Emergency Escape Manoeuvre of a Faulty Truck in a Platoon Formation Moving in Highway

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Master of Science Thesis

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Abstract

The platooning of trucks provides significant benefits in the existing transportation systems regarding social, economic and environmental aspects. Due to the platoon's high dependence on sensors, it is critically important to have fault-tolerant countermeasures that deal efficiently with failures by achieving minimal risk condition. This thesis tackles designing an emergency escape manoeuvre for a faulty truck that has lost its ability to monitor the driving environment while moving in a platoon formation on a highway. A fallback strategy is proposed that leads the faulty truck to park on the shoulder of the road and allows the rest of the platoon participants to continue their journey. To solve this problem, first, a functional platooning system should be designed. Therefore, a nonlinear bicycle dynamic model is employed, while a new Bidirectional (BD) Cooperative Adaptive Cruise Control (CACC) system is utilized for control purposes. The emergency escape manoeuvre has to be pre-computed and ready to be triggered when the failure occurs, as concerning defined specifications, limitations and constraints. It is generated using a quintic splines methodology, while a new optimization approach regarding the minimization of jerk peaks is adopted, enhancing the efficiency of the design procedure. Furthermore, a gap-closing controller is employed and tuned accordingly to reform the platoon after the faulty truck abandons the formation. Moreover, a suitable decision logic is defined to achieve smooth transition among regular performance and fallback state at both platoon and inter-vehicle level. The functionality of each component is firstly evaluated individually, based on specific performance metrics. Finally, all the mentioned components are put together and the fallback strategy that executes emergency escape manoeuvre in platoon context is derived. Several simulation tests illustrate proof of principle for the proposed framework. It is shown that the proposed strategy indeed achieves minimal risk condition for the faulty truck achieving minimal tracking errors. A global applied strategy is adopted for the gap-closing controller by making healthy follower(s) travel with the maximum possible acceleration. At the same time, the leading truck of the formation maintains a constant speed until the time gap between them becomes $0.8s$, before the switch back to the CACC, to complete this action as fast as possible and safety issues in the driving performance. Additionally, the CACC system is evaluated to ensure that the string stability criterion is satisfied in the mode of operation. Moreover, a virtual leader mechanism is introduced to fill in faulty truck's blind spot in the road that arise from the sensor failure. It is shown that it

can provide a sufficient window of movement for the platoon before switching to the fallback strategy.

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Chapter 1

Introduction

Platooning is a particular category of intelligent transportation systems that applies autonomous driving, where multiple trucks travel following each other autonomously behind a manually driven leader. Unfortunately, several hazardous events may come up during such a formation. The leader's impaired driving behavior, the dangerous driving performance by the rest of the traffic participants, or the failure of trucks' automation components (e.g. exteroceptive sensors) are a few examples. Although sensors are vital for such vehicles because they provide them with all the required information for their proper functionality, they make them more vulnerable to faults. Even though an obvious solution could be to enhance software and hardware redundancy by designing a reliable scheme able to perform fault diagnosis and accommodation [28], [16], alternative options have to be examined too. Maintaining full redundancy of all components provide fault tolerance, but is an expensive option. It is worth mentioning that the presence of faults and errors [16] in a system does not necessarily lead it to fail because it can recover from faulty states or operate under degraded performance. Nevertheless, if the fault is severe then it is required to reach minimal risk condition [24]. In this thesis, a crucial case as a sensor failure in an automated truck is examined. Therefore, an emergency escape manoeuvre is designed to make the truck reach a minimal risk condition, ensuring that the safety of both the passengers and the rest of the traffic participants is provided at the highest possible level.

1-1 Motivation

The application of platooning in public roads in the future can upgrade the existing transportation into a cleaner, safer, and more efficient version. Firstly, driving in platooning leads to a decrease in fuel consumption and reduces CO2 emissions. The constant speed, as well as the closer spacing among the trucks in the platoons, provides an improved aerodynamic behavior, which results in lower drag coefficients, which is translated to increased fuel savings [53]. Secondly, in cases of emergency scenarios in the roads, the automated followers would take action, having as small as possible reaction time, by eliminating human error and improving the safety of both platoon participants and other road users [2]. Furthermore, platooning provides a general optimization of road usage as traffic flow is improved. Driving at closer distances provides a reduction in traffic congestion, which results in increased traffic throughput too. Based on experiments, the application of platoons could provide two or even three times higher throughput in urban roads [35].

Platooning has managed to gain many researchers' and funding organizations' interest. Several projects related to it have already been operated in order to test and evaluate its capabilities. They mainly focused on achieving better performance by taking advantage of modern technologies and control techniques, keeping up with legislation, standard regulations and examining possible side effects. Consequently, it can be noticed that there is still an absence in the literature with projects that examine fallback strategies in platoon context in case of emergencies.

Undoubtedly, trying to find ways to improve the performance of platoons is very important because of all the benefits that they can provide. But, applying research in concepts that perform emergency escape manoeuvres in platoon context when a failure occurs, is a life-critical problem and any proposals derived can help to bring closer platoons in real traffic applications. Furthermore, extra motivation and challenge are provided due to the fact that there are currently no other similar applications in the literature.

1-2 Problem Formulation

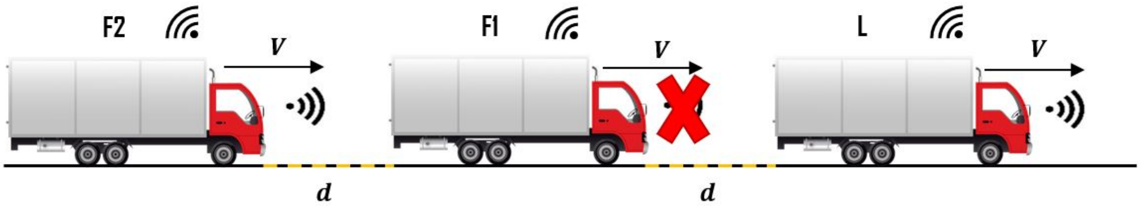


Figure 1-1: Problem formulation of 3-vehicle platoon

Assume a platoon formation P that consists of a leader L and two fully autonomous follower trucks denoted as F_1 and F_2, respectively. The vehicles are supposed to be moving at the desired speed V while maintaining a desired distance d between them. They are equipped with front sensors that enable them to measure the distance to the vehicle in front. Besides, a communication module allows inter-vehicle communication and a localization module provides information regarding truck's position. At a random time during the movement, a sensor failure occurs to the second vehicle of the formation (F_1). Therefore it is no longer available to monitor the environment around it. Consequently, information regarding the position of the vehicle in front cannot be extracted. The platoon controller cannot compute the correct signals to achieve the desired speed and gap following policy of the formation. Thus, the faulty truck's movement can become unstable and the risk of collision is very likely to increase. Thus, emergency actions need to be taken to prevent hazardous events, both for the faulty truck and the rest of the platoon participants. More specifically, the faulty vehicle will abandon the formation by performing an emergency escape manoeuvre, while the rest of the platoon moves on. It is important to mention that only sensor failure to the middle truck is assumed, while the rest components of the platoon are operating correctly.

Platooning systems make use of a layered control architecture as explained below. Typically, this involves a common platoon supervisory control layer, individual vehicles' supervisory, high-level, and low-level control layers (as can be seen in Figure 1-2 and [54]).

1. In the platoon supervisory layer, it is required to define an inter-vehicle protocol that conducts the vehicles' cooperative performance in the formation.

2. In the vehicle supervisory layer, an expanded supervisory logic has to be defined in the form of state-machines to switch the mode of operations for each vehicle independently.

3. In the high-level control layer, three different controllers have to be implemented:

   - A gap regulator controller to handle the platooning operations of the trucks.
   - An emergency trajectory planner that executes the escape manoeuvre.
   - A gap closing controller that will allow rest of the participants to continue their journey.

4. In the low-level control layer a motion regulator has to be employed to apply higher layers' desired actions.

The related layers and the actions required are presented in Figure 1-2. With color are marked the contributions of this thesis while addressing the problem as explained in the following section.

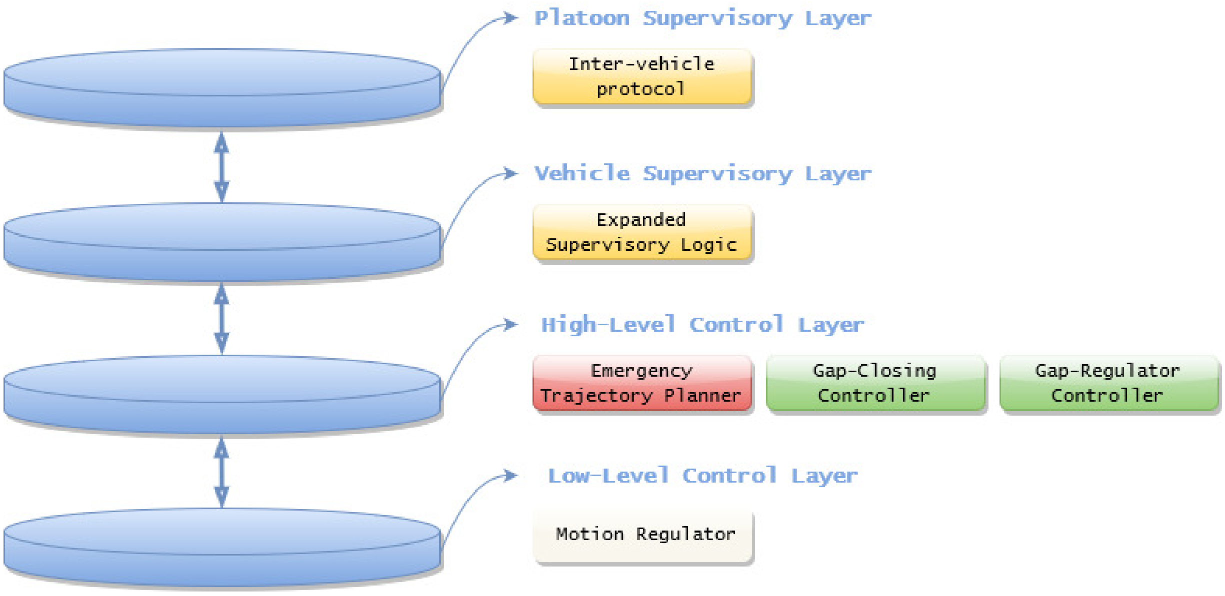


Figure 1-2: Problem formulation in the multi-layer scheme

1-3 Objectives, Focus and Scope

In general, the research area that focuses on handling hazardous events in fully automated vehicles is relatively new, as most of the released scientific papers denote. Unfortunately, during the research on the related work regarding the emergency escape manoeuvres in platoons, no systematic approaches in the context of platooning were found. Therefore, this thesis aims to develop a solution to the problem mentioned above by defining a proper fallback strategy that does not compete with previous methodologies or approaches but instead merges several advances from different areas in the literature to provide a functional and feasible application. The fallback strategy consists of the execution of the escape manoeuvre and the transition of the formation from a 3 to 2-vehicle platoon. Therefore, the scope of the thesis is to examine the transition of the normal performance of platoon to an emergency state and backwards, after executing an emergency escape manoeuvre for the faulty truck. More specifically, the thesis focuses on the feasibility and the characteristics of the emergency escape manoeuvre that has to be pre-computed, ready to be triggered and achieve minimal risk condition for the faulty truck. Furthermore, this thesis is focused to the gap-closing manoeuvre that would enable the remaining trucks to continue their journey.

As a result, the main research objective of the thesis is ***propose a fallback strategy for a 3-truck platoon formation in order to execute an emergency escape manoeuvre for the faulty truck and then form a 2-truck platoon formation that maintains desired speed and spacing policy.***

The main objective can be further simplified by dividing it into the following sub-objectives:

- *Achieving a platoon formation under healthy conditions.*
- *Implementing and executing an emergency escape manoeuvre.*
- *Deal with compromised modules of the faulty truck.*
- *Achieving a transition from 3-vehicle platoon to 2-vehicle platoon.*

1-4 Contributions

This thesis aims to fill in the literature gap of handling a severe failure in vehicles moving in the middle of a platoon by proposing a scheme that takes the faulty vehicle out of the formation. The main contribution is to use, adapt, extend, and interconnect separate existing methods on vehicle control, trajectory planning and supervisory control to achieve a new integrated application. Furthermore, the introduced scheme's proof of principle can be used as a solid foundation for further improvements and research in more depth around the topic in the future.

More specifically, the main contributions of this thesis are:

- Design a supervisory logic in both platoon and vehicle level in order to achieve smooth transition from normal performance to fallback strategy and back to normal.

- Implementation of an emergency planner that achieves minimal risk condition using Quintic Splines. The limitations that are denoted in the used methodology are extended by proposing a new yaw rate peak minimization approach and a non-symmetric velocity profile.
- Employment of a customized velocity scale mechanism in order to enhance robustness of the emergency escape manoeuvre regarding initial conditions.
- A new string stable Bidirectional (BD) Cooperative Adaptive Cruise Control (CACC) responsible for the platooning operation mode of the formation.
- Design and tune a gap-closing controller that restores the desire movement values of the remaining vehicles.
- Achieve a temporary movement of the platoon under faulty conditions before the execution of escape manoeuvre with the introduction of a virtual leader mechanism.

1-5 Outline

The rest of the thesis is structured as follows. Chapter 2 summarizes the fundamentals of platooning, trajectory generation techniques, and fallback strategies in single vehicles. Chapter 3 describes the vehicle dynamics used for the platoon formation. Chapter 4 explains and evaluates the implementation of the emergency escape manoeuvre. Chapter 5 presents the platoon controller in charge while the formation is moving under healthy conditions. In Chapter 6, the complete proposed control framework is presented and validated. Finally, chapter 7 presents conclusion remarks among with recommendations for future work.

Chapter 2

Preliminaries

As already discussed in the introduction, in order to address the problem of the emergency escape manoeuvre in platoon context, there are many components that have to be included in the design scheme. This chapter aims to present the necessary information that need to be taken into account before proceeding to the implementation and the selection of the suitable parts. Firstly, fundamentals in platooning are presented including their functionality, control strategies, as well as, common manoeuvring while the formation is on the move. Secondly, the state of the art related in path planning and trajectory generation is reviewed, in order to examine which approach appeals the most for this work. Finally, related work in emergency fallback strategies in single autonomous vehicles is reviewed in order to extract useful mechanisms that can be applied in this research too.

2-1 Platoon System Description

The vehicle platooning consists of two or more vehicles with similar destination goals moving at a close and constant distance from one another [25]. It is a cooperative form of driving since the platoon participants communicate using wireless technology [2]. The vehicle moving in front of the formation is the manually driven leader, while the rest of the vehicles are the followers that automatically tail after it. A follower's purpose is to maintain the desired distance, orientation and velocity concerning its corresponding leader. Figure 2-1 presents a typical platoon formation consisting of a leader and a follower truck. All participants must be equipped with sensors measuring essential values as distance, speed or acceleration. This information is vital to achieve the desired performance of the platoon that is derived from the control module. As explained later, the received data to each truck comes from one or more trucks according to the structure of the formation. Therefore, the platoon participants are usually equipped with Radar sensors for measuring the Inter-vehicle distance (IVD) and relative velocity. Furthermore, other vehicle's acceleration or velocity can be obtained using wireless vehicle to vehicle (V2V) communication. Moreover, trucks are equipped with cameras to estimate their position within the lanes in order to regulate their lateral position. Finally, platoons have to be equipped with GPS or a similar tool because of the need to synchronize the measured data for localization purposes [8].

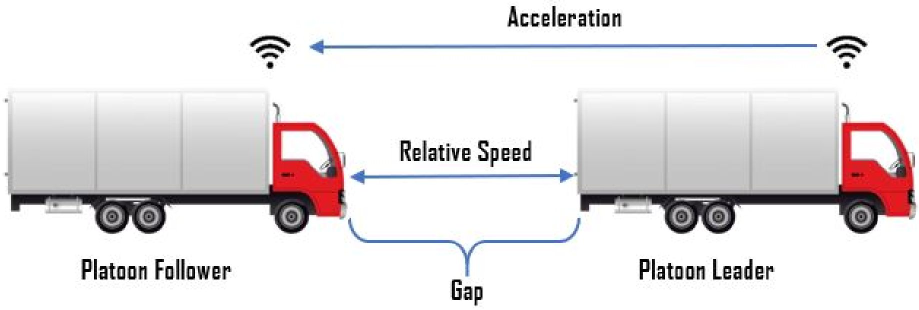


Figure 2-1: Platoon formation consisting of one follower

Platooning of course can be analyzed further with respect to the technical aspects of the formation. According to [13] a specific platoon system can be described using a four-component framework that consists of:

1. Node Dynamics
2. Information Flow Topology
3. Control Architecture
4. String Stability

These aspects are explained in more detail next.

2-1-1 Node Dynamics

These are the vehicle dynamics that describe the platoon participants. They are classified according to their complexity (linear, nonlinear, second-order, third-order). Furthermore, the variety of vehicle dynamics participating in a formation can define the heterogeneity or homogeneity of the platoon correspondingly. In general, in the literature, there are several models representing vehicle dynamics. All of them describe how the received input signals (velocity, acceleration, torque, brake, steering angle, etc.) are related to the vehicle's position and orientation. They are usually classified based on their characteristics and complexity.

- Point-mass models that treat vehicles as particles. They provide large tracking errors for path planning applications because they neglect a lot of dynamic capabilities. Besides mass, no other physical dimensions are taken into account, while acceleration is usually selected as a constant term [15]. They are useful in applications that require reduced computational burden or the attention is paid to other modules of the design and simplified models does not affect the outcome.

- Kinematic models are of increased complexity and they are generated with respect to the geometric characteristics of vehicle's movement. They still miss a lot of information like load transfer, rolling and pitching, tyre slip etc. As a result they are not recommended for complex manoeuvres, especially when precision is required and the performed movement is analyzed in depth [27].
- Dynamic models use the equations of motion combined with the non-linear interaction among road and tires [5].

2-1-2 Information Flow Topology

This characteristic describes the way platoon participants exchange information between them. More specifically, the direction of the wireless communication. The most common Information Flow Topology (IFT) can be seen in the Figure 2-2.

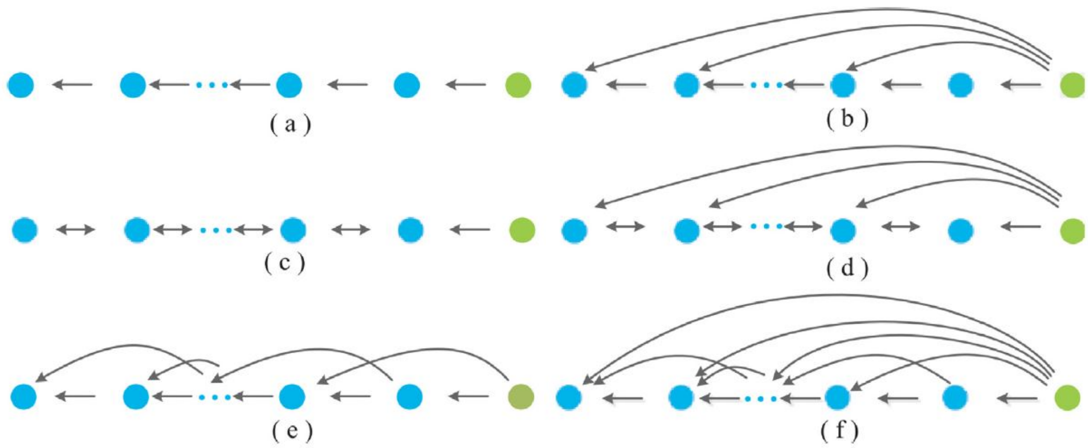


Figure 2-2: Typical IFT for Platoon. Green corresponds to the leader, rests are the followers. (a) Predecessor Following, (b) Predecessor Leader Following, (c) Bidirectional (d) Bidirectional Leader, (e) Two-Predecessor Following, (f) Two-Predecessor Leader Following [13]

It can be noticed that the different types are formed based on the direction of the communication and on which vehicles communicate together. In Predecessor Following (PF), each vehicle communicates in one direction with the predecessor. Therefore, any change in the formation is propagated backward, starting from the leader. Unlike the previous topology, in Predecessor Leader Following (PLF), along with the predecessor, each vehicle communicates with the leader of the formation too. In Bidirectional (BD), there is a two-way communication among a vehicle and its predecessor. Compared to the previous topology, in Bidirectional Leader (BDL), each vehicle also communicates with the leader. In Two-Predecessor Following (TPF), there is one-way communication with predecessors plus received information from the vehicle that is located two positions in front. Finally, in Two-Predecessor Leader Following (TPFL), besides the previous communication structure, every vehicle receives information from the leader.

Each of IFT has both advantages and disadvantages. The most common evaluation metrics are the topology's quality and whether it appeals to the desired application. The topology quality is measured by the time delay or packet loss during the exchange of information among the vehicles. Moreover, in this thesis, it is desired to select an IFT that can handle Intermediate Vehicle Actions (IVA) and reform a new one. Obviously, IFT that supports direct communication with the leader of the formation reacts instantaneously to new commands. However, due to distance limitations and interference with other operations in the formation, they are unscalable. A summary of the characteristics for the rest of the IFT is presented in Table 2-1.

Table 2-1: Summary of information flow topologies advantages and disadvantages

Technique	Advantages	Disadvantages
PF	Low interference	Slow reaction in IVA Require large IVD Vulnerable to error propagation
BD	Fast reaction in IVA Scalable	Vulnerable to error propagation
TPF	Support effectively IVA	Increased complexity High interference

2-1-3 Control Architecture

A platooning system has a complex control architecture consisting of multiple layers, as illustrated in Figure 1-2 of Chapter 1. The top layer is the platoon supervisory logic that is handled completely by the leader of the formation. Here, the platoon's driving characteristics are determined concerning participants' condition, road infrastructure, and traffic flow. More specifically, the IVD range policy of the trucks and the target velocity are selected. It can be noticed that the dynamic driving environment affects the characteristics that must be adjusted per the occasion. The set points that arise from the top layer are transmitted to a vehicle supervisory layer that manages every follower truck's decision logic. Its purpose is to adapt the trucks' movement with respect to the leader's commands. Consequently, reference signals are generated to influence the high-level control layer to act accordingly.

A high-level controller is responsible for establishing all the decisions provided by the above-mentioned layers. The design of such a system is usually divided into longitudinal and lateral control. However, in modern works that address vehicle platoons' control problem, combined approaches regarding lateral and longitudinal control have been introduced [6]. Forming a platoon and tracking a trajectory were considered problems that needed a separated design but they are highly related. The longitudinal controller is responsible for maintaining the desired velocity of a vehicle and keeping the desired distance from the vehicle moving in front of it [32]. It consists of two parts that handle acceleration and tracking correspondingly. In the first part, reference signals for velocity or acceleration are generated through information collected by sensor measurements and communication. The lateral controller is responsible for providing proper steering to the vehicle's wheels to maintain its position inside the lane (more specifically in the center). At the same time, not violate the driving comfort [32]. In general, lateral control is achieved by taking the difference of the heading to the lane and the corresponding yaw angle. Moreover, it can be applied either by tracking the preceding vehicle or by taking into account the lane marks [51]. Finally, the signals derived from the high-level control layer are transmitted to the low-level control, where the values used for motion regulation are calculated like throttle and brake [51].

2-1-4 String Stability

In platooning, it is essential to ensure that participants are individually stable, while the string of trucks is stable too. The stability of each truck individually is derived when proper tracking performance of the reference trajectory is achieved. In general, string stability is defined in several ways. Disturbances or perturbations that arise from initial conditions or external factors can affect the leader or/and the rest of the formation. Therefore, for a string of trucks, control errors and disturbances must be attenuated as they propagate from the front to the back. As a result, string stability for a platoon is achieved if and only if the controller satisfies two objectives: The spacing error among vehicles must tend to be eliminated (and not otherwise) and the magnitude of the state error (position, velocity, acceleration) should increase starting from the last follower to the leader [4]. Otherwise, unwanted side effects may arise that threaten the safety of the platoon and the rest of the traffic participants.

Discussion

As already mentioned, this thesis focuses on implementing a platoon formation that is moving initially under healthy conditions on a highway. The driving on highways is executed on straight roads (with slight slope) most of the time. Besides, complicated cornering manoeuvres in the platoon context are out of the scope for the current work. Furthermore, it has to be noted that the truck that has to perform a cornering manoeuvre during the fallback strategy, is handled by a different controller as is explained in detail in Chapter 4. By taking into account the above-mentioned statements, it is possible to simplify the platoon's control strategy by concentrating only in the longitudinal direction. Since the platoon's movement would be on a straight line, the application of a Cooperative Adaptive Cruise Control (CACC) controller is sufficient for the purpose [41]. Moreover, CACC system is more than enough to test and evaluate opening and closing gaps for the formation as they are required in the building of the emergency strategy protocols.

2-2 Trajectory Planning

A proper escape manoeuvre from a platoon formation design requires extensive research on trajectory planning techniques. However, a planning structure in automated driving is much more complicated. Therefore, before reviewing and evaluating trajectory planners, it is important to describe important motion planning elements in general.

A path is the pure geometrical representation that a vehicle should follow throughout its journey. It must also lead the vehicle to its target position while avoiding any obstacles. Consequently, a path planner finds a feasible path that connects the vehicle's initial configuration (position and heading angle) to a final desired one. A feasible path satisfies several constraints like collision avoidance, road and lane boundaries, etc [26].

A trajectory is a series of states reached by the vehicle, parameterized by time and velocity. As a result, a trajectory generator assigns velocity and acceleration profile to the path generated by the corresponding planner. More specifically, it is responsible for the vehicle's feasible transition through the states by taking into account the vehicle's kinematic limits and capabilities [26].

There is a hierarchy of planning elements that end up influencing the trajectory planning and consists of route planning and manoeuvre planning. The route planning takes into account real time traffic information in order to find the best global route that connects starting point to destination. A manoeuvre is a high-level response of a vehicle, affecting its position and speed during the movement. Such responses are (but not limited to) 'going straight', 'turning', 'overtaking' and for the problem that is addressed in this thesis 'parking'. Hence, manoeuvre planning selects the best high-level decision for the vehicle concerning current conditions by evaluating various metrics (path planner's options, a risk to make a manoeuvre, vehicle limitations, etc.) [26].

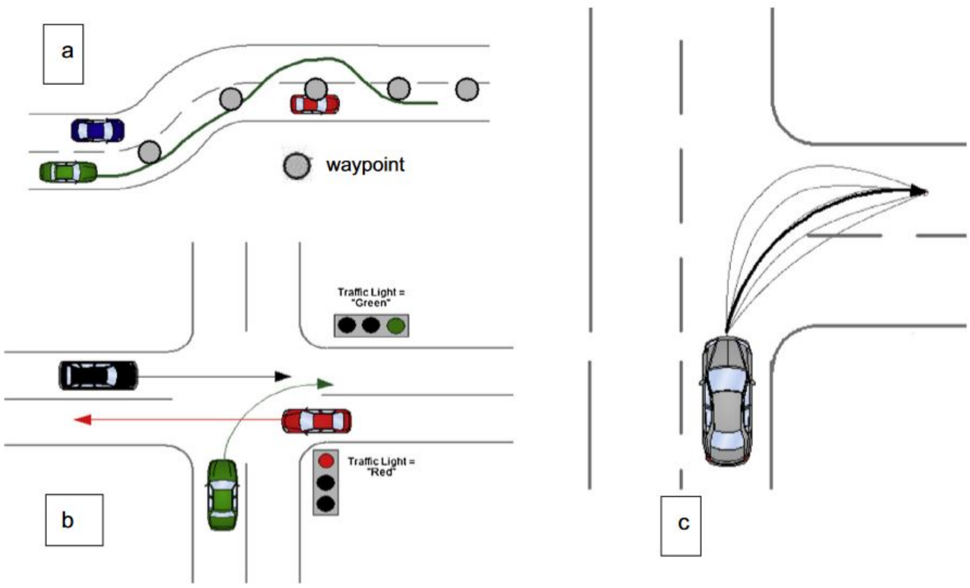


Figure 2-3: a) Path Planning, b) Manoeuvre Planning, c) Trajectory Planning [33]

To sum up, in a complete planning scheme, firstly, a path planner provides a set of a collision-free via-points that form a geometric path. Then, the manoeuvre planner must decide for the next action so the next way-point is reached in time. Last but not least, the trajectory planner by using optimization methods, polynomials or a search procedure, finds the best way to connect the via-points. In this thesis it is assumed that a given set of via-points that satisfies the objective to lead the truck park on the shoulder is known a priori. Therefore, attention is paid into finding a suitable trajectory generator.

2-2-1 Requirements

Before proceeding to review and selecting the methodology to be used to design the escape manoeuvre, all the general requirements of the trajectory generator must be defined. The required characteristics are related to the reference signals provided and the continuity of the derived trajectory. More specifically:

- The emergency escape manoeuvre's total computational time should be minimal.
- The generated path should satisfy a C^1 continuity, which means that the provided reference signals regarding position and velocity should be continuous for the whole movement. Higher levels of continuity enhance the comfort of the movement. However, since the design is related to an emergency scenario, satisfying comfort metrics is beyond the scope.
- The trajectory should also satisfy the geometric continuity G^1 in order to achieve common tangent direction at the joint point of the segments. It has to be noted that the higher the level of continuity, the smoother trajectory is considered to be generated. However, the first level of continuity is sufficient for a smooth appearance.

2-2-2 Techniques

In general, trajectory planning methodologies are classified into two main categories concerning their design process principles. These are Interpolating Curve algorithms and Numerical Optimization approaches. Interpolating Curve algorithms are used in order to provide a smoother solution to the resulted trajectory. A set of provided waypoints that describe a specific path (pre-defined or arise from path planner) are modified in order to produce a new set of data that describe the same path in a better way in terms of feasibility, comfort, vehicle dynamics and dynamic environment [31]. Several interpolation techniques exist in the literature. Most of them are characterized by low computational cost and can provide continuity in the trajectories but may become time consuming and sub-optimal in complicated scenarios. The most common interpolating planners applied in automated driving are [18]:

- **Lines and Circles:** Straight and circular shapes are used to represent a road network consisting of several segments by interpolating known waypoints.
- **Clothoid Curves:** Generate trajectories that are characterized by linear variation in curvature, enabling the design of both straight and curved segments that are smoothly connected.
- **Polynomial Curves:** They interpolate points by taking into account several constraints regarding the position, heading angle, curvature, etc. The desired outcome of a trajectory using this method relies on the curve's coefficients that are determined based on the desired goals and constraints of the initial and final segment. It also has to be noted that the greater the number of constraints to be satisfied, the higher the degree of the polynomials.
- **Bezier Curves:** They are parametric curves produced by control points that are used to form their shape. They are characterized by low computational cost, while the control points are placed to satisfy the desired constraints. Similar to other techniques, higher degrees of such curves can handle more constraints.

- **Spline Curves:** They are piecewise polynomial parametric curves consisting of segments that can be represented as one of the above-mentioned curves. The segments of the curve are usually connected by satisfying strict smoothness constraints.

The Numerical Optimization algorithms [9] solve optimization problems by maximizing or minimizing a cost function concerning several constraints. The cost functions are set up to optimize a specific target like distance from reference path or obstacles. The goal is to provide the best possible trajectory concerning parameters such as velocity, steering, acceleration, jerk (lateral comfort optimization), etc. This approach is very often combined with control engineering with the employment of a Model Predictive Controller (MPC) within the planning module [34]. The future evolution of the vehicle's motion is taken into account to derive the desired constraints. Then the dynamic vehicle model and control inputs are used to solve the optimization problem of trajectory generation. These methods can handle multiple constraints. However, they can be time-consuming and optimal result is not always guaranteed.

Table 2-2: Summary of trajectory planning techniques advantages and disadvantages

Technique	**Advantages**	**Disadvantages**
Interpolating Curves		
Lines and Circles [40]	Low computation cost Simple implementation	Discontinuous trajectory
Clothoids [14]	Linear curvature changes Suitable for roads, highways	Time consuming Not smooth curvature
Polynomials [17]	Low computational cost Comfort	Require high degree Difficult coefficients computation
Beziers [46]	Low computational cost Easily manipulated curve Comfort	Many control points required Sensitive in points placement
Splines [45]	Low computational cost Continuous curvature	Maybe non-optimal
Numerical Optimization Curves		
Function Optimization [56]	Handling multiple constraints	Time consuming

A summary of both the advantages and disadvantages of the trajectory planning techniques is presented in Table 2-2. The only main disadvantage of interpolating curves techniques is that they become slow in computational time when obstacle avoidance and multiple constraints are included. Since obstacle avoidance is out of the scope for this thesis, this disadvantage vanishes. As a result, it can be concluded that they are a more suitable solution than the numerical optimization techniques. The next step is to select an appropriate methodology among the available interpolating curves options. It can be seen that there are many available options in the literature and the final decision is taken as a trade-off among the design specifications and the complexity of the solution. Spline methodologies can satisfy all the points that have been mentioned in the previous subsection. More information related to the specific spline methodology used is explained analytically in Chapter 4.

2-3 Fallback Strategies in Single Vehicles

As already mentioned, there is no related work in the literature regarding emergency escape manoeuvres in the platoon context. However, platoon exiting is a closely related manoeuvre. An exit manoeuvre is performed when a truck chooses to abandon the platoon and continue its journey as a free agent or park on the shoulder. It is executed in three basic steps: request, response and implementation. It can be noticed that inter-vehicle communication play impact role in order to execute the manoeuvres successfully. The truck(s) that want to exit the platoon send exit requests to the leader who responds positively or negatively based based on platoon's current situation. If no other action is still in process then the manoeuvre can proceed to the next step. However, if the platoon is in the middle of another task (i.e. adjusting velocity, lane change) or is struggling with other issues (inter-platoon failures) then the manoeuvre has to be abandoned. After the completion of request and response steps, a gap opens among the exiting vehicle and the vehicle in front of it. The exiting vehicle using its side sensors (and communication with last vehicle of the platoon) performs a lane change safely in order to separate itself from the rest of the formation. After the manoeuvre is completed leader sends a signal to the corresponding follower to close the gap. Finally, the rest of the platoon continues its journey, while the exited truck follows its own trajectory [11].

It has to be noted that the procedure described above refer to an exit procedure that is performed while the platoon is working under under healthy conditions. Therefore, these steps cannot be repeated in the fallback strategy that this thesis is trying to address without proper modifications. However, it provides a good understanding of how such manoeuvre is performed and points out the steps that are affected without the presence of the perception module. The derived solution for this work is presented more analytically in later chapters.

It is also useful to look into fallback approaches that handle hazardous events on single automated vehicles facing sensor failures. The goal is to examine whether some of the proposed methodologies can be applied (with proper modifications) in platooning too. It is also important to mention that the faulty truck can actually be treated as a single autonomous vehicle that follows a different strategy than the rest of the platoon participants during the fallback state. The categorization can be seen in the Table 2-3. A few works indeed provide interesting proposals that could be used in the fallback strategy this thesis aims to form.

The several works are classified concerning the type of manoeuvre (braking, parking on the side, swerving, etc.), the reason for triggering the manoeuvre (driver condition, dangerous traffic, technological failure, etc.), the safe state reached (stopped, parked, etc.), the context of the manoeuvre (passenger car highway, passenger car-pedestrian crossing, etc.) and the required technology for the performed manoeuvre (no sensors, camera, lidar, radar, etc.). The above-mentioned characteristics have been chosen to classify the related works because they are relevant from the point of view of the problem definition provided in Chapter 1 regarding operating conditions of the platoon and taken assumptions. As a result, they are suitable criteria to decide whether an approach can apply to this thesis' addressed problem.

Table 2-3: Categorization of fallback strategies in single autonomous vehicles

Paper	Type	Reason	Action	*Context*	Technology
[22], [23]	Swerving	Dangerous Traffic	Lane Change	Highway	-
[37]	Swerving	Dangerous Traffic	Collision avoidance	Highway	Video data
[21]	Swerving	Dangerous Traffic	Lane Change	Highway	Environment sensors
[50]	Park on the side	Unspecified	Park on the side	Highway	Safety monitor GPS, Radar
[52]	Park on the side	Front sensors failure	Park on the side	Highway	Localization Side-rear sensors
[10]	Continue movement	Technological failure	Exit dangerous road	Highway	Localization Communication

Based on this literature review, it can be noticed that the minimal risk condition can be varied concerning the emergency scenario, including parking to a safe parking zone, immediate stop, or completing a path. Initially, this work's main focus is to consider the safe stop at a parking zone as the minimal risk condition and then examine the option to continue the journey for a while after the failure occurrence and then stop.

A beneficial mechanism that can be included in the design is using a virtual leader during the emergency state. It would be responsible for filling the missing information from the environment since the faulty follower can no longer measure its distance from the actual leader as employed in [52],[10]. The virtual vehicle is supposed to provide the follower the state (distance, velocity, etc.) of the actual leader when the failure happens and then assume a standard driving performance. Therefore, this option is beneficial because allows re-using the existing control infrastructure when performing the fallback strategy.

2-4 Summary

To sum up, in this chapter, a familiarization with all the important aspects that are required in order to design a proper framework for emergency escape manoeuvres in platooning has been described. Important information has been obtained about the characteristics of platoons and how to design such systems. The platoon control architecture has been explained and it was selected to work with a CACC system, which is sufficient for this application. Moreover, it was pointed out that the controller has to be designed concerning the formation's string stability. Furthermore, a detailed analysis, of the available options in the literature, regarding node dynamics and information flow topologies of the formation has been done. Both their advantages and disadvantages have been presented and the selection of these aspects is explained more analytically in the following chapters.

Furthermore, all the emergency escape manoeuvre concept design specifications and requirements have been defined and a clear research direction is achieved. Therefore existed techniques and algorithms of trajectory generators have been reviewed and selected interpolating curves as the most suitable option. Additionally, an extensive review of existing works that handled emergency scenarios in single automated vehicles focusing on sensor failures was done. A significant gap in existing knowledge around this subject was noticed, as just a few of these works refer exclusively to that kind of issue. Based on the review of these works, it was concluded that the virtual leader mechanism could play a key role in counteracting the sensor failure.

Based on state of the art, the smooth transition from normal performance to the fallback state to achieve minimal risk condition can be defined. Therefore, the thesis implementation can be divided into two parts. The first part consists of the emergency escape manoeuvre's design by treating the faulty truck as an autonomous single vehicle. The second part is the use of the manoeuvre in the platoon context. The platoon has to adapt from normal performance to emergency state and back to normal.

Finally, a plan for the emergency escape manoeuvre's general control structure can be designed regarding all the major components that have to be put together. The scheme can be seen in Figure 2-4. The first module corresponds to the vehicle dynamics that describe the trucks' movement and will be presented in Chapter 3. The module marked with red will be discussed in Chapter 4. It represents the structure responsible for the generation, execution and tracking of the emergency escape manoeuvre. The third module corresponds to the controller responsible for the platooning mode of operation, including the gap-closing action that has to be performed after executing the escape manoeuvre. It also has to be mentioned that the act of the rest of the healthy participants during the fallback state are handled by the platoon controller. These aspects will be discussed in Chapter 5. Both green and red modules receive signals from localization and communication modules for their proper functionality, while the perception module will be unavailable after the failure occurrence. Furthermore, a supervisory logic is responsible for switching the controllers and trigger the fallback state at the required time. This module will be presented in 6 as part of the fully derived fallback scheme and consists of modules regarding both vehicle and platoon level.

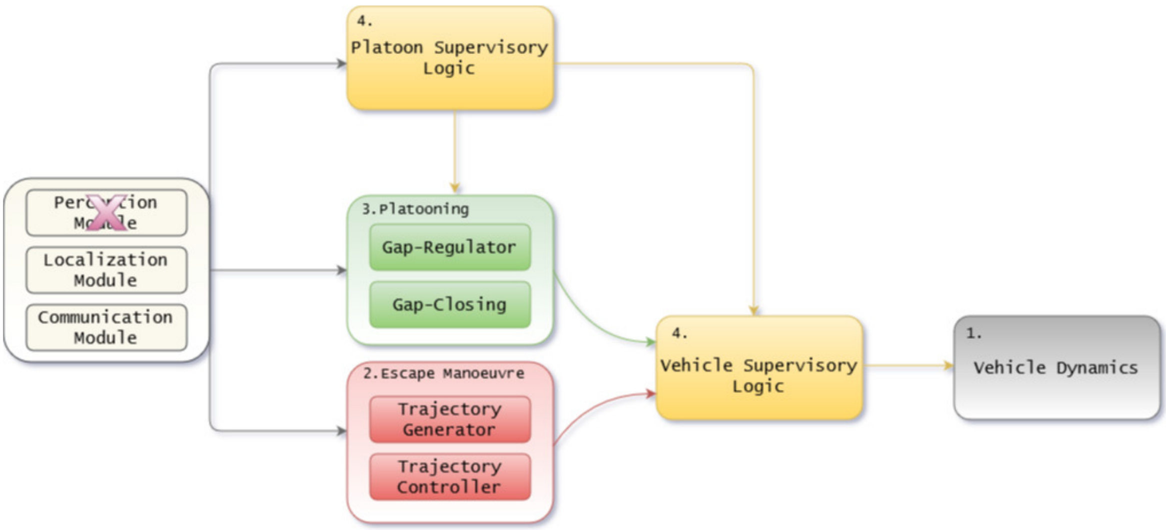


Figure 2-4: Control Structure of the Emergency Escape Manoeuvre Platoon Scheme

Chapter 3

Vehicle Modeling

This chapter presents the vehicle dynamics of the selected model and discusses the reasons for the selection. In this thesis, the simulated trucks need to perform cornering and stopping manoeuvre, velocity fluctuation in high speeds, and accurate tracking. Moreover, this work mainly focuses on high-level control while extensively studying vehicle engineering aspects is beyond its scope. Consequently, the most suitable model is selected concerning the performance requirements and a trade-off among detail and complexity.

As a result, the nonlinear bicycle (dynamic) model is chosen because it considers the vehicle's most important dynamics. As already mentioned, the motion control work is separated into two parts, a movement in a straight line and a cornering manoeuvre. Steering movements are of increased complexity because a precise trajectory is determinant to ensure an attainable traveling performance for vehicle's limitations as defined by physics laws. Therefore, mass, dimension and friction forces are significant to reveal the boundaries for this purpose. In general, bicycle vehicle models are used to approximate four-wheel vehicle models since they consider a single front wheel and a single rear wheel. Thus, it is the simplest model to start with building the proposed fallback strategy. It can capture the basic behaviors needed for an initial analysis of the possibilities, which this thesis does, and provide reasonable proof of principle.

3-1 3-DoF Bicycle Model

The 3-Degrees of Freedom (DoF) bicycle model merges the front wheels into one and the back wheels into another. It takes into account longitudinal, lateral and yaw motion. It is also assumed that the mass of the vehicle concentrated in the rigid base completely. Furthermore, the pitch and load transfer are considered [36].

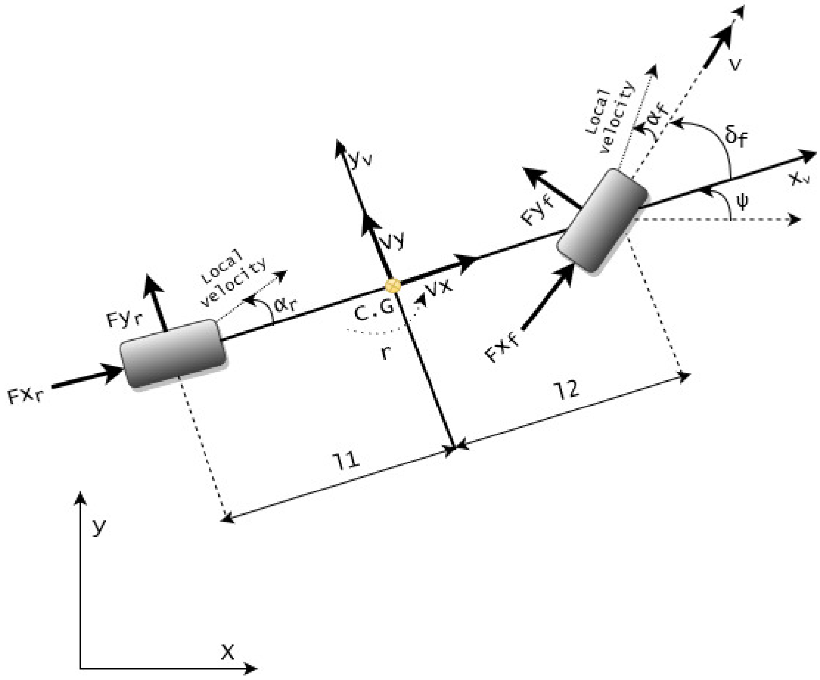


Figure 3-1: Nonlinear 3-DoF Bicycle Model Schematic

3-1-1 Equations of Motion

The vehicle dynamics are calculated by Newton's second law of motion and take into account the longitudinal and lateral forces acting on the tyres, as well as, vehicle's physical dimensions [47]:

Table 3-1: Equations (3-1-3-4) Terms and Parameters

Symbol	Description
m	Vehicle Mass
$\dot{V}_x$	Longitudinal Acceleration
$\dot{V}_y$	Lateral Acceleration
r	Yaw Rate
ψ	Heading Angle
l_1	Length from the centre to front wheel
l_2	Length from the centre to rear wheel
F_{x_f}, F_{x_r}	Front and Rear Longitudinal Forces
F_{y_f}, F_{y_r}	Front and Rear Lateral Forces
I_z	Yaw Inertia

$$m\ddot{x} = m\dot{y}\dot{\psi} + 2(F_{x_f} + F_{x_r}) \tag{3-1}$$

$$m\ddot{y} = -m\dot{x}\dot{\psi} + 2(F_{y_f} + F_{y_r}) \tag{3-2}$$

$$I\ddot{\psi} = 2(l_1 F_{y_f} - l_2 F_{y_r}) \tag{3-3}$$

$$r = \dot{\psi} \tag{3-4}$$

3-1-2 Tyre Forces

It is important that the model accurately describe the tyre forces because they are fundamental to describe the vehicle cornering dynamics. The longitudinal forces $F_{x_{f,r}}$ are modeled with respect to the longitudinal slip ratio k, while the lateral forces $F_{x_{f,r}}$ with respect to the slip angle α.

The slip ratio expresses the slipping behavior of the wheel that arise from the longitudinal forces acting on tire [47]. It can be described as:

$$k_r = (\dot{x} - v_r)/v_r \tag{3-5}$$

$$k_f = -(\dot{x} - v_f)/v_f \tag{3-6}$$

where $v_{f,r}$ is the linear velocity of the tyre which is simultaneously used as the first control input for the vehicle system.

The slip angle is the angle that presents the difference among the pointing direction of the wheel and the pointing direction that the vehicle is currently driven [47]. The slip angles for front and rear wheels are described as:

$$\tan(\alpha_r) = \frac{\dot{y} - l_2 r}{\dot{x}} \tag{3-7}$$

$$\tan(\alpha_f) = \frac{-\dot{x}\sin\delta_f + (\dot{y} + l_1 r)\cos\delta_f}{\dot{x}\cos\delta_f + (\dot{y} + l_1 r)\sin\delta_f} \tag{3-8}$$

where δ_f is the front wheel steering angle and is the second control input of the system.

In the literature there are many available options to calculate the longitudinal and lateral forces. Probably the most popular is the Magic Formula [44], a semi-empirical model that needs many experimental coefficients and sometimes lacks of accuracy. Consequently, in this thesis a piecewise-linear tyre model is used as is developed in [36]. This method uses much less coefficients and takes advantage of the linear region of tyre forces while normal driving is executed. It was evaluated and compared with a 14-DoF full car model providing a very good approximation. Consequently, the piecewise linear approximation, though slightly less accurate, is accurate enough for this thesis purposes.

Therefore, the longitudinal tyre force is described by:

$$F_x = C_x k_{f,r} \tag{3-9}$$

$$C_x = C_{xn}(1 + \frac{F_z - F_{zn}}{F_{zn}}) \tag{3-10}$$

while, the lateral tyre forces is defined as:

$$F_y = -C_y \alpha_{f,r} \tag{3-11}$$

$$C_y = C_{yn}(1 + \frac{F_z}{F_{zn}}) \tag{3-12}$$

where C_x and C_y are the longitudinal and lateral stiffness correspondingly. The terms C_{xn}, C_{yn} and F_{zn} are model parameters for nominal longitudinal and lateral stiffness and load transfer respectively taken from [12].

The forces F_{z_f}, F_{z_r} are the normal forces at front and rear tyres from pitch and load transfer. They are calculated as:

$$F_{z_f} = \frac{mgl_2}{2(l_1 + l_2)} \tag{3-13}$$

$$F_{z_r} = \frac{mgl_1}{2(l_1 + l_2)} \tag{3-14}$$

where g is the gravity constant.

3-1-3 Trajectory Position

The vehicle's position in the absolute inertial frame are calculated by:

$$\dot{X} = \dot{x}\cos\psi - \dot{y}\sin\psi \tag{3-15}$$

$$\dot{Y} = \dot{x}\sin\psi + \dot{y}\cos\psi \tag{3-16}$$

where X and Y are the longitudinal and lateral positions of the vehicle in the inertial frame respectively.

3-2 Discussion

The equations presented in the previous sections describe the dynamic vehicle model that is used in the platoon formation of this work. This model takes as inputs the tyre's linear velocity and the steering angle of the front wheel. Obviously, some more extensive models examine the performance of the vehicle in more detail. However, focusing on the vehicle's dynamics in more depth is out of this work's scope. Therefore, components in low-level layers like actuators are not included in the design. Expanding the model by adding actuators can enhance the precision of the required braking and accelerating actions. Nevertheless, attention is paid to the higher design layers' target velocities and not to the throttle and braking signals that produce the corresponding values. Furthermore, there are models in the literature that consider full vehicle description (four wheels). A four-wheel model with higher

DoF provides a better understanding of the vehicle's response since the left and right wheels' performance differs. These issues do not affect the implementation of the emergency escape manoeuvre concept, as the selected model is detailed enough to provide a good approximation of a vehicle's behavior.

When starting to build a completely new framework is safer to start with simpler models in the beginning. Once a proof of concept is provided with this model, more precise control designs using more realistic models can be addressed. This upgrade is considered a future work for this thesis and is explained in more detail in the last chapter.

Finally, it is significant to mention a specific characteristic of the selected model that affects the rest of the decisions taken in the selection of the components of the framework. If the vehicle is moving on a straight path, it yields that the steering angle equals zero and ideally, no lateral forces are acting on the tyres. As a result, the model's lateral dynamics are neglected, and the vehicle's performance can be fully described using only the longitudinal dynamics. Consequently, the platoon control problem under healthy conditions can be simplified by assuming a linear behavior of the vehicle dynamics and proceed with the design accordingly. This approximation, of course, is used only in the Cooperative Adaptive Cruise Control (CACC) system does not affect the escape manoeuvre part. More details regarding this important note are presented in the next chapter.

Chapter 4

Design of Emergency Escape manoeuvre

This chapter describes the emergency escape manoeuvre's design using a trajectory generator method using a pre-defined set of via-points. Firstly, the design approach is explained based on assumptions and constraints pointed out to clearly support the manoeuvre's selected method. Secondly, a Quintic Splines trajectory generator methodology is presented as developed in [1]. In this work, the methodology from [1] is modified accordingly to fit the current application's needs. A trajectory tracking controller is then employed to evaluate the designed manoeuvre and check if all the requirements are fulfilled. Finally, a simulation analysis is presented in order to evaluate the performance of the control scheme.

4-1 Assumptions

Before proceed is important to define the assumptions made regarding the movement and the capabilities of the platoon, as well as, the road and traffic characteristics. In this way, the environment for the simulation purposes is set up.

- It is assumed that the platoon is moving the right lane the moment of the failure occurrence. As a result, no lane-change manoeuvres before the execution of the escape manoeuvre are required.
- It does exist a free space on the shoulder of the highway where the faulty truck can park and achieve the minimal risk condition.
- There are currently no other traffic participants.
- The communication module of the truck still works perfectly and signals can still be exchanged among the platoon participants.

4-2 Constraints

The constraints of the manoeuvre have a key role to the design procedure. Besides the required characteristics of the trajectory generator it should also be able to execute the manoeuvre with respect to the following limitations:

- Movement of the vehicle should start at the centre of the active lane and finish at the centre of the shoulder.
- As per the Dutch law the maximum speed limit for trucks in highways is $90km/h$, while the lowest is $60km/h$.
- The maximum deceleration for a truck that is not considered as extreme is around $3.5m/s^2$.
- In order to prevent unwanted rollover situations the maximum lateral deceleration should be less than $4.90m/s^2$.

4-3 Approach

Based on all the specifications mentioned in the subsections above, it can be concluded that the emergency escape manoeuvre of this thesis can be treated like a lane-change manoeuvre. During such manoeuvres, the vehicles usually maintain the same speed or increase it slightly. However, this work aims to lead the faulty truck to park on the highway's shoulder and not overtake another car. Thus, a speed profile that decelerates the vehicle's speed until it stops (known as linear ramp profile) is applied.

As already mentioned, it was selected to employ a spline trajectory generator. Splines vary according to their order and take as inputs specific via-points in the x-y plane and manage to generate polynomials that connect each segment. According to [1], Cubic Splines produce extremely high peaks on jerk (yaw rate) at the beginning of every segment. These peaks cause an infringement of the rollover safety constraint. Consequently, the quintic splines combined with optimization mechanisms can be a successful candidate that guarantees continuity, satisfies constraints, and affords the design scenarios. It has to be noted that higher-order splines provide further advantages but either increase complexity or do not apply to this application.

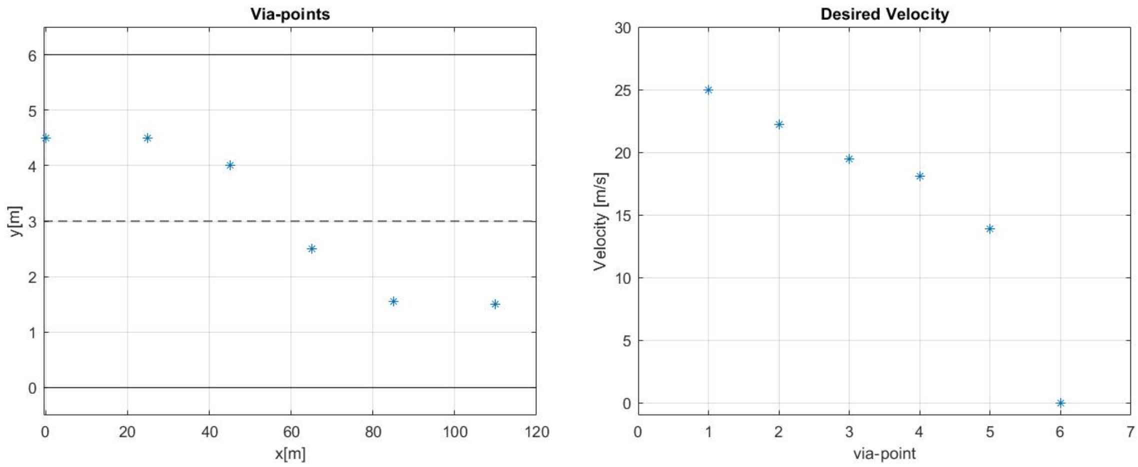
4-4 Quintic Splines

In [1], a quintic splines trajectory generator is developed that employs a unique time parameterization method. The goal of [1] was to design a lane-change manoeuvre in a highway scenario at low-speeds. In this work, the methodology described in [1] is adopted by applying slight changes to match the defined needs. In [1], their methodology has the limitation of using symmetric speed profiles to satisfy comfort goals. Furthermore, their selected method of minimizing jerk peaks caused extra oscillations that required further design consideration. In this work, the relaxed comfort requirements allow simpler velocity profiles using elementary physics law. Furthermore, it is shown that it is possible to avoid oscillations and skip extra steps to reduce yaw rate spikes by choosing the proper optimization method.

In the rest of the section, the procedure of designing the emergency escape manoeuvre using quintc splines methodology from [1] is presented analytically. Firstly, the input-output structure of via-points and segments is explained. Then, calculating the unknown coefficients of the splines concerning boundary conditions that satisfy the continuity requirements is described. Finally, the time-parameterization method applied is presented with the selected linear ramp velocity profile.

4-4-1 Inputs

In order to generate the emergency escape manoeuvre using the quintic splines trajectory generator a set of via-points with the desired velocity at each point are passed as inputs. The via-points are described in the inertial framework coordinate system (x, y). Since the emergency escape manoeuvre has to be calculated online and ready to be re-planned, the only known information at every time iteration is the current via-point and desired velocity and the coordinates and desired velocity of the next via-point. The generator produces an interpolating curve that connects these two points that with initial and final velocity the corresponding desired values of each via-point. A pair of connected via-points is called a segment and as soon as the vehicle reaches a via-point the next becomes known information and is passed as a new input to the generator.



(a) Set of via-points **(b)** Desire velocity at every via-point

Figure 4-1: Inputs for quintic splines trajectory generator

In Figure 4-1a can be seen a representation of a desired emergency escape manoeuvre on the x-y plane. The horizontal line at $y = 3$ denote the separation of active lane with the shoulder in the highway. It can be noticed that it looks very similar with a lane change manoeuvre. The vehicle starts its movement in the middle of the active lane (0, 4.5), and after a few via-points reaches the middle of the shoulder (110, 1.5) (distance is explained in following sections) to park while smoothly abandons the lane. The via-points and the corresponding desired velocities have been defined a priori such that the generated trajectory can satisfy the requirements. Thus, the length of the emergency escape manoeuvre will be always the same. In Figure 4-1b can be seen the desired velocities of the corresponding via-point. One approach is to let the faulty truck decelerate while still moving on the active lane and eventually stop completely its movement in the shoulder. It is important to mention that the distance among via-points and the corresponding velocities are chosen in that way in order to satisfy all the above mentioned constraints with respect to traffic laws. More specifically vehicle's speed in active lane does not get below $60km/h$ and the deceleration value remains close to $3.5m/s^2$.

Recall from Chapter 2 that besides the trajectory generator there is also a path planner and a manoeuvre planner. Following [1], in this work it is assumed too that the via-points are selected based on a collision-free path, arising the corresponding module and a manoeuvre planner assigns the desired velocities.

4-4-2 Computation of Coefficients

The equations describing a quintic splines trajectory are given by:

$$x_{ref,k}(t) = a_{0,k} + a_{1,k}u + a_{2,k}u^2 + a_{3,k}u^3 + a_{5,k}u^5|_{u=u(t)} \tag{4-1}$$

$$y_{ref,k}(t) = b_{0,k} + b_{1,k}u + b_{2,k}u^2 + b_{3,k}u^3 + b_{5,k}u^5|_{u=u(t)} \tag{4-2}$$

where ref denotes the resulted reference signal and k corresponds to the current segment. The term u is the time-parameterization function and $a_0..a_5$ and $b_0..b_5$ are the spline coefficients. In this subsection is explained how these coefficients are calculated following [1] methodology. Specific boundary conditions are defined such that continuity in position, tangent direction and yaw rate is achieved. It is also assumed that in every segment $u_{init} = 0$ and $u_{final} = 1$. It can be noticed that a fourth order term is missing from the Equations (4-1) and (4-2) and is actually substituted with a fifth order term. This is chosen in order to avoid even number for the highest order of u. As denoted in [19] due to the symmetric property of polynomials with even order oscillating trajectories are produced when trying to keep up with tangent angle continuity constraint. Furthermore, in [1] is explained that by choosing that form of equations this problem is solved and only four coefficients are enough to achieve the designing goals. Below the way all the coefficients are calculated is presented as derived in [1]. The calculations are based in boundaries regarding initial and final position, heading angle and yaw rate continuity among segments, as well as, minimization of jerk peaks.

a0 and b0

The coefficients $a_{0,k}$ and $b_{0,k}$ are related with the initial position of the vehicle at every segment. Since $u = 0$ at the beginning of every segment and by substituting it in Equations (4-1) and (4-2) it yields that:

$$x_{ref,k}(0) = a_{0,k} \tag{4-3}$$

$$y_{ref,k}(0) = b_{0,k} \tag{4-4}$$

Therefore, the solution is to assign the two coefficients to the starting coordinates of each segment as:

$$a_{0,k} = x_{init,k} \tag{4-5}$$

$$b_{0,k} = y_{init,k} \tag{4-6}$$

where $x_{init,k}$ and $y_{init,k}$ is actually the k^{th} via-point.

a1 and b1

This pair of coefficients are calculated based on boundary conditions regarding the initial tangent direction of every segment. The final tangent direction of the previous segment should be the initial tangent direction the current k segment. In order to extract the relation that connects the coefficients with this specific continuity constraint the following procedure is applied.

The tangent of the trajectory on each direction is given by the partial derivatives of $x_{ref,k}(u)$ and $y_{ref,k}(u)$ over u as:

$$x'_{ref,k}(u) = a_{1,k} + 2a_{2,k}u + 3a_{3,k}u^2 + 5a_{5,k}u^4|_{u=u(t)} \tag{4-7}$$

$$y'_{ref,k}(u) = b_{1,k} + 2b_{2,k}u + 3b_{3,k}u^2 + 5b_{5,k}u^4|_{u=u(t)} \tag{4-8}$$

In order to establish the continuity of the tangent angle of various length segments, the unit tangent to the trajectory is calculated as:

$$\hat{p}_k(u) = \frac{p'_k(u)}{|p'_k(u)|} \tag{4-9}$$

where $p'_k(u) = [x'_{ref}(u), y'_{ref}(u)]^T$. By expanding Equation (4-9) it yields that

$$\hat{p}_k(u) = \frac{\begin{bmatrix} a_{1,k} + 2a_{2,k}u + 3a_{3,k}u^2 + 5a_{5,k}u^4 \\ b_{1,k} + 2b_{2,k}u + 3b_{3,k}u^2 + 5b_{5,k}u^4 \end{bmatrix}}{\sqrt{(a_{1,k} + 2a_{2,k}u + 3a_{3,k}u^2 + 5a_{5,k}u^4)^2 + (b_{1,k} + 2b_{2,k}u + 3b_{3,k}u^2 + 5b_{5,k}u^4)^2}} \tag{4-10}$$

Then by substituting $u = 0$ to the unit tangent at the beginning of segment k is:

$$\hat{p}_k(0) = \frac{\begin{bmatrix} a_{1,k} \\ b_{1,k} \end{bmatrix}}{\sqrt{a_{1,k}^2 + b_{1,k}^2}} \tag{4-11}$$

Next, by setting equation 4-11 equal to the previous segment's unit tangent's final value, which is known, the following expression arises:

$$\frac{\begin{bmatrix} a_{1,k} \\ b_{1,k} \end{bmatrix}}{\sqrt{a_{1,k}^2 + b_{1,k}^2}} = \hat{p}_{k-1}(1) \tag{4-12}$$

Finally, by setting $\sqrt{a_{1,k}^2 + b_{1,k}^2} = 1$ (tanget magnitude equals 1) a unique solution can be found for coefficients $a_{1,k}$ and $b_{1,k}$ such that continuity in heading angle is guaranteed among the segments.

a2 and b2

These two coefficients are tuned in that way such that two segments are connected having a continuous yaw rate (time derivative of heading angle).

The heading angle is defined as:

$$\psi_k(t) = \arctan\left(\frac{\dot{y}_{ref,k}(t)}{\dot{x}_{ref,k}(t)}\right) \tag{4-13}$$

where

$$\dot{x}_{ref,k}(t) = x'_{ref,k}(u)\dot{u}(t)|_{u=u(t)} \tag{4-14}$$

$$\dot{y}_{ref,k}(t) = y'_{ref,k}(u)\dot{u}(t)|_{u=u(t)} \tag{4-15}$$

By substituting Equations (4-14) and (4-15) in Equation (4-13) a new expression of heading angle arises as:

$$\psi_k(t) = \arctan\left(\frac{y'_{ref,k}(u)}{x'_{ref,k}(u)}\right) \tag{4-16}$$

Therefore, the yaw rate is calculated as the first derivative of Equation (4-16) as:

$$\dot{\psi}_k(t) = \frac{x'_{ref,k}(t)\dot{y}'_{ref,k}(t) - y'_{ref,k}(t)\dot{x}'_{ref,k}(t)}{x'_{ref,k}(t)^2 + y'_{ref,k}(t)^2} \tag{4-17}$$

where

$$\dot{x}'_{ref,k}(t) = (2a_{2,k} + 6a_{3,k}u(t) + 20a_{5,k}u^3(t))\dot{u}(t) \tag{4-18}$$

$$\dot{y}'_{ref,k}(t) = (2b_{2,k} + 6b_{3,k}u(t) + 20b_{5,k}u^3(t))\dot{u}(t) \tag{4-19}$$

Consequently, the full expression for the yaw rate is given by:

$$\dot{\psi}_k = \frac{(a_{1,k}+2a_{2,k}u+3a_{3,k}u^2+5a_{5,k}u^4)(2b_{2,k}+6b_{3,k}u+20b_{5,k}u^3)\dot{u}-(b_{1,k}+2b_{2,k}u+3b_{3,k}u^2+5b_{5,k}u^4)(2a_{2,k}+6a_{3,k}u+20a_{5,k}u^3)\dot{u}}{(a_{1,k}+2a_{2,k}u+3a_{3,k}u^2+5a_{5,k}u^4)^2+(b_{1,k}+2b_{2,k}u+3b_{3,k}u^2+5b_{5,k}u^4)^2}\Big|_{u=u(t)} \tag{4-20}$$

Similarly to the procedure followed for the previous pair of coefficients, the initial yaw rate of k^{th} segment ($u = 0$) must be equal to previous segment final yaw rate ($u = 1$). This is translated as:

$$\dot{\psi}_k(0) = \dot{\psi}_{k-1}(1) \tag{4-21}$$

As a result, the full expression is given by:

$$\frac{2v_k(0)(a_{1,k}b_{2,k} - b_{1,k}a_{2,k})}{\sqrt{a_{1,k}^2 + b_{1,k}^2}(a_{1,k}^2 + b_{1,k}^2)} = \dot{\psi}_{k-1}(1) \tag{4-22}$$

where $v_k(0)$ is the initial velocity of k^{th} segment.

Finally, by setting $\sqrt{a_{1,k}^2 + b_{1,k}^2} = 1$ as in the previous pair, the expression is further simplified to the following equation and a unique solution is found for the two coefficients in order to establish continuous yaw rate among the segments.

$$2v_k(0)(a_{1,k}b_{2,k} - b_{1,k}a_{2,k}) = \dot{\psi}_{k-1}(1) \tag{4-23}$$

a3 and b3

The coefficients a_3 and b_3 are calculated with respect to segment's desired final position which the coordinates of the next via-point. Therefore, by setting $u = 1$ the final position for the segment k is given by:

$$x_k(1) = a_{0,k} + a_{1,k} + a_{2,k} + a_{3,k} + a_{5,k} \tag{4-24}$$

$$y_k(1) = b_{0,k} + b_{1,k} + b_{2,k} + b_{3,k} + b_{5,k} \tag{4-25}$$

By setting the right hand side of the equations equal to the known final coordinates $(x_{k,final}, y_{k,final})$ of the k^{th} segment it yields that:

$$x_{final,k} = a_{0,k} + a_{1,k} + a_{2,k} + a_{3,k} + a_{5,k} \tag{4-26}$$

$$y_{final,k} = b_{0,k} + b_{1,k} + b_{2,k} + b_{3,k} + b_{5,k} \tag{4-27}$$

Thus, the solution for the coefficients a_3 and b_3 is given by:

$$a_{3,k} = a_{0,k} + a_{1,k} + a_{2,k} + x_{final,k} + a_{5,k} \tag{4-28}$$

$$b_{3,k} = b_{0,k} + b_{1,k} + b_{2,k} + y_{final,k} + b_{5,k} \tag{4-29}$$

Obviously, at this stage information is missing regarding coefficients $a_{5,k}$ and $b_{5,k}$ and the process of their computation is explained below.

a5 and b5

This pair of coefficients is tuned accordingly to ensure that no extremely high yaw rate peaks occur that violate the lateral acceleration limit. Recall the full expression for yaw rate as given in Equation (4-20). By substituting Equations (4-28) and (4-29) only $a_{5,k}$ and $b_{5,k}$ remain unknown. Therefore, by solving the following minimization problem with respect to $a_{5,k}$ and $b_{5,k}$ a solution arises.

$$\begin{aligned} \min_{a_{5,k}, b_{5,k}} \quad & |\dot{\psi}_k(t)|_\infty \\ \text{s.t.} \quad & -1 \leq a_{5,k} \leq 1 \\ & -1 \leq b_{5,k} \leq 1 \\ & 0 \leq u \leq 1 \end{aligned} \tag{4-30}$$

Recall also that a constraint regarding the maximum acceptable lateral acceleration have been set. Moreover, in this work neither extreme cornering manoeuvres or comfort are examined. One may wonder that defining an upper bound limitation for the yaw rate might be a more straightforward solution. However, the possibility to achieve minimal yaw rate enhance the scalability of the proposed scheme. In addition, it is an extra benefit without much computational cost. Last but not least, by choosing an optimization method a more general solution is provided which enables the scheme to be extended more easily in future works.

The cost function of Equation (4-30) can be further simplified by eliminating time depended terms. Firstly, it can be re-written as:

$$\dot{\psi}_k(t) = f(u)_k . v_{ref,k}(t) \tag{4-31}$$

where $f(u)_k$ is a function of u and $v_{ref,k}$ a function of time.

According to [39] it holds that

$$|\dot{\psi}_k(t)|_\infty \leq |f(u)_k|_\infty . |v_{ref,k}(t)|_\infty \tag{4-32}$$

Since the vehicle performs a decelerating movement the infinity norm of the time function equals to the initial velocity of each segment which is already known $|v_{ref,k}(t)|_\infty = v_{init,k}$.

As a result, the final optimization problem for minimizing yaw rate peaks can be expressed as:

$$\begin{aligned} \min_{a_{5,k}, b_{5,k}} \quad & v_{init,k} |f(u)_k|_\infty \\ \text{s.t.} \quad & -1 \leq a_{5,k} \leq 1 \\ & -1 \leq b_{5,k} \leq 1 \\ & 0 \leq u \leq 1 \end{aligned} \tag{4-33}$$

It has to be noted that looking for a solution outside the interval [-1,1] does not lead to improved result rather than increases the computation time. In addition, function $f(u)_k$ can be defined as:

$$f(u)_k = \frac{x'_{ref,k}(u)y''_{ref,k}(u) - y'_{ref,k}(u)x''_{ref,k}(u)}{(x'_{ref,k}(u)^2 + y'_{ref,k}(u)^2)^{3/2}} \tag{4-34}$$

while the full expression is:

$$f(u)_k =$$

$$\frac{(a_{1,k}+2a_{2,k}u+3a_{3,k}u^2+5a_{5,k}u^4)(2b_{2,k}+6b_{3,k}u+20b_{5,k}u^3)-(b_{1,k}+2b_{2,k}u+3b_{3,k}u^2+5b_{5,k}u^4)(2a_{2,k}+6a_{3,k}u+20a_{5,k}u^3)}{[(a_{1,k}+2a_{2,k}u+3a_{3,k}u^2+5a_{5,k}u^4)^2+(b_{1,k}+2b_{2,k}u+3b_{3,k}u^2+5b_{5,k}u^4)^2]^{3/2}} \tag{4-35}$$

In [1] it was chosen to avoid optimization algorithms. Therefore, the optimization problem was solved by trying to find the pair of $a_{5,k}$ and $b_{5,k}$ that provided the lowest peak of $f(u)_k$ by evaluating numerical combinations. However, the result of this optimization process provided oscillating reference paths and further actions were required to improve the outcome.

In this work, by examining the objective function the most suitable optimization method is derived. It is a non-linear, non-convex objective function, while its Hessian and gradient are difficult to compute. As a result, the minimization problem can be solved using *multi-start Simulated Annealing (SA)* [55] or *multi-run genetic algorithm Genetic Algorithm (GA)* [38]. GAs are parallel global search optimization techniques developed with respect to the mechanics of natural selection and survival of the fittest. They look for the optimal value of different parameter vectors, named as population based on a fitness criterion. On every iteration the population changes and adapts by generating new individual vectors that are fitter and yield to improved performance. The algorithm is terminated when maximum number of iterations is reached or if new generated individuals do no provide significant improvement to the fitness function. The SA algorithm is also inspired by the natural process of annealing in metal work. It is a random search probabilistic method that starting from an initial point aims to minimize an objective function. At every iteration a new point is generated at a distance affected by the probability distribution proportional to the temperature. Every new point that provides lower value of the objective function is accepted. However, the algorithm also accepts points that worsen the objective based on some probabilistic restrictions. In that way it avoids getting trapped in local minima and can explore other neighborhoods too. The temperature is systematically decreased during the iterations and the extent of search is reduced accordingly until algorithm converges to the global minimum. They are similar techniques but the SA is significantly faster and based on that is chosen to be applied for solving this optimization problem.

4-4-3 Time - Parameterization

The Equations (4-1) and (4-2) consist of a $u(t)$ term which is a unique time-parameterization as derived in [1] using the used velocity profile which is explained later. The parameter u allows the design and execution of the defined velocity profile throughout the trajectory of every segment with respect to the specifications.

The reference velocity of a moving vehicle is given by:

$$v_{ref,k}(t) = \sqrt{\dot{x}_{ref,k}(t)^2 + \dot{y}_{ref,k}(t)^2} \tag{4-36}$$

Then, by substituting the time derivatives derived in Equations (4-14) and (4-15) it leads to the first-order non-linear differential function of $u(t)$ which can be solved numerically as:

$$\dot{u}(t) = \frac{v_{ref,k}(t)}{\sqrt{x'_{ref,k}(u)^2 + y'_{ref,k}(u)^2}} \tag{4-37}$$

which is proven to have a unique solution [1].

The Equation (4-37) is solved using a numerical integration method due to the difficulty to find an analytical solution caused by its non-linearity. The Classical Runge-Kutta (RK4) method is applied. The differential equation is defined as:

$$\dot{u}(t) = f(u, t) \tag{4-38}$$

with initial condition $u(t_0) = 0$. Then by using RK4 the next value of both u and time t are approximated until the the final time of each segment is reached. The computation of final time t_f is the next session.

$$u_{n+1} = u_n + \frac{h}{6}(k_1 + 2k_2 + 2k_3 + k_4) \tag{4-39}$$

$$t_{n+1} = t_n + h \tag{4-40}$$

for $n = 0, 1, 2...$ The term h is the time-step, while $k_{1,2,3,4}$ are calculated as:

$$k_1 = f(u_n, t_n) \tag{4-41}$$

$$k_2 = f(u_n + h\frac{k_1}{2}, t_n + \frac{h}{2}) \tag{4-42}$$

$$k_3 = f(u_n + h\frac{k_2}{2}, t_n + \frac{h}{2}) \tag{4-43}$$

$$k_4 = f(u_n + hk_3, t_n + h) \tag{4-44}$$

It has to be noted that the smaller the time-step the more accurate the result becomes. However, a trade-off needs to be taken in order have a good balance among computational time and accuracy.

4-4-4 Velocity Profile

In general, there are several ways to define a reference velocity profile. The velocity profile basically presents the transition among the desired velocities of the via-points. Simple linear ramp or trapezoidal profiles are very common in the literature of autonomous driving vehicles. For stop scenarios the trapezoidal profile is the most recommended because it leads the vehicle to decelerate to a constant slower speed before stopping. Thus, the comfort is enhancing but is not the target of this approach. In [1] a symmetric sigmoid velocity profile was selected in order to take advantage of the symmetric properties of the profile to compute the missing final time of the segment. A sigmoid velocity provides a Gaussian shape for the deceleration of the vehicle. Therefore, the required distance and time to complete a segment become higher. In addition, that kind of profile might be unrealistic for real applications due to its sigmoid structure. In this work, a linear ramp velocity profile is selected for every segment. Although it leads to discontinuities in acceleration, it is not a problem for this thesis goals, because driving comfort is not essential in emergency situations (especially in driver-less vehicles). Since, the total arc length of the segment, as well as, initial and final velocities are known, the final time can be estimated using elementary physics equations.

Firstly, the length of the k^{th} has to be calculated. By taking advantage that the spline coefficients have already been found, the length can be determined as:

$$L_k = \int_0^1 \sqrt{x'_{ref,k}(u)^2 + y'_{ref,k}(u)^2}\, du \tag{4-45}$$

The deceleration of the movement at each segment is given by:

$$dec_k = (v_{f,k}^2 - v_{0,k}^2)/(2L_k) \tag{4-46}$$

where $v_{0,k}$ and $v_{f,k}$ are the initial and final velocities of the vehicle at the segment respectively.

Therefore, the final time of the segment can be calculated as:

$$t_{f,k} = \frac{(v_{f,k} - v_{0,k})}{dec_k} + t_{0,k} \tag{4-47}$$

where $t_{0,k}$ is the starting time of the segment.

Therefore, the reference velocity for every segment of the manoeuvre is given by:

$$v_{ref,k}(t) = v_{0,k} + dec_k * (t - t_{0,k}) \tag{4-48}$$

An example of a reference velocity using a linear ramp with negative slope can be seen in the Figure 4-2 below. It has to be noted that the desired velocity at every via-point was selected such that the maximum deceleration of every segment does not exist the desired value. It can also be noticed that the deceleration of the last segment is bigger than the previous segments. At that last segment the vehicle is moving completely in the shoulder and a more aggressive stopping could be applied (always below the acceptable upper bound). It also has to be noted that v_0 of the first segment varies according to truck's initial moving speed.

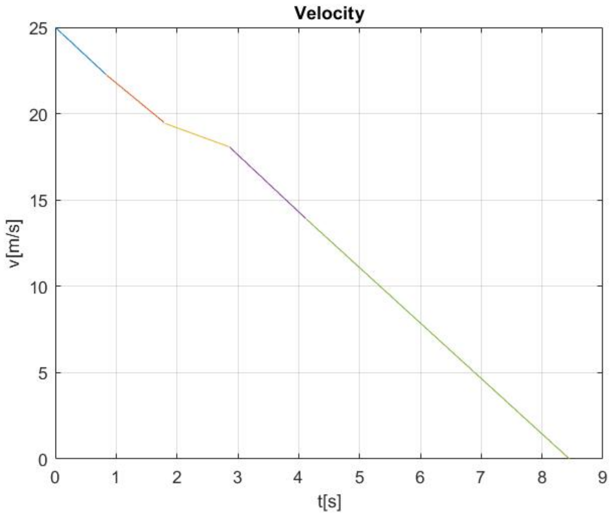


Figure 4-2: Linear ramp reference velocity with negative slope

4-4-5 Discussion

So far, it has been presented the whole procedure of designing a trajectory generator by using a quintic splines methodology. The performance of the generator has to be evaluated with respect to the provided trajectory and whether satisfies or not the requirements that have been defined. In Figure 4-3 can be seen a typical reference path.

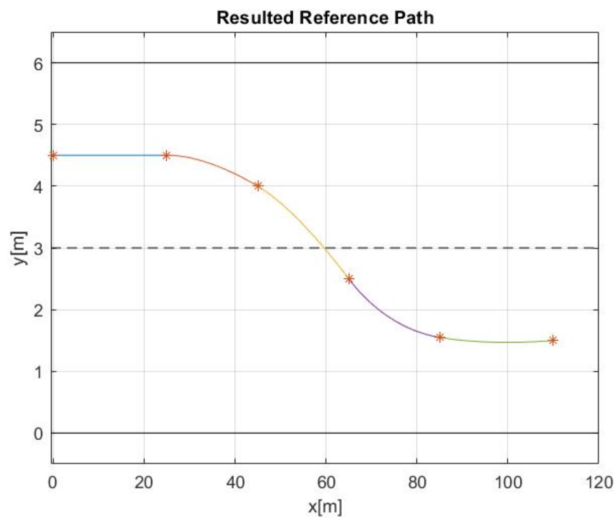
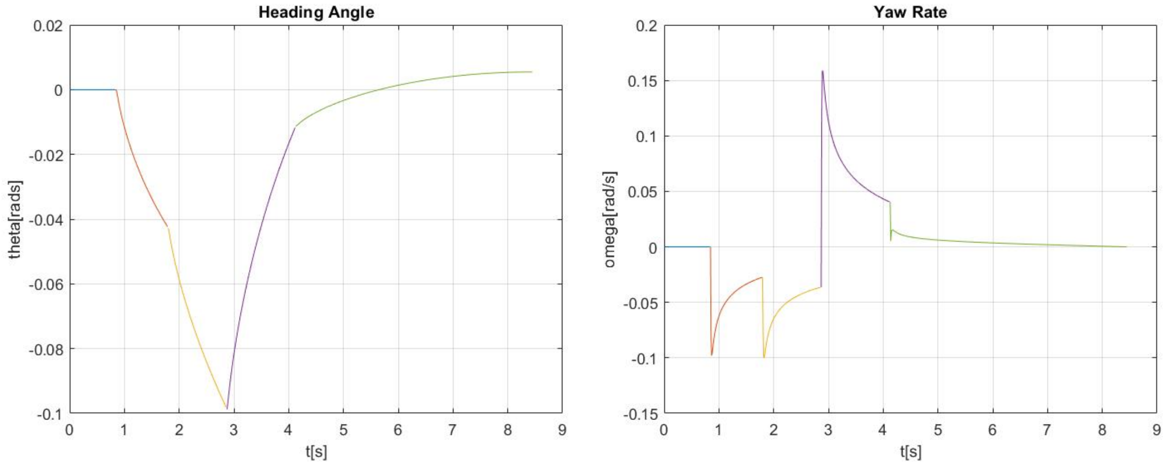


Figure 4-3: Reference path using quintic spline method

Indeed the generator provided a trajectory that lead the vehicle from the centre of the active lane to stop at the centre of the shoulder. The whole length of the manoeuvre is $110m$. while the required time to perform the manoeuvre is around $8.5s$ (the duration of the trajectory varies with respect to truck's initial velocity). The Figures 4-4a and 4-4b below show the reference heading angle and angular velocity for the path presented in Figure 4-3. The followed methodology and the selected velocity profile provide the desired C^1 and G^1 continuity. In addition, the peaks of yaw rate that occur at the beginning of every segment are held in values that do not violate the maximum acceptable lateral deceleration (which is calculated as the multiplication of yaw rate and velocity). It is also important to mention that the average computational time of each segment is $0.4s$ which denote that the manoeuvre is possible to be computed online. Overall, it seems that all the requirements that have been set are satisfied and the trajectory provided can be considered as a feasible option to be followed in practise.



(a) Reference heading angle

(b) Reference angular velocity

Figure 4-4: Reference signals arise from the quintic splines methodology

4-5 Trajectory Tracking

After the successful validation of designed emergency escape manoeuvre that was described in previous section, it is time to test the outcome in a closed-loop formation with the vehicle dynamics and a controller. The following signals that are generated following the quintic splines methodology described above, are the reference inputs to the trajectory controller.

- Longitudinal Position: x_{ref}
- Lateral Position: y_{ref}
- Heading Angle: ψ_{ref}
- Linear Velocity: v_{ref}
- Angular Velocity: $\dot{\psi} ref$

It has to be noticed that the first three signals (x_{ref}, y_{ref}, ψ_{ref}) correspond to the reference state of the vehicle s_{ref}, while the last two (v_{ref}, $\dot{\psi}_{ref}$) to the reference velocity profile. The typical tracking problem is to design suitable control inputs such that the system performs a proper tracking of a specified trajectory.

The reference values described above are defined in the world frame. Therefore the global error regarding the vehicle's current state s_v and reference state can be defined as:

$$\begin{bmatrix} e_x \\ e_y \\ e_\psi \end{bmatrix} = \begin{bmatrix} x_{ref} - x_v \\ y_{ref} - y_v \\ \psi_{ref} - \psi_v \end{bmatrix} \tag{4-49}$$

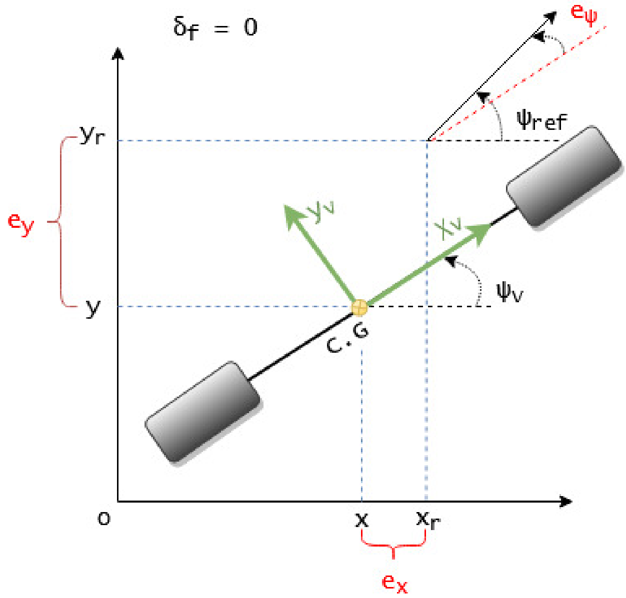


Figure 4-5: Global error that arises from vehicle's current and reference state

Then, by using the global error one can define the local error which is the translation from the world coordinates to vehicle's coordinate frame. A simple rotational matrix that arises from the projection of vehicle's frame to world frame can provide the relation regarding the lateral and longitudinal local errors as:

$$\begin{bmatrix} e_{x_l} \\ e_{y_l} \end{bmatrix} = \begin{bmatrix} -\sin\psi_v & \cos\psi_v \\ \cos\psi_v & \sin\psi_v \end{bmatrix} \begin{bmatrix} e_x \\ e_y \end{bmatrix} \tag{4-50}$$

4-5-1 Controller

The errors defined above provide a solid foundation for designing a trajectory tracking controller. There are many proposed controllers available in the literature, however, in this work the controller implemented in [29] is adopted. This controller produces a feedback based controller with respect to the tracking error dynamics. The controller guarantees global asymptotic reference tracking of both trajectory and velocity profile. In addition, it is highlighted that the proposed scheme is able to minimize tracking errors (especially fast converge of lateral error is pointed out). Last but not least, the controller is tuned fast and easily. Based on all these characteristics the controller of [29] can be considered as a suitable option for handling the execution of the emergency escape manoeuvre.

The control laws that derived in [29] regarding the tyre's longitudinal velocity (with respect to vehicle's frame) and angular velocity respectively are:

$$v_x(t) = v_{ref}(t)\cos e_\psi(t) + r_x \tanh k_x e_{xl} \tag{4-51}$$

$$\omega(t) = \dot{\psi_{ref}}(t) + k_y v_{ref}(t)\sin c(e_\psi(t))e_{yl}(t)\sqrt{\frac{c}{1+c(e_{xl}^2+e_{yl}^2)}} + r_\psi \tanh k_\psi e_\psi(t) \tag{4-52}$$

where the positive constants $(c, k_x, k_y, k_\psi, r_x, r_\psi)$ are the tuning parameters of the controller. They are intuitively by observing the performance in the time domain.

In Chapter 3 it was explained that the inputs for the 3-Degrees of Freedom (DoF) dynamic vehicle model are the steering angle δ_f and the linear tyre velocity v. Thus, they have to be calculated by taking into account the signals derived above. According to [30], by considering trigonometric relations it is derived that:

$$v(t) = \frac{v_x(t)}{\cos\delta(t)} \tag{4-53}$$

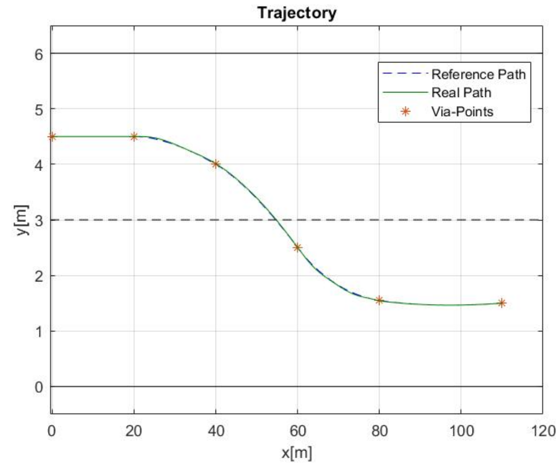
$$\delta_f(t) = \arctan(\frac{(l_1)\omega(t)}{v_x(t)}) \tag{4-54}$$

4-5-2 Evaluation

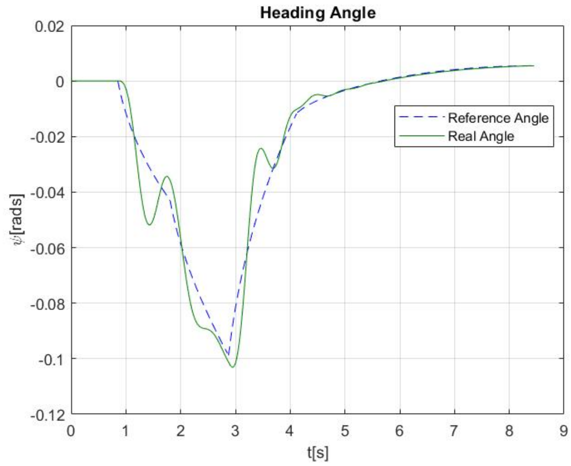
The emergency escape manoeuvre is executed in a closed-loop formation with the tracking controller. It is important to examine whether the designed escape manoeuvre can be tracked efficiently while simultaneously maintaining the desired velocity profile. The metrics that would be taken into account are the tracking errors and the deviation from the reference velocity. Since this thesis is trying to address a real problem in active lanes it is important to ensure that the error that arises between the desired and realized trajectory in values that do not cause safety issues. More specifically, if the lateral error is too big it means that a part of the vehicle still lies into the active lane. Therefore, the minimal risk condition is not achieved and the emergency escape manoeuvre is has failed to fulfill its target.

It has to be noted that in this section, a single emergency escape manoeuvre is evaluated. As explained in the next section this manoeuvre is used as a prototype that forms the basis for further extension of the design scheme to cope with different initial conditions (providing corresponding emergency escape manoeuvre for each occasion). As a result, it is important to ensure that the trajectory tracking performance of the prototype manoeuvre is sufficient before proceeding to the robustness analysis.

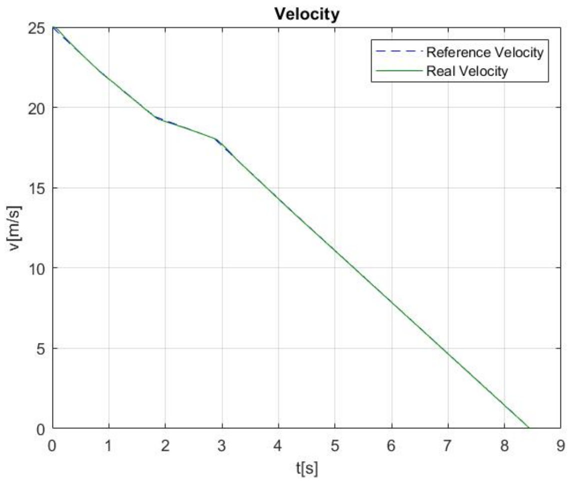
The Figures 4-6a and 4-6b show the tracking performance of the applied controller during the execution of the prototype emergency escape manoeuvre regarding truck's position and orientation. It can be seen that the emergency escape manoeuvre can be tracked properly. The vehicle starts from the middle of the active lane and by performing an S-shape manoeuvre reaches the middle of the shoulder after $110m$. At both figures it seems that the tracking errors are very small and there is not much deviation among reference and real values. Similarly, in Figure 4-6c the tracking performance of the desired speed profile is presented. It can be noticed that besides a slight overshoot at the beginning of the movement and at the beginning of segments with significant change in deceleration, the overall performance is very good and very small error is achieved too.



(a) Tracking of the emergency escape manoeuvre in longitudinal and lateral coordinates



(b) Tracking of heading angle of the emergency escape manoeuvre



(c) Reference and desired velocity response

Figure 4-6: Tracking performance of the emergency escape manoeuvre

However, in order to have a better understanding a closer look must be taken to the numerical values of the tracking errors. Besides the maximum values, another interesting and widely used metric to evaluate the performance of the emergency escape manoeuvre is the Root Mean Square Error (RMSE) between vehicle's state (position, heading angle, velocity) and reference state. RMSE is the average error among compared quantities and is considered to be a generally accurate metric. The formula of RMSE is given by:

$$RMSE_s = \sqrt{\frac{\sum_{i=1}^{n}(s_i - \hat{s}_i)^2}{n}} \tag{4-55}$$

where i is the variable index, n the number of data points, s is the observed time series and $\hat{s}$ is the referenced time series. The outcome is presented in Table 4-1.

Table 4-1: RMSE between vehicle's state and reference state

State	RMSE	Max Error	Final Error
$x[m]$	0.0290	0.0486	0.0100
$y[m]$	0.0070	0.0200	0.0027
$\psi[rads]$	0.0066	0.0221	0.0008
$v[m/s]$	0.0344	0.1537	0.0104

Table 4-1 illustrates the most interesting insights regarding the emergency escape manoeuvre's tracking performance. It presents the RMSE of the several states compared to the reference value throughout the manoeuvre's execution, the maximum error noticed during the execution and the converged error value after the execution.

The worst tracking performance based on RMSE is regarding the truck's longitudinal position and velocity. They are around five times bigger than the corresponding errors of lateral position and heading angle, which are around 0.0070 meters and rads, respectively. In terms of maximum error, lateral position and heading angle have the lowest deviation from the reference values, striking around 0.0200 meters and rads correspondingly. Meanwhile, the maximum error noticed in the longitudinal direction is just around 0.02 meters higher than the corresponding lateral maximum error. However, the velocity error seems to peak at $0.1537m/s$, much higher than the rest error. Furthermore, it is essential to notice that all states manage to converge to a value very close to the reference one, as denoted by the final errors. More specifically, the final error regarding the longitudinal position and velocity is around 0.01 meters and meters per second, respectively, while the other states have a value close to zero.

Overall, it can be noticed that a good tracking performance of the prototype emergency escape manoeuvre is achieved. The error throughout the movement regarding the lateral position and heading direction denotes minimal deviation from the desired values. More specifically, these values practically mean that the vehicle stops in the desired location entirely outside of the active lane. As a result, minimal risk condition is achieved. Slightly worse performance is seen regarding the longitudinal direction but remains in low values. The error regarding velocity is slightly higher and as already mentioned, arises from small overshoots at the beginning of each segment. This is denoted by the difference between the $RMSE_v$ and the corresponding maximum error, which supports the argument that the deviation from the reference value is reduced throughout the rest of the manoeuvre. It has to be noted that the performance regarding velocity and longitudinal position can be improved if bigger corresponding controller gains are applied. However, this leads to a violation of deceleration's defined requirements.

Completing the evaluation is also required to check for the maximum absolute value of lateral and longitudinal deceleration that occurs throughout the movement. The truck's maximum lateral deceleration while executing the escape manoeuvre is found at $4.5142m/s^2$. The corresponding value for the longitudinal direction is $3.6149m/s^2$. Both values satisfy the design specifications defined.

4-5-3 Robustness

So far, the emergency escape manoeuvre has been evaluated based on a pre-computed single escape manoeuvre. However, it is crucial to proceed with a further examination to analyze how the system responds to varying parameters and check its robustness according to different operational conditions. Then it will be possible to conclude whether the controller performance is indeed satisfying.

In this work, it is assumed that a manoeuvre planner assigns velocity to the corresponding via-point. As a result, the structure of the path and velocities are known a priori. Nevertheless, even if the via-points and the path are fixed, the trajectory is not fixed, as the speed profile would be different for different initial speeds. Therefore, the emergency escape manoeuvre should be triggered at any time and adjust the velocity profile concerning initial speed. In this work, it is proposed to have a pre-computed escape manoeuvre that will adjust to different initial conditions and still provide the desired outcome.

Triggering the escape manoeuvre is achieved at any time by shifting the initial position of the first via-point with respect to the truck's current position. However, it is required to scale down the corresponding velocities at each via-point and then re-compute the manoeuvre to achieve robustness regarding changes in the truck's initial speed. Since the emergency escape manoeuvre structure was initially designed concerning maximum allowable speed in the highway, scaling down velocities does not expect to violate any other restrictions that could yield a non-feasible trajectory. It is guaranteed that no violation of maximum desired deceleration is caused because lower velocities at the same distances will be considered. However, it is essential to ensure the restriction of keep satisfying the lowest allowable speed limit in the active lane. Additionally, it is needed to see how tracking error changes at different speeds.

It is *a priori* known that the truck exits the active lane just before the fourth via-point. Consequently, the design of the scaling down can be separated into two cases. The procedure followed to achieve this can also be seen in the Algorithm 1.

The pre-computed vector v assumes an initial speed of $v(1) = 90km/h$. If v_{init} (current velocity of truck) is less than $90km/h$ and $v(4) * \frac{v_{init}}{v(1)}$ is greater than $60km/h$, then the whole velocity profile can be scaled down by simply multiplying it by a scaling factor P which is calculated as:

$$P = \frac{v_{init}}{v(1)} \tag{4-56}$$

Then the new velocity vector is given by:

$$v_{new} = Pv \tag{4-57}$$

Otherwise a scale and shift method is applied in order to set the first four elements of velocity vector start from truck's initial velocity and ends to 60km/h. The rest elements of the velocity vector remain the same.

First the initial and final velocities of the existed vector (taking account only first four elements) are defined:

$$A = v(1) \tag{4-58}$$

$$B = v(4) \tag{4-59}$$

Recall that $v(1) = 90$ and $v(4) = 65$. Then the first four elements of the velocity vector are adjusted as:

$$v_{new}(1:4) = Pv(1:4) + L \tag{4-60}$$

where P and L are the scaling and shifting coefficients respectively, such that:

$$PA + L = v_{init} \tag{4-61}$$

$$PB + L = 60 \tag{4-62}$$

where v_{init} and 60 are the new maximum and minimum desired values respectively for the vector that is scaled. In the end, the vector v_{new} is filled with rest elements of initial velocity vector v.

Algorithm 1: Algorithm to scale down via-points velocities in order to execute the emergency escape manoeuvre in under different initial velocities

Scale or scale and shift velocity

Input : Velocity vector $v \in \mathbb{R}^6$ and initial velocity $v_{init} \in \mathbb{R}$

Output: Updated velocity vector $v \in \mathbb{R}^6$

$P = \frac{v_{init}}{v(1)}$

$v_{new} = Pv$

if $v_{new}(4) \geq 60$ **then**

  $v = v_{new}$

  return v

else

  $A = v(1)$

  $B = v(4)$

  $P = \frac{(v_{init} - 60)}{A - B}$

  $L = 60 - PB$

  $v_{new}(1:4) = Pv(1:4) + L$

  $v(1:4) = v_{new}(1:4)$

  return v

end

The scheme is tested for multiple initial velocities between 60km/h to 90km/h with precision of 1 decimal place. The metrics used for evaluation are the manoeuvre's desired specifications, the maximum allowable lateral acceleration (α_{lat}) and truck's velocity before exiting the active lane (v_{exit}). In addition, the tracking performance of the controller is considered by the means of RMSE. For terms of simplicity the outcomes of the analysis are presented in

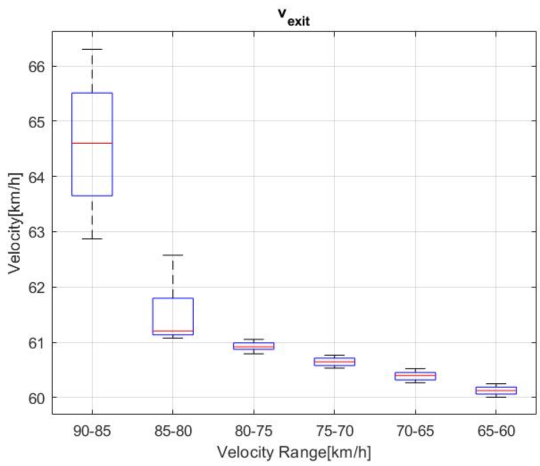
Table 4-2: Robustness Analysis

	Average RMSE					
v_{init} [km/h]	$x[m]$	$y[m]$	$\psi[rads]$	$v[m/s]$	Min v_{exit} [km/h]	Max $\alpha_{lat}[m/s^2]$
90 - 85	0.0263	0.0059	0.0054	0.0316	62.8695	4.7169
85 - 80	0.0220	0.0052	0.0045	0.0258	61.0762	3.9569
80 - 75	0.0193	0.0051	0.0043	0.0215	60.7899	3.7733
75 - 70	0.0173	0.0050	0.0042	0.0192	60.5319	3.9036
70 - 65	0.0164	0.0049	0.0041	0.0187	60.2674	4.0466
65 - 60	0.0159	0.0048	0.0039	0.0183	60.0054	3.9063

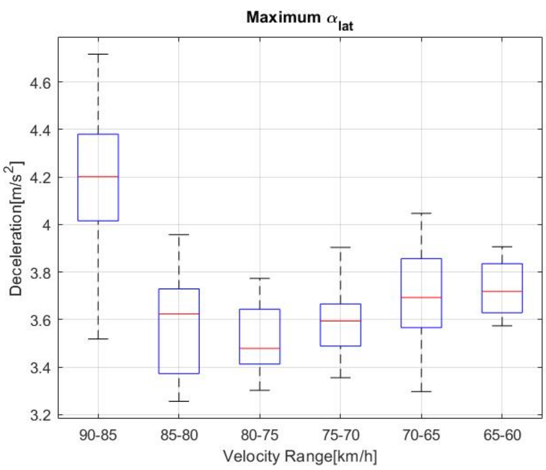
group of velocities. Average values for RMSE and maximum and minimum values that were noticed on every velocity group range regarding v_{exit} and α_{lat} are summarized in Table 4-2.

Table 4-2 illustrates the robustness analysis operated to evaluate the control scheme of the emergency escape manoeuvre. It can be seen that the scheme can react positively in different velocity initial conditions. The tracking performance and the driving objectives are at the same levels as the prototype manoeuvre. More specifically, the average RMSE of every velocity group (regarding truck's states comparing to reference values) is still held in small values. As a result, the designed scheme's tracking performance is robust to changes in the truck's current velocity when the escape manoeuvre has to be triggered. It also has to be noted that the lower the truck's initial velocity, the better the control scheme's tracking performance is noticed. The average RMSE of longitudinal and lateral position in group velocity of $65 - 60km/h$ is around $0.01m$ and $0.001m$, respectively. Similarly, the $RMSE_v$ and the $RMSE_\psi$ of the last group of velocities are around 0.02 meters per second and rads respectively smaller than the first ones. Furthermore, the proposed velocity vector scaling algorithm that aims to impart robustness to the designed scheme successfully considers the limitations regarding maximum acceptable lateral deceleration and minimum allowable speed in the active lane accordingly. It can be seen that on every occasion, the highest value of α_{lat} does not exceed the upper limit of $0.5g$. As expected, since the position of via-points remains unchanged, scaling the prototype escape manoeuvre down to lower velocities does not cause any issues. It has to be noted that the same argument holds for not violating the maximum desired linear deceleration of around $3.5m/s^2$. Moreover, the lower the initial velocity gets, the lower the exit velocity becomes. In lower initial velocity scenarios, the truck's deceleration in the active lane is minimal due to the shift and scale algorithm that adjusted the via-points velocities concerning the lowest limit of $60km/h$. The difference between the lowest exit velocity noticed between the first and last group velocities is around $3m/s$.

A more analytical representation of the metrics values regarding each velocity range is shown in Figures 4-8 and 4-7 in groups of data through their quartiles. In box-plots, one can notice in every group of data the lowest and largest data point (black lines), the median value of the dataset (red line), as well as the median of the lower half and upper half of the dataset (horizontal box lines). In Figure 4-8 each subfigure presents the RMSE for the corresponding depicted truck's state. It can be seen that there is a minimal deviation of the generated values comparing to the average values for each group that is shown in Table 4-2 for every state. Obviously, the velocity range of $90 - 85km/h$ has a bigger fluctuation concerning the error value. As it is concluded from Table 4-2, the trend is to have a better tracking performance (lower RMSE) at smaller velocities. However, it seems the RMSE tends to converge to a closer range of values as the speed gets lower only regarding Longitudinal(Figure 4-8a) and Velocity(Figure 4-8d) cases. Figure 4-7a shows that the exit velocity is harmonically adjusted concerning the initial truck's velocity. As the velocity range is getting smaller, there is a slight shift in each group's median value. In contrast, in Figure 4-7b, there is a random trend regarding both convergence and magnitude for the rest groups besides the first group of velocities.

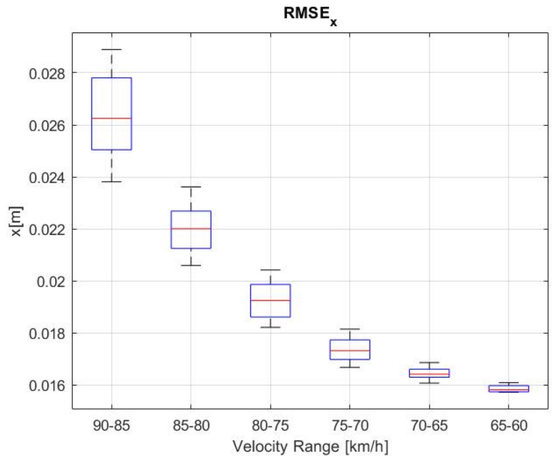


(a) Distribution of the exit velocities that were noticed during the simulation at the different velocity ranges

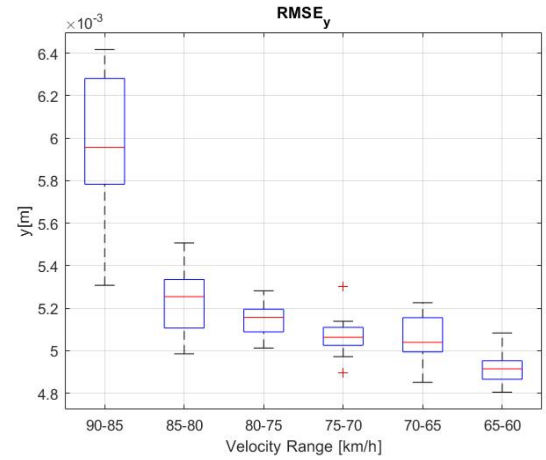


(b) Maximum lateral deceleration distribution presented in absolute values that was noticed during the different velocity ranges

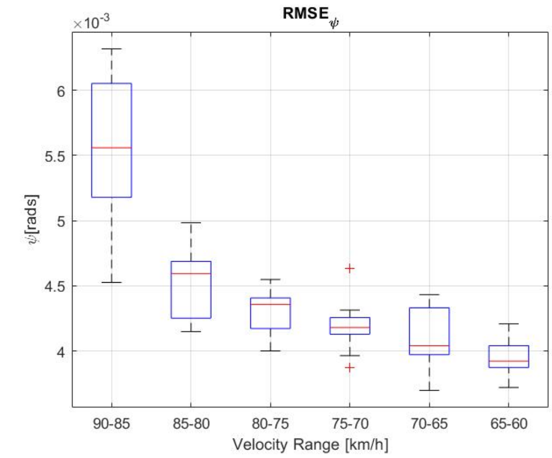
Figure 4-7: Distribution of all the exit velocities and the maximum lateral deceleration of the simulation tests



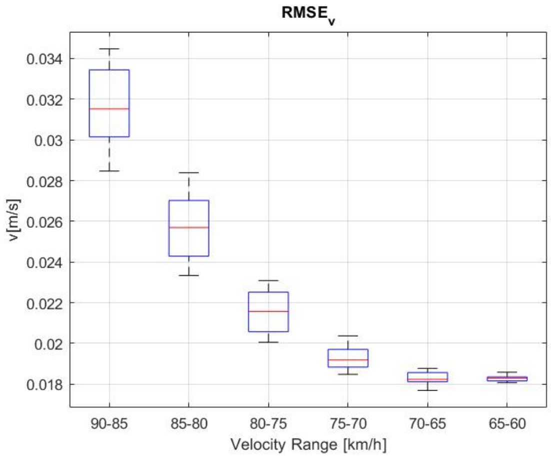
(a) Longitudinal RMSE for different velocity ranges



(b) Lateral RMSE for different velocity ranges



(c) Heading angle RMSE for different velocity ranges



(d) Velocity RMSE for different velocity ranges

Figure 4-8: Analytical RMSE regarding longitudinal and lateral position, heading angle and velocity

4-6 Summary and Remarks

This chapter presented the procedure of designing, implementing, tracking and evaluating the emergency escape manoeuvre. Specifications, constraints and desired characteristics of the manoeuvre were specified for traffic laws and vehicle dynamics. Moreover, all the design specifications aimed to be as much as close to a real-life application. In the literature, there were many available methodologies for generating a trajectory using a corresponding module. It was decided to employ a quintic splines methodology in this work. As already explained, the specific methodology matched all the requirements that have been set and could provide the desired outcome.

In this work, a non-symmetric velocity profile was proposed. The use of elementary physics enabled us to overcome the problem of estimating each segment's final time as denoted in quintic splines methodology of [1]. Furthermore, the utilization of a SA optimization algorithm yielded to minimize yaw rate's high peaks with low computational time and without oscillations in the resulted path. Consequently, extra tuning steps proposed in [1] to overcome such issues were not required. Thus, no violation of the maximum acceptable lateral deceleration was caused. The designed trajectory generator provided a smooth path that led the faulty truck from the middle of the active lane to the middle of the shoulder. Additionally, the velocity profile provided a decelerating movement with deceleration bounded in the limited value. Therefore, all the defined requirements were satisfied.

A typical trajectory tracking controller was then applied to evaluate the tracking performance of the generated manoeuvre. The controller produced its control inputs by taking into account global and local tracking errors. Furthermore, the vehicle dynamic model's inputs regarding tyre velocity and steering angle of the front wheel were computed. The metrics used to evaluate the performance were the RMSE between the trucks' state's simulated values and reference values (position, heading angle, velocity). Additionally, both longitudinal and lateral deceleration were monitored to ensure requirements satisfaction.

As was noticed, the control scheme performed overall at an acceptable level since errors kept very small throughout the movement and converged to values very close to zero. However, the error regarding longitudinal position and velocity tended to reach higher values. It was required to tune the controller such that both driving constraints and good tracking performance were satisfied. Thus, improving the error would cause violations in the longitudinal deceleration limit—consequently, a trade-off between tracking performance and fulfilling design requirements needed to be made. The resulted outcome denoted that it was guaranteed that the truck would escape the active lane and achieve a minimal risk condition following a feasible reference direction. Furthermore, the low computational time required to compute each segment denotes a promising ability to apply the scheme in a real-life scenario.

After successfully evaluating the escape manoeuvre, the control scheme was checked for robustness regarding initial starting conditions. This work proposed utilizing a mechanism that scales and shifts the prototype manoeuvre for several starting velocities by always maintaining the driving objectives. The scheme was tested to a series of initial velocities between 90-60km/h while the same metrics used as in the prototype manoeuvre. The results denoted that the designed control scheme was robust enough since it had similar tracking performance in a variety of initial velocities without violating any constraint. Furthermore, it was concluded that the lower the moving speed, the smaller the tracking errors between real and reference trajectory values. Nevertheless, it is worth mentioning the limitations noticed regarding the scaling mechanism. The length and the shape of the manoeuvre remain always the same. Therefore, it is not efficient in terms that the truck could have stopped in a much shortest distance at several occasions. Furthermore, in a dynamic driving environment a continuously computed emergency manoeuvre is more suitable. However, in order to achieve a time-varying manoeuvre additional modules are required in the design scheme. More explanation regarding how this work can be further extended can be seen in Chapter 6.

During the emergency escape manoeuvre design, it was noticed that the via-points' selection was very critical to the whole performance. The resulted prototype trajectory was very sensitive concerning the location of each via-point. Misplaced via-points could cause increased peaks in yaw rate or violation of the maximum acceptable deceleration. A straightforward solution was to design the manoeuvre with respect to its duration by setting the maximum deceleration for every segment. However, this was not possible because it provided shorter segments with unfeasible cornering because of vehicle dynamics limitations. Another solution could be adopting a velocity profile that keeps a constant velocity throughout the cornering part of the manoeuvre and performs braking while outside of the active lane. This solution may be the most efficient to the side effects caused to the rest of the platoon participants. Unfortunately, executing cornering at high speeds caused too high peaks at the yaw rate. As a result, it was concluded that the vehicle has to slow down during its movement to the active lane.

To sum up, the manoeuvre presented arise from trade-offs regarding all the aspects mentioned above. It is guaranteed to provide a feasible solution for all the defined specifications but is not optimal in any direction. Future work may include optimization in order to maximize velocity and minimize covered distance and total time needed. Furthermore, the introduction of additional modules in the scheme could enable the escape manoeuvre's complete recomputation to adjust the length according to the velocity.

Chapter 5

Platoon Controller

This chapter presents the platooning operation control scheme that is adopted by the vehicles as they move under healthy conditions. This controller has to be able to maintain the desired speed and spacing gap among the vehicles as they move in a straight line in the highway. Moreover, it should be able to provide a good response in the basic platooning manoeuvring like opening and closing gaps that would be used while applying the emergency scenario protocols. As already stated, Cooperative Adaptive Cruise Control (CACC) systems can match the above requirements. A Bidirectional (BD) controller and a customized tuned function controller are derived for the Gap-Regulator and Gap-Closing modes of the platooning controller.

5-1 CACC Design

For the CACC system design the approach presented in [41] is adopted. The CACC system in [41] was designed, implemented and tested on a four-vehicle platoon, with a similar theoretical vehicle dynamics as the one described in Chapter 3. That controller consists of two operating modes. The first mode corresponds to a gap-closing controller that handles the reducing of distance occurred between rest platoon participant(s) and the leading truck (after the faulty truck performed the escape manoeuvre). The second mode denotes a gap regulation controller that takes over after the completion of the join manoeuvre. A constant time-gap spacing policy is applied by providing three available gap settings, 0.6s, 0.9s and 1.1s. The leading is responsible to select the desired time-gap followed by the formation. The values have been selected concerning estimations that guarantee crash avoidance under emergency conditions [7].

The controller in [41] was initially designed as a Predecessor Leader Following (PLF) based CACC, as denoted in Figure 2-2. Therefore, information on the preceding and leader vehicles received from every following vehicle. Influenced by this controller's structure, the scheme has been modified to a BD topology in this thesis. It seems to fit better for the emergency scenario that has to be carried on. As already discussed in Chapter 2 under the BD topology, every vehicle receives information from both the preceding and following vehicles. As a result, when a fluctuation in the velocity occurs at the back of the platoon formation, the interconnected vehicles in front can be notified and adjust accordingly.

Additionally, by setting a two-way communication, the leader can also be influenced by the control actions that arise from the followers' emergency actions. As a result, the leader reacts immediately to the second vehicle's disruption. Its velocity is automatically adjusted, so there is no longer need to examine how leader should respond during the emergency state by introducing additional modules to the control scheme.

5-2 Gap Regulation Controller

As already mentioned the CACC gap regulation controller is responsible for handling and maintaining the car-following policy according to the selected time gap and velocity. The CACC system structure can be seen in the Figure 5-1. The controller is designed with respect to a typical PD-control structure [43] that aims to reduce the errors described in Equations (5-1) - (5-4) below. It can be seen that all the relevant information is collected from the corresponding vehicles and eventually the desired speed is calculated and passed as control signal u_i to vehicle dynamics. It has to be noted that x_{i-1}, x_i, x_{i+1} represent the position of preceding, ego and following truck respectively, while v_{i-1}, v_i, v_{i+1} the corresponding velocities. Moreover, the target speed u_{i-1} is the control signal of the preceding vehicle and acts as a feed-forward term in the controller.

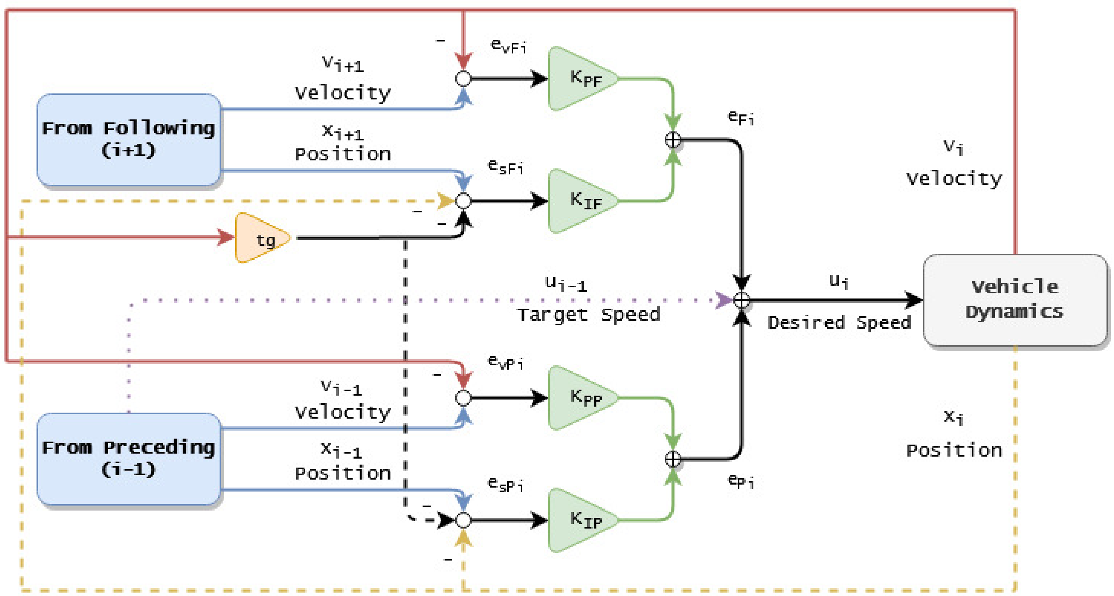


Figure 5-1: CACC vehicle i control structure

The controller is formulated by taking into account errors relative to the corresponding following and preceding vehicle. These errors are denoted as $e_{F_i}(t)$ and $e_{P_i}(t)$ respectively and are defined as:

$$e_{F_i}(t) = K_{PF} e_{vF_i}(t) + K_{IF} e_{sF_i}(t) \tag{5-1}$$

$$e_{P_i}(t) = K_{PP} e_{vP_i}(t) + K_{IP} e_{sP_i}(t) \tag{5-2}$$

where $e_{sF_i}(t)$ and $e_{sP_i}(t)$ are the spacing errors, while $e_{vF_i}(t)$ and $e_{vP_i}(t)$ are the velocity errors. Furthermore, K_{PF}, K_{IF}, K_{PP} and K_{IP} are the controller gains.

The spacing and velocity errors relative to the following vehicle are defined as:

$$e_{sF_i}(t) = x_{i+1}(t) - x_i(t) - t_g v_i(t) \tag{5-3}$$

$$e_{vF_i}(t) = v_{i+1}(t) - v_i(t) \tag{5-4}$$

Similarly, the spacing and velocity errors relative to the preceding vehicle are defined as:

$$e_{sP_i}(t) = x_{i-1}(t) - x_i(t) - t_g v_i(t) \tag{5-5}$$

$$e_{vP_i}(t) = v_{i-1}(t) - v_i(t) \tag{5-6}$$

5-2-1 String Stability

The Gap-Regulator controller can be easily tuned in order to guarantee stability in the formation. However, in [49] it was shown that is not enough to ensure string stability too. According to [13] there are many available options in the literature to check for string stability for vehicular platoon control. As already mentioned, a successful string stability test is a decisive metric for the platoon controller evaluation. Recall that platoon controller is applied under healthy conditions when the formation is supposed to travel on a straight line. Therefore, as denoted in Chapter 3, the lateral dynamics of the vehicle model are canceled out on this occasion. As a result, the nonlinear dynamics can be assumed as a linear system under this region of operation. For this purpose, a linear approximation of the dynamics is sufficient to proceed with the string stability test.

In [42] string stability is defined in the frequency domain as:

$$|SS(s)| = |\frac{x_i(s)}{x_{i-1}(s)}| \leq 1 \tag{5-7}$$

where i is the place of vehicle in the formation.

In [41] a string stability analysis has been executed in the frequency domain. The BD controller used in this work has the same structure as in the PLF topology used in [41]. The difference is that the signal coming from the following truck substitutes the signal coming from the formation leader for each truck. Therefore, in this work the same analysis can be replicated using the mathematical relations derived in [41]. It is also important to mention that there are already in the literature approaches that prove string stability of PLF and BD structures simultaneously [48].

According to [41] the control structure presented in Figure 5-1 can be represented as control structure block diagram as denoted in Figure 5-2.

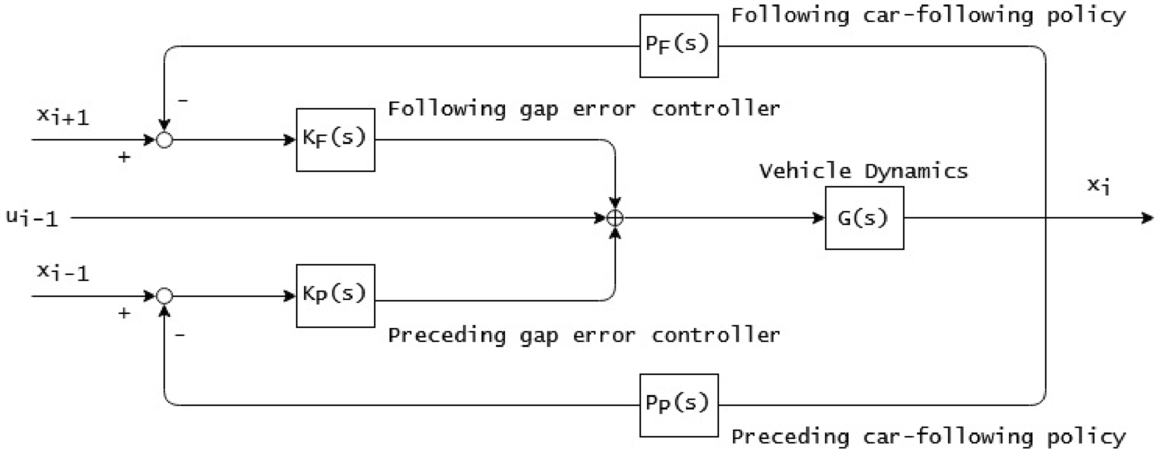


Figure 5-2: CACC control structure block diagram

As a result, the transfer function describing the connection between the ego-vehicle and its predecessor is calculated as:

$$x_i(s) = \frac{G(s)K_P(s)}{1 + G(s)[K_P(s)P_P(s) + K_F(s)P_F(s)]} x_{i-1}(s) \tag{5-8}$$

The PD controller in frequency domain is translated as:

$$K_P(s) = k_1 s + k_2 \tag{5-9}$$

$$K_F(s) = k_3 s + k_4 \tag{5-10}$$

where k_1, k_2, k_3, k_4 are the gains.

Furthermore, car-following policies are given by:

$$P_P(s) = h_P s + 1 \tag{5-11}$$

$$P_F(s) = h_F s + 1 \tag{5-12}$$

where h_P and h_F are the desired time-gap values.

Finally, the position for a vehicle in the formation is defined as:

$$x_i(s) = G(s)u_i(s) \tag{5-13}$$

where $G(s)$ is the transfer function of vehicle dynamics and u_i is the target speed command used as control input.

Vehicle Dynamics Transfer Function

As in [41], a transfer function of the vehicle dynamic model has to be extracted. It is used in the evaluation of the string stability of the controller. The identification procedure is executed concerning the vehicle model's behavior to speed changes applied in the form of a reference composed of multiple sinusoids with various frequencies. The input is selected as per the suggested instructions when applying a system identification procedure for a nonlinear system. The input regarding the steering angle is set to zero. The test data can be seen in Figure 5-3 below.

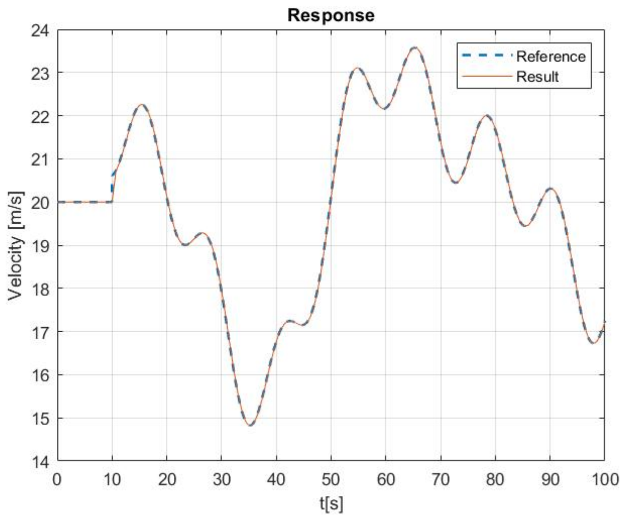


Figure 5-3: Vehicle Dynamics Longitudinal Response

Using the black box identification method, a transfer function can be extracted from the vehicle dynamic model. According to the structure of the linear approximation of the dynamics, a second-order model has to be selected (correspond to the two remaining states regarding longitudinal dynamics). Among the candidate transfer functions, it was decided to proceed with one consisting of one zero and two poles which had the greatest matching percentage. This candidate provided a fit estimation of 98.54%. The identified model that arise from the test data has the following form:

$$G(s) = \frac{8216s + 2694}{s^2 + 8275s + 2694} \tag{5-14}$$

Tuning in the Frequency Domain

The controller is tuned based on Equation's (5-7) criterion regarding string stability. The procedure is operated using the MATLAB toolbox and the target is to maintain the Bode magnitude below the unity gain. Final tuning is also executed concerning the platoon's performance in terms of the time-gap following and speed target policies.

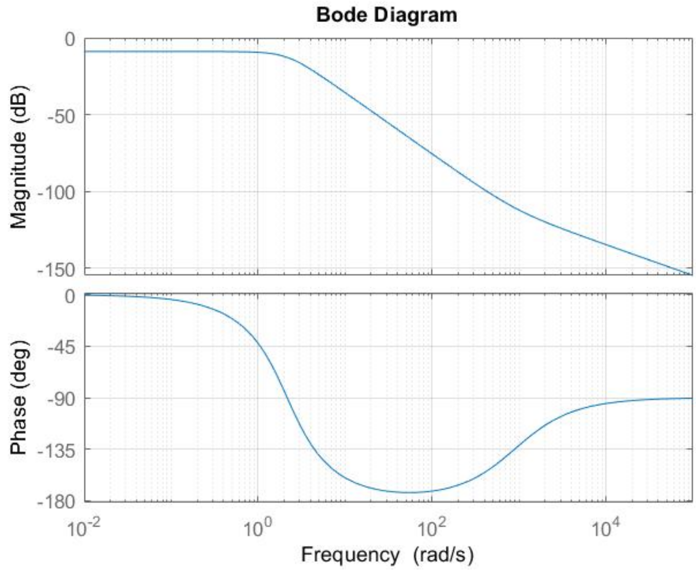


Figure 5-4: String Stability Frequency Analysis

Figure 5-4 shows that the string stability criterion is satisfied during the tuning of the CACC. Of course, much information can also be extracted by looking at bode plots of a system, but further analysis is out of this work's scope. The derived control gains are presented in Table 5-1. It can be noticed that the gain aiming to minimize the error of the velocity with the following vehicle was higher than the corresponding error regarding the preceding truck velocity. On the other hand, the gain to reduce the time gap error with the preceding truck is significantly higher than the one related to the following truck. The reason is that the controller has to keep up with maintaining both the desired time-gap and velocity. As a result, one action affects the other as the performance related to both the preceding and the following truck is equally essential for the ego truck. Moreover, the feed-forward term increases the sensitivity of the control actions related to the preceding truck. Therefore, gain $k2$ holds very small in order to avoid unstable outcomes of the controller. It has to be noted that the same control gains were used for the different time-gap following policies that mentioned in the beginning of this chapter since they still satisfied the string stability criteria.

Table 5-1: K_P and K_F Controller Gains

k1	k2	k3	k4
0.9	0.001	0.6	0.9

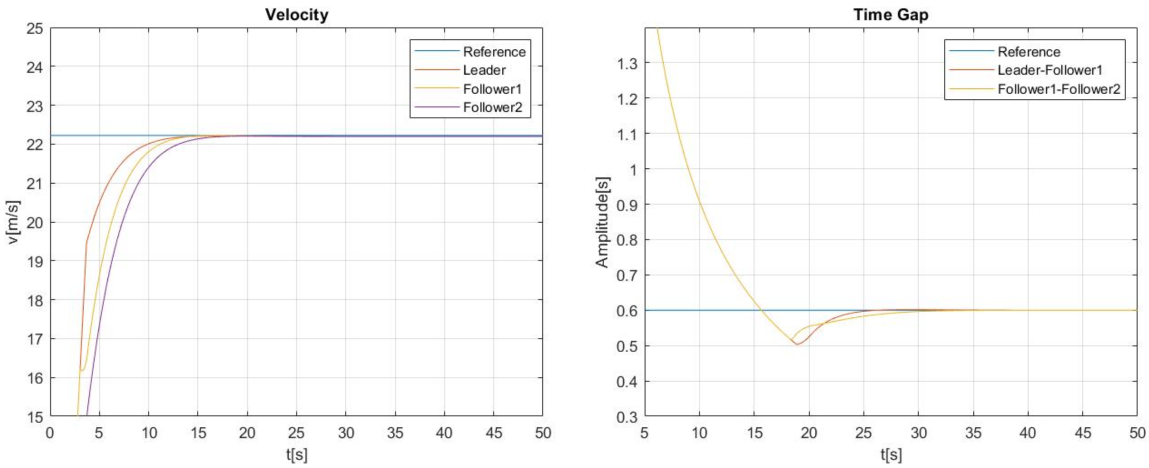
5-2-2 Evaluation

Several tests have been executed to evaluate the derived controller's functionality by providing various signals for the desired speed and the following policy. It is important to mention that the employed tests were performed on the full model of vehicle dynamics.

- Constant Gap - Constant Speed

For the first test scenarios for the evaluation of the CACC system, a simple task is assigned. The platoon vehicles are required to maintain a constant speed of $80km/h$ ($22.22m/s$) while following each other from a distance of $0.6s$.

In Figures 5-5a and 5-5b it can be seen that the vehicles of the platoon formation smoothly reach the desired speed and selected time-gap following policy. Figure 5-5a shows that the leader of the formation reaches the desired speed at around the 32^{th} second. Although it seems like a small delay in the response, the lag arises from the constant time-gap following policy. Figure 5-5b shows an undershoot occurrence in both cases' response before stabilizing at the desired time-gap. It is caused because the truck's initial position was greater than $1.1s$ and the gap-closing controller mode was not included in this series of simulations. The results illustrate that all trucks converge to the desired platoon requirements. Therefore the formation and maintenance test is satisfied.



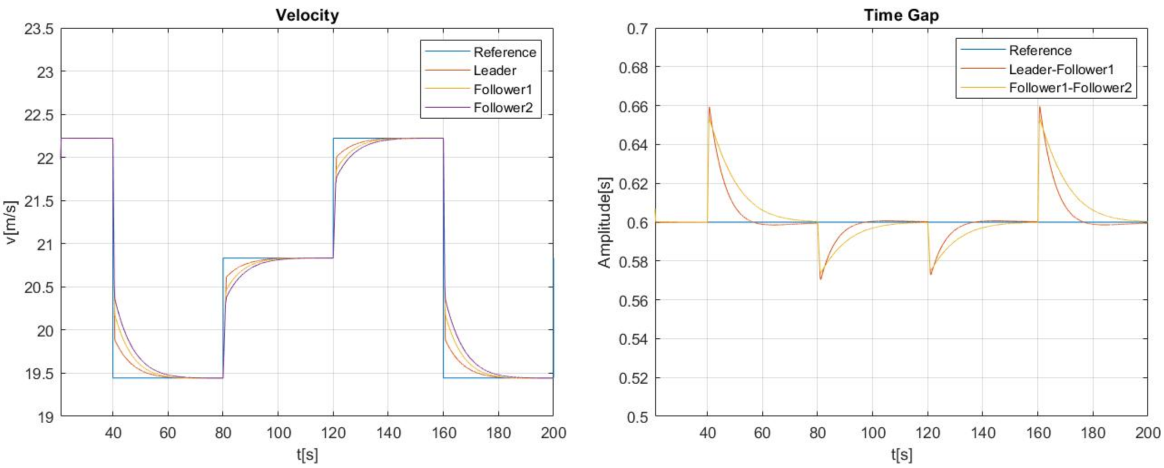
(a) Constant Velocity Target **(b)** Constant Time Gap Target

Figure 5-5: Vehicle responses in desired platoon target values

- Constant Gap - Change Speed

In the second test the CACC system has to be able to maintain a constant gap of 0.6s among the vehicles, while the vehicles fluctuate their velocity among $80km/h - 70km/h$ ($22.22m/s - 19.50m/s$). Initially, the vehicles are moving with $80km/h$ with $0.6s$ spacing between them.

Figure 5-6a shows that all the trucks can track the desired speed and respond well at both acceleration and deceleration needs. It can also be noticed that there is a lag in the speed response of both of the followers. The lag arises from the fact that the used CACC system is a time-gap following policy and not a spacing following policy. As a result, each truck's velocity is changed as the goal to maintain the desired gap needs to be achieved too. Figure 5-6b presents the attempt to maintain the trucks' desired spacing policy. As expected, at the points where speed change is triggered, there is an obvious spacing gap error. The error arises from the difference in the trucks' velocity response explained in the previous figure. However, on every occasion, the time gap of both Leader-Follower1 and Follower1-Follower2 converges to the desired value.

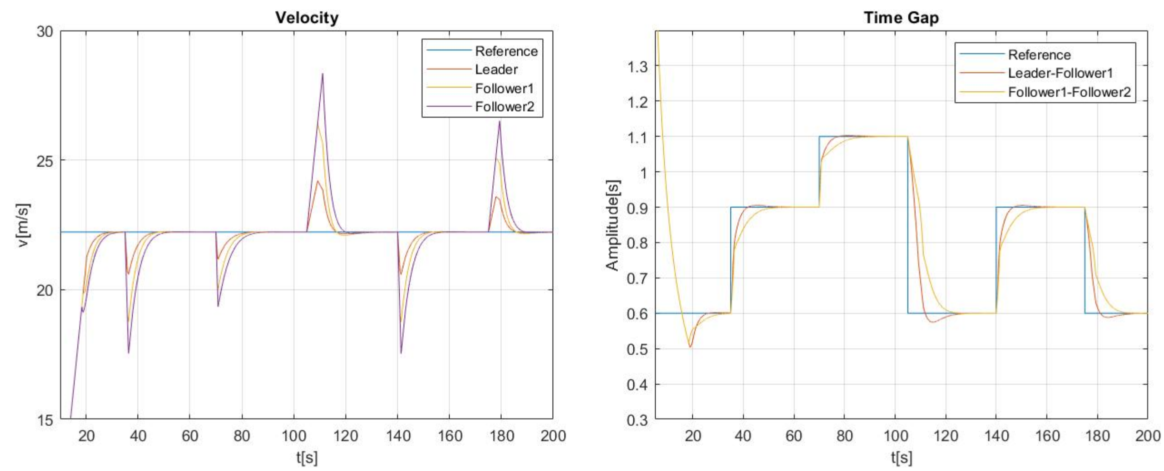


(a) Changing Velocity while on the move **(b)** Impact on the Time Gap

Figure 5-6: Vehicle responses in desired platoon target values

- Change Gap - Constant Speed I

In the third test the behavior of the CACC system is examined when a change in the time-gap preference occurs. The controller has to be able to maintain a constant speed of $80km/h$ ($22.22m/s$) for the platoon formation, while the time-gap among the trucks is fluctuated. Every $35s$ the desired time-gap changes from $0.6s$ to $0.9s$ and $1.1s$ circularly.



(a) Impact in the Velocity **(b)** Changing Time Gap while on the move

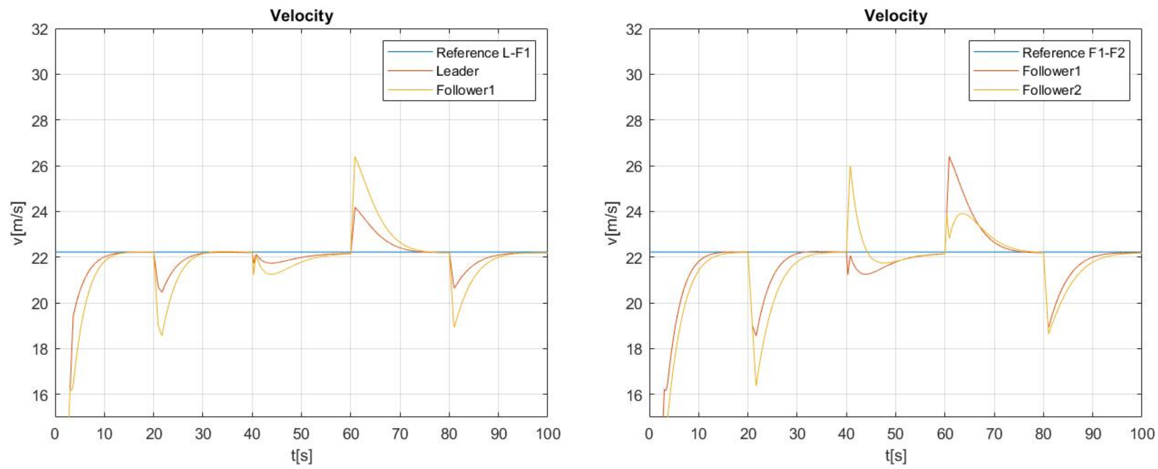
Figure 5-7: Vehicle responses in desired platoon target values

Figure 5-7b shows that the trucks need to achieve the following policy of $0.6s$ at the beginning of their movement. It can be noticed that the initial attempt of the controller results in a significant undershoot. It is caused because the trucks are initially located in a distance more significant than $1.1s$ between them and the gap-closing controller is not used in this set of tests. The gap-closing controller's presence can eliminate that kind of response, as shown in later chapters. Then on the 35^{th} second, the desired time-gap is set at $0.9s$. The time-gap in both cases reaches the desired value. One can say that the transition of the Leader - Follower1 time-gap to the desired one is slightly smoother than the one regarding Follower1 - Follower2. However, both exhibited performances do not present any overshoot or extreme sharp change. The next transition to the $1.1s$ time-gap setting has the same behavior. Finally, the trucks are required to return from the longest to the closest following policy and no significant change in the well-performed response can be noticed. In Figure 5-7a the impact of the time-gap setting changes on the platoon participants' velocities can be seen. It can be noticed that trucks accelerate or decelerate according to whether opening or closing the gap is required. It has to be noted that the response is bounded to accelerating and decelerating limitations of the vehicles, but no limit is set for the maximum and minimum available speeds. Therefore, at every change in the gap setting, the trucks initially take advantage of their maximum acceptable acceleration or deceleration and linearly change their velocity. Afterward, every truck's speed smoothly converges to the desired speed simultaneously to the desired gap, as noticed in Figure 5-7b. The sharp response at the beginning of every change is due to the instantly received change in the time-gap setting. As expected, the velocity error regarding trucks and desired velocity increases as moving to the end of the platoon. This is due need for the platoon's last vehicle to minimize larger position error with respect to the leader.

- Change Gap - Constant Speed II

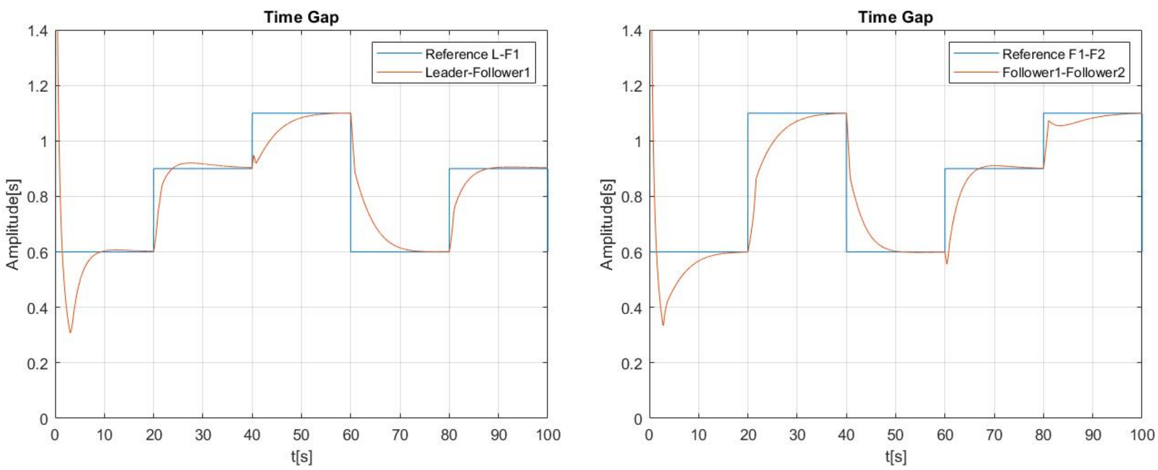
Emergencies required the platoon formation to follow heterogeneous strategy regarding the following policy (open gap in a specific place). Therefore, in this test, an extreme scenario is executed. The desired time-gap of each pair is different from the other. The formation also has to maintain a constant speed while on the move.

Figures 5-9a and 5-9b present the response of each pair of trucks regarding the time gap change correspondingly. It can be seen that the same level of performance is maintained as before in both cases. It can also be noticed that the transition of the time gap between Follower1 and Follower2 is slightly smoother than the homogeneous test. It probably happens because Follower2 is required to follow a different strategy (receives a different signal) and it is not affected that much by the changes happening in front. There are also two points (around 65s and 83s) where a slight undershoot occurs but does not affect the overall good performance. The fluctuations in the velocities as shown in Figures 5-8a and 5-8b are similar as before. It can be observed that sometimes the preceding truck has a higher speed error than the corresponding vehicle behind. It arises because of the heterogeneous gap policies applied simultaneously and the different spacing distance that needs to be covered for every vehicle.



(a) Impact in the Velocity Leader - Follower1 **(b)** Impact in the Velocity Follower1 - Follower2

Figure 5-8: Vehicle responses in desired platoon target velocity



(a) Changing Time Gap while on the move Leader - Follower1 **(b)** Changing Time Gap while on the move Follower1 - Follower2

Figure 5-9: Vehicle responses in desired platoon target time gap

5-3 Gap-Closing Controller

The Gap-Closing Controller is the state of the CACC system that handles the smooth transition from closing a large gap to the regular platoon driving of desired values. This mechanism in [41] was designed to smoothly introduce a preceding vehicle to the platoon as it approaches the formation. However, the Gap-Closing Controller used in this work aims to close the gap between the leader and the remaining truck after the faulty one escapes the formation.

It is a linear function that handles the input velocity signals to the trucks depending on their distance between them and the desired acceleration applied (concerning truck capabilities and traffic speed limits). The goal is to close the gap as soon as possible. Therefore, the acceleration provided for the follower should be greater than the one for the leader. The Gap-Closing controller must be tuned in the complete fallback scheme to define a distance close enough that provides a smooth (without overshoot or undershoot) transition to the gap regulator. In other words it is needed to determine its duration before switching back to the Gap-Regulator controller. Furthermore, the corresponding acceleration of the vehicles has to be determined (TBD) too during the simulation tests.

Algorithm 2: Linear function used as a gap-closing controller

```
Input  : Leader's current position and velocity x_L, v_L
         Follower's current position and velocity x_F, v_F
Output: Leader's desired velocity u_L
         Follower's desired velocity u_F
while trucks not close enough do
    a_L ← TBD constant %Leader's acceleration
    a_F ← TBD constant %Follower's acceleration
    u_L ← adjusted accordingly
    u_F ← adjusted accordingly
end
```

5-4 Discussion

This chapter has presented the design, development and evaluation of the platoon controller that would be used under healthy conditions in the formation. As already explained, a CACC system is enough to handle all the required tasks for this thesis's purpose. A previously designed PLF CACC system was used as a base to derive a BD CACC system. The vehicle-following policy is set with desired time gap space among the vehicles. The produced controller consists of two parts: a gap regulator state and a gap closing state. The first part is responsible for handling changes in the desired velocity and following policy setting. The second part provides a smoother transition from larger gaps among the vehicles to normal platoon distances. In other approaches, it can be considered as the mode that initially connects extra vehicles to a platoon while on the move.

The CACC system has successfully been tested for string stability in the frequency domain. The controller was designed based on a linear approximation of the nonlinear vehicle dynamics using a second-order system. Nevertheless, the string stability could still be claimed because the demonstrated analysis is valid, as long as the vehicles move in the linear region of operation as denoted by the longitudinal dynamics due to the absence of steering movement. In the evaluation stage, it was indeed shown that the controller kept the state errors in reasonable values while satisfying the string stability criterion. Furthermore, the CACC system was also tested for the platoon's behavior to different demanding changes. More specifically, the formation provided a nice overall performance regarding opening and closing gaps as well as accelerating and decelerating during the movement. These manoeuvres under healthy conditions are essential for the whole emergency escape manoeuvre scheme. They play a vital role in the preparation before executing the escape manoeuvre and enabling the platoon to continue its journey afterward. For these reasons, it was essential to ensure that they can be executed too.

It is also important to mention that the gap closing controller was not used for evaluation at this stage. It was meant to eliminate the undershoots that occasionally occurred on some of the tests demonstrated above. Most of them took place at the beginning of the movement because initially, the trucks started at rest and slightly distant. Emphasizing in joining manoeuvres of new trucks to the platoon was out of the scope. As a result, there was no need for further evaluation at this point. This controller will be used and evaluated when the whole scheme is completed. It will be responsible for merging Leader and Follower2 after Follower1 abandons the formation.

Chapter 6

Complete Fallback Strategy Scheme

In this chapter, the complete fallback strategy consisting of the emergency escape manoeuvre of a faulty truck in a platoon formation is executed. The proposed control framework is presented by putting all the components together. According to the occasion, a specific safety protocol has to be followed before, during and after the manoeuvre's execution. Two protocols have been derived: the first one triggers the emergency manoeuvre immediately after the failure occurrence and the second after a while. The second protocol application requires a virtual leader vehicle to fill the blind gap of faulty follower caused by its compromised sensor module. In both cases, the rest of the platoon continues its journey after the escape manoeuvre's execution. During the first protocol evaluation, the gap closing controller is tuned as selections are made for the remaining trucks' accelerating profile and the duration before switching to the gap regulator mode. It is important to mention that once protocol 1 is used for tuning the controller there is no need for re-tuning each time protocol 1 is triggered. The second protocol is evaluated concerning the provided time window before executing the escape manoeuvre for the faulty truck.

6-1 Platoon Supervisory Logic

The platoon supervisory logic is derived with respect to the highway's most straightforward scenario while the platoon is on the move. It is assumed that the moment the failure occurs, the faulty truck can immediately execute the escape manoeuvre. Figure 6-1 presents the platoon supervisory logic in the form of a communication protocol. All platoon participants have to apply the protocol until faulty truck parks on the shoulder and rest restore the initial healthy conditions. At a random point of the movement, a fault detection module is assumed to recognize the compromised sensor module of Follower1. Then, platoon participants are informed about the failure with a corresponding signal and the leader immediately permits Follower1 to exit the platoon. While the escape manoeuvre is executed, both Leader and Follower2 adjust their speed accordingly to Follower1, which is still a member of the formation. Due to the Bidirectional (BD) topology of the platoon, the deceleration of Follower1 while executing the emergency escape manoeuvre forces both Follower2 and Leader to decelerate too. As already mentioned it was selected to follow this strategy regarding Leader's movement in order to avoid causing a huge gap between remaining healthy trucks. In addition, keeping the total distance between Leader and Follower2 as small as possible will provide a faster and safer transition back to the normal platoon performance. Once Follower1 is outside the active lane, Leader and Follower2 are informed about their new leader following roles. The exit of Follower1 causes a gap between Leader and Follower2 greater than $1.1s$. Therefore, the gap closing controller is triggered before re-applying the gap regulator mode.

As already mentioned, the challenge in applying this protocol is to tune the gap-closing controller as per its duration and the control signals that it produces. More specifically, it has to be determined how close the trucks have to be brought to achieve a smooth transition to the gap regulator controller. Furthermore, by considering that the maximum acceleration of a truck is around $1m/s$ [3], an appropriate strategy has to be defined regarding the target accelerations for each truck. After several attempts, it was noticed that the Cooperative Adaptive Cruise Control (CACC) controller was unable to achieve both the desired velocity and closing the time-gap to the desired value after the execution of manoeuvre. As a result, a proper ratio according to trucks' acceleration must be derived to implement the protocol successfully.

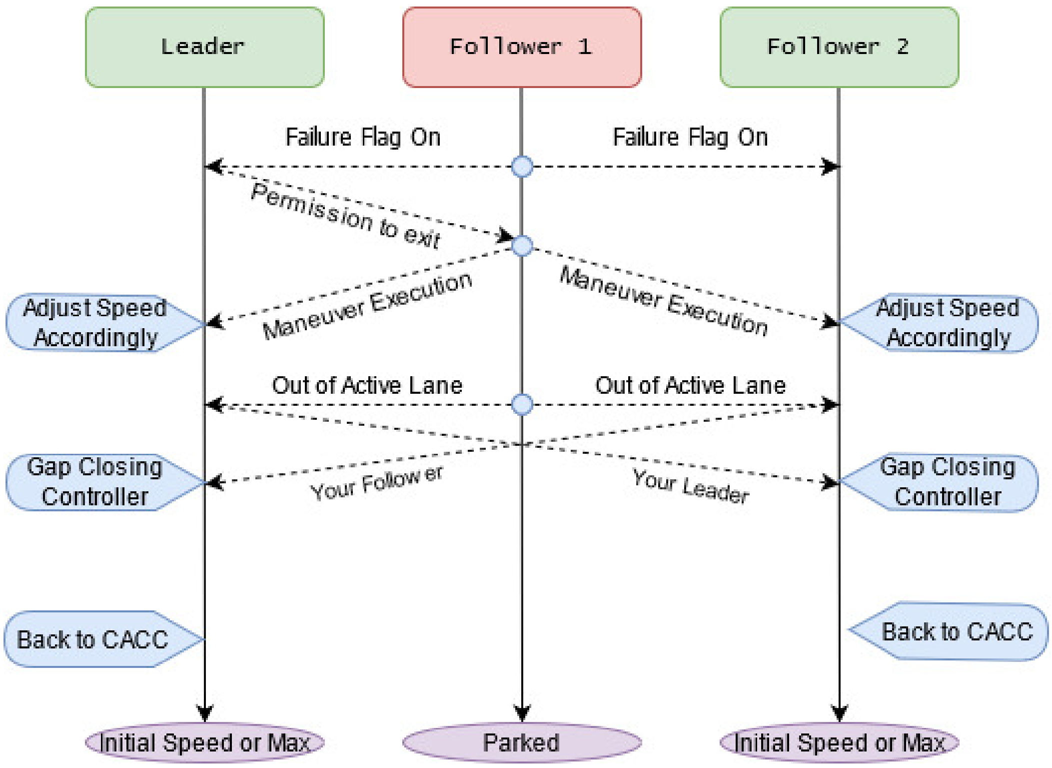
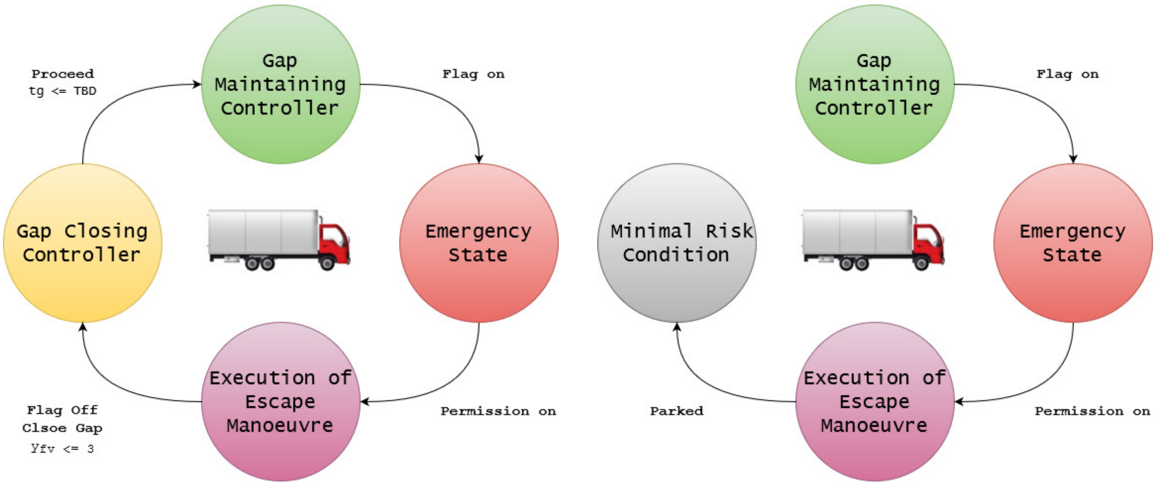


Figure 6-1: Platoon supervisory logic in the form of a communication protocol diagram

6-2 Vehicle Supervisory Logic

The supervisory logic defined in the previous section has to be extended to each truck individually. The proposed emergency escape manoeuvre framework consists of 4 modes of operation as per the functionality and target goal that is applied regarding the healthy and faulty trucks respectively. The schematic of the state machine can be seen in Figure 6-2.



(a) State Machine of healthy vehicle operation modes **(b)** State Machine of faulty vehicle operation modes

Figure 6-2: State Machines of single vehicle operation modes

1. **Gap-Maintaining Controller:** The controller employed under healthy conditions is responsible for maintaining desired velocity and spacing policy. When the failure is detected, a flag is signal is on. Therefore, if $flag == 1$, then transition to the next state.
2. **Emergency Strategy:** In this state Gap-Maintaining controller still can adjust velocity and spacing policy as per the protocol. The leader is responsible for providing permission to execute the escape manoeuvre if the driving conditions allow. Consequently, If $Permission == 1$. then transition to the next state.
3. **Execution of escape manoeuvre:** In this state faulty truck performs the emergency escape manoeuvre that is handled from the trajectory tracking controller. It proceeds to its final state when the escape manoeuvre is completed. The rest of the platoon is controlled by the Gap-Maintaining Controller, which is affected by the faulty truck. It tries to maintain the spacing policy among vehicles. When the faulty truck is outside of the active lane, it is no longer part of the platoon. As a result, if $y_{fv} \leq 3$, then transition to the next state (for healthy truck), while $flag = 0$ and $CG = 1$ (y_{fv} is the lateral position of faulty truck and CG is close gap signal).
4. **Minimal Risk Condition:** This state corresponds only to the faulty truck and refers to the parking mode when it finishes the execution of the escape manoeuvre.
5. **Gap-Closing Controller:** Similarly, this state corresponds only to the healthy trucks. They are connected with their new leader and follower accordingly and the Gap-Closing

controller is applied to reduce the gap between the remaining trucks as caused by the escape manoeuvre. If $tg \leq TBD$, then transition back to the Gap-Maintaining Controller and smoothly retain desired velocity and time gap spacing policy $Proceed = 1$. (tg is the time gap).

6-3 Evaluation

The derived protocol shown in Figure 6-1 has been tested in a series of simulations to evaluate its functionality and efficiency. In the utilized scenarios, the sensor failure occurs at the 60^{th} second of the movement. Initially, trucks are moving with velocity varying between $90km/h$ to $60km/h$ and maintain a time gap of $0.6s$ among each other. After the execution of the escape manoeuvre the newly formed 2-vehicle platoon continues its movement with by restoring the initial velocity and spacing gap, while Follower1 remains steady at the shoulder.

Several strategies have been attempted to define the ratio among the trucks' acceleration and controller duration during the gap closing controller's tuning. The goal was to define the parameters such that not extreme undershoot (provides collision danger) is caused in the time gap spacing policy and allows vehicles to restore movement's desired values and not stuck to unwanted values. Furthermore, it is preferable to complete this process as fast as possible. A global strategy that can adapt under several circumstances is to set Follower2 to travel with the maximum possible acceleration. At the same time, the Leader maintains a constant speed until the time gap between them becomes $0.8s$, before switching to the gap maintaining controller.

The derived control strategy has been evaluated in two different scenarios. In the first one the two-truck platoon has to restore the initial velocity and time gap that were applied before the execution of the emergency escape manoeuvre. In the second one, the trucks have to restore the initial time gap, but proceed with the maximum possible velocity. The utilization and the outcomes of the evaluation are presented in the following subsections.

- Restore initial velocity and time gap

Figure 6-3 shows the platoon participants' position during the movement of one simulation test. It can be seen that Follower1 successfully performed the emergency escape manoeuvre while the rest of the platoon continue their movement.

Not much information can be further extracted from this figure. Thus, it is of great interest to examine the time-gap response among Leader and Follower2 during the movement. Figure 6-5 presents the fluctuation in these two trucks' following policy for different simulated initial velocities. It can be seen that the time-gap between Leader and Follower2 was held at $1.2s$ due to the gap maintaining controller. During the escape manoeuvre's execution, the trucks' distance was increasing until it reached a maximum value. It can be noticed that the higher the velocity of the trucks, the bigger time gap between Leader and Follower2 occurs. The biggest time gap occurs when truck travelled with initial speed of $90km/h$ at around $1.74s$. The time gap between the trucks while moving at $60km/h$ did not increase at all because Follower1 decelerates outside of the active lane and does not affect rest of the trucks.

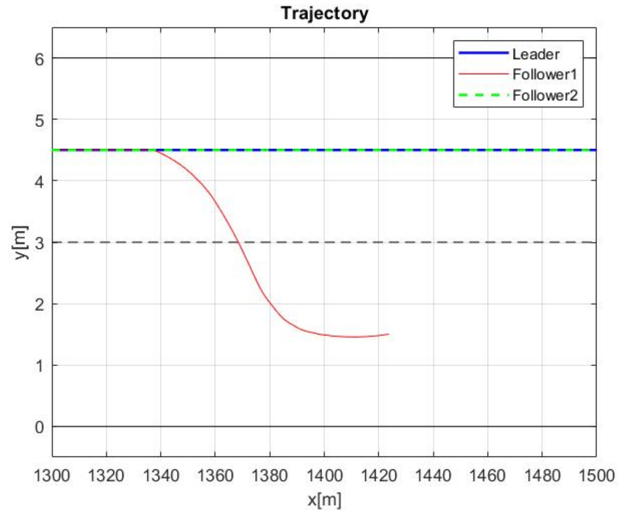


Figure 6-3: Trajectory of the platoon participants

Moreover, at around $63^{th}s$, the Follower1 was outside of the active lane. Consequently, the new 2-vehicle platoon was formed. Afterward, the gap-closing controller managed to reduce the time gap distance to $0.8s$ and then the gap maintaining controller took over again. It can be seen that the bigger the caused time gap, the slower the gap maintaining controller is triggered. Similarly, the smaller the target velocity (same as the initial one for each occasion) the faster the convergence to the desired time gap of $0.6s$. The biggest undershoot occurs when trucks' velocity was at $85km/h$ around 3.5% but do not cause any further issues. Additionally is worth mentioning that the movement of the vehicles can be divided into four parts: healthy movement, fallback movement, gap closing movement and back to healthy movement again. It can also be concluded that the continuous switch of controllers affected the time gap's response at the corresponding stage of the movement.

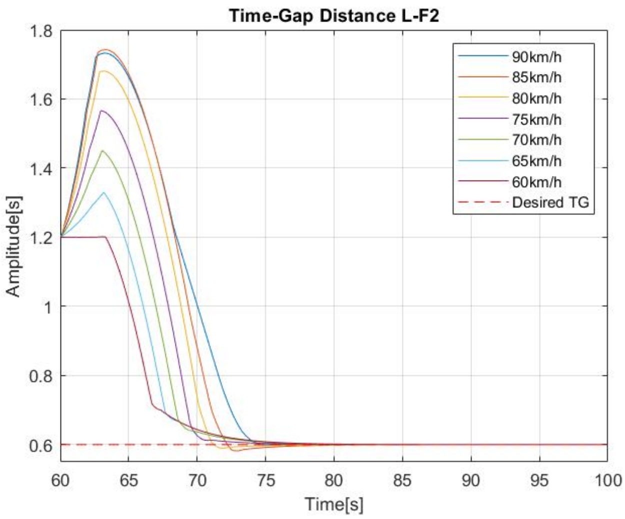


Figure 6-4: Time-Gap distance between Leader and Follower2

During their movement, the trucks' velocity is observed to understand the platoon's performance better while applying the emergency protocol. The velocity profile of Follower1 is already known and has been presented and evaluated in the previous chapter. As a result, Figure 6-4 shows the velocity response of the Leader and Follower2 for the several simulated tests. In general, it can be observed that after the $60^{th} s$, when the emergency escape manoeuvre is executed, both trucks decelerate (besides test at $60 km/h$ where trucks proceed with constant speed). At around the $63^{rd} s$, Follower1 is no longer part of the platoon. Therefore, Leader stops decelerating and continuous with constant speed, while Follower2 accelerates to close the gap. They continue their movement as the gap regulator controller adjusts their speed accordingly and smoothly retains the desired target. Moreover, the velocity error of Follower2 is much higher than Leader's because it is required to travel a greater distance. It can also be seen that the movement of Leader is a lot simpler than Follower2, which requires accelerate and decelerate at a higher rate.

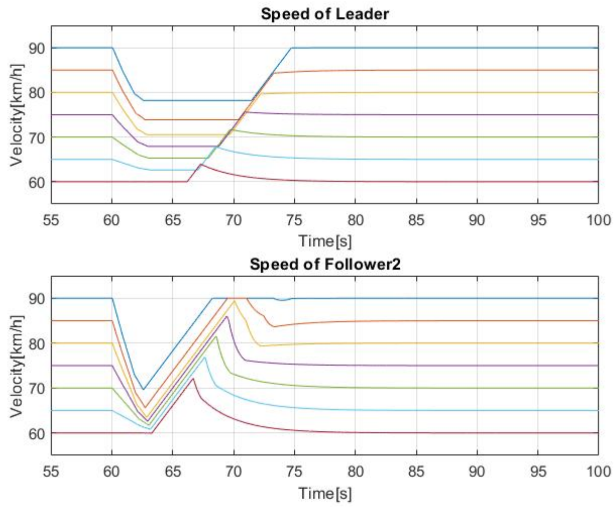


Figure 6-5: Velocity response of Leader and Follower2

- Restore initial time gap and reach maximum velocity

Figure 6-6 shows the time-gap distance between Leader and Follower2 when trying to proceed with the maximum possible velocity ($90 km/h$) after Follower1 abandons the active lane at around $63^{rd} s$. It can be noticed that the response is similar to the previous scenario. However, it is evident that the smaller the trucks' initial velocity (as noticed in the legend), the bigger the undershoot occurrence when they try to close the gap. The selected gap-closing strategy causes it. As a result, at velocities where the resulted gap from the execution of the emergency escape manoeuvre was not very big, the gap closing controller's performance was not that desirable. Although there is space for improvement, it does not violate any safety issues between the platoon participants. Moreover, neither prevents the platoon from converging to the desired target speed.

Similar to the previous scenario, it is of great interest to look at the trucks' velocity response on the different simulations. Figure 6-7 presents that information. It can be seen that, as expected, both trucks starting at different initial velocities decelerate while the emergency escape manoeuvre is executed. Afterward, the Leader continuous with a constant speed, while Follower2 accelerates to close the gap. It can be noticed that the time the gap regulator controller takes over differs according to the initial velocity of the trucks. Although Leader's velocity response is very smooth in terms of fluctuations, Follower2 needs to decelerate and accelerate again during the gap regulation mode. It is caused because the gap maintaining controller tries to satisfy both the desired time-gap and desired velocity targets. Of course, it would be preferable to avoid that kind of fluctuations for Follower2, but the resulted outcome is successful as desired speed is reached.

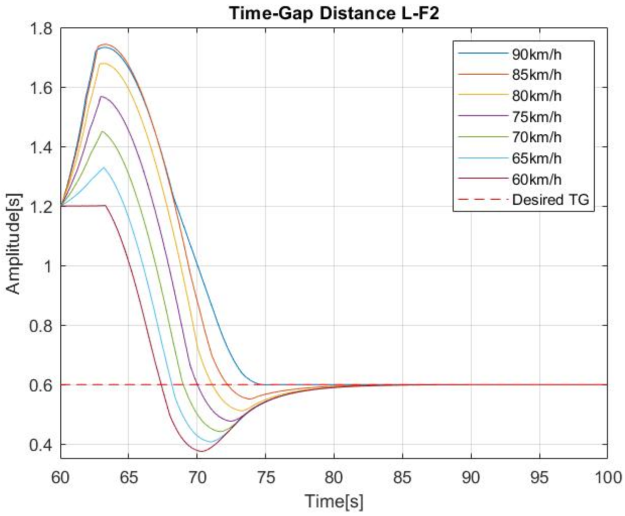


Figure 6-6: Time-Gap distance between Leader and Follower2

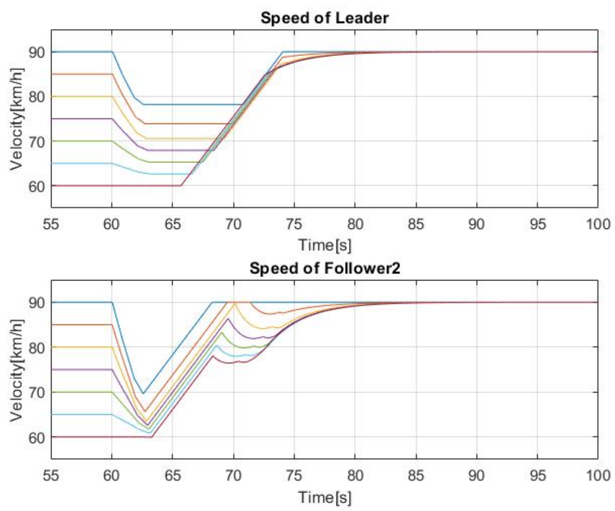


Figure 6-7: Velocity response of Leader and Follower2

6-4 Discussion

This protocol aims to apply the proposed fallback approach in a simple scenario. Assuming clear traffic and an available shoulder to park, the manoeuvre could be executed immediately after detecting the failure. It was shown that the designed framework was able to keep up with the emergency since all of the components worked smoothly. The performance of the vehicles was operated for traffic laws and limitations that had been set. In the first scenario, Leader and Follower2 restore initial velocity and time-gap, while they moved with the maximum possible velocity in the second scenario. Although the outcome of both scenarios was successful, a few limitations were denoted in the second scenario. More specifically, it seems that that the global strategy regarding the gap-regulator controller, as explained in previous sections of this chapter, is not that efficient. The reason is that lower initial velocities cause a bigger undershoot regarding the spacing policy target and Follower2 fluctuates its velocity before stabilizing at the desired value during the gap regulator mode. One solution is to employ an adaptive strategy concerning the initial velocities of trucks (before the manoeuvre execution), but further research around this topic is required. Other than the observed limitations, it can be concluded that the applied scenarios have proved that the protocol followed, guarantee safety among the platoon participants, achieve minimal risk condition when needed and enable rest of the platoon to remain unaffected from the emergency event. Furthermore, the maximum spacing gap between Leader and Follower2 does not affect the wireless communication between them.

6-5 Virtual Leader Mechanism

The previous protocol presented a fallback strategy that leads the truck to stop immediately when the sensor failure was detected. However, there are situations when a more complicated manoeuvre has to be executed before the truck exits from the active lane. Especially in platoon formations as already presented in Chapter 2 when an exit manoeuvre is performed, the trucks are stabilized at a desired velocity. Then the vehicle about to exit opens a gap with its predecessor. Here means that the platoon requires traveling for a few meters before the Leader permits the exit. The problem here is that the faulty truck has a sensor failure. Therefore, it can no longer sense the environment and be a reliable member of the platoon. So, this protocol is derived by overcoming this issue by preparing the conditions for exiting manoeuvre. First of all, influenced by [52], [10], the mechanism of a Virtual Leader is introduced. The Virtual Leader is triggered when the failure occurs and receives the position, velocity and acceleration of the actual Leader at the moment of failure. Therefore, the blind spot of faulty Follower1 is replaced by adopting virtual Leader as its current Leader. In [52] and [10] the virtual leader is simply a double integrator forced to decelerate with the highest possible rate. However, no actual vehicle was supposed to be moving in front of the faulty vehicle in those works. Thus this selection was sufficient. In contrast, there is an actual vehicle (Leader) in this work moving in front. Since the participant vehicles' dynamics are known, they can be used as the virtual Leader too.

The issue here is that Follower1 and Follower2 are affected by the virtual Leader's reaction, which has no connection with the rest of the platoon. As a result, it is expected to notice a slight difference in the performance between the virtual Leader and the actual Leader

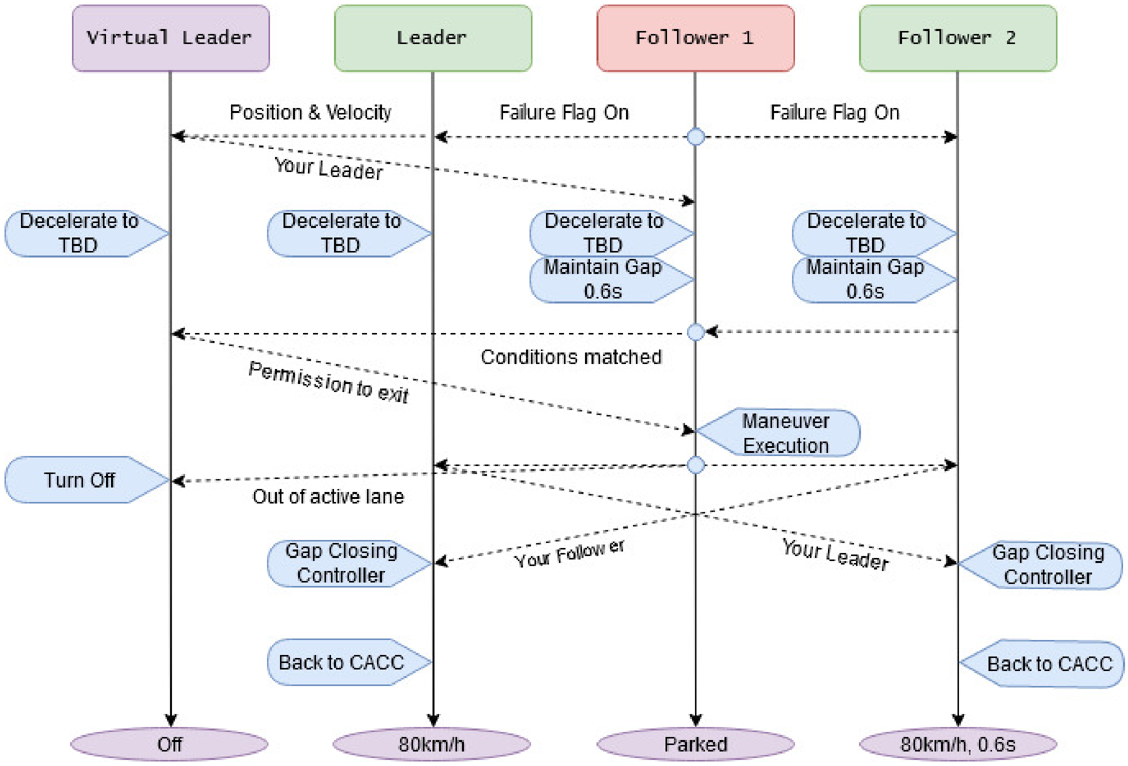


Figure 6-8: Fallback Protocol II to handle the emergency event by allowing a continue of movement for a limited window

who is still influenced by its predecessors' movement but not the other way around. Thus, the protocol must be tested to absorb external disturbances that cause a fluctuation in the velocity. The highest the perturbation in the velocity, the highest decline among the leaders' response is caused. If the speed of the platoon remains unchanged, no disturbance will be noticed. After the manoeuvre execution, the rest of the protocol follows the same steps as the protocol in Figure 6-1. Consequently, this protocol is evaluated just to determine how the reliability of this mechanism when trucks need to decelerate before executing the manoeuvre. Therefore, the extensive analysis presented in the previous section is not included in the remaining subsections.

6-5-1 Evaluation

In this subsection, the protocol is applied with varying the desired speed before the manoeuvring of faulty truck. The trucks are initially moving at $80km/h$ and maintain $0.6s$ space between them. The failure occurs at the $50^{th}s$ of the simulation. The performance of the protocol is tested using the desired speed of $65km/h, 70km/h, 75km/h$, separately before triggering the emergency escape manoeuvre. The platoon follows the virtual Leader's velocity but is, of course, of high interest to check the difference in the velocity between actual and virtual Leader. Figure 6-9 presents the error between the velocity of virtual and actual Leader for every velocity occasion.

It can be noticed that the two vehicles initially were decelerating simultaneously, but at around the $51^{th}s$, the performance was different. The reason is that the followers converge to the desired speed and time gap concerning the virtual Leader. The actual Leader who is still affected by the movement of Follower1 cannot react differently since the platoon controller has locked as the target gap and velocities were satisfied. From Figure 6-9 it can be extracted that indeed the greater change in the velocity, the higher steady-state error arises. More specifically, the steady-state error for $65km/h, 70km/h, 75km/h$ are $0.017, 0.01, 0.0056$ correspondingly.

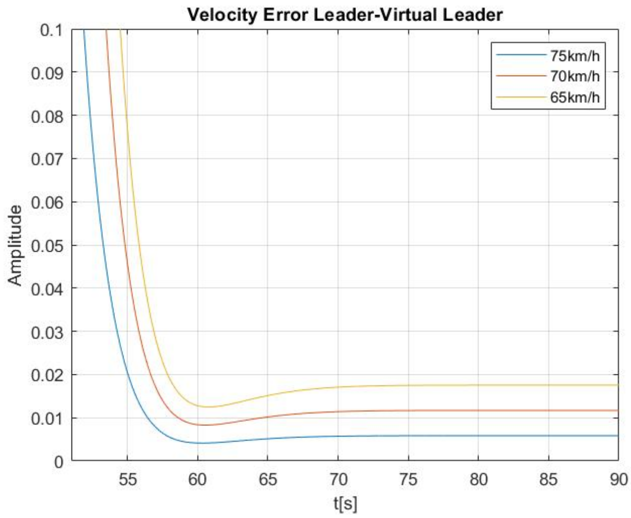


Figure 6-9: Error among the change of the velocity between leader and virtual leader

6-5-2 Discussion

The Protocol II design aims to provide the platoon's ability to continue its journey for a while before performing the emergency escape manoeuvre. It was essential to check the virtual Leader's capability to handle the external disturbances that lead the platoon to reduce its velocity. The results showed that the mechanism is able to provide a sufficient window for the platoon to perform the emergency escape manoeuvre. Nevertheless, it can be noticed that this window is limited and the escpae manoeuvre has to be performed before vehicles come very close to each other. According to Protocol II, the distance that the platoon can travel safely without collision danger can be further increased if a gap-open manoeuvre is performed among the Leader and Follower1. Since there is no limitation defined in the simulation scenarios regarding when the escape manoeuvre has to be executed, the opening gap parameter cannot be further examined. Moreover, designing a Time to Collision (TTC) [20] avoidance controller is out of the current work scope.

Chapter 7

Conclusions

7-1 Conclusions and Discussion

To conclude this thesis, a new application was introduced that executed an emergency escape manoeuvre of a faulty truck in a platoon formation by allowing the rest of the participants to continue their journey. All the required components for implementing the proposed framework were successfully put together and provided a functional and feasible outcome. More specifically:

- A platoon formation under healthy conditions was formed by using a customized Bidirectional (BD) Cooperative Adaptive Cruise Control (CACC) system that guaranteed string stability in the region of operation. This system's structure enabled the leader's automatic response to the emergency without the need for further consideration.
- The designed emergency escape manoeuvre fulfilled all the specified requirements and constraints defined concerning traffic limits and vehicle capabilities as denoted by physics laws (acceleration/deceleration limitations, rollover).
- By introducing a customized scale mechanism enabled the emergency escape manoeuvre to be robust regarding different initial conditions of faulty truck's state.
- A Simulated Annealing (SA) optimization algorithm was selected for the optimal utilization of quintic splines to reduce the peaks in the reference yaw rate that occur at the beginning of every segment. The selected approach was able to provide improved minimization results without causing oscillations and slowing down needed computational time.
- The trajectory tracking controller used for the execution of the escape manoeuvre resulted in minimal tracking errors that allowed us to conclude that the goal of achieving minimal risk condition for the faulty truck was satisfied.

- The decision logic designed for switching among the different operation modes provided a smooth transition to every state.
- A gap-closing controller was introduced to close the gap created by the escape manoeuvre's execution. It played a vital role in the fast form of the 2-vehicle platoon that continues its journey on the same conditions as before the emergency came up.
- A virtual leader mechanism was also introduced in the proposed fallback strategy. Although it seems that this mechanism is vulnerable to external disturbances for this application, it manages to provide a sufficient window for the execution of the manoeuvre. This flaw that was detected also denoted that the emergency escape manoeuvre was indeed required to ensure that the sensor failure would not lead to a collision.
- Closed-loop simulations were performed using nonlinear dynamic bicycle models. The proposed protocols were evaluated in realistic scenarios at high speeds on the highway, providing an opportunity to successfully use all the design components.

7-2 Recommendations and Future Work

A few ideas are listed below that could be addressed to extend this thesis as future work. These proposals aim to improve the current progress and help to bring closer the implementation of the application in a real-life test:

- **Vehicle Dynamics:** The proposed fallback strategy could be tested using a more complex vehicle model that would provide more realistic results and enable a more extensive analysis of its performance. For example, adding actuators can provide the ability to study the braking and accelerating capabilities of the vehicles and calculate more precisely the required braking distance.
- **Motion Planner:** The employed trajectory generator can be further extended to a generalized motion planner by adding a path planning module. The proposed emergency escape manoeuvre was pre-computed. Thus, it has the limitation of not being able to adapt in different driving environments. Furthermore, it always has the same structure, whereas it could vary in terms of length and shape as per the occasion. The introduction of a motion planner can provide an emergency escape manoeuvre that can be re-computed continuously while the truck is moving. Thus, it can deal with any possible scenario and enhance the scheme's robustness as it is supposed to be applied in a dynamically changing environment.
- **Optimization of the Escape Manoeuvre:** The escape manoeuvre was designed to provide a functional and feasible outcome, but it did not have a specific optimization target. The escape manoeuvre's target goal can be analyzed in more depth, such as provide an outcome that guarantees the shortest traveling time, shortest traveling distance, or fastest form of the 2-vehicle platoon.
- **Adaptive Gap-Closing Controller:** The simulation series regarding the complete fallback strategy's second applied scenario denoted a few limitations in the gap-closing

controller. They can be improved by applying an adaptive selection of the duration of this mode of the platooning control concerning the initial and final velocity of trucks before and after completing the emergency escape manoeuvre correspondingly.

- **Simulation Environment:** More simulating scenarios could be employed to figure out how to react on different occasions. Other traffic participants can be included and study how they affect the whole design and what different mechanisms have to be included in the framework to ensure all the traffic participants' safety.

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Glossary

List of Acronyms

CACC	Cooperative Adaptive Cruise Control
TTC	Time to Collision
GA	Genetic Algorithm
SA	Simulated Annealing
DoF	Degrees of Freedom
MPC	Model Predictive Controller
PF	Predecessor Following
PLF	Predecessor Leader Following
BD	Bidirectional
BDL	Bidirectional Leader
TPF	Two-Predecessor Following
TPFL	Two-Predecessor Leader Following
RMSE	Root Mean Square Error
IFT	Information Flow Topology
IVA	Intermediate Vehicle Actions
IVD	Inter-vehicle distance
TBD	to be determined