T.C.
ISTANBUL OKAN UNIVERSITY
INSTITUTE OF GRADUATE SCIENCES

THESIS

FOR THE DEGREE OF

MASTER OF SCIENCE

IN AUTOMOTIVE MECHATRONICS AND

INTELLIGENT VEHICLES

Osamah Mohammed AZAM

(203005006)

CLOSE FOLLOW UP TRUCK PLATOONING USING IPG AND MATLAB/SIMULINK

THESIS ADVISOR

Assoc. Prof. Dr. Ömer Cihan KIVANÇ

ISTANBUL, November 2023

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ISTANBUL, November 2023

ABSTRACT

CLOSE FOLLOW UP TRUCK PLATOONING USING IPG AND MATLAB/SIMULINK

In this thesis, an algorithm is developed for vehicle-to-vehicle (V2V) communication such that the drive will be autonomous in a convoy of trucks. It is simulated with different scenario-based cases using IPG automotive simulation software for Heavy-Duty vehicles by analyzing the time gap and the safe distance to travel in a convoy. This is done by implementing a controller in MATLAB/Simulink which creates an algorithm that collects data by using a set of sensors attached to the truck and finds solutions autonomously, this thesis will analyze the system behavior to develop and strategies for the mentioned cases.

Keywords: Platooning, PID, MATLAB, IPG, Vehicle to Vehicle Communication

KISA ÖZET

YAKIN TAKİP KAMYON KONVOYUNUN MATLAB VE IPG KULLANILARAK MODELLENMESİ

Bu tezde, araçlar arası haberleşme (V2V) kullanılarak otonom kamyon konvoyları için bir algoritma geliştirilmiştir. Çalışmada IPG simülasyon ortamında farklı senaryo tabanlı durumlar oluşturularak ağır vasıtalar için otonom yakın takip sürüş gerçekleştirilmiştir. Böylelikle ideal zaman aralığında bir konvoy için güvenli mesafe analizi simüle edilmiştir. Kamyon üzerine yerleştirilmiş bir takım sensörler kullanılarak veri toplanmıştır. Sensörlerden elde edilen verilere göre MATLAB/Simulink ortamında bir kontrolör tasarlanmıştır. Yapılan çalışmalar sonucunda olası konvoy senaryoları için geliştirilen algoritma test edilmiştir.

Anahtar Kelimeler: Konvoy, PID, MATLAB, IPG, Araçlar Arası Haberleşme

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ABBREVIATIONS

HDV	Heavy-Duty Vehicle
CACC	Cooperative Adaptive Cruise Control
V2V	Vehicle to Vehicle
V2I	Vehicle to Infrastructure
V2N	Vehicle to Network
DSRC	Dedicated Short Range Communication
OBU	On-Board Unit
RSU	Roadside Unit
NHTSA	National Highway Traffic Safety Administration
FOV	Field of View
IPG	Integrated Planning and Guidance
MATLAB	Matrix Laboratory
IVI	Inter-Vehicle Information
TMS	Traffic Management System
LIDAR	Light Detection and Ranging
RADAR	Radio Detection and Ranging
GPS	Global Positioning System
HGV	Heavy Good’s Vehicle
SAE	Society of Automotive Engineers
IEEE	Institute of Electrical and Electronic Engineers
ISO	International Organization for Standardization
TCP	Trajectory Planning and Control

BLIS	Blind Spot Information System
AEB	Automatic Emergency Braking
LDW	Lane Departure Warning

I. INTRODUCTION

1.1 Overview

According to the analysis done on traffic congestion and its impact on travel time [1] a major problem a major problem every driver face is traffic. It is a dynamic phenomenon that necessitates precise selection of movements, such as acceleration, deceleration, braking etc. which are time consuming and cause delays in the daily life of a person. Therefore, there are differences by which direct observation of attributes is possible. These could include the volume of traffic in a stream and the number of vehicles per length etc. Traffic jams are directly proportional to the increased density of vehicles and the rate of moving traffic. However, researchers are using new ways to direct traffic and to use the groundwork as efficiently as possible. Platooning being one of the ways towards reduced traffic and efficient fuel usage. Platooning is when a group of vehicles moving at the same speed with limited space between are moving in a systematic manner, [2] this is commonly referred to as cooperative adaptive cruise control (CACC). Truck platooning refers to the automatic driving of a truck with a small convoy at a short distance, providing a smooth traffic flow, improve traffic safety, conserve fuel, and reduce CO_2 emissions.

However, all approaches relating to the formation of platoons with fixed distances between vehicles has shown that an infrastructure dedicated to this type of road train should be implemented. The fuel economy and the other benefits of platooning should be considered without paying any attention to the price as being the right approach. This solution is extremely expensive to implement and cannot be used on most of the existing roads. This is because the longer the train, the more cars to overtake the train but the platoon can be limited to up to 8-25 vehicles in platoon, which should help limit the problem. For vehicle types, this prerequisite is not the main goal. To simplify the first concept of the system, let us look at the highway scenario. The formation of platoon on national highways poses additional challenges and problems, for that further analysis is required. It can only be achieved if there is certainty that all vehicles using this road will have the same autonomous capabilities and it is certain that it will not happen soon. Even though the technology is still in the field of experimentation, transportation decision makers in several countries have developed a road map that includes legal and technological stages that will progressively bring the technology to the market. the European Union, for example recently proposed a roadmap that anticipates multi brand truck platooning on European roadways by 2025 [3]. There are multiple ways for implementation of an algorithm however in this thesis we will focus on the use of IPG automotive simulation software with the use of MATLAB/Simulink by creating a controller to create an algorithm that allows the trucks to follow the front following coupled truck autonomously and keep a safe distance according to the lead trucks speed and acceleration. This is done by modeling the simulation to test different platooning configurations and strategies in a virtual environment and analyzing the data results and understanding the complex dynamics of truck platooning systems and to identify potential problems [4].

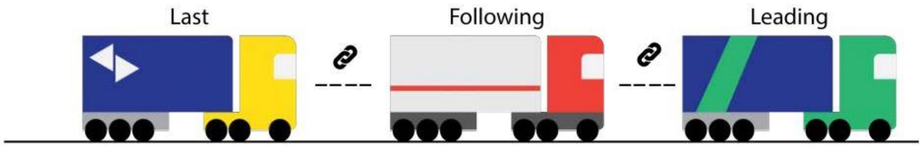


Figure I.1. Illustration of a three-truck platoon [5].

The trucks in the platoon are closely spaced, and they are all traveling at the same speed. The trucks are also electronically connected, as evidenced by the black cables that are connecting them in Figure I.1. These cables allow the trucks to communicate with each other and coordinate their movements. Truck Platooning is still in its initial stages of development, but it has the potential to revolutionize the trucking industry. By reducing fuel consumption, increasing traffic flow, and reducing the risk of accidents, truck platooning can make the trucking industry more efficient, safer, and more sustainable [5].

1.2 Problem Statement

There are various problems that need to be addressed for example the safest distance between truck and the ability to travel without drivers' assistance, so we focus on creating a detailed simulation model of truck platooning using the powerful modeling and simulation capabilities of MATLAB/Simulink and the comprehensive vehicle dynamics and sensor models provided by IPG Automotive. This model can be used to study the behavior of truck platoons under various operating conditions and traffic scenarios, enabling the evaluation of different control strategies and optimization techniques. By developing a control algorithm that enables trucks in a platoon to communicate with each other and coordinate their movements. IPG Automotive provides communication capabilities that allow trucks to exchange information about their positions, speeds, accelerations. MATLAB/Simulink offers the tools to design and implement control systems, making it an ideal platform for developing a cooperative control algorithm. By investigating the safety implications, we analyze the truck platooning by simulating various scenarios that could pose potential risks. IPG Automotive's sensor models provide realistic representations of the environment surrounding the trucks, allowing for accurate simulations of scenarios involving sudden braking, lane changes, and other potential hazards. IPG Automotive models can provide real-time information about the state of the platoon and the surrounding environment and optimize the platoon's performance by a control algorithm that take the decision for the truck for better performance.

1.3 Literature Analysis

V2V communication has emerged as a transformative technology with the potential to revolutionize transportation by enhancing safety, efficiency, and comfort. By enabling vehicles to exchange information with each other and with roadside infrastructure, V2V communication has the power to transform the way we drive, making roads safer, traffic flow smoother, and the driving experience more enjoyable for drivers [6]. The core principle of V2V communication lies in the establishment of wireless networks between vehicles, allowing them to share real time data about their positions, speeds, and intentions. For instance, V2V communication can be employed to implement cooperative adaptive cruise control (CACC) systems. CACC allows vehicles to maintain a safe following distance by exchanging information about their speeds and positions, effectively preventing rear-end collisions [7]. Moreover, V2V communication can facilitate the development of personalized infotainments systems that tailor information and entertainment options to individual preferences and driving conditions.

1.4 Aims of Thesis Research

With the use of MATLAB/Simulink an algorithm is to developed and the tools that are provided by IPG TruckMaker, the thesis is mainly focused on creating a system that controls the truck and decide what is the best possible outcome to have while in a convoy using the algorithm to have a safe distance and comfort for the driver this is done by exchanging information between vehicles that means it will use the decisions based on V2V Operations.

II. BACKGROUND STUDY

2.1 Heavy-Duty Vehicles

The competition for industrial autonomous cars is well underway among leading organizations and academic institutes. They have the capacity to vastly adjust how we view and use transportation [8]. Because heavy-duty vehicles (HDV's) contribute to 5% of the worlds carbon emissions, there is a constant need for more fuel-efficient HDV's [9]. In addition to having an impact on the environment, using fuel account for one-third of all operational expenses for an HDV. As a result, developing techniques to improve the fuel efficiency of HDV operations is helpful both environmentally and economically [10]. Controlling a group of heavy-duty vehicles at a close inter-vehicle distance is known as truck platooning. The platoons overall air drag is reduced, boosting the platoons' average fuels economy [11]. According to read tests, a 10m space between trucks saves 13 percent of energy, while a 4.7m separation saves 18 percent. According to a recent study, the greatest dual savings might be 14.2 percent [12].

The demand for freight transportation has been increasing in recent years, as the global economy has grown. This has led to an increase in the number of heavy-duty trucks on the road according to the international transport forum (ITF), which estimates that global freight transport will grow by 3.3% per year between 2022 and 2050 [13].

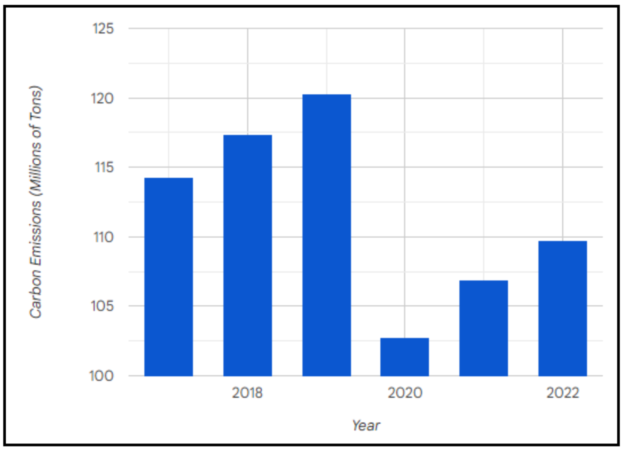


Figure II.1. Carbon Emissions from heavy duty Trucks in the United States, 2017-2022 [2].

The impact of usage on heavy-duty trucks over a period of five years as shown in Figure II.1 the impact of usage on heavy duty trucks has been increasing over time due to longer travel distances over the years as they travel longer distances this is due to factors such as the consolidation of warehouses and the globalization of supply chain according to the U.S. department of transportation (DOT), which estimates the average length of haul for a truckload shipment increased from 244 miles in 1977 to 500 miles in 2022 [14]. Heavy duty trucks are also carrying heavier loads due to the growth in e commerce and the increasing popularity of just-in-time manufacturing according to the American Trucking Association (ATA), which estimates the average weight of a truckload shipment increased from 20 tons in 1977 to 40 tons in 2022 [15].

2.1.1 Types of Heavy-Duty Vehicles

Depending upon their purpose, there are various type of HDT’s such as [16] tractor trailers, they are a large combination trucks consisting of a tractor unit that pulls a semi-trailer. Consisting of single unit HDT’s with a fixed cargo area behind the cab. Consisting of large hydraulic operated container that can be raised and lowered. Trucks equipped with a large tank for transporting liquids such as gasoline, oil, and water. Consisting of trucks equipped with a rotating drum that mixes concrete. Consisting of insulated compartments and refrigeration units to maintain a controlled temperature for transporting perishable goods. Consisting of specialized HDT's designed to transport multiple cars or other vehicles. Consists of HDT's equipped with containers and mechanisms for collecting and transporting waste. Specially designed HDT's are equipped with firefighting equipment, including water tanks, pumps, and hoses and some are equipped with medical equipment [17] and supplies to provide emergency medical care and transport patients to hospitals.

2.1.2 Modes of Platoon Scheduling System

The first platooning demonstrations took place in 1997 at the Intelligent Transportation Systems (ITS) World Congress in Tokyo, Japan. Since then, there have been a number of platooning demonstrations and trials around the world [18]. Their modes of scheduling a platooning system are a general way to control the operation. Platoon-level vehicles, roadside controllers, and cloud servers all communicate with each other via vehicle-to-everything (V2X) technology. Numerous bits of vehicle related data are constantly transferred between modules and devices,

- Vehicle to Network (V2N)
- Vehicle to Infrastructure (V2I)
- Vehicle to Vehicle (V2V)

It makes measures to ensure that a large-scale platoon system can function effectively as a whole and give more consideration to the state of all platoon-related systems in a particular area. All applications require different sort of engineering and algorithms but for the purpose of this research we will focus only on Vehicle to Vehicle (V2V).

2.2 Vehicle to Vehicle Communication

Vehicle-to-Vehicle communication is a crucial technology that enables trucks to communicate directly with each other, enabling the formation and operation of truck platoons. In truck platooning, multiple trucks travel closely together in a coordinated manner, utilizing V2V communicating to exchange information such as speed, distance, and braking intentions.it typically employs dedicated short-range communication (DSRC) technology, which operated in the 5.9 GHz band and provides a high data rate and low latency for reliable communication [19]. DSRC enables trucks to exchange information up to several times per second, ensuring timely updates and synchronized actions. Each truck is equipped with onboard units (OBUs) that house the DSRC transceivers, processing units, and software necessary for communication and coordination. The OBUs receive information from nearby trucks and utilize this information to control the truck's speed, acceleration, and braking.

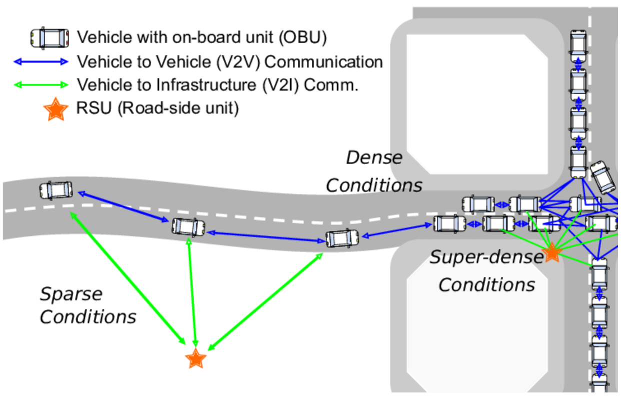


Figure II.2. General Structure of vehicular networks, consisting of OBU and RSU units working in harmony due to V2V communication [19].

2.3 Sensors

A Sensors are an essential component of vehicle-to-vehicle communication. Providing the data that is used to generate and transmit messages between vehicles. These messages contain a variety of information, such as the vehicles speed, position, heading, and braking status. This information can then be used to improve safety, efficiency, and comfort for drivers and passengers [20]. The data from the sensors on a vehicle is processed by an onboard computer, which generates a V2V message that is then transmitted to other vehicles. The message can include information and other relevant data. This specific information depends on the type of sensor and the application [20]. For example, a message from a radar sensor might only include the distance and speed of a detected object, while a message from a camera might include the type and location of the object [21]. As V2V technology continues to develop, we can expect to see even more innovative application for this technology in the future.

2.4 Sensor Fusion

Sensor fusion is the process of integrating data from multiple sensors to create a more comprehensive and accurate understanding of the environment. In the context of vehicle-to-vehicle (V2V) communication, sensor fusion plays a critical role in enabling vehicles to share detailed information about their position, speed, acceleration, and intention. This information can be used to improve safety, efficiency, and overall performance on the road [22]. Truck platooning works fuel efficiently by up to 10% as trucks are able to draft off of each other, reducing wind resistance and fuel consumption maintaining a safe following distance and avoid unnecessary braking and acceleration [23]. Sensor fusion is expected to be a key enabler for commercial truck platooning. A recent study by the National Highway Traffic Safety Administration (NHTSA) found that sensor fusion could enable widespread adoption of truck platooning by 2030 [24]. According to the review of cooperative Driving: Application, challenges, and research directions [25] a study is made that found sensor fusion reduced rear end collisions by 40%.

2.5 Cooperative Adaptive Cruise Control (CACC)

To Design and examine our issue for the uncertainties of V2V systems, Cooperative Adaptive Cruise Control is used as it helps in designing and providing a way to solve complex issues that affect the actor in the simulation or in real world aspect. Implementing the use of CACC system for V2V communication in truck platooning involves developing an algorithm that allows trucks to learn from their interactions and make informed decisions to optimize platooning performance. The state space represents the current situation of the truck platoon, including the position, speed and acceleration of each truck, along with environmental factors like road condition and traffic patterns which is defined. Then the initialization of the reward function is done which assigns positive or negative values to different outcomes, incentivizing safe and efficient platooning behavior [26]. The algorithm is designed to adapt to changing environmental conditions and traffic patterns. This can be achieved by incorporating real-time information from V2V communication and sensor data. As the data is received the algorithm learns over time, refining its policy and improving its ability to optimize platooning performance [27]. This continuous learning ensures that the trucks remain effective in adapting to new scenarios and maintaining optimal performance.

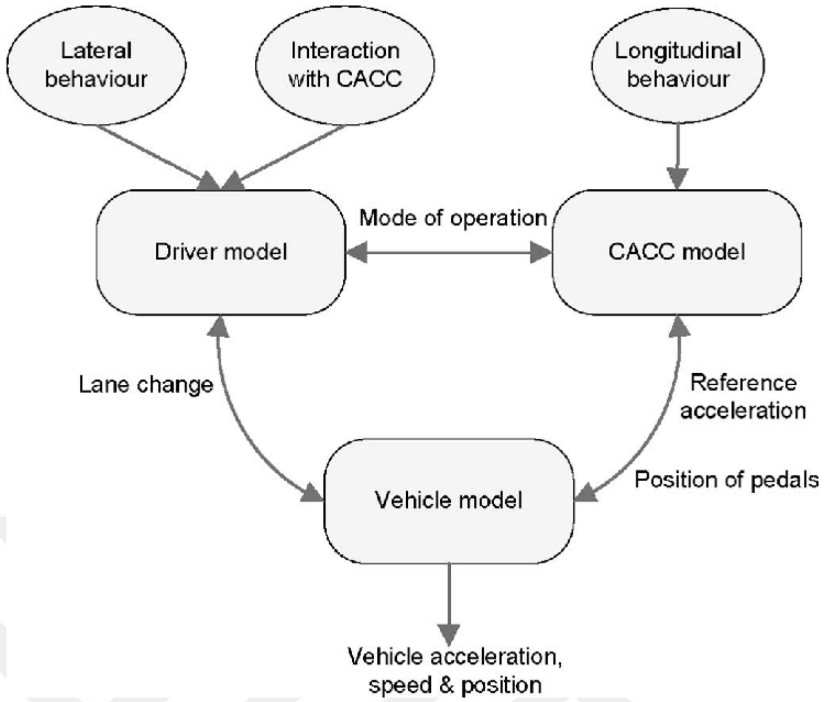


Figure II.3. Typical CACC model in a vehicle body [29].

2.5.1 Cooperative Platoon Management Algorithms

Cooperative platoon management algorithms are designed to coordinate the movement of vehicles within a platoon. Several algorithms have been proposed each with its strengths and weaknesses, CACC is used which extends the concept of adaptive cruise control (ACC) to include V2V communication. In CACC, each vehicle's acceleration is determined not only by the distance to the preceding vehicle but also by information received from other vehicles in the platoon. This allows for a more coordinated and efficient response to traffic conditions [28]. The other type of algorithm that can be devised is the cooperative virtual structure of the platoon as the leader vehicle being in the front of the platoon and the follower vehicles behind. The leader vehicle determines the desired trajectory for the platoon, and the follower vehicles use V2V communication to synchronize their movements with the leader [29]. This approach is particularly effective for maintaining safe inter-vehicle distances. This choice of algorithms depends on several factors, including the specific objectives of the platoon, the communication capabilities of the vehicles, and the computational resources available. As shown in the Figure II.3, it illustrates the interaction between a driver model, a vehicle model, and a cooperative Adaptive Cruise Control (CACC) model in a vehicle platoon. The driver model dictates high-kevel commands done by V2V communication to transfer data accordingly to each block then the CACC model translates them into vehicle-specific instructions, and the vehicle model executes those instructions, influencing both lateral and longitudinal behavior. The CACC mode can be active, where the system controls the vehicles speed and acceleration, or passive, where it provides driver assistance. The system can be either active or passive. In active mode, the CACC system controls the speed and acceleration of the vehicle. In passive mode, the system monitors the traffic and provides the driver with information and warnings [29].

2.5.2 Framework of the Control System

In this section we provide a brief overview of the ACC as well as new control system design that has the ability to meet platooning needs. In most cases, the ACC serves as an extension of the CC. The ACC will not engage if a target is not identified or if the leading vehicle is driving faster than the CC's predetermined speed. If a target is in the same lane and moving at the same or slower speed, the ACC will adjust the relative distance based on the desired time gap setting. It will not change the pace of vehicles traveling in separate lanes. The ACC will look for a new target when the leading vehicle changes lanes (turns off). If no target is found, the system switches to constant speed mode (CC). Furthermore, a commercial ACC is primarily meant to maintain a comfortable relative distance by delivering suitable requests to the engine and other brake system included in a vehicle. It isn't built with the best fuel efficiency in mind. The relative distance is calculated by allowing the driver to select a desired time gap distance which is proportional to the relative distance, with time gap 1 being the shortest relative distance [30]. Due to safety concerns, a short relative distance will necessitate the ACC to take stricter control actions.

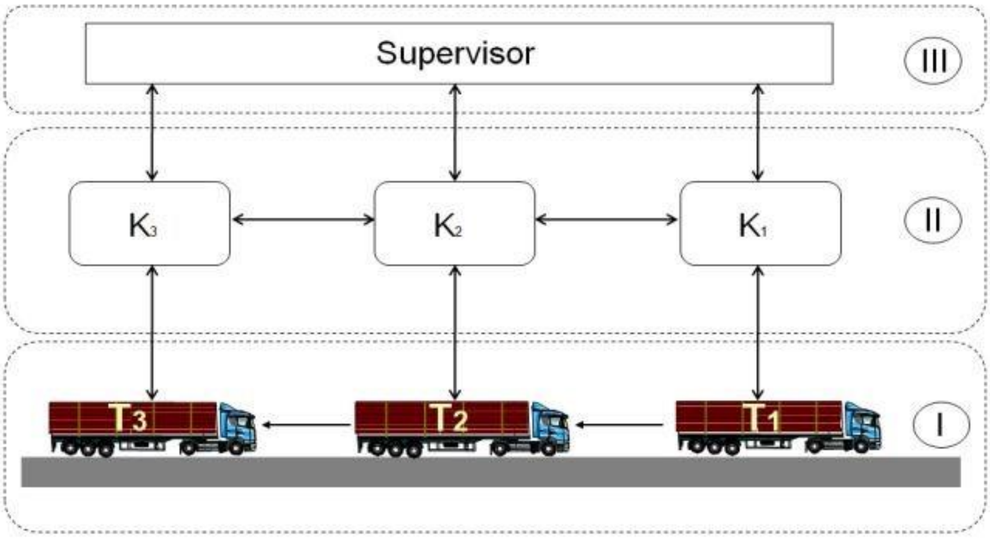


Figure II.4. Three layers are depicted in the diagram with arrows denoting information flow direction (The communication nodes are shown with K1, K2 and K3) [30].

In Figure II.4 we suggest a new three-layer hierarchical control system architecture. It is primarily intended for use in platooning control application. Starting at the bottom, layer I contains feedback information acquired from a radar sensor on the relative distance and velocity of the vehicle ahead. The major purpose of this layer is to ensure safety by avoiding collisions with the vehicle ahead of it as well as making fuel-efficient control decisions [30]. With the addition of wireless nodes, layer II extends the controller's decisions space. Its job is to transmit information to the ACC about the intentions and behavior of the nearby vehicles. As a result, the ACC will be able to make decentralized fuel-optimal judgements based on vehicles within spatial range of its wireless transmitter, all while maintaining safety [27]. Finally, layer III adds a third dimension to the decision space, making it more expansive. Wireless information will be used to give dynamic route planning, route assigning, platoon formation, route topology, and other services to the ACC. As a result, the ACC will be able to make strategic decisions based on future and global events, increasing fuel efficiency and even more.

III. IMPLEMENTATION AND METHODS

Once the main subject is understood of the platooning database, it becomes a real dispute to achieve the accurate results. We will implement an algorithm and a controller to drive the platoon this is done by building scenarios and achieving the result that proves the algorithm. We will focus on making a controller using MATLAB/Simulink and using IPG TruckMaker to prove our algorithm.

3.1 IPG Automotive Simulation Software

The use of IPG TruckMaker is proposed and used to implement MATLAB/Simulink. IPG Automotive is a leading provider of simulation software solutions for the automotive industry. Their suite of products, including CarMaker, TruckMaker, and MotorcycleMaker, enables engineers to virtually test and develop vehicles in a realistic and controller environment [31]. The use of IPG Truckmaker is the software solution designed for the development and testing of heavy-duty vehicles, including trucks, buses, construction vehicles, and other special vehicles. It enables to virtually test the vehicle systems and functions in a realistic and controlled environment as show in Figure III.1. The simulation is developed with an actor vehicle being a Renault Magnum with a three axle semi-trailer attached as it approaches the platoon ahead to keep a safe distance and adjust the speed and acceleration according to the platoon of four trucks.

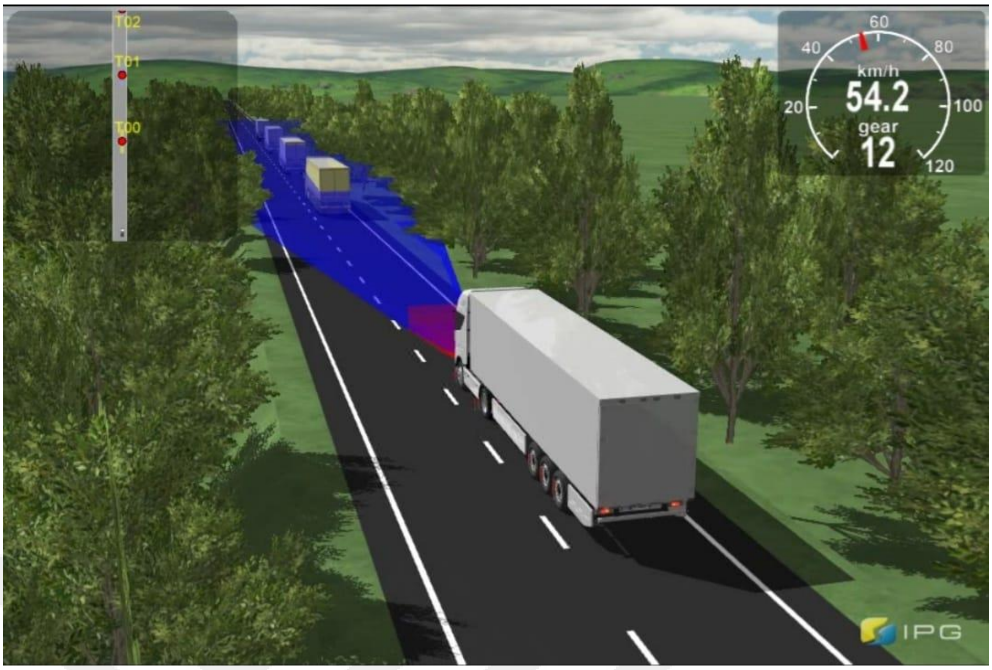


Figure III.1. Simulation Model of a Renault Magnum with 3 axle semitrailers in IPG TruckMaker.

The high-fidelity simulation environment conveys a sense of motion and realism as the truck approaches the platoon it decreases its velocity to adjust according to the platoon that is directly ahead of the truck the Radar sensor detects 4 trucks ahead and the truck uses that information to connect with the platoon so it can start joining the platoon and keep a constant speed, at this point the driver can let the wheel go and the truck will start following the platoon autonomously. This is modeled using IPG however the main implementation is done by building an algorithm with the use of the IPG block in MATLAB/Simulink. As shown in Figure III.2 the main blocks that we work with are the IPG vehicle block and the vehicle control block in the block diagram as we will use these to create an algorithm that controls the gas and the distance of the truck autonomously and without driver assistance.

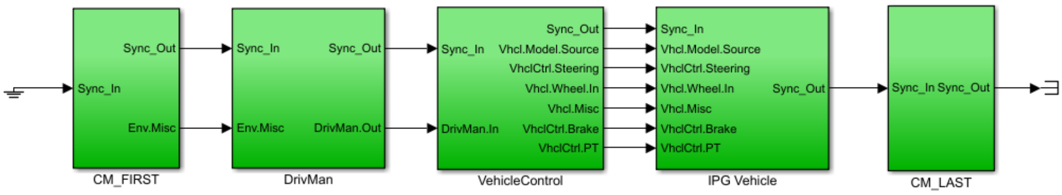


Figure III.2. IPG Truck Maker blocks in MATLAB/Simulink.

The overall structure of the block diagram suggests a modular and hierarchical approach to vehicle control, with different blocks handling specific tasks and coordination with each other to achieve the desired vehicle behavior. We develop a controller that determines the distance by reading the sensor information provided from the simulation in real time and uses it to achieve he optimal safe distance to travel in a platoon ahead.

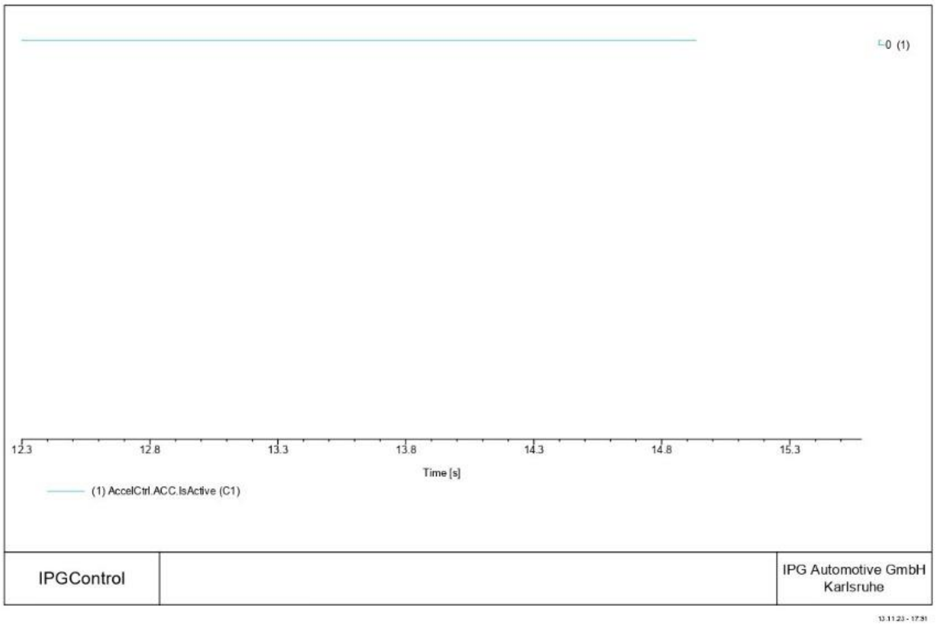


Figure III.3. Proof that the controller block is active as the ACC is being recognized as active in IPG.

3.2 Algorithm Parameters

To control the vehicle without any human interaction an algorithm is developed. This thesis works with the implementation of the controller to show it in real time in the IPG simulation software. To gain the advantage of a real time result initial parameters are determined and set to give an initial setting, this thesis not only builds the algorithm but also solve the problem in real time as shown in the Table III.1.

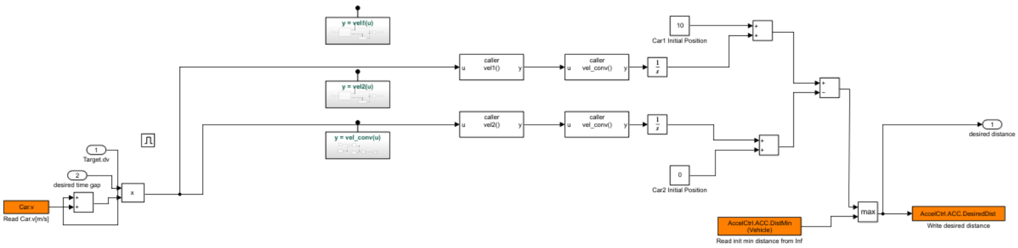
Table III.1. Simulation Parameters.

Speed	22.4 m/s
Distance	20 m
Time Gap	1.80 s
Lead vehicle initial position	50 m

This thesis develops a smart algorithm which identifies suitable time for V2V communication and acts upon the different scenarios that affect it in real time in the real scenario.

3.3 Controller

An algorithm is built upon the vehicle model of IPG truck maker in MATLAB/Simulink by utilizing IPG Truck Maker API to simulate the vehicle dynamics and control system within MATLAB. This approach provides data accurately and in real time with the database able to learn and correct itself according to the circumstances occurring in the scenario. As shown in the Figure III.4, the block diagram represents a simplified model of a vehicle control system which contains a vehicle dynamic which is a block model the dynamic behavior of the truck, including its longitudinal and lateral motion, tire-road interaction, and suspension dynamics.



FigureIII.4: MATLAB/Simulink block diagram for IPG controller for vehicle body.

This block implements the vehicle's control algorithms, such as engine control, transmission control, and braking control. It receives inputs from the vehicle dynamics and powertrain blocks and generates outputs to control the truck's actuators. The blocks also represent the environment that generated in the simulation, such as road conditions traffic conditions, and weather. The environment block sends signals to the control system, which uses them to adapt the vehicle's behavior to current conditions.

3.3.1 IPG Scenario Generation

Scenario generation plays a crucial role in the development of safe, efficient, and reliable vehicles. By simulating a wide range of driving scenarios, this way we can identify potential problems and ensure that vehicles are able to handle a variety of conditions. Figure III.5 shows the scenario made in IPG Truck Maker with a long highway of 1500 m with a round left turn circle with a diameter of 50 m and trees around the track for the scenario to be able to simulate perfectly without any errors which is calculated by the PI controller.

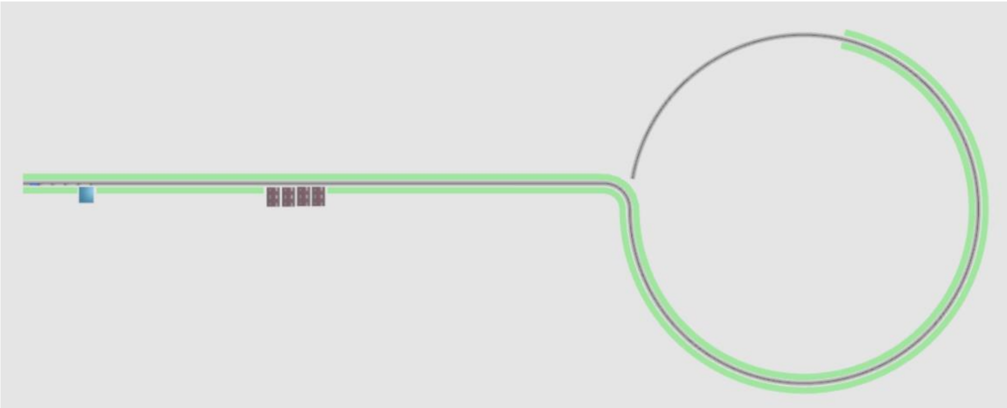


Figure III.5. Scenario generated in IPG TruckMaker.

There are five trucks in total with the actor truck being represented by a Renault Magnum which follows a platoon of four trucks that are ahead on the highway moving at a constant speed of 30 m/s the actor truck joins the platoon by reducing speed and getting into a platoon and follows entirely till the end of the highway track.

Table III.2: Scenario parameters for the simulation

Simulation Parameters	
Cruising Speed	80 km/h
Simulation Duration	200 s
Highway total distance	2616.10 m
Diameter of the circle road	530 m
Max longitudinal acceleration	$3\ m/s^2$
Max Engine speeds	1800 RPM

3.3.2 PI Controller

A PI controller, or proportional- integral controller, is a type of feedback controller that continuously adjusts the output of a system to maintain a desired setpoint. It works by calculating the difference between the current output and the desired setpoint and then adjusting the output proportionally and integrally to the error. This combination helps to ensure that the system quickly reaches the setpoint and then stays there, even if there are disturbances. It works by calculating the proportional and integral terms of the control signal. The proportional term is proportional to the current error, and the integral term is proportional to the integral of the error over time. The sum of the proportional and integral terms is the control signal [32].

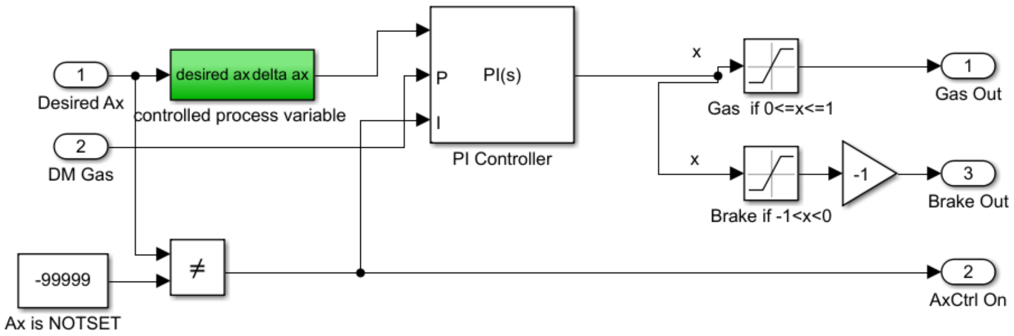


Figure III.6: PI controller used in the controller for the IPG algorithm implementation.

The PI controller block calculates the error as shown in Figure III.6 and adjusts the output accordingly and basically adapting to the trucks that are ahead by controlling the amount of gas needed for the truck to stay in a constant and same speed as the trucks ahead also controlling the brake in order to reduce speed depending on the trucks ahead.

3.3.3 PID Controller Design

A PID controller (proportional-integral-derivative controller) is a type of feedback controller that continuously adjusts the output of a system to maintain a desired setpoint. In the context of the thesis, a PID controller can be used to control the distance between trucks in the platoon. The controller works by measuring the current distance between the trucks and comparing it to the desired setpoint. The controller then calculates the error between the current distance and the desired setpoint. The controller then uses the error to calculate a control signal that is sent to the trucks ahead in the platoon. The trucks use the control signal to adjust their speed and maintain the desired distance between them [33].

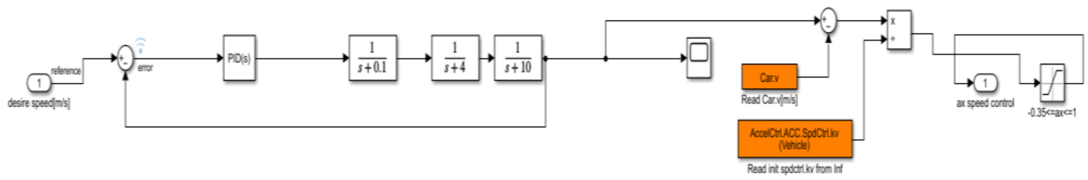


Figure III.7. PID controller block controlling the speed and acceleration.

With this, the PID controller helps by maintaining a consistent speed it does this by measuring the current speed of a truck and compares it to the desired speed. As shown in Figure III.7, it then calculates the error between the current speed and the desired speed. It can then use the error to calculate a control signal which is sent to the trucks. They are quite valuable and are simple to implement, they help by improving fuel consumption, safety and traffic congestion. The control signal is sent to the trucks through V2V communication and made easy due to the controller being able to send signals in real time keeping the trucks at a consistent speed and acceleration and safe from any disturbances and errors,

3.4 Sensors Used in the Simulation

To detect the trucks ahead or any type of object, sensors are used, in this case radar sensor is used as they can detect the object ahead and give feedback to the controller for it to determine the distance of the truck ahead. The sensors are attached on the trailer and the truck separately with the truck having the radar sensor placed on the frame just under the radiator so it can detect the traffic ahead with no disturbances, the trailer on the other hand has two radar sensors placed on the frame one is place on the left side of the trailer and another is place on the right side of the trailer the parameters of the sensors on the truck and trailer are as follows,

Table III.3: Parameters for Truck and Trailer Sensor Mounts.

	Trailer	**Truck**
Field of view h/v [deg]	160/20	16/8
Range [m]	5	150
Observation Radius [m]	500	500

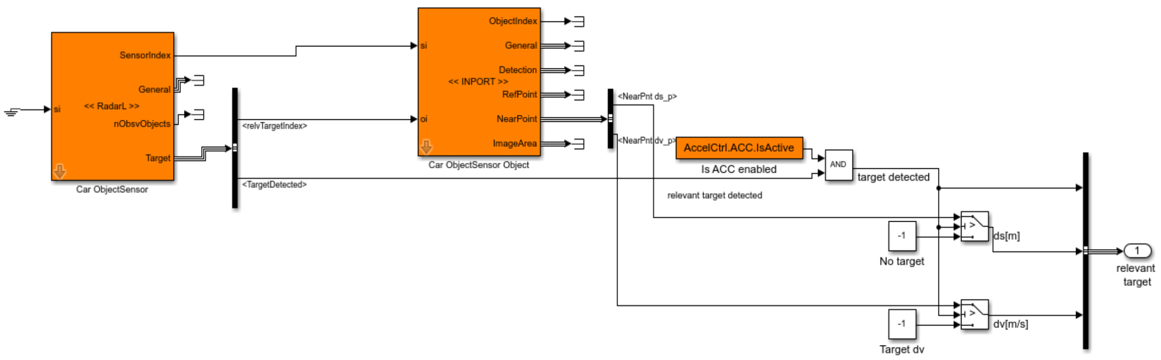


Figure III.8. Closed-loop truck platooning system with a PI controller.

A closed-loop platooning system is devised for the sensors so that they can function with V2V communication as shown in the Figure III.8 the target index selects the target vehicle that the ACC system will follow and that is done by the truck object sensor which detects the distance and relative velocity of the target vehicle. The target detected block indicates whether a relevant target vehicle has been detected which in this case are the trucks ahead on the highway track. The ACC system will adjust the truck’s acceleration to maintain a safe distance from the target vehicle. The system will also consider the truck’s speed and other factors, such as rain, when calculating the desired acceleration.

IV. RESULTS

4.1 Desired Vehicle Output

In Figure IV.1, it is proven the truck moves at a desired speed of 22.4 m/s and keeps a constant speed until the end of the simulation as we had discussed in Section III. While the MATLAB/Simulink runs in the background and provides the results in real time.

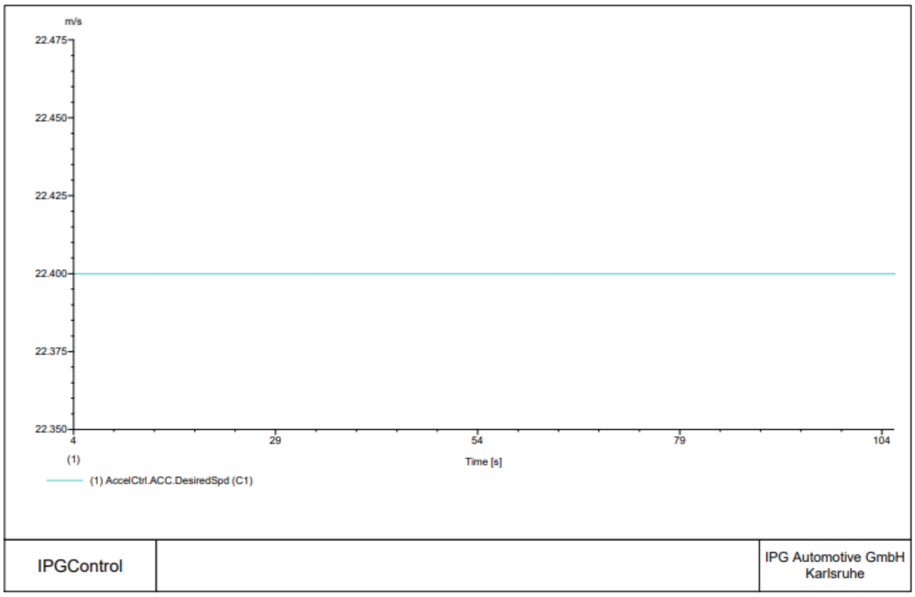


Figure IV.1. Desired speed obtained result.

Figure IV.2 indicates the acceleration of the truck the first section from 0 to 27 seconds shows the car accelerating from 0 to 100km/h. the acceleration is smooth and constant, with a few small dips. While the second section from 27 to 177 seconds shows the car using the ACC system to maintain a safe distance from the lead vehicle. The acceleration is more variable in this section, as the truck needs to adjust its speed to match the speed of the lead vehicle. Overall, the acceleration profile shows the system is capable of providing smooth and efficient acceleration when following another vehicle closely.

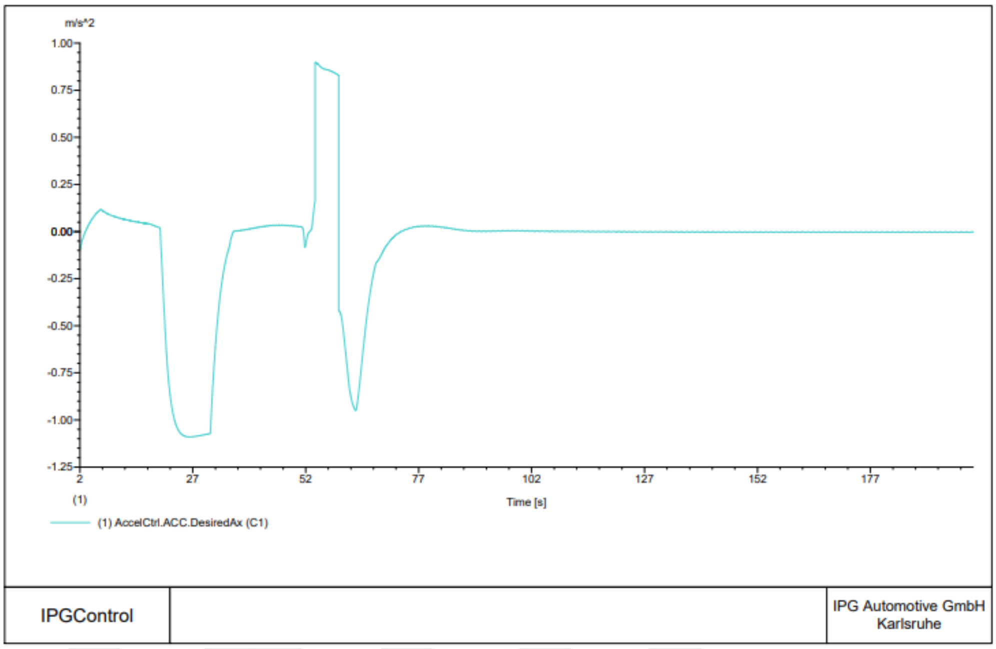


Figure IV.2. Desired acceleration for Actor Truck.

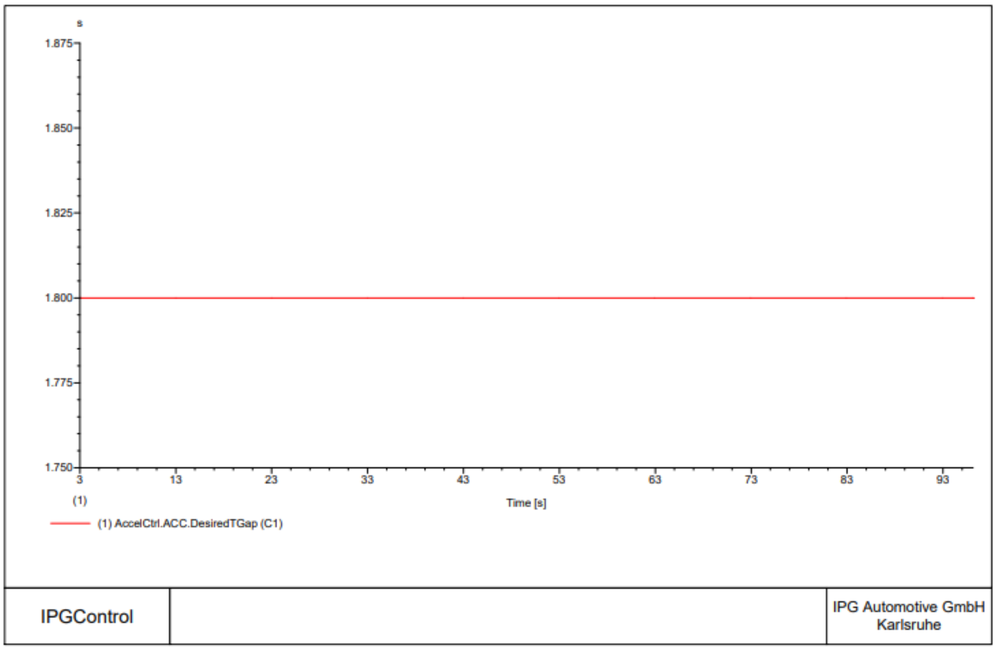


Figure IV.3. Desired time gap between vehicles.

Figure IV.3 shows the desired time gap between the trucks as shown the truck maintain a safe distance with a time gap of 1.8 seconds all the way till the end of the simulation hence proving the ACC system to work effectively in the scenario.

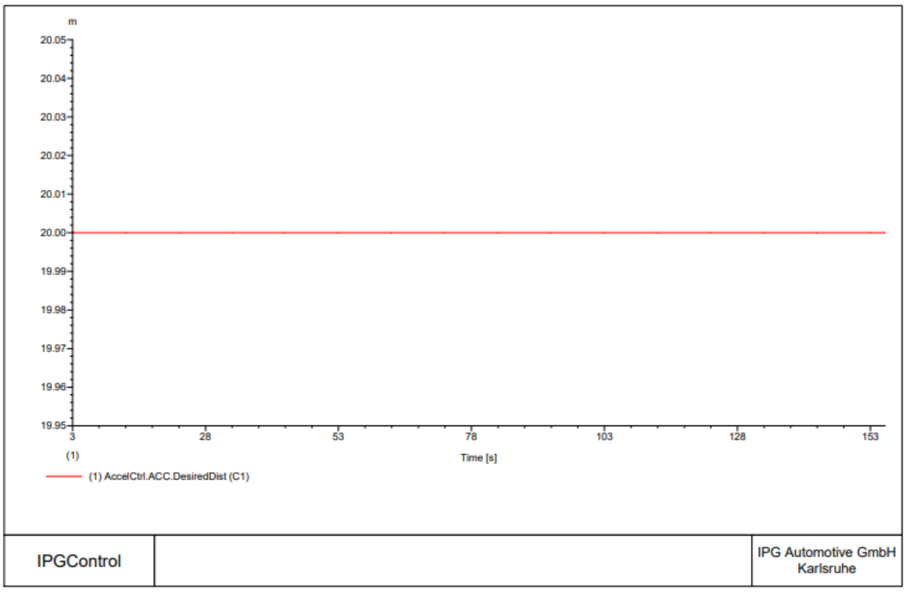


Figure IV.4. Desired safe distance between trucks.

Figure IV.4 indicates that the desired distance is kept constant all the way through effectively and maintain a safe following distance between trucks, even when the lead truck changes speed rapidly. This is important because it helps to reduce the risk of collisions in the event that the lead truck braked suddenly.

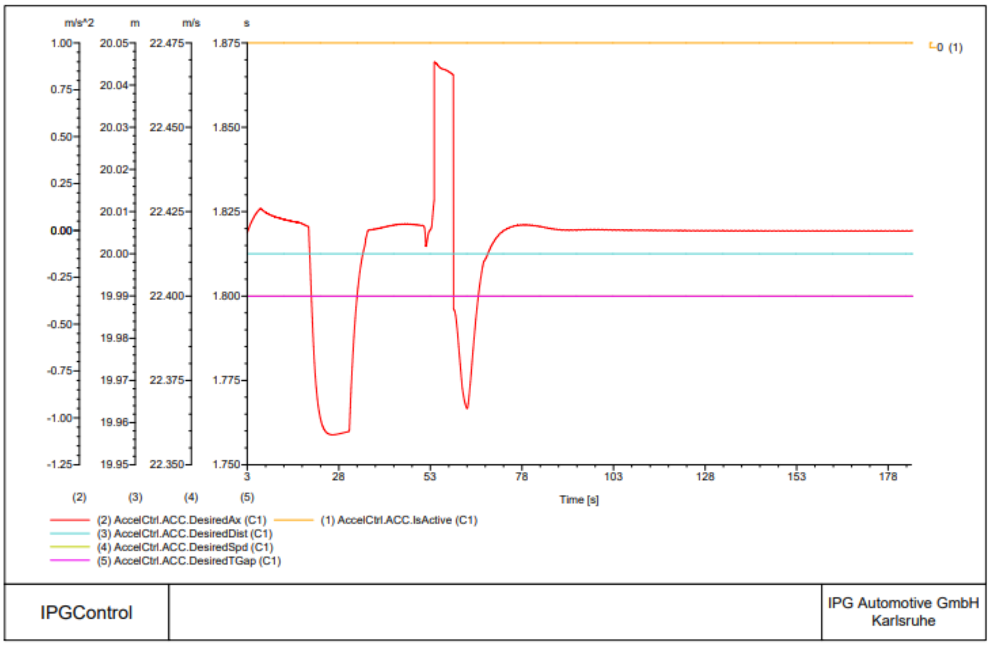


Figure IV.5. Desired safe distance between trucks.

Figure IV.5 shows all the results combined in one graph and show that the ACC system controller is working effectively and controls the truck autonomously and gives directions to the truck according to the directions of changes that occur for the truck ahead.

4.2 Sensor Output for Truck and Trailer

The sensors work together to provide us the readings as discussed in Section III. We ran the simulation to get the results of the sensors that detect the trucks ahead and provide the proof that the sensors are working efficiently and detect the object currently without any disturbances from external entities.

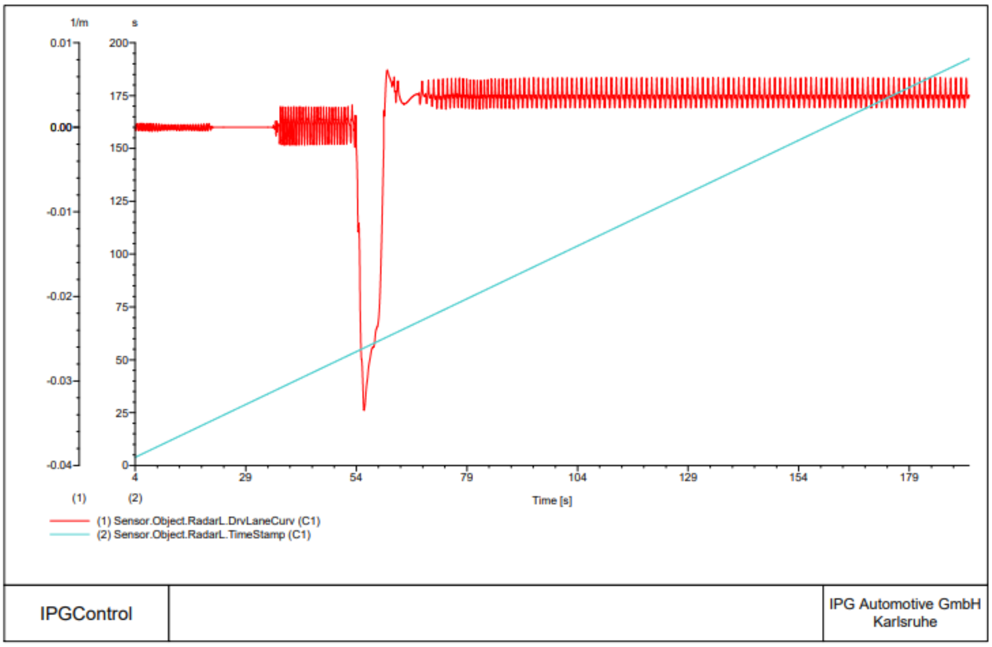


Figure IV.6. Object radar sensor output from the Truck.

The red line is the radar sensor representation as shown in the Figure IV.6, the radar sensor output is inversely proportional to the distance to the object. This means that as the distance to the object decreases, the radar sensor output increases. From section 0 to 35 seconds the radar sensor detects that the vehicle is still far away until after section

35 to 54 seconds the vehicle is detected after that the section from 54 to 67 seconds the distance starts to decrease between the truck ahead as the it is braking. Then from section 70 to 200 seconds the distance is constant between the trucks which proves that the ACC is working properly. Figure IV.7 shows that the radar sensor output stays constant over time. This means that the trailer does not detect any vehicle on its left side of the trailer but detects the lane and keeps a constant value accordingly.

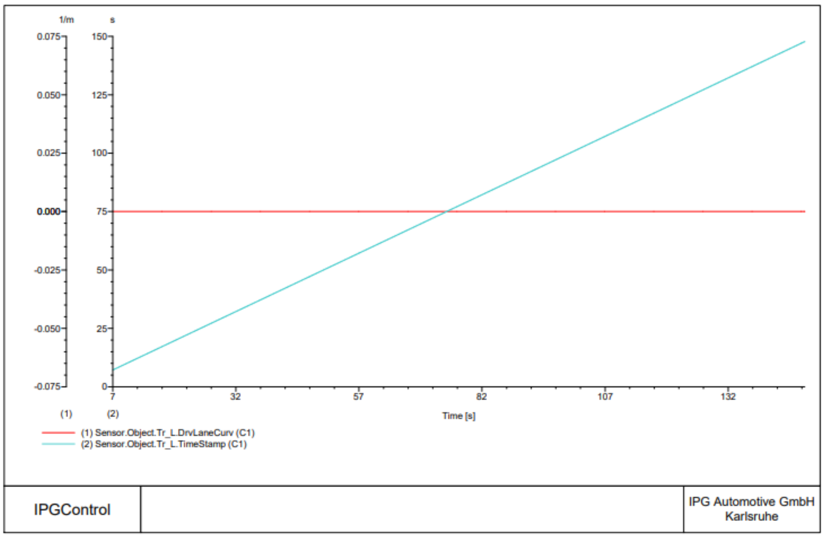


Figure IV.7. Radar Sensor output for trailer (Left).

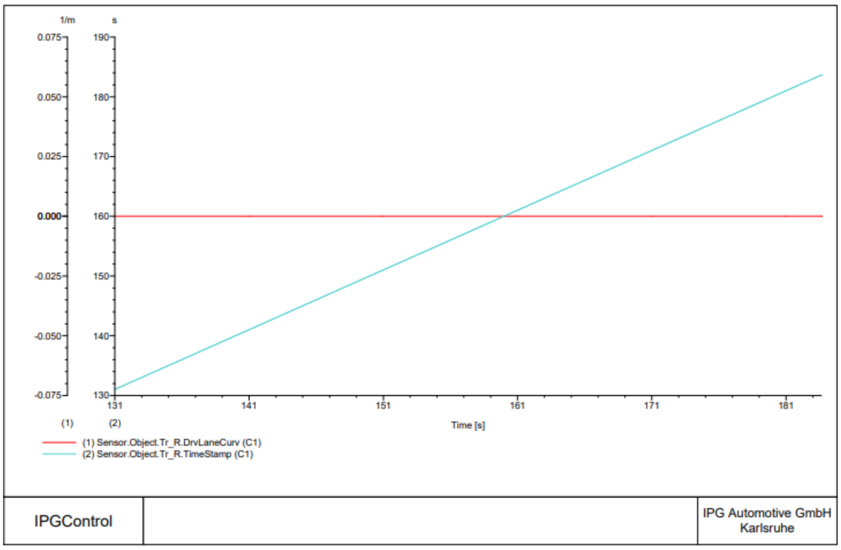


Figure IV.8. Radar Sensor output for trailer (Right).

Figure IV.8 shows that the radar sensor output stays constant over time. This means that the trailer does not detect any vehicle on its right side of the trailer but detects the lane and keeps a constant value accordingly.

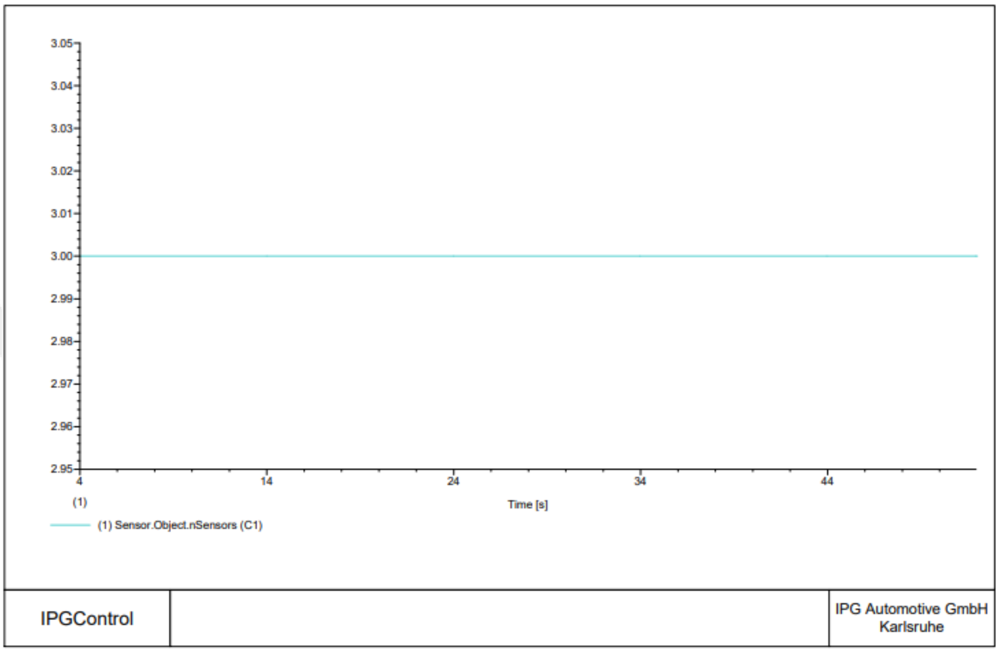


Figure IV.9. Sensor for detecting no. of trucks is in the field of view of the truck.

Figure IV.9 shows that the radar sensor detects a number of 3.05 trucks according to the graph form the section 0 to 14 seconds. As the truck comes closer to the trucks ahead it detects 3 trucks until the end of the simulation at 200 seconds.

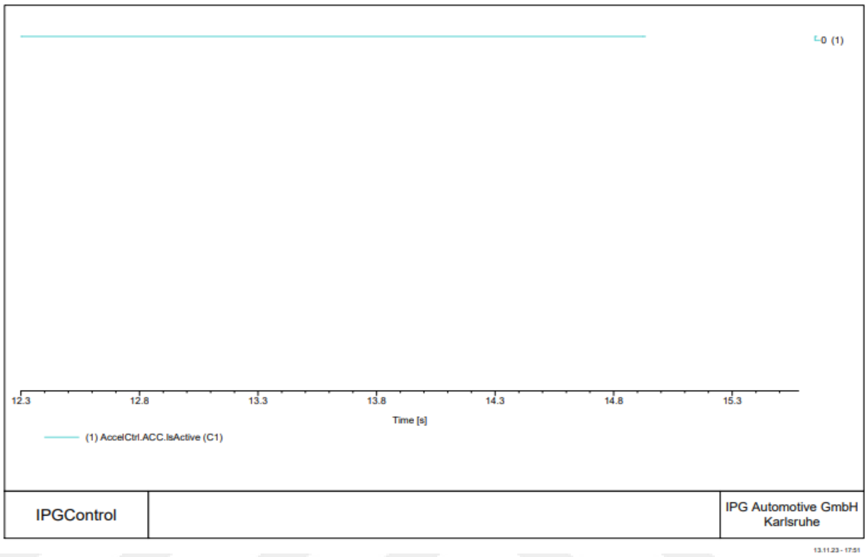


Figure IV.10. Sensor output detecting the ACC is active and running.

Figure IV.10 shows the output of the Adaptive Cruise Control controller working efficiently and without a disturbance. The overall trend of increasing the number of times the ACC is activated can be attributed to the fact that the vehicle is being driven in stop-and-go traffic. The ACC is designed to maintain a safe distance from the vehicle in front and is more likely to be activated when the user determines a set distance. Figure IV.11 shows the output of steering behavior done by the truck when it approaches the round highway. Form section 0 to 53 seconds the truck travels in a straight line and without any obstructions as the road ahead changes to a round highway the steering is turned to the right from section 53 to 70 seconds until from section 74 to 200 seconds the steering is kept at a constant left turn until the end of the simulation.

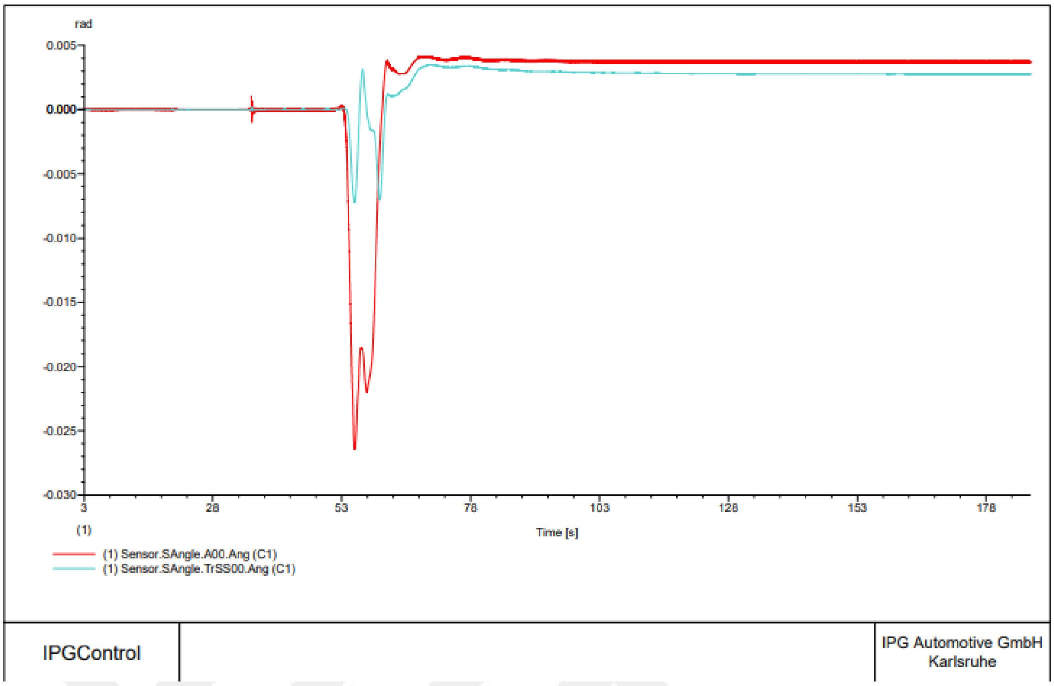


Figure IV.11. Steering behavior of the truck.

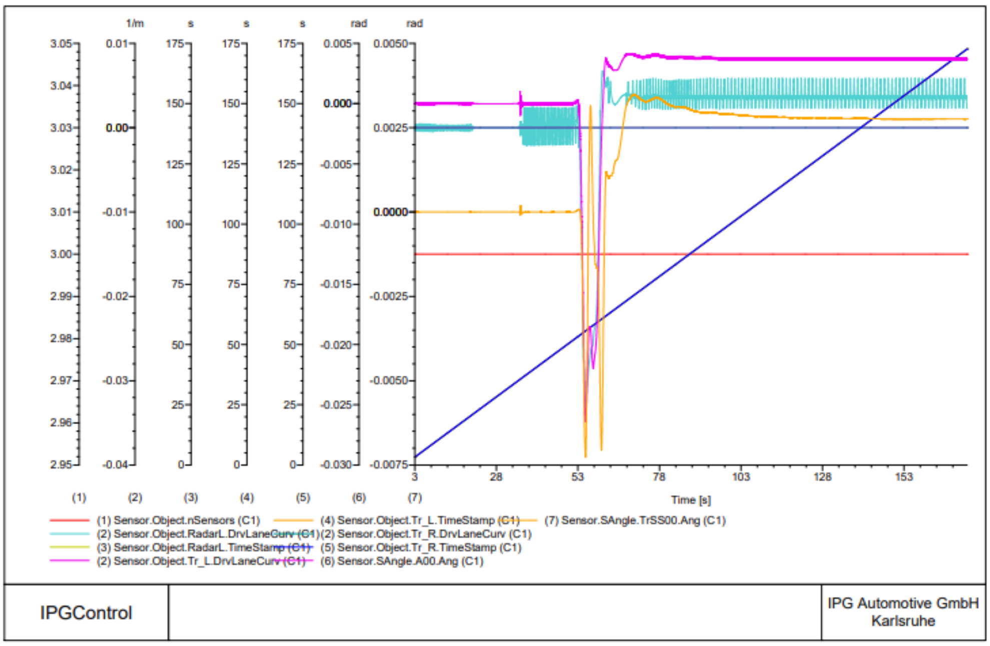


Figure IV.12. Output for all the sensors combined.

Figure IV.12 shows the output for all the sensors working together in harmony hence proving that the sensors send feedback to the ACC system and the truck follows the lead truck, continues a constant path, and keeps a safe distance.

4.2 Vehicle Behavior

The algorithm uses information about the trucks in the platoon to control the movement of the truck while active in a platoon. This information is used to coordinate the trucks movements to optimize the flow of traffic and avoid collisions.

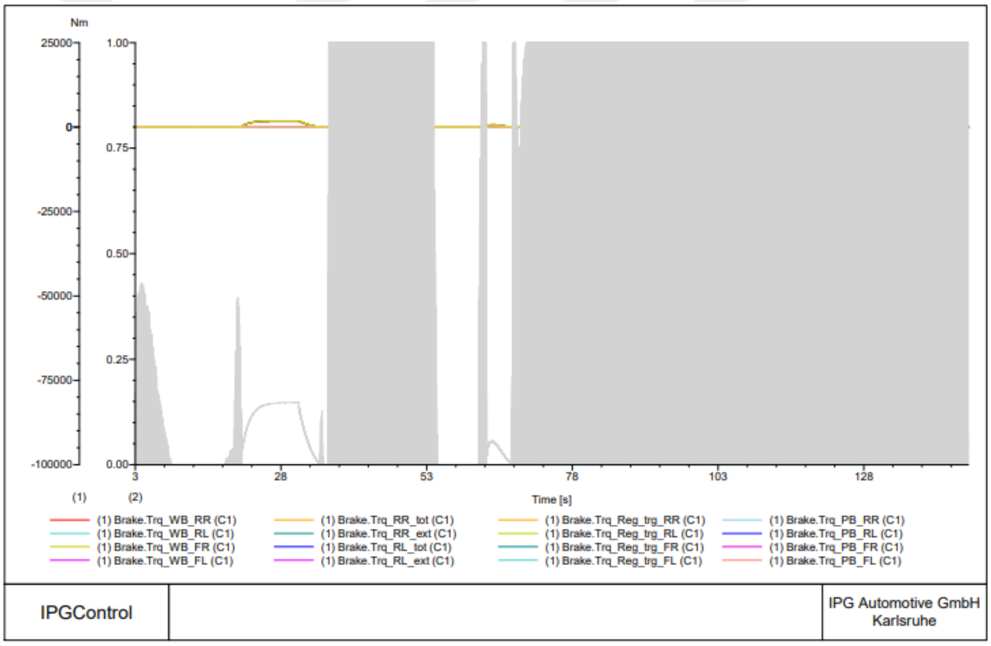


Figure IV.13. Output for brake behavior.

Figure IV.13 shows that the brake behavior of the truck IPG control system uses a brake-by-wire system that uses individual wheel torque control to improve vehicle stability and braking performance. The other four lines represent the brake torque at the other three wheels in the same order. The figure shows that the brake torque at each wheel is controller to be equal to the brake torque setpoint. This ensures that all four wheels are braking evenly, and that the vehicle is stable. For example, when the truck is cornering the IPG control system will apply more brake toque to the outside wheels to help the vehicle turn. The IPG control system is a complex system, but it is essential for ensuring the safety and stability of vehicles with brake-by-wire system.

V. CONCLUSION

This thesis studies the algorithm for implementation of a controller to work with IPG which is developed in MATLAB/Simulink. It uses V2V communication for trucks to be able to work together and overcome the traffic issues faced in day-to-day commutes. The proposed controller is based on a combination of feedback and feedforward control. The feedback component is the controller uses sensors to measure the current state of the vehicles in the platoon and then calculates the control signals necessary to maintain the desired inter-vehicle spacing. The feedforward component of the controller uses a model of the vehicles and the road to anticipate future disturbances and calculate ethe control signals necessary to counteract them. The controller is implemented in MATLAB and uses the IPG framework to combine planning and control. The planning component of the controller generates a trajectory for each vehicle in the platoon, while the control component of the controller calculates the control signals necessary to follow the trajectory. In this thesis the results indicated a successful behavior as expected by the controller and the IPG system framework. The algorithm developed in the thesis has shown to be robust to various disturbances, including changes in road conditions and driver maneuvers. The algorithm is able to adjust inter vehicle spacing even when the vehicles are subject to sudden changes in speed and acceleration. The result of this thesis suggest that the algorithm is a promising approach for close follow up truck platooning. It is effective in achieving the desired objectives and has the potential to significantly improve transportation efficiency and safety as well as assist in future development with its algorithm infrastructure.

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