A Safety and Comfort Lane Change for Sportive Highly Automated Driving Truck

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A Safety and Comfort Lane Change for Sportive Highly Automated Driving Truck

MASTER OF SCIENCE THESIS

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The major goal of this master thesis is to improve truck safety and comfort during lane change manoeuvres. This thesis focuses on the scenario of the driver doing sports exercises inside the cabin when the vehicle is driving automatically on a highway. This topic is one of the foci of the international GlobalDrive project from Technical University of Munich, which aims at sports exercises inside highly automated driving truck cabin by 2030. Using a special chair, drivers are able to do different types of exercises in the cabin. However, the acceleration, deceleration and jerk of normal highly automated vehicles can hardly satisfy the safety and comfort requirements for sports exercises, especially during lane changes. It is very difficult for the driver to keep balance when the lateral or longitudinal jerk and acceleration reach a certain level. In order to provide a suitable environment for exercises, a multi-level control architecture has been designed to satisfy the safety and comfort requirements from an ergonomics aspect. The proposed control scheme will make it easier for the driver to keep balance. Prevention of rollover is included in the architecture, while a Cruise Control (CC)-Adaptive Cruise Control (ACC)-Cooperative Adaptive Cruise Control (CACC) strategy is responsible for the longitudinal safety of the truck. Simulations in realistic and safety-critical scenarios show the effectiveness of the approach.
# Table of Contents

Acknowledgements xi

## 1 Introduction 1

1-1 About transportation ................................................. 1
1-2 Automated driving .................................................. 1
1-3 TRUCKletics ......................................................... 3
1-4 The TRUCK2030 cabin .............................................. 5
1-5 Assumptions and structure of the Algorithm ...................... 8

## 2 High-Level Controller 11

2-1 Background ......................................................... 11
2-2 Time to Collision (TTC) ........................................... 12
2-3 Braking distance ................................................... 15
2-4 Risk prediction for lane change ................................. 18

## 3 Middle-Level Controller 21

3-1 Longitudinal Controller Design .................................. 21
3-1-1 Introduction ..................................................... 21
3-1-2 CC ............................................................. 22
3-1-3 ACC ........................................................... 26
3-1-4 CACC .......................................................... 28
3-2 Trajectory Planner .................................................. 32
3-2-1 Overview of trajectory selection .............................. 32
3-2-2 Considerations and assumptions .............................. 33
3-2-3 Shape of the trajectory ....................................... 34
3-2-4 Time for the lane change ..................................... 36

Master of Science Thesis

Yangyu Zhang
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Low-Level Controller</td>
<td></td>
</tr>
<tr>
<td>4-1</td>
<td>Requirements of the controller</td>
<td>39</td>
</tr>
<tr>
<td>4-2</td>
<td>Sensors selection</td>
<td>40</td>
</tr>
<tr>
<td>4-3</td>
<td>Bicycle model with roll degree of freedom</td>
<td>41</td>
</tr>
<tr>
<td>4-4</td>
<td>Robust controller for rollover prevention</td>
<td>43</td>
</tr>
<tr>
<td>4-5</td>
<td>Simulation and results</td>
<td>44</td>
</tr>
<tr>
<td>5</td>
<td>Emergency Scenarios Simulation</td>
<td>53</td>
</tr>
<tr>
<td>5-1</td>
<td>Fast lane change for high speed scenario</td>
<td>53</td>
</tr>
<tr>
<td>5-2</td>
<td>Fast lane change for low speed scenario</td>
<td>56</td>
</tr>
<tr>
<td>5-3</td>
<td>Front vehicle cut in</td>
<td>58</td>
</tr>
<tr>
<td>5-4</td>
<td>Change target vehicle after lane change</td>
<td>59</td>
</tr>
<tr>
<td>6</td>
<td>Conclusions and Future Work</td>
<td>65</td>
</tr>
<tr>
<td>6-1</td>
<td>Conclusions</td>
<td>65</td>
</tr>
<tr>
<td>6-2</td>
<td>Future Work</td>
<td>66</td>
</tr>
<tr>
<td>A</td>
<td>MATLAB Code</td>
<td>69</td>
</tr>
<tr>
<td>A-1</td>
<td>Main program</td>
<td>69</td>
</tr>
<tr>
<td>A-2</td>
<td>High Level Controller</td>
<td>70</td>
</tr>
<tr>
<td>A-3</td>
<td>Robust Controller</td>
<td>72</td>
</tr>
<tr>
<td>A-4</td>
<td>Trajectory Generator</td>
<td>73</td>
</tr>
<tr>
<td>A-5</td>
<td>Change Target Vehicle</td>
<td>73</td>
</tr>
<tr>
<td>B</td>
<td>Simulink</td>
<td>75</td>
</tr>
<tr>
<td>Glossary</td>
<td></td>
<td></td>
</tr>
<tr>
<td>List of Acronyms</td>
<td>79</td>
<td></td>
</tr>
<tr>
<td>List of Symbols</td>
<td>79</td>
<td></td>
</tr>
</tbody>
</table>
List of Figures

1-1 Levels of Automated Driving [1] ......................................................... 2
1-2 Prototype of the inside of the cabin ....................................................... 4
1-3 Sport inside the cabin ................................................................. 5
1-4 Exterior design of the Truck2030 [2] .................................................. 5
1-5 Assembly of the cabin frame [2] ......................................................... 6
1-6 Measurements of the cabin including side and top view [2] [3] .......... 7
1-7 Multifunctional seat in seating and stand-up position [3] ................. 7
1-8 Topological structure of the algorithm ............................................... 8
1-9 Environment information for lane change ......................................... 9

2-1 Recall of the complete overview diagram of the algorithm with highlighted the two part of the system where the collision risk is included: TTC Prediction and the Distance Prediction (red). ................................................... 12
2-2 Graphical representation of the time to collision in case of car in front on the same lane (a) and car on the right lane with predicted lane change (b). ................................................... 13
2-3 Graphical representation of the time to collision in case of car in front on the same lane ................................................... 14
2-4 Schematic of vehicle speed and position at the time of brake initiation in a lead vehicle stopped, rear-end collision. ................................................... 14
2-5 Safety distance for truck on the dry asphalt ..................................... 17
2-6 Merging scenario of the obstacle vehicle ........................................ 17
2-7 Scenario for host vehicle doing lane change ..................................... 18

3-1 Initial configuration in scenario 1 ......................................................... 23
3-2 Change reference speed on the high way in scenario 1 .................... 23
3-3 Initial configuration in scenario 2 ......................................................... 24
3-4 $d_1$ on the high way in scenario 2 ..................................................... 24

Master of Science Thesis

Yangyu Zhang
3-5 Speed of the host vehicle in scenario 2 ........................................ 25
3-6 $d_1$ on the high way in scenario 3 ........................................ 25
3-7 Speed of the host vehicle in scenario 3 ........................................ 26
3-8 $d_1$ and $d_{1\text{ref}}$ in scenario 4 ........................................ 27
3-9 $d_1$ and $d_{1\text{ref}}$ in scenario 4 ........................................ 28
3-10 Initial configuration in scenario 5 ........................................ 28
3-11 Speed control in scenario 5 ........................................ 29
3-12 Safety distance in scenario 6 ........................................ 29
3-13 $d_1$ and $d_{1\text{ref}}$ in simulation with sine wave acceleration in scenario 7 ........................................ 30
3-14 $d_1$ and $d_{1\text{ref}}$ in simulation with zero mean unit variance random acceleration in scenario 7 ........................................ 31
3-15 Speed control of the scenario 8 ........................................ 31
3-16 Safety distance of the scenario 9 ........................................ 32
3-17 Recall of the complete overview diagram of the topological structure of the algorithm ........................................ 33
3-18 Distribution of the duration of the lane change [4] ........................................ 35
3-19 Lateral acceleration (left) and jerk (right) during a lane change ........................................ 36
3-20 Effect of frequency of oscillation on equivalent comfort contours for lateral oscillation. Contours normalised to represent discomfort equal to that caused by lateral acceleration at 0.5 Hz 0.20 ms$^{-2}$ r.m.s. on a rigid seat with backrest [5] ........................................ 37
3-21 Lateral acceleration (left) and jerk (right) for lane change in 7 s ........................................ 38

4-1 The diagram of the robust controller ........................................ 45
4-2 Steering angle in 10s ........................................ 45
4-3 Different braking force in 10s ........................................ 46
4-4 LTR with and without robust controller ........................................ 47
4-5 The comparison of Slide slip angle, yaw rate, roll rate, roll angle with and without the robust controller in 10s ........................................ 47
4-6 The comparison of Robust controller, PID controller, no controller when the speed of host vehicle is 70 km/h ........................................ 49
4-7 The comparison of Robust controller, PID controller, no controller when the speed of host vehicle is 80 km/h ........................................ 50
4-8 The comparison of Robust controller, PID controller, no controller when the speed of host vehicle is 90 km/h ........................................ 51
4-9 The comparison of Robust controller, PID controller, no controller when the speed of host vehicle is 60 km/h ........................................ 52

5-1 LTR for a lane change in 2 s with robust controller ........................................ 54
5-2 LTR for a lane change in 2 s with random acceleration (left). The longitudinal velocity of the host vehicle (right) ........................................ 55
5-3 LTR for a lane change in 3.5 s with constant speed ........................................ 56
5-4 LTR for lane change in 3.5 s with random acceleration ........................................ 57
### List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-5</td>
<td>Starting condition of the scenario</td>
<td>58</td>
</tr>
<tr>
<td>5-6</td>
<td>t=5 s of the scenario</td>
<td>58</td>
</tr>
<tr>
<td>5-7</td>
<td>Distance between the host vehicle and front vehicle</td>
<td>59</td>
</tr>
<tr>
<td>5-8</td>
<td>The velocity of the host vehicle</td>
<td>60</td>
</tr>
<tr>
<td>5-9</td>
<td>The acceleration of the host vehicle</td>
<td>61</td>
</tr>
<tr>
<td>5-10</td>
<td>Starting condition of the scenario</td>
<td>62</td>
</tr>
<tr>
<td>5-11</td>
<td>Condition of the scenario at t=3 s</td>
<td>62</td>
</tr>
<tr>
<td>5-12</td>
<td>Distance between the host vehicle and front vehicle</td>
<td>63</td>
</tr>
<tr>
<td>B-1</td>
<td>Overall view of the controller</td>
<td>76</td>
</tr>
<tr>
<td>B-2</td>
<td>Environment simulator</td>
<td>76</td>
</tr>
<tr>
<td>B-3</td>
<td>Middle-Level Controller</td>
<td>77</td>
</tr>
<tr>
<td>B-4</td>
<td>Low-level Controller</td>
<td>77</td>
</tr>
<tr>
<td>B-5</td>
<td>Vehicle model</td>
<td>78</td>
</tr>
</tbody>
</table>
## List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>Friction Coefficient for different road condition</td>
<td>15</td>
</tr>
<tr>
<td>2-2</td>
<td>Braking distance for different kings of vehicle and speed ($km/h$) [6]</td>
<td>16</td>
</tr>
<tr>
<td>4-1</td>
<td>Vehicle model parameters [7]</td>
<td>42</td>
</tr>
</tbody>
</table>
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This chapter gives an insight to the state of art that is faced and dealt with by the TRUCK-letics project. Existing conditions and prerequisites of the project are shown by providing an introduction to automated driving as well as its past and possible future developments. Here is, after a quick overview on existing automated vehicle, a description of the complete DAVI Project with an overview on all his aspects and then a section with a description in detail of the proposed project.

1-1 About transportation

The transportation volume worldwide is growing constantly. By the year 2030, it is expected that the transport capacity within Europe will grow by another 35 % [8]. In the area of road transportation, the truck is the most important transport device. Thus the number of professional truck drivers is also increasing. In Germany alone, the number of professional drivers reported by the Federal Labour Office in 2014 was 538,010.

Another current progress related to the worldwide traffic is the rapid technological development and the increasing innovation regarding Highly Automated Driving (HAD). As the driver does not have to focus on the driving task any more, this development allows the driver to perform additional activities while driving in the highly automated mode. The possibility to engage in other tasks while driving creates new opportunities for truck drivers.

1-2 Automated driving

Nowadays automated driving is one of the most revolutionary developments that is being researched for in the automotive industry. Besides globalization, developments in truck technology such as HAD belong to the mega trends that will influence the truck drivers’ society, environment and their working conditions as well as the field of economy they are engaging in.
Concerning the levels of automation the German automobile industry has agreed on a unified understanding based on the Bundesanstalt für Straßenwesen (BASt) working group "Legal consequences of increasing vehicle automation".

There are six different stages of automated driving to be distinguished. During manual driving the driver has to perform all aspects of the dynamic driving task including longitudinal and lateral driving control permanently. Assisted driving makes use of a driver assistance system that conducts either longitudinal or lateral driving control. The remaining driving dimensions have to be covered by the driver. Anti-lock Braking System (ABS), Electronic stability control (ESC) and speed control are possible examples for this level of automation. Partly automated driving describes the combining of lateral and longitudinal driving control. Still the driver has to monitor and control the assistance system permanently. Highly automated driving allows the driver not to continuously monitor and control the assistance system. The complete dynamic driving task is carried out by the system as long as the driver is prompted to take over within a defined period of time. The driver is able to override the automated system at any time. Higher degrees of automation such as fully automated and autonomous driving are able to manage traffic and driving control safely and without the necessity for a driver[1].

In 2014 Mercedes-Benz presented an automated driving truck at the International Motor Show (IAA) for commercial vehicles. This so-called 'Future Truck 2025' uses vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, including radar based sensors for far and near range detection, stereo cameras for the identification of movable or non-movable objects, pedestrians, road conditions, etc. and thus is able to interact with the surrounding traffic by slowing down, speeding up, steering to the left and to the right. Based on existing driver assistance systems and their fast development in recent times, the TRUCKletics team assumes that by 2030, trucks will be able to drive automated under specific, not too complex conditions (highway, 80km/h,..) but still need a driver for taking over in situations that cannot
be handled by highly automated driving[9].

In this context it is necessary that legal background conditions are being adjusted as current legislation demand to the driver to actively control the vehicle all the time. According to the "Vienna Convention on Road Traffic" from 1968 automated driving is just allowed to speeds up to 10 km/h and the steering systems are only allowed to correct the driver's wish. Adjustments of the Vienna Convention concerning automated driving are already conducted. Furthermore German legislation defines its role as an enabler instead of an obstacle to introduce automated driving in Germany as stated by Prof. Dr. Dr. Eric Hilgendorf during a speech at the 7th. Conference of Driver Assistance in Munich.

As mentioned above, highly HAD allows the driver to switch from his original task (driving of the truck) to subsidiary tasks. As the driving task will occupy much less time of the working time, former main activities become less important and former subsidiary activities gain in importance. The job of the truck driver will change, but still the cabin remains the place of interaction between driver and truck.

Considering trends in truck technology, it is very likely that by 2030 automated driving will exist at least on highways, where road and traffic conditions are not as complex as one finds them in urban areas. Besides the advantage of a more efficient way to transport goods on the road, HAD will influence the field of tasks and responsibilities that come with a truck driver's job. As mentioned above, HAD generates a time frame that the driver can use for other activities. This implies the need to transform the common truck cabin in a way that it considers tomorrow's truck drivers' needs and offers possibilities to use the cabin for other non-steering activities during HAD.

1-3 TRUCKletics

In 2008, Technische Universität München started the project globalDrive to improve transportation systems. This year’s sub-project, called TRUCKletics, aims to create options for the truck driver to use phases of highly automated driving meaningfully by performing health-enhancing sports exercises in 2030. The sports exercise system is responsible for attracting more people to be truck drivers.

Research in the domain of long-haul truck driving shows that in general, truck drivers’ working conditions are characterised by long working hours, low salary, and high physical as well as mental stress [10].

Work related stress factors include the environmental conditions as for example climate, noise, dirt, light, exhaust gas pollution or the ergonomic conditions of the driver’s cabin [11]. Work related physical stress is primarily caused by sitting for long periods and a sedentary lifestyle. Irregular working hours, shift work including weekend and night shifts and a high long term concentration while driving are related to an increased fatigue experienced by long-haul drivers. Mental stress is often caused by time pressure given by the employer and by social isolation, which due to spending too much time alone on the roads [12].

It has also been shown that a large amount of truck drivers suffer from back problems, headaches, muscle and joint problems, digestion problems and sleep disturbances [13]. Furthermore, issues with obesity, poor nutrition, hypertension, cardiovascular and heart disease...
and diabetes are common in this profession [14]. According to the survey of Center for Disease Control and Prevention, the average live expectancy for a commercial truck driver is 61 years. To reduce the risk of long-term health issues of truck drivers a preventive approach is essential.

The goal of this project is to integrate a system in the driver’s cabin, which ensures a positive work experience and motivates the driver to live a physically and mentally healthy life. In this context, it will be a main task to identify and test appropriate sports equipment that will enable the driver to perform specific exercise sequences based on his needs. For this purpose, an innovative multifunctional stand-up seat has been developed by last year’s globalDrive team Truck2030. The seat increases movement possibilities as it enables the driver to move to a stand-up position whilst still being belted. Since the exercises will mainly be executed during phases of highly automated driving, the drivers’ safety is another important topic. Active safety aspects will be considered in this project particularly obstetrical avoidance and motion sickness. The development of an adequate user-interfaces which allows the driver to perform exercises will be essential to the project. A challenge will be to not only address the truck driver but to motivate him to use the system to perform sports.
1-4 The TRUCK2030 cabin

The following section deals with the existing prototype of a futuristic truck cabin that was designed and constructed by last year’s Global Drive team. A more detailed description of the different components of the cabin such as frame, seat and interior is given. Advantages as well as disadvantages are presented, followed by a summary that points out why the TRUCKletics project chose to use this cabin.

The following picture shows the design and the shape of the cabin. The shape of the cabin is mainly influenced by the two factors: Cabin space and aerodynamics. The exterior design is characterised by its wedge-shaped front and its rounded edges. Combined with the tilted front window a low drag coefficient (cw) can be achieved. Besides the wedged shape, the back shifting of the A-pillars contributes to an extensive field of view and thus allows all around visibility.

The frame consists of six main modules that were manufactured separately. They include the floor, the two sides, the roof, the rear and the front of the frame. All modules are made of square steel tubes welded or screwed together. For the integration of the seat, an attachment module was used that is mounted to the floor of the frame. The roof provides an attachment for a crane to lift the cabin.

Detailed measurements and free spaces of the cabin are shown in the following pictures. The frame has a length of 2700 mm and a height of more than 2200 mm. It is 2200 mm wide.
so that a bed can be placed in the rear. The rear is designed in a modular way so that on
the one side the bed functions as a resting area. On the other side when folded up it can be
used as a table that can be reached by two seats that are installed in the back of the cabin.
The seat has a central position and can turn to a workplace including a movable desk that is
installed on the right side of the frame. The cabin’s access is from the frame’s left side [2].

The multifunctional seat is a crucial element of the cabin and its concept idea. It is located
in the center of the cabin and offers a lot of functions that help improve the ergonomic conditions
for the driver. The seat is able to move forward and backward on a circular platform that
can also be turned around (90 degrees to the left, 180 degrees to the right). By the use of two
smaller electric motors rotating and translational motion is realized. The movement functions
of the seat are controlled by a steering panel that is installed underneath the right armrest.
The very special feature of the seat is its stand-up function that the driver can use to get in
an upright position during HAD. Ergonomic studies have shown that permanently working
in a seated position influences the muscle-skeleton system in a negative way. The occasional
switch into a standing position is considered to help preventing health problems Figure 1-7.
Thus blood circulation and ergonomic conditions are improved, as the driver may take on
different postures in the truck cabin during work [15].

The stand-up feature is realized by a parallelogram mechanism that is attached to the suspen-
sion and the backrest of the seat. A parallel movement of the backrest during the transition
from seating to standing position supports the driver’s lower back. The seating cushion is
split so that in an upright position on the one side the front part of the cushion is tilted
in order to guarantee legroom. On the other side the rear part is fixed at the backrest and
acts as a supporting cushion while standing. Hence a more comfortable driving position is
provided [3].
**Figure 1-6:** Measurements of the cabin including side and top view [2] [3]

**Figure 1-7:** Multifunctional seat in seating and stand-up position [3]
1-5 Assumptions and structure of the Algorithm

Some assumptions were made to define the scenarios where the algorithm can be applied to.

1 Highway The Highly Automated Driving (HAD) algorithm is focused on the highway. The maximum speed is set as 130 km/h in all scenarios for all obstacle vehicles and 90 km/h for the host vehicle. There are no pedestrians, bicycles, animals, or motorcycles on the highway.

2 Lane change for obstacle vehicle The host vehicle will not change the lane when detect or notice obstacle vehicle is changing the lane or will going to change the lane.

3 Mixed traffic There are two kinds of vehicles on the highway in the algorithm, with or without Vehicle to Vehicle (V2V) communication. Only the vehicle with V2V can do Cooperative Adaptive Cruise Control (CACC).

4 Road The road is assumed to be even and without uphill or downhill. Dry asphalt is assumed to be the road condition.

5 HAD In HAD scenario, driver can’t steer, accelerate, or decelerate.

In order to achieve the goals mentioned in the previous section, a special trajectory for sport inside the cabin was designed. The algorithm architecture proposed in this thesis, as shown in Figure 1-8, is composed of four main elements, described below, developed using Matlab and Simulink. During the simulation, Environment information block will generate information of obstacle vehicle and transmit to all three levels controllers. The high level controller is

Figure 1-8: Topological structure of the algorithm

Yangyu Zhang

Master of Science Thesis
1-5 Assumptions and structure of the Algorithm

Figure 1-9: Environment information for lane change

response to make a decision to doing a lane change or not based on the prediction of the risk of the lane change and the speed of the obstacle vehicle in front. Middle level controller can doing a Cruise Control (CC), Adaptive Cruise Control (ACC), CACC. It can also plan a comfortable trajectory for lane change when getting a command from high-level controller. Once the trajectory was planning, low-level controller will be use to tracking the trajectory with delay of sensors and actuators. A robust controller will be used to prevent roll over.

Environment Information

Environment information block generate the information of three obstacle vehicles: A, B, C in Figure 1-9. The acceleration of this three vehicle can be generate by constant, sinusoidal wave or random number depends on the different scenarios. Velocity, and longitudinal displacement can be calculate by the integrator in Simulink. Data will be transmitted to all level controller with a sensor delay 0.1 second. Sensors’ range was considered to be 200 meters in this thesis. Host vehicle was assume to be able to get the information of the obstacle vehicles’ acceleration, speed, and position from 200 to 0 meter with 360 degrees on the 2D map.

High-Level Controller

This block use to decide to lateral behaviour of the host vehicle. Information of the environment and the host vehicle will be sent to this block and the controller will decide whether to change the lane. A 7 s prediction of the longitudinal position of the obstacle vehicle will be made by this block. The sampling time is 0.01 s to balance the computational cost and accuracy. For the safety reason,

Middle-Level Controller

Two functions can be realise in this block. The first function is the longitudinal control. CC, ACC, CACC can be choose depends on the traffic situation and car to car communication. The second function is to plan a minimum jerk trajectory once the High-Level Controller decide a lane change. The trajectory should be both safety and comfortable. The time for the lane change is 7 s.

Low-Level Controller

A Four Degree of Freedom (DOF) model was built to describe the vehicle dynamics. The model has very low computational cost and also contains the degree of roll angle. The Robust Controller is responsible for rollover prevention with the differential braking actuator.

In the following chapters, the parts of the system described above will be shown and analysed in detail.
Chapter 2

High-Level Controller

The main goal of the High-Level Controller is to decide the host vehicle to do a lane change or not. The decision will be made based on the prediction of position of the host vehicle and the obstacle vehicle. This chapter contains, in the first part, an overview on the methodologies available in literature to estimate the safety and the risk of collision, with a discussion on the possibility to apply them to the autonomous vehicle studied in this thesis. The chapter continues then with a detailed description of the proposed solution to evaluate the risk of collision, with a complete explanation of how the risk of colliding with another vehicle is estimated for lane change and how it can be connected to the other parts of the system.

2-1 Background

The aim of the project is to build a system able to drive an autonomous vehicle on highway scenarios capable to manage even safety-critical situation, the only estimation of other vehicles behaviour is not sufficient. An effective estimation of the safety evaluation and of the risk of collision during the phase of planning of the future trajectory of the host vehicle is necessary. This section contains the risk of collision estimation techniques, together with the introduction of new risk assessment strategies, with advantages and disadvantages of each solution. In Figure 2-1 is reported the scheme of the complete presented project where the collision risk assessment parts are highlighted.

These characteristics, that considerably influence the risk estimation and the path selection, can be listed as follow:

* homogeneous travelling direction - all the vehicles travel in the same direction on the road, the lanes travelling in the opposite direction are completely separated;

* subdivision in lanes - for the rules of the road vehicles are bounded inside a single lane and they are not allowed to travel across two lanes, except for the lane change maneuvers;
* velocity - being the highway usually as straight as possible, a contrast is observed between the velocity in longitudinal direction, very high, and in lateral direction, considerably low;

* safety distance - due to the high speed the braking spaces are large and for this reason a safety distance needs to be considered in the risk of collision;

* merging and exit lanes - the singularity of these parts of the highway makes hard to predict the behaviour of the vehicles entering/ exiting the road; in autonomous driving they constitute always a critical condition to test the algorithms.

An effective risk estimation algorithm has to be capable of dealing with all those aspects to be reliable and to strongly contribute to the safety of the final system.

2-2 Time to Collision (TTC)

They are variety kinds of method to estimate time to collision, the most comment one is to assume the velocity of host vehicle and front vehicle is constant. If the host vehicle $V_{host}$ is faster than the obstacle vehicle $V_{obstacle}$ and nothing variate, the time to collision is than computed as follow:

\[
TTC = \frac{d_1}{V_{host} - V_{obstacle}}
\]
Figure 2-2: Graphical representation of the time to collision in case of car in front on the same lane (a) and car on the right lane with predicted lane change (b).

Where $d_1$ is the actual distance between the two vehicles. If the obstacle vehicle is in another lane, an algorithm that estimates if the vehicle is changing lane can be applied, and the time to collision can be implemented before the obstacle vehicle actually enters the lane where the host vehicle is. As shown in situation b of Figure 2-2 a lane change is detected and a TTC can be computed.

Equation 2-1 is very easy to apply and has relatively low computational cost. However, if the host vehicle is a heavy truck, the braking distance and deceleration will be different from normal vehicle. Problems of Equation 2-1 algorithm are listed as follow:

* TTC algorithm does not take into account the value of velocity of the host vehicle and the obstacle vehicle. Recalling the Equation 2-1, the denominator of the equation is calculated by $V_{host} - V_{obstacle}$, which means the relative velocity between the host vehicle and the obstacle vehicle. However, if the host and obstacle vehicle running with relatively high speed and the difference of the speed for both vehicles is small, the probability of rear-end collision will increase significantly. For example, the 10 meters distance for two vehicle on the city is safe but when the speed increased (e.g. on the highway) is very dangerous;

* TTC algorithm does not take the acceleration into account the braking distance for truck is normally longer than the smaller vehicles. The difference is up to more than 50 meters (based on different kinds of vehicle, vehicle velocity, road condition and weather condition). For example, in Figure 2-3, the relative speed between two vehicles is only 1 m/s and the distance between two vehicles is 30 meters. TTC is 30 s calculated by Equation 2-1. In DAVI project, the Trajectory Finder will not be activated unless
the TTC is shorter than 15 s, which means 30 seconds is a safe value. But if the front vehicle takes an emergency stop, the rear-end collision might happen due to the different braking distance.

One possible solution to calculate the TTC with the acceleration was presented in [16]. Figure 2-4 shows a schematic of vehicle position and speed of the striking vehicle in a lead vehicle stopped rear-end collision. When the driver applies the brakes to avoid a collision, the vehicle is travelling at a speed of $V_{host}$ and is a distance of $d$ from the obstacle vehicle.

The $v_{host}$ is evaluated as the vehicle speed at the time when braking began. The initial range at that same point in time is estimated by assuming a constant vehicle deceleration, $a$, during the braking time. For constant braking deceleration, the distance between the host vehicle and the obstacle vehicle, $d_1$, is

$$d_1 = \bar{d}_1 - (v_{host} - v_{obstacle}) \cdot t + \frac{1}{2} at^2 \quad (2-2)$$

where $t$ is the time after braking started and $a$ is the magnitude of deceleration. $\bar{d}_1$ is the distance between the host vehicle and the obstacle vehicle in the beginning, $a$ is the
negative acceleration. The delay of the brake system activation is assumed to be negligible. Substituting equation Equation 2-1 into Equation 2-2 at the time prior to the impact when braking initiated, $t_s$, yields an expression for TTC:

$$TTC = \frac{-(v_{host} - v_{obstacle}) \pm \sqrt{(v_{host} - v_{obstacle})^2 + 2ad_1}}{a}$$

(2-3)

This algorithm take into account the deceleration for the host vehicle and assume the velocity of the obstacle vehicle is constant. But the computational cost is much higher than Equation 2-1, Equation 2-3 it is non-linear and difficult to apply in 7 s prediction. The assumption of constant velocity on the high way for lane change is more reliable than the constant acceleration. However, if the obstacle decelerating, TTC is not enough to prove safety. TTC combine with Braking distance might be an alternative choice to improve safety reliability.

### 2-3 Braking distance

Recall the Figure 1-9, before lane change of the host vehicle, the value of $d_2$ and $d_3$ should exceed the safety distance. The safety distance is depends on the communication between vehicles, the maximum deceleration and the speed of the vehicles. Because the maximum deceleration of the obstacle is higher than the host vehicle, $d_2$ should be higher than the difference of braking distance.

Table 2-1 shows that comparing with the hi-performance vehicles, the friction coefficient is smaller for truck Table 2-1. Truck has longer braking distance than the hi-performance vehicles on average. In order to prove safety, the distance between the host vehicle (truck) and the front vehicle should be longer than small size automated driving vehicle(e.g., Google self-driving car). Table 2-2 shows that the different of friction coefficient for truck and hi-performance vehicle on different road condition. On the Dry asphalt/concrete, the truck has smaller friction Coefficient, this requires the truck keeping a relatively longer distance to maintain security.

The calculation of real braking distance is quite sophisticated, depends on air drag force, different road surface, braking system and so on. Since the parameters of the truck are still uncertain, a simplifier method was introduced in Equation 2-4 to calculate braking distance, only taken into account the friction coefficient. $d_{braking}$ is the braking distance for the vehicle. $\mu$ is the friction coefficient. $v_0$ is the initial speed just before braking. $g$ is the acceleration of gravity.

$$d_{braking} = \frac{v_0^2}{2\mu g}$$

(2-4)
Table 2-2: Braking distance for different kinds of vehicle and speed (km/h) [6]

<table>
<thead>
<tr>
<th></th>
<th>80km/h</th>
<th>90km/h</th>
<th>100km/h</th>
<th>110km/h</th>
<th>120km/h</th>
<th>130km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck on dry asphalt</td>
<td>31.49</td>
<td>39.86</td>
<td>49.2</td>
<td>59.54</td>
<td>70.86</td>
<td>83.16</td>
</tr>
<tr>
<td>Hi-Performance on dry asphalt</td>
<td>25.19</td>
<td>31.88</td>
<td>39.36</td>
<td>47.63</td>
<td>56.68</td>
<td>66.53</td>
</tr>
<tr>
<td>Truck on wet asphalt</td>
<td>45.80</td>
<td>57.97</td>
<td>71.57</td>
<td>86.60</td>
<td>103.07</td>
<td>120.96</td>
</tr>
<tr>
<td>Hi-Performance on wet asphalt</td>
<td>35.99</td>
<td>45.55</td>
<td>56.23</td>
<td>68.04</td>
<td>80.98</td>
<td>95.04</td>
</tr>
</tbody>
</table>

Based on the friction coefficient and equation Equation 2-4, the braking distance for a variety of vehicles and velocity was shown in Table 2-2.

Since the braking distance for the truck is normally longer than the small vehicle, the active safety system is more challenging to design. One of the challenges is to define the safety distance. The safety distance is calculated by Equation 2-5

\[ S_{\text{safety}} = \frac{v_{\text{host}}^2}{2\mu_{\text{host}}g} - \frac{v_{\text{obstacle}}^2}{2\mu_{\text{obstacle}}g} + v_{\text{host}}T \] (2-5)

Where \( S_{\text{safety}} \) is the safety distance. \( v_{\text{host}} \) and \( \mu_{\text{host}} \) are the velocities and friction coefficient of the host vehicle. \( v_{\text{obstacle}} \) and \( \mu_{\text{obstacle}} \) are the velocity and friction coefficient of the obstacle vehicle. \( T \) is the sampling time which is 0.2 s. Figure 2-5 shows the safety distance between the truck and Hi-Performance vehicle when \( v_{\text{host}} > v_{\text{obstacle}} \). In general, host vehicle should keep the obstacle further when the speed increased. When the difference of the speed for two vehicles reduced, the safety distance will also decrease. \( d_2 \) should be higher than the \( S_{\text{safety}} \) before the lane change.

Even if the host vehicle keep the safety distance with the front vehicle, in some cases, vehicle cut in from other lane will reduce the braking distance significantly, which endangers the host vehicle. As shown in Figure 2-6, the host vehicle is in automated driving mode and no other vehicle is on the same lane in sensors’ range. Suddenly the obstacle vehicle A cut in front of the host vehicle and the safety distance between two vehicle will soon decrease from the sensor range to the real distance between host vehicle and obstacle vehicle A.

Since another obstacle vehicle B on the middle lane, it is impossible for the host vehicle to change the lane. They are two simple ways to solve this question:

* From the safety aspect, the host vehicle should take an emergency braking in order to have a shorter time exposed to danger. However, it is less comfortable for the driver and even worse for driver doing sport inside the cabin. What’s more, if there is another vehicle behind the host vehicle in the same lane, the risk of rear-end collision will increase. Even if no vehicle behind the host vehicle, emergency braking is not that common on the high way.

* From the comfort aspect, the host vehicle should brake pedal slowly in order to reduce the impact from deceleration. The value of deceleration can be set as the maximum deceleration driver can tolerant for sport or sitting comfort, whereas the vehicle will stay in risky for longer time. This way is less aggressive and more similar to human driver.

Yangyu Zhang Master of Science Thesis
Figure 2-5: Safety distance for truck on the dry asphalt

Figure 2-6: Merging scenario of the obstacle vehicle
The way to solve this problem is quite complex. On one hand, emergency braking is very aggressive on the highway and make the driver feel uncomfortable even horrible. On the other hand, emergency braking could improve safety. In order to solve this problem, the probability of cut in and emergency of front vehicle should be taken into consideration. Since the data is still missing, emergency braking when no vehicle behind the sensors’ range might be more conservative way to apply. When there is a vehicle detect behind the host vehicle, the deceleration should be take in to account the distance between all obstacle vehicle, the speed of obstacle vehicle, TTC and the possibility to change lane. This problem will be solve in the next chapter.

2-4 Risk prediction for lane change

A driver takes $0 - 3$ s to realise other vehicle’s lane change [17]. Before the lane change, the TTC must be long enough to give drivers in obstacle vehicles plenty of time. In this thesis, a lane change will be taken only when the speed of the front vehicle is lower than 80 $km/h$. Recalling Table 2-2, braking distance for the truck with the speed 90 $km/h$ is around 40 $m$. An emergency lane change will at least take 3 $s$, which means 75 $m$ during this period. Because of the long shape of, it can hardly avoid cash unless it finishes the lane change. An emergency lane change to avoid obstacle will not be taken due the truck dynamics reason.

To improve the efficiency, host vehicle can change the lane automatically when $v_a$ is below the lower bound. Before that, the risk of collision needs to estimate. The estimation will take the TTC and safety distance into account. $d_2$ need to be higher than the different braking distance. $d_3$ should be higher than twice of the reference distance for Adaptive Cruise Control (ACC) or Cooperative Adaptive Cruise Control (CACC) which will be explain in the next chapter.

\[
\begin{bmatrix}
  x_1(k) \\
  x_2(k) \\
  x_3(k)
\end{bmatrix} =
\begin{bmatrix}
  v_x(k) \\
  v_b(k) \\
  v_c(k)
\end{bmatrix}
\]

(2-6)

\[
\begin{bmatrix}
  x_1(k+1) \\
  x_2(k+1) \\
  x_3(k+1)
\end{bmatrix} =
\begin{bmatrix}
  v_x(k) \\
  v_b(k) \\
  v_c(k)
\end{bmatrix} +
\begin{bmatrix}
  0 \\
  0 \\
  0
\end{bmatrix} u = x(k)
\]

(2-7)
$u$ is the lateral acceleration $a_x$ calculated by the CACC controller. $T_s$ is the sampling time. $y(k)$ is the $d_2$ and $d_3$ in each steps. $y_1'(k)$ is the TTC between host vehicle and obstacle vehicle $c$, $y_2'(k)$ is the TTC between obstacle vehicle $c$ and host vehicle.

$$y(k) = \begin{bmatrix} y_1(k) \\ y_2(k) \end{bmatrix} = \begin{bmatrix} d_2(k) \\ d_3(k) \end{bmatrix}$$ \hspace{1cm} (2-8)

$$y'(k) = \begin{bmatrix} y_1'(k) \\ y_2'(k) \end{bmatrix} = \begin{bmatrix} \frac{y_1(k)}{x_3(k) - x_1(k)} \\ \frac{y_2(k)}{x_3(k) - x_1(k)} \end{bmatrix}$$ \hspace{1cm} (2-9)

$$y_{(k+1)} = \begin{bmatrix} y_1(k+1) \\ y_2(k+1) \end{bmatrix} = \begin{bmatrix} x_2(k+1) - x_1(k+1) + d_1(k) \\ x_1(k+1) - x_3(k+1) + d_2(k) \end{bmatrix} = \begin{bmatrix} -1 & 1 & 0 \\ 1 & 0 & -1 \end{bmatrix} \begin{bmatrix} x_1(k) \\ x_2(k) \\ x_3(k) \end{bmatrix} + \begin{bmatrix} d_1(k) \\ d_2(k) \end{bmatrix}$$ \hspace{1cm} (2-10)

To make the lane change safe enough, the risk will be estimated by the safety distance before steering. Safety distance and TTC can be calculated by Equation 2-5 and Equation 2-1. The high level controller is responsible for estimate the risk for the lane change. In this thesis, the time for a whole lane change will takes 7 seconds for safety and comfort. The High-Level Controller will be activated each 0.01 s to save computational cost. In Simulink model, this method will reduce more than 80 % of the computational time compared with estimating the risk in each step.

During the lane change, the longitudinal acceleration of the host vehicle was calculated by the CACC controller to maintain the longitudinal safety distance with obstacle vehicle. The velocity of obstacle vehicle B, C and A is assume with a constant speed. The sampling time for the speed is 0.01 s.

Once the High-Level Controller was activated, $d_1$ and $d_2$ will be estimates each time step. The step size is defined as 0.1 second in the High-Level Controller. $d_1$ and $d_2$ should be larger than the safety distance before lane change was taken. $y_1'(k)$ and $y_2'(k)$ should always be longer than 15 s during the lane change prediction. Safety distance is define by the maximum of the different braking distance between two vehicles for the obstacle vehicle B, and twice the distance of the systems for the obstacle vehicle C. TTC is the second parameter need to be considered. During the estimation of 7 s, if $v_b(k) < v_x(k)$ or $v_c(k) > v_x(k)$, TTC should be larger than 15 in each step.
Chapter 3

Middle-Level Controller

The Middle-Level Controller contains two parts: Longitudinal Controller and Trajectory Planner. Longitudinal is always activated in Cruise Control (CC), Adaptive Cruise Control (ACC), or Cooperative Adaptive Cruise Control (CACC) mode (depends on the communication and the position of the obstacle vehicle). The Trajectory Planner will be activated only when the High-level controller decides to change the lane.

3-1 Longitudinal Controller Design

This section contains, a brief introduction on the state of the art of CC, ACC, and CACC, after that, formulation details and simulation results will be shown in following three subsections.

3-1-1 Introduction

In recent years, ACC and CACC developing very fast for mainly three advantages:

1. Reduce energy consumption significantly. 10 – 20 % of the fuel can be saved because of the air resistance was reduced; CACC, compared with ACC, has smaller a gap between two vehicles, so it is more environmentally friendly.

2. Improve highway traffic flow. Congestion can be reduced when the average gap is getting smaller.

3. Fewer traffic collisions. The longitudinal distance between two vehicles will be controlled automatically which is more reliable than most drivers.

In this thesis, three scenarios can be chosen in the Middle-Level Controller: CC, ACC and CACC. All scenarios assume the vehicle can detect the lane and keep the host vehicle in the middle of the Lane unless the host vehicle starts to change the lane. Once the lane change
is begins, the vehicle will tracks the trajectory from trajectory planning block on lateral direction.

CC will be applied when no obstacle vehicle is detected in sensors range. When the host vehicle is in ACC or CACC mode, safety distance $d_1$ between obstacle vehicle A and host vehicle shown in Figure 1-9 should be maintained. In ACC or CACC mode, the acceleration of the obstacle vehicle A is necessary to be known by the controller. Sensors like Radar, Camera, Lidar should be responsible to measure the acceleration, velocity of obstacle vehicle A and the value of $d_1$ of Vehicle A in ACC scenario. CACC realises longitudinal automated vehicle control. In addition to the feedback loop used in the CACC, which uses Radar or LIDAR measurements to derive the range to the vehicle in front, the preceding vehicle’s acceleration is used in a feed-forward loop. The preceding vehicle’s acceleration is obtained from the Cooperative Awareness Messages it transmits using Dedicated Short-Range Communications (DSRC) or Wireless Access in Vehicular Environments (WAVE) technology. These messages are transmitted several times per second by future vehicles equipped with Intelligent Transportation System (ITS) capabilities.

Three technologies above were required to provide safe and smooth trajectory. In the following sections, simulation results will be discussed to explain the smooth and robust of the transition period.

In Figure 1-9, if vehicle A move to the left lane, host vehicle will change form ACC or CACC to CC. When the vehicle move to the left lane, ACC or CACC will change to CC, ACC or CACC depends on the position of obstacle vehicle B. When the safety distance $d_2$ is larger than 200 meters which is beyond sensors range and car to car communication is not available, CC will be apply. Otherwise ACC or CACC will be used depends on the car to car communication. If the s

\[ a_{hx} = 0.58(v_{ref} - v_{hx}) \]  

(3-1)

where $a$ is the longitudinal acceleration of the host vehicle, $v_{ref}$ is the reference velocity, $v_{hx}$ is the longitudinal velocity. This algorithm will be test in the following scenarios:

**Scenario 1: Change reference speed in CC mode**
This scenario is used to test truck’s CC mode when the speed limitation change on the highway. In Figure 3-1, the host vehicle is in CC condition at $t_0 = 0$ s with the maximum speed $v_{x0} = 90$ km/h. At $t_1 = 5$ s, the speed limitation of the high reduce to $v_{x1} = 80$ km/h, so the truck need to decelerate. Figure 3-2 shows that the real longitudinal velocity of the host vehicle (blue line) reduced to the reference speed (red line) from 5 s to 15 s smoothly.

**Figure 3-1:** Initial configuration in scenario 1

**Figure 3-2:** Change reference speed on the high way in scenario 1

**Scenario 2: CC mode to ACC mode**

This scenario is used to test the transition from CC mode to ACC mode on the highway. In the beginning, $d_1 = 250$ m, $v_x = 90$ km/h, $v_a = 85$ km/h, vehicle is in CC mode. $v_a$ is assume to be constant in this scenario. In the beginning, vehicle A is beyond the sensors range so the host vehicle is in CC mode. When $d_1$ is smaller than 200 m, host vehicle detect the obstacle vehicle B and activate the ACC controller. The gap between two vehicle will reduce steadily until the $d_1$ reach the feasible value. The ACC
algorithm will be shown in the next section.

![Figure 3-3: Initial configuration in scenario 2](image)

**Figure 3-3: Initial configuration in scenario 2**

![Figure 3-4: $d_1$ on the high way in scenario 2](image)

**Figure 3-4: $d_1$ on the high way in scenario 2**

Figure 3-4 shows the distance between the host vehicle and the obstacle vehicle A in 300 s (blue line), it first reduced until $d_1$ equal to the safety distance. The red lane in Figure 3-4 shows the reference value of $d_1$, when the $d_1$ reach the steady state, tracking error became 0. Figure 3-5 shows the velocity in 300 s, when two vehicle getting closer to safety distance, the speed of the host vehicle (blue line) change varying from 90 km/h to 80 km/h (red line) in around 40.8 s. After that the host vehicle keeping the same speed as the vehicle A.

**Scenario 3: CC mode to CACC mode**

This scenario is used to test the transition from CC mode to CACC mode on the highway. The initial configuration and value is the same as scenario 2. Only thing different is that two vehicles have car to car communication when the $d_1$ smaller than
200 m. The steady state value of $d_1$ will be smaller than previous scenario. The CACC algorithm will be shown in the CACC section.
Figure 3-7: Speed of the host vehicle in scenario 3

Figure 3-6 and Figure 3-7 shown similar characters as previous scenario. Since the safety distance is smaller in CACC scenario, it will take around 3 s longer to converge.

3-1-3 ACC

Autonomous cruise control (ACC; also called adaptive cruise control, radar cruise control, or traffic-aware cruise control) is an optional cruise control system for road vehicles that automatically adjusts the vehicle speed to maintain a safe distance from vehicles ahead. It makes no use of satellite or roadside infrastructures nor of any cooperative support from other vehicles. As one of the most important system of Advanced Driver-Assistance (ADA), ACC getting popular in the past 20 years. The equations for the speed and distance controller have been derived from [18].

\[
\begin{align*}
a_{hx} &= a_a + 0.58 \cdot (v_a - v_{hx}) + 0.1 \cdot (d_1 - s_{ref}) \\
&s_{system} = 1.4 \cdot v_{hx}
\end{align*}
\]  

(3-2)  

(3-3)

Where \(a_a\) and \(v_a\) are the acceleration and velocity of obstacle vehicle A, \(v_{hx}\) is the longitudinal velocity of the host vehicle. The reference clearance \(s_{ref}\) is defined as a maximum among safe following distance \(s_{safety}\) defined by Equation 2-5, following distance according to the system time setting \(s_{system}\), and a minimum allowed distance \(s_{min}\), set at 2 m. This controller will be tested in the following scenarios:
Scenario 4: Tracking target vehicle

This scenario is used to check the ACC controller maintain the safety distance when the speed of obstacle vehicle A is change. Figure 3-8 shows that the host vehicle tracking a target vehicle with a sine wave acceleration. The velocity of the obstacle vehicle is constantly 85 km/h plus the integration of the sine wave acceleration with amplitude 0.1 and frequency 0.2 rad/s. The maximum tracking error is smaller than 0.15 m in the simulation. Figure 3-9 shows that tracking a random acceleration with zero mean unit variance. The maximum tracking error is around 1 m.

![Figure 3-8: d₁ and d₁ref in scenario 4](image)

Scenario 5: ACC to CC transition

In this scenario shown in Figure 3-10, the host vehicle is started in ACC mode and tracking the front vehicle. At 5 s, vehicle A changed to the middle lane, and the host vehicle accelerate to CC mode. Figure 3-11 shows the longitudinal speed of the host vehicle and the reference speed. From 0 – 5 s the reference speed is the same as the front vehicle. After 5 s the reference velocity became 90 km/h which is the speed of CC.

Scenario 6: ACC to CACC transition

In this scenario, the host vehicle was in ACC with car to car communication from 0 – 5 s. After 5 s, the car to car communication was built and the gap between two vehicles will be smaller. Figure 3-12 shows the d₁ converge to d₁ref after the reference safety distance between two vehicles changed.
3-1-4 CACC

CACC is the future of transportation in which trucks drive cooperatively at less than 1 second apart made possible by automated driving technology. Transportation companies benefit from lower fuel consumption and improvements in (driver) productivity, while society benefits from fewer accidents, safer traffic and less congested roads, and lower carbon emissions. The algorithm of CACC is defined in Equation 3-4 and Equation 3-5.

\[
a_{hx} = a_a + 0.58 \cdot (v_a - v_{hx}) + 0.1 \cdot (d_1 - s_{ref}) \quad (3-4)
\]

\[
s_{system} = 0.5 \cdot v_{hx} \quad (3-5)
\]
Where $a_a$ and $v_a$ is the acceleration and velocity of vehicle A, $v_{hz}$ is the longitudinal velocity of the host vehicle. The reference clearance $s_{ref}$ is defined as a maximum among...
safe following distance \((s_{\text{safty}})\) defined by Equation 2-5, following distance according to the system time setting \((s_{\text{system}})\), and a minimum allowed distance \((s_{\text{min}})\), set at 2m. The only thing different from ACC is the \(s_{\text{system}}\) is longer. This algorithm will be tested in the scenarios 7, 8, 9.

**Scenario 7: Tracking the target vehicle**

This scenario is used to check the CACC controller maintain the gap when the speed of obstacle vehicle A changing periodically or randomly. Figure 3-13 shows that the host vehicle is tracking a target vehicle with a sine wave acceleration. The velocity of the obstacle vehicle is constantly 85 km/h plus the integration of the sine wave acceleration with amplitude 0.1 and frequency 0.2 rad/s. The maximum tracking error is smaller than 0.05 m in the simulation. Figure 3-14 shows that tracking a random acceleration with zero mean unit variance. The maximum tracking error is around 0.34 m.

![Figure 3-13: \(d_1\) and \(d_{1,\text{ref}}\) in simulation with sine wave acceleration in scenario 7](image)

**Scenario 8: CACC to CC transition**

Recall the Figure 3-10 in Scenario 5, this scenario is CACC instead of ACC. The host vehicle is started in CACC mode and tracking the front vehicle. At 5 s, vehicle A changed to the middle lane, and the host vehicle accelerates to CC mode. Figure 3-15 shows the longitudinal speed of the host vehicle and the reference speed. From 0 − 5 s the reference speed is the same as the front vehicle. After 5 s the reference velocity became 90 km/h which is the speed of CC.

**Scenario 9: CACC to ACC transition**

In this scenario, the host vehicle was in CACC with car to car communication from 0 − 5 s. After 5 s, the car to car communication is not available, and the gap between
Figure 3-14: $d_1$ and $d_{1\text{ref}}$ in simulation with zero mean unit variance random acceleration in scenario 7

Figure 3-15: Speed control of the scenario 8
two vehicles will be bigger. To realise that goal, $v(x)$ was reduced. $d_{1ref}$ was also fallen from $5 - 7$ s because the longitudinal velocity of the host vehicle is reduced to enlarge $d_1$. When two vehicles getting enough gap between them, the host vehicle accelerates again to keep the same speed as target vehicle. So $d_{1ref}$ will increase after $7$ s. Figure 3-16 shows the $d_1$ converge to $d_{1ref}$ after the reference safety distance between two vehicles is change.

![Figure 3-16: Safety distance of the scenario 9](image)

### 3-2 Trajectory Planner

This section contains a description of what concerns the selection of the reference trajectory for the host vehicle. The first part introduce the problem of the definition and selection of the trajectory in the highway environment, focusing on the two most important aspects that influence the final selection: comfort and risk of collision. A solution is then proposed, with a fixed trajectory for lane change and it will be applied only when getting the permission from High-Level Controller.

#### 3-2-1 Overview of trajectory selection

As a recall, the diagram with the general structure of the system is reported in Figure 3-17 with highlighted the part of the system analysed in this chapter, the trajectory finder. In this section, the problem of selecting a trajectory will be analysed. The existing solutions used to compute a proper planning of the trajectories to be followed often
defined, especially in the robotics field, in a free space, where the possible trajectories are basically infinite, being the robot free to move in any position within the free space. In the case of use the vehicle on a highway, the problem needs to be redefined, due to the existence of constraints on the path and the presence of road rules that have to be respected. Moreover, other constraints are introduced due to the dynamic of the host vehicle, that needs to be necessarily taken into account to avoid that the selected scenario exceeds the dynamic limits of the car. In highway scenario, as it will be described in the following sections, some assumption and simplification can be used to reduce the problem complexity, being possible to suggest a suitable solution for the thesis.

3-2-2 Considerations and assumptions

Regarding to the specific operating environment of the system, the highway, some consideration and comparisons with other environments can be done to reduce the complexity of the problem.

First, to better understand the following considerations, a recall on the general behaviour of the complete system is given. The selection of the final trajectory that the vehicle will follow is divided into two steps. The first selection of a suitable trajectory will be made with the part of the system that has been called trajectory planning, highlighted in Figure 3-17. In this part, the High-Level Controller will decide whether it is safe to do a lane change. The Middle-Level Controller will plan a trajectory with suitable acceleration and jerk. For this reason, the reference trajectory has to satisfy the comfort requirements and also can be selected using the risk evaluation method described in chapter 3, even if that method involves a prediction of the risk of collision over the entire trajectory.
3-2-3 Shape of the trajectory

In highway environment for a vehicle, the number of rules and constraints related to the position is considerable. Moreover, the velocities that can be reached are high, and the environment in which the host vehicle is moving is changing dynamically at every moment in time. For this reason, the method used to understand the variation of the environment result to be essential, being the prediction of the other vehicle behaviour determinant in the selection of the proper collision-free trajectory. The safety distances from the other vehicles in the scenario, to ensure the safety and the collision avoidance in case of critical situation, act as a restriction on the available trajectories.

A further limitation is given by the presence of the lanes, that separates the vehicles that are travelling at different velocities. One of the fundamental rules of the highway is that the position of the vehicle in normal driving condition needs to remain inside a lane, as central as possible, except in the case of a lane change, where the movement across the lanes is allowed. Even if this can be seen as a complex constrain, from the point of view of the number of possible trajectories it can be used instead as a huge simplification. This, in fact, means that the only trajectories allowed are those that bring the vehicle from the center of a lane to the center of an adjacent one. This limits the lateral displacement to a fixed value equal to the distance between the two lane centers, that is known from the map data, assumed in the simulations to be equal to 3.5 m. In this way, all the possible trajectories that starts or finish in a point that is not centered with respect to the lane are excluded.

Moreover, a suitable behaviour when travelling on the highway is that if a lane change scenario is started, it is followed and performed completely until the end, avoiding to interrupt the scenario halfway unless it is absolutely necessary. Considering instead a straight road the only trajectory that can differ from a lane change is a straight trajectory, to follow the actual lane.

If the lateral displacement of a lane change scenario is fixed, the other variable parameters remaining are two: the time $T_{Lane\ Change}$ necessary to complete the lane change scenario, and the shape of the trajectory.

Regarding the time necessary to perform the lane change, some studies are available in the literature, described below, that shows through experimental tests that the time necessary for a lane change can be expressed as a log-normal distribution with mean value included between 4 and 5 seconds [19]. The distribution of duration in Figure 3-18, shows that the time necessary for a lane change can go from a minimum time of 1 second up to a maximum of about 14 seconds.

Instead of the shape of the lane change, many studies in literature analysed the problem and suggested some different ways to express the shape of a lane change. In [20] four methods to express the lane change scenario are described and compared:

* circular trajectory;
* cosine trajectory;
5th order polynomial trajectory is the most suitable trajectory for this project among these four methods. According to [21], 5th order polynomial trajectory minimises the sum of the squared jerk along its trajectory. For a particularly trajectory \( y(t) \) that starts at time \( t_i \) and ends at time \( T_{LC} \), smoothness can be measured by calculating a jerk cost:

\[
\int_{t=t_i}^{T_{LC}} \dddot{y}(t)^2 dt 
\]  

(3-6)

and the minimum jerk trajectory would be:

\[
y(t) = Y_{LC} \left\{ 10\left( \frac{t}{T_{LC}} \right)^3 - 15\left( \frac{t}{T_{LC}} \right)^4 + 6\left( \frac{t}{T_{LC}} \right)^5 \right\}
\]  

(3-7)

where \( Y_{LC} \) is the lateral displacement, equal to 3.5 m. \( t \) is the time instant computation of the lateral position \( y(t) \) is computed.

The value of Jerk and acceleration should be minimised in the project due to the comfort aspect. The maximum acceleration obtained from the experimental tests performed with the instrumented Fiat Croma of Politecnico di Milano. As explained in the

Master of Science Thesis  
Yangyu Zhang
description of the performed tests, the final limit selected as maximum level is equal to:

\[ A_y \text{ Limit} = 2 \text{m/s}^2 \] (3-8)

Based on the limitation of acceleration, the time for a lane change should be longer than 3.2 s to prove comfort. The acceleration and jerk for a lane change are shown in the Figure 3-19. The lateral acceleration for a lane change is similar to the sine wave, the peak value and the minimum value is around the 1/4 and 3/4 period. The jerk is similar to a cosine wave in its time for the lane change.

From ergonomics aspect, discomfort is mainly caused by low-frequency lateral oscillation, roll oscillation and roll-compensated lateral oscillation [5]. The comfort contours for lateral oscillation and roll oscillation are compared with those reported previously in Figure 3-20. The figures show increasing sensitivity to lateral acceleration from 0.2 to 2.0 Hz, but decreasing sensitivity at higher frequencies. In the present study, as the frequency of oscillation increased from 0.5 to 1.0 Hz, the acceleration required for equivalent discomfort decreased by approximately 5 dB per octave for lateral acceleration, by 12 dB per octave for the lateral acceleration caused by roll and by 12 dB per octave for the lateral acceleration associated with fully roll-compensated lateral oscillation. For lateral oscillation and roll oscillation of a rigid seat with backrest and harness, equivalent comfort contours from 0.2 to 1.6 Hz declined at approximately 6 dB and 12 dB per octave, respectively [22], broadly consistent with the current findings. In the next section, the value of the duration for lane change will be decided based on this comfortable requirement.

3-2-4 Time for the lane change

After determining the shape of the trajectory for a lane change, a proper time for lane change will be chosen to plan the trajectory. There are two requirements of choosing the time. The High-Level Controller uses a linear model with the assumption of constant speed to predict the position of the obstacle vehicle in the prediction horizon. However, obstacle vehicle might accelerate or decelerate during the host vehicle change the lane
and will cause the error of the estimation. The error will be accumulate with the time. So a long time lane change will increase the uncertainty of estimation and risk. Another requirement is the comfort. A short time lane change has a large value of lateral jerk and acceleration, which will influence driver’s comfort and balance for sports exercise. A large jerk might hurt the driver when doing sport exercise in the cabin. To reduce risk, system should remind driver to stop exercising for a while before a lane change.

To satisfy those two requirements above, the time for lane change was chosen as short as possible but do not influence comfort and safety. Based on the requirement on Figure 3-20 Reciprocal of $W_d$, 7 s was chosen to be the time for the lane change. The frequency of the sine wave of the acceleration is around 0.14 Hz. The lateral acceleration and jerk for 7 s lane change are showed in Figure 3-21.

The lane change starts at 0 s and finish at 7 s in the simulation. The peak value of the acceleration is 0.4124 m/s$^2$ at 1.75 s. The peak value of jerk is 0.6115 appear in both begin and end of the lane change.

**Figure 3-20:** Effect of frequency of oscillation on equivalent comfort contours for lateral oscillation. Contours normalised to represent discomfort equal to that caused by lateral acceleration at 0.5 Hz 0.20 m/s$^{-2}$ r.m.s. on a rigid seat with backrest [5]
Figure 3-21: Lateral acceleration (left) and jerk (right) for lane change in 7 s
In this chapter, a lower level robust controller was designed to tracking the signal of the steering angle and acceleration from the Middle-Level Controller and prevent rollover. The model takes into consideration the braking force from both the left and right side. Powertrain model was neglect to simplify the model to reduce the power of calculation. The simulation results show that the truck model with a robust controller has low computational cost and can be stabilized under disturbance during the lane change.

4-1 Requirements of the controller

When we design the Low-Level Controller system, many factors should be taken into consideration, such as the response speed, the economy factor, robustness and reliability. The specific requirements are as follow:

* **Accurate** The system should detect rollover as accurate as possible. If rollover will occurs, the system can take proper action to alleviate it. It is one of the most important requirements of the system.

* **Fast** The system should respond quickly if the system detects and judge that the rollover of the vehicle will take place. The fastness is particularly important for the system because most of the vehicle rollover take place in a sudden. The Rate of convergence of the Load Transfer Ratio (LTR) also should be fast.

* **Reliable** The system should take action correctly if vehicle rollover occur and the system should detect and judge the rollover correctly at any time and cannot fail to work when the vehicle is driving.

* **Handling** There is always a compromise between drivability, comfort and cost. When we consider the other factors, drivability should not be lost. The system’s behaviour should be repeatable.
*Robust* The system should be designed to function properly provided that uncertain parameters or disturbances are found within some (typically compact) set.

When Roll-over occurs, the lateral force increases and inner tire lose contact with the ground and so the roll angle increases. When it reaches its threshold, the rollover accident will take place. The rollover sensors should be capable of sensing all of the necessary information, such as the vehicle’s roll angle and both lateral and vertical acceleration in the event of an impending rollover.

### 4-2 Sensors selection

In this section, suitable sensors will be chosen to improve the reliability of the system. The accelerometer is the general choice for the rollover mitigation system since we can measure lateral force, if lateral accelerate exceed the threshold, the accelerometer will give us alarm that we need to take action to reduce the lateral acceleration immediately to prevent the occurrence of the rollover accident. However, this is not always the case since the measurement will not be very accurate since our vehicle may not be level relative to earth. Thus a single sensor measuring the suspension travel would not be enough because the sensor may be triggered if the vehicle is driving over a bump. In the following, we come up with three possible combinations of sensors which can measure the dynamics of vehicle rolling:

1. **Combine wheel load sensor bearing with accelerometer** Load sensor bearing can measure the lateral and vertical load of the wheel. The bearing can be replaced by load sensing bearing. When vehicle rollover occurs, the load is different between inner tires and outer tires. Thus we use the load sensor bearing which can provide this data with the capability of delivering load information to all four corners of the vehicle, for both driven and non-driven wheels. If vertical load distribution on wheels has exceed the threshold, it will trigger an alarm that rollover of the vehicle may occur, and we need to take an action on it. Load sensor bearing has a long lifespan, and it is easy to use. However, the load sensor bearing is expensive. Thus it is not the common choice for the rollover mitigation system.

2. **Combine angular rates sensors with micro-displacement sensors** Micro-displacement can measure displacement, distance, and position of electrically conductive targets with high precision. It can be used to measure the variation in distance between the vehicle body and its support. If the distance difference of vehicle body and its support between both sides exceed the threshold, the system should trigger an alarm. Micro-displacement sensor has high reliability and precision. But it is expensive and it will become inaccurate if the body or the support have plastic deformation.

3. **Combine angular rate sensors with accelerometers** We can use angular rate sensors to measure the rate of roll around the axis. If we integrate the roll over time, we
will get angles as a function of time. We can get the forces caused by rolling from the accelerometer. This combination is the most regular sensor group in vehicle rollover mitigation system. Angular rate sensor is a gyroscopic sensor that measures the angular velocity of roll motion. Compared with the wheel load sensor bearing, it is inexpensive and easy to use so it is a common choice for nowadays vehicle rollover sensor.

In conclusion, plan three was chosen since its advantages outweigh its drawbacks. Having a good braking system is necessary and crucial for any vehicle. Here we would like to have the electro-mechanical braking system because of its reliability. Active Differentials allow for electronically controlled torque repartition. With this actuator, the risk of rollover can be significantly reduced when doing a lane change or rounds a curve. Although the price is higher than the traditional passive differentials, it is useful for the large vehicle with a higher height of the center of gravity. The actuator delay was considered to be 0.1 s.

### 4-3 Bicycle model with roll degree of freedom

Heavy truck rollover poses a threat to highway safety which may result in disastrous consequences and great losses. In the United States, approximately 35,000 rollover accidents involving heavy commercial trucks are reported every year. Overall, the loses of rollover accidents in the UK can be estimated to be 40–60 million annually, excluding environmental losses and losses arising from traffic delays, and at the same time the accidents can cause serious injuries and death [7].

According to the literature study, the roll angle, roll rate, slip angle, lateral acceleration, the center of gravity height have been considered to be essential parameters which are highly correlated to estimate truck’s rollover. Differential braking [23], active steering [24], active suspension [25], and active roll stabiliser bars have been used as actuators to prevent rollover for the heavy trucks.

Two kinds of vehicle models are commonly used for simulation. The first one is the standard reference system for passenger vehicle defined by Society of Automotive Engineers (SAE) in document J670 [26] with three degrees of freedom. This model do not take roll angle into consideration which means it is not possible to prevent rollover directly. Another model is 9 degree of freedom model in [27]. This model has very expensive computation cost and difficult to simulate in real time.

In this thesis, the bicycle model with roll degree of freedom was used to generate the heavy truck’s behaviour for a lane change. The dynamics of a vehicle represented by such a model can be described by Equations below [28] [29] [30]. The steering input $\delta$ directly affects both roll and lateral dynamics of the vehicle as expected. The second input $u$ is the total differential braking force on the wheels. This force is a signed quantity and is positive if the effective braking is on the right wheels and negative otherwise. The total differential braking force will change the yaw rate and reduce the LTR which will be discussed in the next section.
Table 4-1: Vehicle model parameters [7]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>Vehicle Mass</td>
<td>14300</td>
<td>kg</td>
</tr>
<tr>
<td>g</td>
<td>Gravitational Constant</td>
<td>9.81</td>
<td>m/s^2</td>
</tr>
<tr>
<td>$J_{xx}$</td>
<td>Roll moment of inertia at the CG</td>
<td>24201</td>
<td>kgm^2</td>
</tr>
<tr>
<td>$J_{zz}$</td>
<td>Yaw moment of inertia at the CG</td>
<td>34917</td>
<td>kgm^2</td>
</tr>
<tr>
<td>L</td>
<td>Axle separation</td>
<td>2.5</td>
<td>m</td>
</tr>
<tr>
<td>T</td>
<td>Track width</td>
<td>1.99</td>
<td>m</td>
</tr>
<tr>
<td>l_v</td>
<td>Longitudinal CG w.r.t. front axle</td>
<td>1.99</td>
<td>m</td>
</tr>
<tr>
<td>l_h</td>
<td>Longitudinal CG w.r.t. rear axle</td>
<td>1.54</td>
<td>m</td>
</tr>
<tr>
<td>h</td>
<td>CG height over ground</td>
<td>1.15</td>
<td>m</td>
</tr>
<tr>
<td>c</td>
<td>Suspension damping coefficient</td>
<td>10000</td>
<td>Nms/rad</td>
</tr>
<tr>
<td>k</td>
<td>Suspension spring stiffness</td>
<td>457000</td>
<td>Nm/rad</td>
</tr>
<tr>
<td>$C_v$</td>
<td>Front tire stiffness coefficient</td>
<td>582000</td>
<td>N/rad</td>
</tr>
<tr>
<td>$C_h$</td>
<td>Rear tire stiffness coefficient</td>
<td>783000</td>
<td>N/rad</td>
</tr>
<tr>
<td>$\delta$, $\beta$, $\phi$</td>
<td>steering angle, side slip angle, roll angle respectively</td>
<td>varying rad</td>
<td></td>
</tr>
<tr>
<td>$\psi$, $\dot{\phi}$</td>
<td>Yaw rate, roll rate, respectively</td>
<td>varying rad/sec</td>
<td></td>
</tr>
<tr>
<td>u</td>
<td>the total differential braking force on the wheels</td>
<td>varying N</td>
<td></td>
</tr>
<tr>
<td>vx</td>
<td>Longitudinal speed</td>
<td>varying m/s</td>
<td></td>
</tr>
</tbody>
</table>

\[ \dot{x} = Ax + B_\delta \delta + B_u u \]  \hspace{1cm} (4-1)

\[ A = \begin{bmatrix} \frac{\sigma J_{xx}}{mJ_{xx}v_x} & \frac{\rho J_{xx}}{mJ_{xx}v_x^2} & -1 & -\frac{hc}{J_{xx}v_x} & \frac{h(mgh-k)}{J_{xx}v_x} \\ \frac{\rho}{J_{xx}} & -\frac{J_{xx}v_x}{h} & 0 & 0 & 0 \\ \frac{J_{xx}}{h} & \frac{J_{xx}}{J_{xx}v_x} & \frac{c}{J_{xx}} & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} \]  \hspace{1cm} (4-2)

\[ B_\delta = \begin{bmatrix} \frac{C_v J_{xx}}{mJ_{xx}v_x} & \frac{C_h l_v}{J_{xx}} & -\frac{hC_v}{J_{xx}} & 0 \end{bmatrix}^T \]  \hspace{1cm} (4-3)

\[ B_u = \begin{bmatrix} 0 & -\frac{T}{2J_{xx}} & 0 & 0 \end{bmatrix}^T \]  \hspace{1cm} (4-4)

\[ x = [\beta \, \dot{\psi} \, \dot{\phi} \, \phi] \]  \hspace{1cm} (4-5)

The meaning and value of the variables were shown in Table 4-1.

To simplify the matrix, matrices $\sigma$, $\rho$, $\kappa$ and $J_{xx}$ was introduced. The equations of above four matrices were calculated as follow:

\[ \begin{align*}
\sigma &= C_v + C_h \\
\rho &= C_h l_h - C_v l_v \\
\kappa &= C_v v_x^2 + C_h l_h^2 \\
J_{xx} &= J_{xx} + mh^2
\end{align*} \]  \hspace{1cm} (4-6)
Once the vehicle model receives the information of longitudinal speed and steering signal from the higher level controller, new states will be generated by Equation 4-1. The braking force is assumed to determine the speed of the vehicle as \( \dot{v}_x = (F_x - |u|)/m \) where \( F_x \) is the acceleration force in the longitudinal direction. When the total differential braking force on the wheels was generated by the robust controller to reduce the value of LTR, \( F_x \) will compensate the change of \( u \) to tracking the reference acceleration \( \dot{v}_x \).

### 4-4 Robust controller for rollover prevention

In this section, a robust controller will be designed to minimise the risk of rollover. The risk will be estimated by the value of LTR. LTR represent the distribution of the vertical force on the wheel. When the absolute value of LTR is increasing, it means the load the truck was distributed unevenly on the left and right side, which may cause a rollover. LTR can be calculated by Equation 4-7.

\[
LTR = \frac{F_R - F_L}{F_R + F_L} \tag{4-7}
\]

Where \( F_R \) and \( F_L \) are the vertical load of the right wheel and left wheel. LTR varies within \([-1, 1]\), and for a perfectly symmetric vehicle that is driving straight, it is zero. The extreme are reached in the case of a wheel lift-off of one side of the vehicle, in which case LTR becomes 1 to \(-1\) depending on the side that lifts off. When the absolute value of LTR is larger than 0.9, the truck is considered to be dangerous. From literature [7], torque balance for the unsprung mass about the assumed roll axis in terms of the suspension torques and the vertical wheel forces can be written as

\[
-F_R \frac{T}{2} + F_L \frac{T}{2} - k\phi - c\dot{\phi} = 0 \tag{4-8}
\]

Now substituting the \( F_R \) and \( F_L \) from Equation 4-8 to Equation 4-7, yield the Equation 4-9 be known as dynamic LTR.

\[
LTR = \frac{2(c\dot{\phi} + k\phi)}{mgT} = Cx \tag{4-9}
\]

Where

\[
C = \begin{bmatrix} 0 & 0 \\ -\frac{2c}{mgT} & -\frac{2k}{mgT} \end{bmatrix} \tag{4-10}
\]

To obtain a rollover prevention controller, we desire that \(|LTR| < 0.9\) and \(|u| < 0.8 mg\) for the largest braking force. A stabilising \(H_\infty\) optimal Linear Time-Invariant (LTI)/State Space (SS) controller \(K\) for a partitioned LTI plant \(P\) is given as Equation 4-11.
\[ P = \begin{bmatrix} A & B_\delta & B_u \\ C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & D_{22} \end{bmatrix} \]  \tag{4-11}

Where
\[ C_1 = \begin{bmatrix} 0 & 0 & \frac{-2c}{mgt} & \frac{-2k}{mgt} \\ 0 & 0 & 0 & 0 \end{bmatrix} \]  \tag{4-12}

\[ C_2 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \]  \tag{4-13}

\[ D_{11} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}^T \]  \tag{4-14}

\[ D_{12} = \begin{bmatrix} 0 \\ \frac{1}{mg} \end{bmatrix}^T \]  \tag{4-15}

\[ D_{21} = D_{22} = \begin{bmatrix} 0 & 0 & 0 & 0 \end{bmatrix}^T \]  \tag{4-16}

The system P is partitioned where inputs to \( B_\delta \) are the steering angle (disturbances), inputs to \( B_u \) are the control inputs, the output of \( C_1 \) is the LTR to be minimised, and outputs of \( C_2 \) are the output measurements provided to the controller. The full matrix of P was given as Equation 4-17.

\[ P = \begin{bmatrix} \frac{-\sigma J_{xeq}}{m J_{xx} v_x} & \frac{-\rho J_{xeq}}{m J_{xx} v_x^2} & \frac{-h_c}{J_{xx} v_x} & \frac{h(mgh-k)}{J_{xx} v_x} & \frac{C_v J_{xeq}}{m J_{xx} v_x} & \frac{-T}{2 J_{xx}} \\ \frac{-\rho J_{xeq}}{m J_{xx} v_x} & \frac{-k}{h \rho J_{xx} v_x} & \frac{-h_c}{J_{xx} v_x} & \frac{h(mgh-k)}{J_{xx} v_x} & \frac{C_v J_{xeq}}{m J_{xx} v_x} & \frac{-T}{2 J_{xx}} \\ 0 & 0 & \frac{1}{mgt} & \frac{-2k}{mgt} & 0 & 0 \\ 0 & 0 & \frac{-2c}{mgt} & \frac{-2k}{mgt} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{mgt} \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \]  \tag{4-17}

### 4-5 Simulation and results

Figure 4-1 shows the PK structure of the robust controller. The controller K was designed to minimise the four states of \( x = \begin{bmatrix} \beta & \dot{\psi} & \phi & \dot{\phi} \end{bmatrix} \) and LTR.
4-5 Simulation and results

Figure 4-1: The diagram of the robust controller.

Figure 4-2: Steering angle in 10s
When the host vehicle decides to do a lane change from 0 to 7 s with the minimum jerk trajectory, the steering angle was shown in Figure 4-2. From 7 to 10 s, the lane change is finished so the steering angle converge to 0.

Figure 4-3 shows that the different braking force calculates by the robust controller and the delay of the actuator is 0.1 s. The peak value of the different braking force is $3.2373 \times 10^4 N$, which is smaller than the maximum value of the truck coefficient braking force $0.8 \times mg = 1.1223 \times 10^5 N$. The weight of the different braking force can be tuning the by the $\frac{1}{mg}$ in matrix $D_{12}$. However, tuning the weight will change the poles of the closed loop system, and the simulation time can be change significantly.

The robust controller reduces the peak absolute value of LTR from 0.3925 (orange line) to 0.2632 (blue lane) which is 32.94 % smaller shown in Figure 4-4. The poles of the system are all on the left half plane, so the system is stable, and LTR can converge to 0 automatically without the controller. The robust controller reduces the time to stabilise the system and lower the probability for rollover and time of the truck in a dangerous situation.

Figure 4-5 shows that similar result as Figure 4-4, robust controller improve the performance under disturbance and has very low computational cost. The absolute value of Slide slip angle, yaw rate, roll rate, roll angle decrease significantly and reduce the setting time.

The value of LTR also related to the longitudinal acceleration of the host vehicle in CACC scenario. When the acceleration is increases, the value of LTR will also increases. Figure 4-6, Figure 4-7, Figure 4-8 showing that the host vehicle with different speed.
Figure 4-4: LTR with and without robust controller

Figure 4-5: The comparison of Slide slip angle, yaw rate, roll rate, roll angle with and without the robust controller in 10s
while doing a lane change. In these three scenarios, the host vehicle detects the front obstacle vehicle A with a speed $55 \, \text{km/h}$. A lane change will be taken when getting the steering angle from Middle-Level Controller.

Because of the different speed of the host vehicle and obstacle A, a deceleration will be generated to maintain the safety distance. Figure 4-8 shows the maximum braking deceleration and also highest LTR.

The Robust controller shows a very good result comparing with the Proportional Integral Derivative (PID) controller and no controller. The PID controller is auto tuning by the PID Tuner from Simulink block. PID controller has a higher peak value than the robust controller and converges slower. When the initial conditions of speed and acceleration changed, PID controller can make the value LTR blow up in some scenarios. When the speed of the host vehicle is lower than $60\, \text{km/h}$, the advantage of the robust controller is less significant. Figure 4-9 shows that the robust controller has higher peak value and converge faster. Since the value of LTR is already very low, the robust controller will not increase the risk when the vehicle driving slowly and will be stable faster.
Figure 4-6: The comparison of Robust controller, PID controller, no controller when the speed of host vehicle is 70 km/h.
Figure 4-7: The comparison of Robust controller, PID controller, no controller when the speed of host vehicle is 80 km/h.
Figure 4-8: The comparison of Robust controller, PID controller, no controller when the speed of host vehicle is 90 km/h
Figure 4-9: The comparison of Robust controller, PID controller, no controller when the speed of host vehicle is 60 km/h
Chapter 5

Emergency Scenarios Simulation

This chapter contains the full description of the experimental simulations performed to test the designed algorithm in emergency scenarios. The responsibility of the three Levels Controller in emergency scenarios is to avoid crash and rollover. Requirements of comfort will be ignored in all the simulation in this chapter.

5-1 Fast lane change for high speed scenario

In this section, Low-Level Controller will be tested during a fast lane change. Fast lane change can be used to avoid the crash and improve safety in some scenarios. With the differential braking system and robust controller, the controller can minimise the Load Transfer Ratio (LTR) to prevent rollover. Although this thesis does not take emergency lane change into consideration, it is a very essential aspect of the truck’s dynamics performance.

In previous chapter, robust controller already show its ability to reduce LTR, which can be influenced by the longitudinal speed and acceleration. Figure 5-1 shows that in high speed scenario, the host vehicle in Cruise Control (CC) mode with the speed 90 km/h, the truck can change the lane in 2 s. The peak value of LTR is 0.8727. When the lane change time is 1.5 s, the peak value of LTR will increase to 1.1258, and it is very high probability to cause a rollover.

The result shows that the program is very reliable to change the lane in a short time in high speed scenario. This property can be use to avoid the obstacle in an emergency situation in the future.

Still in the high speed scenario, with the speed 85 km/h and random longitudinal acceleration of zero mean unit variance. The longitudinal acceleration will influence the LTR. When the vehicle accelerates, LTR will be reduced. The peak value of LTR is 0.8256 in this case.
Figure 5-1: LTR for a lane change in 2 s with robust controller
Figure 5-2: LTR for a lane change in 2 s with random acceleration (left). The longitudinal velocity of the host vehicle (right)
5-2 Fast lane change for low speed scenario

The Robust controller with differential braking system improves safety significantly in high-speed scenario for the lane change. However, as mentioned before in Chapter 5, the advantage of the robust controller is not that distinct in low-speed scenario.

Figure 5-4 shows the LTR value when the host vehicle doing a CC with the constant speed 60 km/h and the host vehicle change the lane in 3.5 s. The maximum absolute value for Robust Controller, PID Controller, and no controller is 0.9173, 1.2817 and 1.1588. The value of proportional and derivative are 0, with the integral \(-6643.0069\). The robust control gain is \(1.0e+06 \times [-2.76430.28950.50580.4792]\) in Figure 5-3.

Figure 5-4 shows the host vehicle with zero mean unit variance random longitudinal acceleration and change the lane in 3.5 s. The system without differential braking system has the maximum absolute value 1.0434. The parameter for Proportional Integral Derivative (PID) controller is calculated by the PID tuning tool in Simulink automatically. Figure 5-4 shows the LTR for the lane change with the maximum absolute value 1.2074 (red line). Meanwhile, the peak value in the same scenario of the robust controller is 0.9747 shown in Figure 5-4 (red line). Both Figure 5-4 and Figure 5-4 shows that the robust controller has the lowest overshoot and converge faster than other two. The parameters in PID controller and the robust controller is the same value as previous.
Figure 5-4: LTR for lane change in 3.5 s with random acceleration
Because the robust can’t improve the performance significantly, change the lane less than 3.5 s is not a safe choice in this system. One solution is to use another shape of the trajectory instead of minimum jerk trajectory. For example, the host vehicle can use a step signal as steering angle to avoid a crash.

5-3 Front vehicle cut in

This scenario is used to test another critical condition that can occur on the highway. At the begin of the simulation three vehicle are positioned inside the scenario: the host vehicle and two obstacle vehicles. The host vehicle and the obstacle vehicle A are in the right lane and the obstacle vehicle B in the left lane. The host vehicle and obstacle A are moving at velocity 90 km/h in Cooperative Adaptive Cruise Control (CACC) mode. Obstacle B is moving at velocity \( v_b = 72 \) km/h. In the simulation, the velocity of two obstacle vehicles is constant. The configuration of the scenario at \( t = 0 \) is shown in Figure 5-5.

After 5 seconds from the begin of the simulation the obstacle vehicle B decide to change to the right lane, without notice of the host vehicle in behind. The positions of three vehicles are in Figure 5-6. Once the host vehicle detects the obstacle vehicle B, it will decelerate and change the CACC mode with the obstacle vehicle A to Adaptive Cruise Control (ACC) mode with obstacle vehicle B.
The distance between the host vehicle and front vehicle in the simulation is shown in Figure 5-7. From 0 – 5 s, the host vehicle maintains the safety distance (12.5 m) with obstacle vehicle A. At $t = 5$ s, the target vehicle switch from obstacle vehicle A to obstacle vehicle B and the distance reduce significantly to 5 m. Since the velocity of the host vehicle is 90 km/h, faster than the obstacle vehicle B 72 km/h, the distance between the host vehicle and obstacle vehicle B will continue to reduce until the velocity is slower than 72 km/h. The velocity of the host vehicle is shown in Figure 5-8.

The acceleration of the host vehicle is shown in Figure 5-9 range from $-8 \text{ m/s}^2$ to $2 \text{ m/s}^2$. From 5 – 7 s the host vehicle decelerate to enlarge the distance between two vehicles. From 7 – 12 s the velocity is increasing to reach the steady state value 20 m/s for ACC. After 12 s, the distance between two vehicles will be maintained.

### 5-4 Change target vehicle after lane change

This scenario is used to test a case that is very critical in literature for CACC: change target vehicle. At the the begin of the simulation three vehicles are positioned inside the scenario: the host vehicle and two obstacle vehicles. The host vehicle and obstacle vehicle A is in the right lane while the obstacle vehicle B is in the middle lane. The host vehicle and the obstacle vehicle A is travelling at 75 km/h (20.83 m/s) in CACC
Figure 5-8: The velocity of the host vehicle
Figure 5-9: The acceleration of the host vehicle
mode, while the obstacle vehicle B is travelling at the velocity of 85 km/h. Both two obstacle vehicles is travelling with constant speed. The configuration of the scenario at t = 0 is shown in Figure 5-10.

After 3 s platooning, the host vehicle decides to change the lane. The configuration of the scenario at t = 0 is shown in Figure 5-11. The lane change will take 7 s and finish at t = 10 s. After the lane change, the host vehicle changes the target to obstacle vehicle B in ACC mode. In Figure 5-12, the distance increasing suddenly at t = 10 s because of the target vehicle changed. After 10 s, the host vehicle accelerates to reduce the gap between two vehicles and reach the steady state around t = 40.8 s. After that, the host vehicle and obstacle vehicle B will maintain the same distance and speed for ACC.
Figure 5-12: Distance between the host vehicle and front vehicle
Chapter 6

Conclusions and Future Work

6-1 Conclusions

This thesis focuses on the safety and comfort for the driver while doing sports inside the cabin when the truck is in automated driving mode. In the presented work, the problem of trajectory planning and path following applied to the autonomous driving field was studied, for application in highway scenarios. Based on the TRUCKletics project, algorithm for improving the performance of the evaluation of collisions, trajectory finder, robust control to prevent rollover was introduced in this thesis.

Multidisciplinary work at the vehicle dynamics, ergonomics, human factors engineering, and control algorithm was collected and will be taken into account in the algorithm on to the next stage. The modular structure of the overall system allows future improvement of the different parts singularly, being possible to adapt easily to the complete systems modification and improvement to the single subsystems.

In the High-Level Controller, the trajectory of obstacle vehicle will be estimated. The estimation based on the linear model with the assumption of the constant velocity. Based on driver’s requirement of the speed, the algorithm can decide in which scenario the vehicle will change the lane. The risk of collision will be checked before the lane change. The Time to Collision (TTC) and safety distant will be predicted in 7 s lane change time. The estimation will be updated each 0.01 s with very low computational cost.

The requirement from ergonomics field will be responsible for improving of the comfort in the Middle-Level Controller. With the minimum jerk trajectory, the lane change will be suitable for diver doing sports inside the cabin. The Cooperative Adaptive Cruise Control (CACC) controller will maintains the safety distant between the host vehicle and the front vehicle. In the simulation, the CACC controller shows reliable and robust performance in different scenarios. This longitudinal control algorithm can also reduce fuel consumption and improve highway traffic flow.
In the Low-Level controller, delay from sensors and actuators will be taken into consideration. Bicycle model with roll degree of freedom was built to simulate the truck model. With the differential braking system and robust controller, Load Transfer Ratio (LTR) will be significantly decreased in high-speed scenario, which means the lower probability of rollover. In low-speed scenario, the robust controller can reject disturbance on both longitudinal and lateral direction.

The implementation of the algorithm in real time is one of the goals of the thesis. Thanks for the high-level controller with a linear model of prediction, it is faster than most of the Model Predictive Control (MPC). In Matlab, the system can finish simulate $1000\ s$ in $300\ s$. With the low computational cost controller, some additional algorithms can be applied in the future to improve the performance.

6-2 Future Work

In regards to future work, the focus will be on improvement of current work and development of the system with new functions and technologies.

In the scope of improvement, the theoretical and experimental studies on vehicle model and integrated control will probably focus on the following issues.

High accuracy mathematical models that capture the dynamics of vehicle system are critical in this design task. An excellent means to determine such models is the use of system identification techniques. Therefore, vehicle model can be obtained from system identification methods. The powertrain might be taken into consideration in the model if there is enough computational power.

More precise tire model which yields higher control precision is essential. The coupled longitudinal and lateral tire forces with non-linearities can be considered. Further investigation is necessary on the details of weight distribution on tire forces and moments for vehicle stability control.

The shape of the trajectory for the lane change in emergency scenario with low speed need to be investigated. The minimum trajectory with the robust controller is not fast enough to do a lane change when the speed is lower.

Although assuming that the velocity of the obstacle vehicle is constant in the high-level controller, the estimation error might increase if the obstacle vehicle accelerate or decelerate constantly. Knowledge of machine learning to predict obstacle vehicle has been studied a lot by big companies like Google and Volvo. Unfortunately, the data of the driver is not easy to get so it is hard to be down as a master thesis. Furthermore, machine learning can study different individual’s driving behaviour which can improve the reliability of the estimation.

With the developments of sensor technology, control system can obtain data from the radar, GPS and camera. 3-D data and telematics technologies can be used for data collection and sensor fusion. Thus, target vehicle selection can be performed more properly, even in cornering situations. Furthermore, pedestrian, cyclist or animal interactions also can be considered.
The requirements of acceleration and jerk for comfort was satisfied in the algorithm. However, volunteers are necessary for testing in the force simulator to see the result. Moreover, machine learning or other artificial intelligence algorithm might be a choice to improve the prediction of the obstacle vehicle on the road instead of the probability density function.
Appendices are found in the back.

A-1 Main program

```matlab
1 clear all
2 clc
3
g=9.81; %Gravitational Constant 9.81 m/s^2
m=14300; %Vehicle Mass KG
v=85/3.6; %Initial longitudinal speed m/s of the host vehicle
va=85/3.6; %Initial longitudinal speed car a m/s (front vehicle)
vb=70/3.6; %Initial longitudinal speed car b m/s
vc=55/3.6; %Initial longitudinal speed car c m/s
d=1.4*va;
d1=25; %space between host and car b
d2=100; %space between host and car c
J_xx=24201; %Roll moment of inertia at the CG kgm^2
J_zz=34917; %Yaw moment of inertia at the CG 1200 kgm2
L=2.5; % Axle seperation m
T=1.99; %Track width m
l_v=1.95; %Longitudinal CG w.r.t. front axle m
l_h=1.54; %Longitudinal CG w.r.t. rear axle m
h=1.15; %CG height over ground m
c=10000; %Suspension damping coefficient Nms/rad
k=457000; %Suspension spring stiffness Nm/rod
C_v=582000; %Front tire stiffness coefficient N/rad
C_h=783000; %Rear tire stiffness coefficient N/rad
Sigma=C_v+C_h;
Rho=C_h*l_h-C_v*l_v;
Kappa=C_h*l_h*l_h+C_v*l_v*l_v;
J_x_eq=J_xx+m*h^2;
```

Master of Science Thesis

Yangyu Zhang
MATLAB Code

```matlab
mpct = 0.01; % MPC sampling time
muh = 0.8; % mu of host vehicle
muo = 1; % mu of the obstacle vehicle
vx = 60 / 3.6; % velocity for robust controller

A = [-Sigma * J_x_eq / (m * J_xx * vx) Rho * J_x_eq / (m * J_xx * vx^2) -1 -h * c / (J_xx * vx) h * (m * g * h - k) / (J_xx * vx);
    Rho / J_zz - Kappa / (J_zz * vx) 0 0;
    -h * Sigma / J_xx h * Rho / (J_xx * vx) -c / J_xx (m * g * h - k) / J_xx;
    0 0 1 0];
B_delta = [C_v * J_x_eq / (m * J_xx * vx); C_v * l_v / J_zz; -h * C_v / J_xx; 0];
B_u = [0; -T / (2 * J_zz); 0; 0];
C_1 = [0 0 -2 * c / (m * g * T) -2 * k / (m * g * T)];

% p = [-2 + i; -2 - i; -1 + i; -1 - i];
% F = place(A, B_u, p);
% G = inv(-C_1 * inv(A - B_u * F) * B_u);

% p = [1; 1; 1; 1]/180/Kappa
[K, CL, GAM, INFO] = hinfsyn(ss(A, [B_delta / Kappa B_u], [C_1; 0 0 0 0; eye(4)])];

INFO.KFI(1:4)
INFO.KFI(1:4)

ts = 0.02; % sampling time
td = 0.01; % sensor delay time

% p = [-Sigma * J_x_eq / (m * J_xx * vx) Rho * J_x_eq / (m * J_xx * vx^2) -1 -h * c / (J_xx * vx) h * (m * g * h - k) / (J_xx * vx);
    Rho / J_zz - Kappa / (J_zz * vx) 0 0;
    -h * Sigma / J_xx h * Rho / (J_xx * vx) -c / J_xx (m * g * h - k) / J_xx;
    0 0 1 0 0 0;]

% K, CL, GAM, INFO = hinfsyn(p, 4, 1)

A-2 High Level Controller

function [s, enable, sign] = A_matrix(vxk, vbk, vck, u, v1, d1, d2)

% u is ax
T = 0.1; % sampling time
if vbk < 0.1
    vbk = 80 / 3.6;

Yangyu Zhang Master of Science Thesis
```
if $v_{ck} < 0.1$
  $v_{ck} = 50/3.6$;
end

if $d_1 < 0.1$
  $d_1 = 25$;
end

if $d_2 < 0.1$
  $d_2 = 100$;
end

$x_k = [v_{xk}; v_{bk}; v_{ck}]$;

$A = \text{eye}(3)$;

$B = [T; 0; 0]$;

$C = [-0.1 0.1 0]$;

$D = [-T/2; T/2]$;

$E = [d_1; d_2]$; %distance

$g = 9.81$;

$enable = 1$; %1 possible lane change, 0 not possible

$s = 0$; %s*10 is time for unsafe

$mu = 0.8$;

$muo = 1$;

$sign = 0$;

for $n = 2:70$
  $x_k = A \ast x_k + B \ast u$;
  $y_k = C \ast x_k + D \ast u + E$;
  $sk1 = [2; 0.4 \ast v_{xk}(1); v_{bk} \ast 2 / (muo \ast g) - v_{xk}(1) \ast 2 / (mu \ast g)]$; %safety distance for car b
  $sk11 = \text{max}(sk1)$;
  $sk2 = [2; 0.4 \ast v_{ck}; v_{bk} \ast 2 / (muo \ast g) - v_{ck} \ast 2 / (mu \ast g)]$; %safety distance for car c
  $sk22 = \text{max}(sk2)$;
  if $y_k(1) < sk11$
    $enable = 0$;
    $s = n$; %s*10 is time for unsafe
    $sign = 5$;
    break;
  else if $v_1 > 60/3.6$ %v1 is the vehicle in front of the host vehicle before lane change
    $enable = 0$;
    $s = n$;
    $sign = 1$;
    break
  else if $y_k(2) < sk22$
    $enable = 0$;
A-3 Robust Controller

```matlab
function [xdot1, xdot2, xdot3, xdot4, LTR] = A_matrix(state1, state2, state3, state4, v2, delta, u)

% parameters
g = 9.81; % Gravitational Constant 9.81 m/s^2
m = 14300; % Vehicle Mass KG
v = 55/3.6; % Initial longitudinal speed m/s
J_xx = 24201; % Roll moment of inertia at the CG kgm^2
J_zz = 34917; % Yaw moment of inertia at the CG 1200 kgm^2
L = 2.5; % Axle separation m
T = 1.99; % Track width m
l_v = 1.95; % Longitudinal CG w.r.t. front axle m
l_h = 1.54; % Longitudinal CG w.r.t. rear axle m
h = 1.15; % CG height over ground m
C_v = 582000; % Front tire stiffness coefficient N/rad
C_h = 783000; % Rear tire stiffness coefficient N/rad
Sigma = C_v + C_h;
Rho = C_h * l_h - C_v * l_v;
Kappa = C_h * l_h + C_v * l_v;
J_x_eq = J_xx + m * h^2;
A = [-Sigma * J_x_eq / (m * J_xx * v2) Rho * J_x_eq / (m * J_xx * v2^2) - h * c / (J_xx * v2) h * (m * g * h - k) / (J_xx * v2)];
Rho / J_zz - Kappa / (J_zz * v2) 0 0;
-h * Sigma / J_xx h * Rho / (J_xx * v2) - c / J_xx (m * g * h - k) / J_xx;
0 0 1 0];
B_delta = [C_v * J_x_eq / (m * J_xx * v2); C_v * l_v / J_zz; -h * C_v / J_xx; 0];
```
B_u = [0; -T/(2*J_zz); 0; 0];
C_1 = [0 0 -2*c/(m*g*T) -2*k/(m*g*T)];

% [K,CL,GAM,INFO] = hinfsyn(ss(A,[B_delta/Kappa B_u],[C_1; 0 0 0; eye (4)],[0 0; 0 1/(m*g); zeros(4,2))],4,1);
% u=INFO.KFI(1:4);
% u=[0 0 0 0];
% p=[-2+i;-2-i;-10000+i;-10000-i ];
% F=1.0e+12*[3.5459 -0.0007 -0.1956 0.3922];
% F=place(A,B_u,p);
state = [state1; state2; state3; state4];
xdot = A*state+B_u*u+B_delta*delta;
xdot1 = 0;
xdot2 = xdot(1);
xdot3 = xdot(2);
xdot4 = xdot(4);
LTR=C_1*state; %LTR varies within [-1, 1], and for a perfectly symmetric vehicle that is driving straight, it is zero.
%The extreme are reached in the case of a wheel lift-off of one side of the vehicle,
%in which case LTR becomes 1 to -1 depending on the side that lifts off.

A-4 Trajectory Generator

function y = fcn(u,u1)
%#codegen
Tlc=7;
Ylc=3.5;
if u<Tlc
y=Ylc+(10*(u/Tlc)^3-15*(u/Tlc)^4+6*(u/Tlc)^5);
else
y=Ylc;
end

A-5 Change Target Vehicle

function [a,v,s,sr]= fcn(s1,sb,v1,vb,a1,ab,s1r,s2r,time)
%#codegen
% 1 previous
% 3 new
% 5 u3 time
if time<10
a=a1;
v=v1;
s=s1;
sr=s1r;
else
a=ab;
13  v=vb;
14  s=sb;
15  sr=s2r;
16  end
Appendix B

Simulink
Figure B-1: Overall view of the controller.

Figure B-2: Environment simulator
Figure B-3: Middle-Level Controller

Figure B-4: Low-level Controller
Figure B-5: Vehicle model
Glossary

List of Acronyms

ABS Anti-lock Braking System
ACC Adaptive Cruise Control
ADA Advanced Driver-Assistance
CACC Cooperative Adaptive Cruise Control
CC Cruise Control
DOF Degree of Freedom
DSRC Dedicated Short-Range Communications
ESC Electronic stability control
HAD Highly Automated Driving
ITS Intelligent Transportation System
LTI Linear Time-Invariant
LTR Load Transfer Ratio
MPC Model Predictive Control
PID Proportional Integral Derivative
SS State Space
TTC Time to Collision
V2V Vehicle to Vehicle
WAVE Wireless Access in Vehicular Environments
Bibliography


[12] “Health and gesundheitsf o promotion of professional drivers.”


