part is the setting of the **midranges values** of the trucks. The midranges values are the values that are going to be considered as 0 in the truck. This means that if we send the value 127 both for **speed** and for **steering**, the truck should be **stopped** and with its **wheels heading straightforward**. If we sent **below** that value, the truck should go **backward** (in the case of the speed value) and **turn left** (in the case of the steering value) and **vice versa for upper values**. The setting of these midranges values is the **first value sent** to the truck **after the connection** is made;

- **2.** A **TCP connection** is created and the PC where the program is running works as a **server** for the **Visualization Tool**. The **first** message sent has the following **format**:

NRoads	Road$_1$ Length	Road$_1$ WP	. . .	Road$_N$ Length	Road$_N$ WP	Scenario Owner

Scenario Name	NTrucks	Bridge Status

- **3.** The **QTM connection** is done in an infinite while loop in order to provide the **latest value** possible;

- **4.a** The **trucks poses** are fetched using the method presented in a **LabVIEW demo** that is installed along with the **LabVIEW QTM Plugin**. Nevertheless, we have changed the block *Q6D Euler.vi*. The following changes were made:

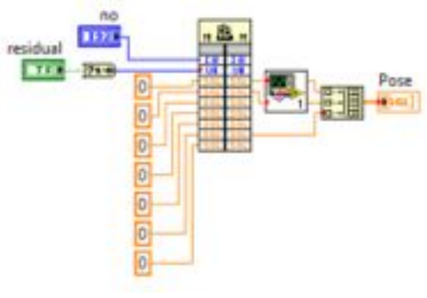


Figure A.31: Q6D Euler.vi modification step 1.

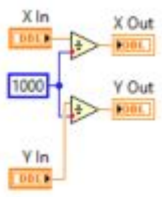


Figure A.32: Q6D Euler.vi modification step 2.

These modifications allow the Q6D Euler.vi to output an **array** with the coordinates x and y in **meters** (instead of millimeters) and the **orientation** yaw in **degrees**. The figure A.32 corresponds to the **subvi** block in figure A.31;

- **4.b** Whenever a **scenario** is selected to run, a **MathScript** will **evaluate** and **change** the control variables in order to run a **user-defined scenario**;

- **4.c** The **decision maker** is the **brain** of the trucks. It decides the **trajectory waypoint** to follow, the **reference speed** changes and the **state transitions**. In this case, each state is a **road lane**. We have an **Outer Lane** (state 1), an **Inner Lane** (state 2) and an **Inner Road** (state 3). It is only allowed to transition between the states 2 and 3;

- **4.d** The **overtaking decision maker** does nothing more often than not. When the **platoon master is changed** and that truck was **already in a platoon**, the new master will **overtake** in order to go to the front of the platoon. The overtaking decision maker decides when the truck should **start its overtaking maneuver** and when it should **finish it**.

  At this point, the **buttons' values** that the user can change in the Main.vi front panel are evaluated.

- **4.e** If there is a **platoon master**, all the trucks in the **same lane** as the master will have its **distance to the master updated**. Since the **Outer Lane** (state 1) and the **Inner Lane** (state 2) have **traffic lights,** the **distance of each truck to them** is also updated. This is only applicable to the states where traffic lights exist.

- **4.f** Using the information given by the decision maker **each truck is controlled using two PID controllers**, one for the **speed** and the other for the **steering**.

- **4.h** All the updated information is sent to the **Visualization Tool** in order to be represented in real-time. The message sent has the following **format**:

STOP	Traffic Lights State	Traffic Lights Position	MasterID	Platooning Reference Distance

Real Speed$_1$	...	Real Speed$_N$	Current State$_1$	...	Current State$_N$

Current WP$_1$	...	Current WP$_N$	Distance to Traffic Lights$_1$	...	Distance to Traffic Lights$_N$

Distance to Master$_1$	...	Distance to Master$_N$	Reference Speed$_i$	...	Reference Speed$_N$

Platoon Array	Stop Array	Truck$_1$ Pose	...	Truck$_N$ Pose	Information String

- **5.** When the button **STOP** is pressed (also called the **panic button**) everything stops. The **trucks stop** and the **connections to QTM**, to the **T-Motes** and to the **Visualization Tool** are **closed**.

A.5.3 Running the LabVIEW program

In order to run the LabVIEW program you just need to know how to use the **Main vi**. The **Main vi front panel** can be seen in Figure A.33 and is the **control panel** of the program. At first, one may think that it is too much information at the same time, but **everything is organized and has its own logic**. Each part of the front panel will be explained in detail.

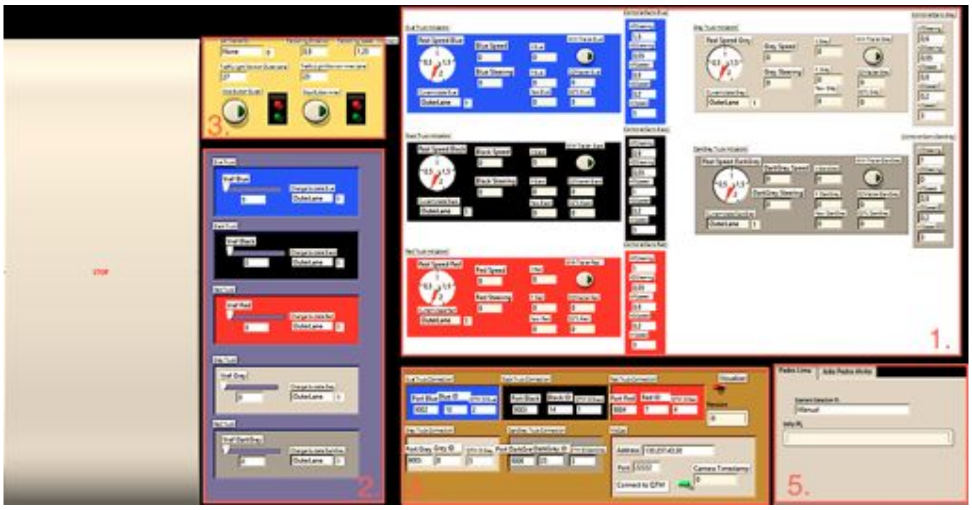


Figure A.33: Main vi front panel.

- **1.** This panel is mostly consisted of **indicators**. There we can see, for each truck, its **Real Speed**, **Current State**, **Current Pose** (x, y and yaw), **Distance to Master**, **Distance to Traffic Lights** and the values of **Speed** and **Steering** in **bits** sent to the truck. Each truck has an associated **panel color** which, naturally, corresponds to its **real color**. In this panel, one can select if the truck has a **trailer** or not, which will influence the program's perception about the **truck's length**. In order to easily tune the controllers for each truck, the **controller gains** are available as well for each truck.

- **2.** If the program is on the **Manual Mode** (see point **5.**) you will do most of the modifications on this panel. With a sliding bar you can change the **Reference Speed** of each truck and you can **Change the State** where the truck is. Naturally, the truck will only change its state in the **transition points**, between the **Inner Road** and the **Inner Lane**. **If the program isn't on the Manual Mode you don't have to worry about this**.

- **3.** Once again, if the program is on the **Manual Mode** (see point **5.**) you can modify several parameters of the system. These parameters are: the **Reference Gap Distance** between trucks when they are on a platoon formation, the **Speed Increment** ($V_{ref} = SpeedIncrement \times V_{Master}$ when the truck starts catching up, the **Traffic Lights Position** in Outer and Inner Lanes and each **Traffic Light Status**. The position of the traffic lights can be hard to understand and to set. The values that are now set by default are **waypoints** of the corresponding lane. In order to change these values you have to do trial and error until you find the position wanted.

- **4.** The **missusage** of the control boxes on this panel can lead to a **strange behavior** of the program. For each truck you can set the corresponding **ID** used in the T-Motes communication, the **Port** used in the T-

Motes serial forwarding (see Chapter A.2) and **QTM ID**, which is the label of that truck on the MoCap (see Chapter A.3). It's also possible to see the **Version** of the LabVIEW where the program is running on and set the **Visualization Tool** "**On**" and "**Off**". If this button is set to "**On**", you **must run the Visualization Tool** (see how to do it in Chapter A.6), otherwise **the LabVIEW won't run**. The program **will not run without having the values from the MoCap**, so if the connection is okay, you will see the **Camera Timestamp** increasing. Always check the **QTM computer IP address** if you notice that the **Camera Timestamp isn't changing**.

- **5.** In this panel you can choose two tabs. The "**Pedro Lima**" **tab** and the "**Joao Pedro Alvito**" **tab**. Those are the names of the authors of the program. The tabs exist in order to **run different scenarios** created by those using the program. In both tabs you have the option "**Manual**" where you can control the trucks using the panels explained above, otherwise you can choose a scenario from the list and **the trucks will execute a predefined set of actions**.
- The **STOP** button on the left is the biggest button in the Main vi. This works as a **panic button** that stops all trucks but also **closes all the connections correctly**. Try to use this button whenever you want to stop the program and **avoid the LabVIEW stop execution button**.

Before you press the LabVIEW run execution button, you have to **move the trucks by hand to strategic positions** . If the truck is set to start on the **Outer Lane**, you have to put the truck in the outer lane of the road network on the **opposite side of the bridge** with **anti-clockwise orientation**. If the truck is set to start on the **Inner Lane** you have to put the truck in the inner lane of the road network on the **opposite side of the bridge** with **clockwise orientation**. Finally, if the truck is set to start on the **Inner Road**, you have to put the truck in the inner road of the road network on the **opposite side of the bridge** with **clockwise orientation**. The truck is set to start at the waypoint number **1**. You can re-set this when fetching the trajectory waypoints (see Chapter A.4)

A.6 Getting Started With The Visualization Tool

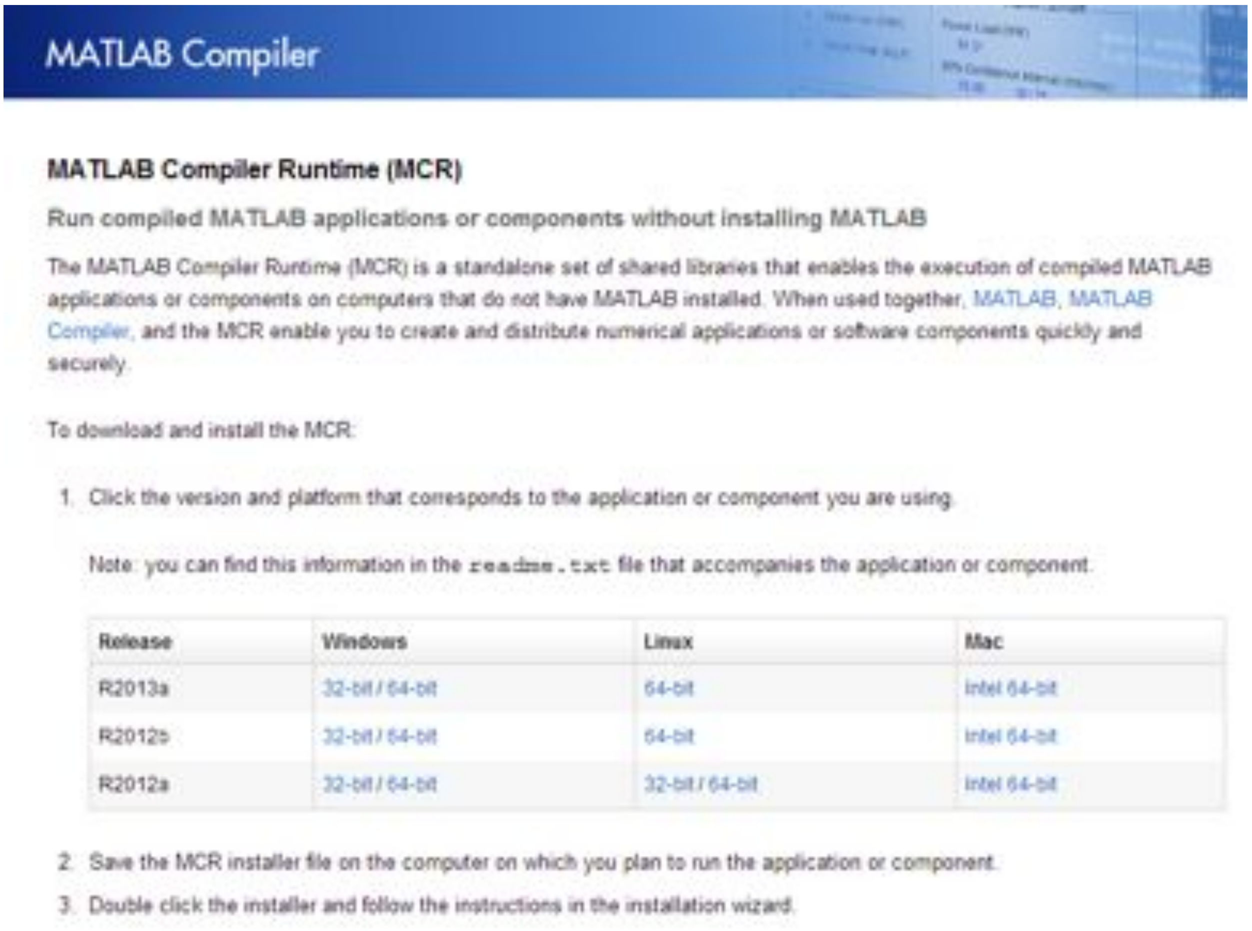
To help with the visualization of the project we created a tool that shows all the important data that the user might need to know in a more user friendly way. This is done by resorting to a communication **TCP/IP** between the computer that is running the **LabVIEW** software and any computer with access to an internet connection. Note that not all the data available is displayed here, but only the sufficient to aid the user understand what is happening at the moment. Also, the data of every run is saved in a **MATLAB** data file type, which will be helpful to posterior data analysis.

A.6.1 Prerequisites

- Once the [20] is already running you only need to run the [20]. Since this tool communicates with another computer via **TCP/IP**, an internet connection is obviously needed.

- Next, you need to have a **MATLAB** version installed in the computer where the **Visualization Tool** is to be run. In case that it is not possible there is an alternative that is to only install the **MATLAB Compiler Runtime** (**MCR**)[8]. After downloading the version that suits your needs, you simply need to run the **executable file** that we generated in case you use **Microsoft Windows**, or, if you use **Mac OSX**, you can run the **app** that we also generated.

[8]`http://www.mathworks.se/products/compiler/mcr/`


MATLAB Compiler

MATLAB Compiler Runtime (MCR)

Run compiled MATLAB applications or components without installing MATLAB

The MATLAB Compiler Runtime (MCR) is a standalone set of shared libraries that enables the execution of compiled MATLAB applications or components on computers that do not have MATLAB installed. When used together, MATLAB, MATLAB Compiler, and the MCR enable you to create and distribute numerical applications or software components quickly and securely.

To download and install the MCR:

1. Click the version and platform that corresponds to the application or component you are using.

   Note: you can find this information in the `readme.txt` file that accompanies the application or component.

Release	Windows	Linux	Mac
R2013a	32-bit / 64-bit	64-bit	Intel 64-bit
R2012b	32-bit / 64-bit	64-bit	Intel 64-bit
R2012a	32-bit / 64-bit	32-bit / 64-bit	Intel 64-bit

2. Save the MCR installer file on the computer on which you plan to run the application or component.
3. Double click the installer and follow the instructions in the installation wizard.

Figure A.34: MATLAB Compiler Runtime (MCR) download.

- The computer that runs the **Visualization Tool** doesn't need any special graphical capabilities. Nonetheless, we recommend that you use a computer with a **considerable processing capability**. This is a requirement because the tool **receives new data** every $100ms$. If the computer isn't capable of processing the data and display it in that time window, at some point it will start processing data that is not updated. This can be seen by a **delay** between what you see in our tool and what is happening in **real-time**.

A.6.2 Running The Visualization Tool

To run the **Visualization Tool**, as mentioned in Section A.6.1, you can run the **executable file** (or the app file in case of **Mac OSX**) or, if you prefer to run it within **MATLAB**, simply run the *SML.m* file. In both cases, the first window to appear is the one in Figure A.35.

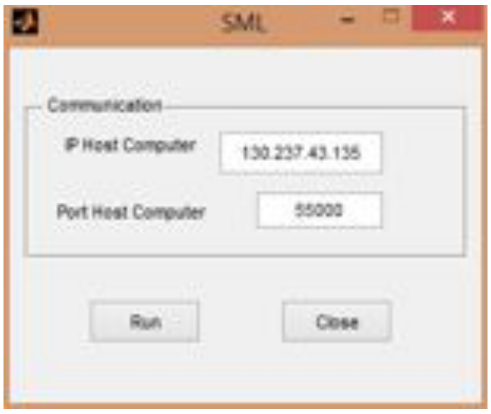


Figure A.35: Connection settings.

Here you have to define the settings for the **TCP/IP** connection between your computer and the computer running the **LabVIEW** program. You have to set both the **IP address** and the **port number** of the remote computer. If you don't know the IP address of the remote computer just type **'ipconfig'** in the command line and the IP address of that computer will be shown. The port number should preferably be a number between $49152 - 65535$, but be aware that it must be the same in both sides. So because the default value in the **LabVIEW** program is 55000, we recommend to use it as port number. If by any chance you want to change it don't forget to change in both places. The values you see in Figure A.35 are the **default values**, only because it is the current configuration in the **Smart Mobility Labs'** computers.

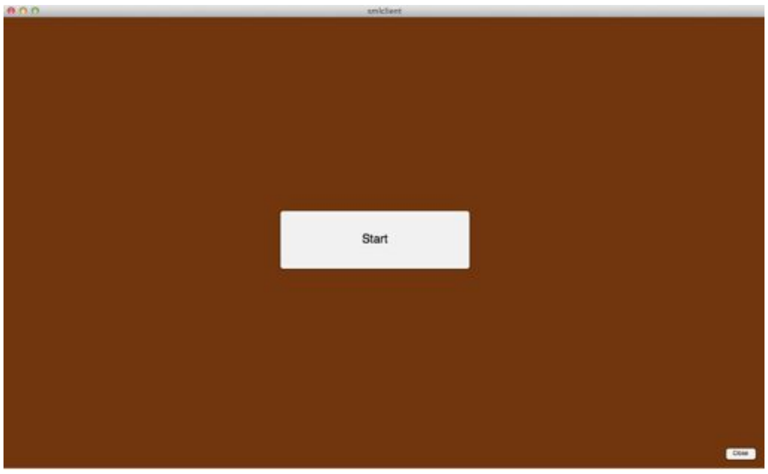


Figure A.36: Start screen of the visualization tool.

After you push the run button your connection settings are defined and a start screen should appear. Preferably, you should push the start button when you have done all the required steps in the **LabVIEW** program-this means that at this point the **LabVIEW** program should be waiting for an order to proceed. If you press it before time, it can cause some connection issues because there is a timeout in the connection. Summing-up: make sure to run the **LabVIEW** program first with the **Visualization Tool** option turned on.

A.6.3 Visualization Tool

Next, we have two examples of our **Visualization Tool**, each one representing the **layout** that we decided that better suited our scenarios. Of course you are free to improve it and adjust it to your needs. Both versions use the same base but one is more concerned in fuel related data and the other more concerned with the traffic lights status. We will briefly explain what each one of the **panels** represents.

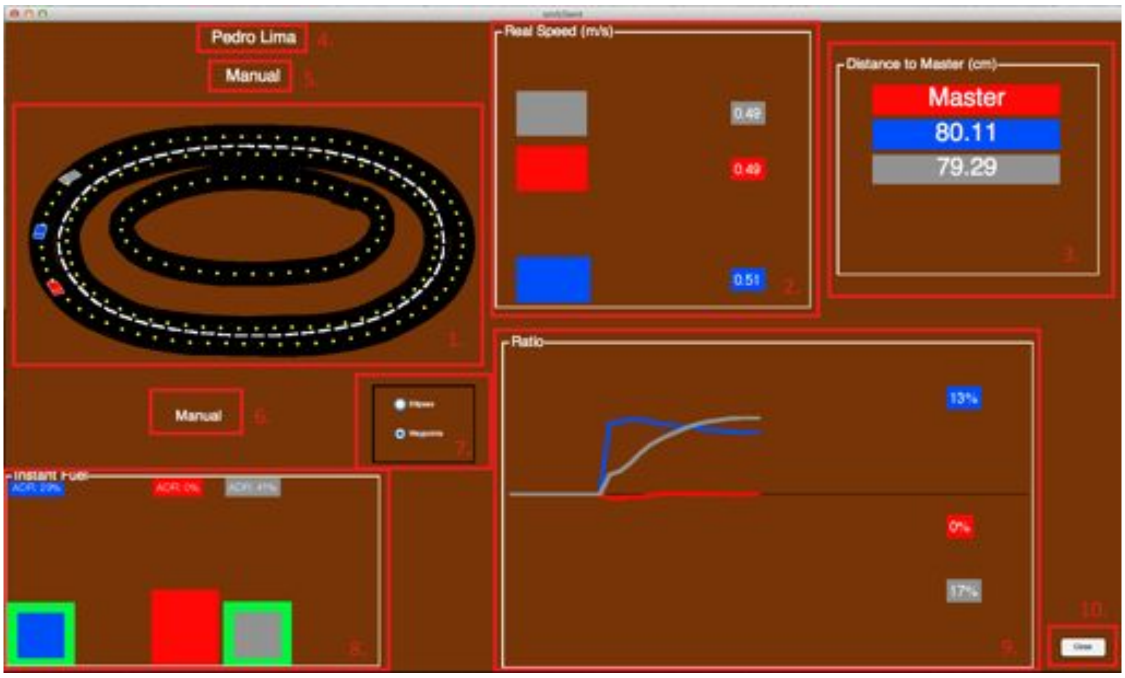


Figure A.37: Visualization Tool (Pedro Lima).

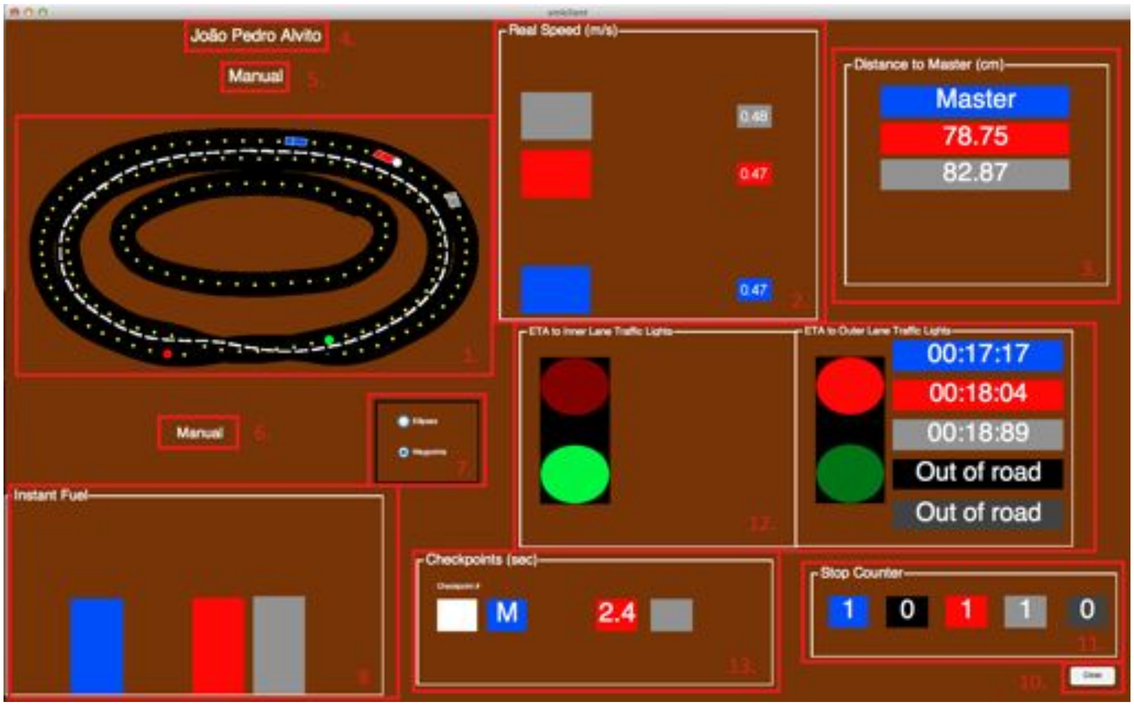


Figure A.38: Visualization Tool (João Pedro Alvito).

- **1.** This is, most likely, our most important block, mainly because it's the one that contains more information. This is basically a transcription of the reality to our display. In it, you can see the current position of each truck that is visible in the **Qualisys** system, through the small rectangular shaped trucks colored accordingly to the real trucks' colors. It's also possible to see how the **road network** looks. The **Visualization Tool** simply receives the waypoints and processes it in order to display the several roads and its lanes in black, and also the **white dashed line** that we usually see in real life. In the lanes, it is possible to display the waypoints, representing them as **yellow dots**. Additionally, in the case of Figure A.38, there are extra colored dots: the **white dot** represents a checkpoint that is used to measure the time distance between each consecutive truck (it is possible to have several checkpoints); there are **two dots** that can be either **red or green**, that at the same time give the **position** of the traffic lights of both lanes and its **status** (either if the traffic light is green or red);

- **2.** This block shows the real speeds of the trucks, *i.e.* in SI units *(m/s)*. To make it easier to distinguish between trucks, we used a color code that translates the user to the real color of the trucks that are being used. There are two fields where it is possible to get information about the speeds: a horizontal bar that is helpful to analyze the **relative speed** between trucks; a text field with the the **absolute speed** value; Note that this block only displays the speed information of the trucks that are being used, so if for example a truck is not being used or even if it is inside the visible zone but is out of the road, its speed information will be suppressed from the display;

- **3.** This block shows the most important information about the platooning that is the **Platooning Distance**. This measurement represents the size of the gap between each consecutive truck that is part of the platoon. For better understanding, we are using the measurement in *cm* and it is the real distance between the trucks and not the **real world** distances. Note that the first truck of the platoon, **the master**, naturally doesn't have any distance to display so it just identifies itself as the **master**. To improve the visualization, the list of the **Platooning Distance's** order reorders itself according for the order in the platoon; this way the information about the platoon order is embedded with the **Platooning Distance**. If a truck isn't part of the platoon the **Platooning Distance** is obviously suppressed from the display;

- **4.** This field simply shows what is the **Platooning Distance** of the current scenario;

- **5.** Here you can see what is the **name** of the current scenario. The names are pretty self-explanatory because this way it is easily understood what the scenario is meant for;

- **6.** This shows a simple explanation of what is happening at each moment. It is an one line sentence that illustrates what might not be obvious; for example, it says what a truck is trying to accomplish or if some event related to a traffic light is taking place;

- **7.** This block contains the optional choices that the user can do. The **”waypoints”** option is simply a radio button that turns ”on” or ”off” the waypoints display in **1.**. This option is defaulted to be ”on” because we believe that the waypoints appearing are a great aid to observe the trucks' trajectory. The other option that we have available is **”ellipses”**. We provide this option because the graphical roads in **1.** are dynamically generated, so sometimes, depending on the trajectory generated, the roads can be displayed in a rather strange way. Since the roads that we created in the **Smart Mobility Lab** are shaped like ellipses we tried to process the road data that we received from the trajectory generation and adjust it to ellipses. Sometimes, this option improves the display of the roads but of course this is not a viable option if the road is not shaped like an ellipse so feel free to try this option and see if it improves the display of the **road network** that you are currently using;

- **8.** Here you can see a relative indication of the **instantaneous fuel consumption**. It allows you to better perceive how much fuel the trucks are consuming in relation to each other. In Figure A.37 there are two extra pieces of information: the percentage of **Air Drag Reduction (ARD)** and, also surrounding the vertical bars of the instantaneous fuel, you can see either **red or green edges**. If that edge is green, it means that for that particular truck it is being beneficial in terms of fuel consumption to be part of the platoon, otherwise the edge will appear red. For more technical information refer to [9] and [20];

- **9.** Here you can see a **fuel ratio** for each truck involved in the scenario. This is the ratio between the accumulated fuel consumption, when the truck decides to do catch up, and the accumulated fuel consumption that the truck would have if it had continued alone. For more technical information refer to [20];

- **10.** This close button, when pushed, closes the program. We do not recommend to use this button as a first choice, it is preferable to use the stop button in the **LabVIEW** program which you can see in Figure A.33. This way the **LabVIEW** program sends a closing order to the Visualization Tool which allows it to close by itself and then closing all the **TCP/IP** connections from both sides;

- **11.** This blocks provides a stop counter that shows the number of times each truck has stopped. This is helpful to see if a truck stopped in a traffic light and how many times it did;

- **12.** This block has two different sub-blocks that are basically the same but the information is divided in inner and outer lane. So on the left side we have the traffic light information about the inner lane and on the right side there appears the same information for the outer lane. These sub-blocks have all the information about the **traffic lights** apart from its position: the status of the **traffic light**, either if it is red or green; the **estimated time of arrival (ETA)** of each truck to the traffic light of the correspondent lane. The time appears in a digital form (minutes:seconds:centiseconds). To improve the display we decided to order the **ETAs**, such that the closest truck to the **traffic light** will always be on the top of the list;

- **13.** Here you can check which are the time distances at a given **checkpoint** (time distance is given in seconds). Note that this feature is only valuable if there is a platoon. If a truck is the master, the letter **'M'** will appear in the same place where it would show the time. Once the master passes through the checkpoint, as showed in point **1.**, all the other fields of the trucks that are in the platoon are erased and updated with the time distance as soon as the respective truck goes trough the same **checkpoint**. You can use several **checkpoints**, but for bigger **Platooning Distances** we recommend to use only one checkpoint. Don't forget that the only values that are shown are the ones from trucks in the platoon.

A.7 Troubleshooting

A.7.1 Trucks

If you have read all the manual and you the trucks are behaving as they supposed to, please go through the following checklist:

- Check if the batteries are **charged**;
- Check if all the **Polulu boards** have a **yellow** led **on** (see Chapter A.2);
- Check for any **”Note: write failed”** or **”unix_error”** in the **Cygwin terminal** (see Chapter A.2);
- Check all the **ID**, **Port** and **QTM ID** in the panel **4.** (see Section A.5.3);
- Check the **IP address of the QTM computer**;
- Check if the value sent for **Speed** and **Steering** in bits present in panel **1.** are different from **127** (see Section A.5.3);
- Check if the **PC’s T-Motes are blinking**, meaning that they are communicating (see Chapter A.2);
- Check if the **trucks’ T-Motes are blincking** as well (see Chapter A.2);
- Check if the truck motors are ”**On**” (see Chapter A.2);
- Check if the trucks are **being recognized by the MoCap** (see Chapter A.3);
- Check if the trucks are **initially positioned** as they should (see Section A.5.3);
- Check if there’s **any commented block**.

A.7.2 Trajectory Creation

One problem that might arise in the trajectory creation, is a message saying **”No Welcome Message Received”**. This happens when the program is trying to connect to the **Qualysis** system and it receives an error probably due to a last connection that wasn’t closed. The most effective solution that we found was restating **MATLAB**.

A.7.3 Visualization Tool

When using the **Visualization Tool** sometimes you might get some error when receiving the data from the road network in MATLAB. We are not completely sure about the source of the problem; nevertheless, this issue can be solved with a simple restart of the **Visualization Tool**.

You still can’t get everything to work? Please, don’t hesitate to **contact us** (`pfrdal@kth.se` and `jpfa@kth.se`).