Study of Disturbance Models For Heavy-duty Vehicle Platooning

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Study of Disturbance Models For Heavy-duty Vehicle Platooning

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Abstract

Transportation-cost is an important factor in the price of products, from groceries to industrial products. These products are conventionally transported using road carriers, both domestic and international. The two largest parts of the transportation-costs using this method are fuel and driver costs. Research has shown that by using platoons, traffic flow is increased and fuel cost is reduced. The aim of this thesis is to study different disturbances and their effect on platoons to enable platooning.

Two types of disturbances have been identified; internal and external. The internal disturbance is delay in the radar of the adaptive cruise control, and external disturbances are different road and traffic scenarios. Throughout this thesis, the disturbances identified have been modeled and implemented on a heavy-duty vehicle platoon of five vehicles. These disturbances have been implemented single and in combinations, trying to identify the properties of a robust adaptive cruise control and platoon.

The simulations show that the adaptive cruise control can manage external disturbances resulting in a robust platoon. But by implementing radar delay, increase of relative velocity and decrease of relative distance are amplified through the platoon.

Further using the vehicle’s collision warning system a correlation has been found, resulting in identification of a robust area for a platoon. This identification could be used to help avoiding collision warnings and collisions in the platoons.
Acknowledgements

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List of Figures

1.1 Three vehicle platoon .................................................. 7
1.2 Traffic Flow Rate ...................................................... 8
1.3 Vehicle dynamics model ............................................... 8
1.4 Effect of vehicle platoon on $C_D$ .................................. 9
1.5 Time gap adjustment button and display ......................... 10
1.6 AiCC enabled and disabled states .................................. 10
1.7 TRW Autocruise AC-20 ................................................ 11
1.8 Different radar antenna beam configurations .................... 12
1.9 Vehicles in the radar’s field of view ............................. 13
2.1 Two different traffic scenarios ...................................... 15
2.2 Sliproad scenario ..................................................... 15
2.3 Cut-in scenario ........................................................ 16
3.1 STARS 2 model in Dymola environment ......................... 19
3.2 Illustration of process flow in the simulink model ............ 20
3.3 Illustration of a vehicle following using AiCC ................. 21
3.4 Platoon of five vehicles ............................................. 21
3.5 Road profile used in simulations .................................. 22
3.6 Two vehicle following with no radar delays .................... 22
3.7 Five vehicle platoon with no disturbances ..................... 23
3.8 Model of vehicle following with radar delay ................... 24
3.9 Vehicle velocity and relative distance in a platoon, 0.5 s delay 24
3.10 Vehicle velocity and relative distance in a platoon, 1 s delay 25
3.11 Model of vehicle following with radar noise .................. 26
3.12 Vehicle velocity and relative distance in a platoon, with 0.005 noise power 27
3.13 Vehicle velocity and relative distance in a platoon, with 0.05 noise power 27
4.1 Layout of CANalyzer .................................................. 29
4.2 Identification of road type ......................................... 30
4.3 Polynomial Designed to fit measured data but failed .......... 31
4.4 Polynomial fitting the measured data ........................... 32
4.5 Mean deviation chart ............................................... 33
5.1 Simulink model of target distance reduction during a cut-in. 35
5.2 Platoon behavior in a curve scenario without any radar delays. 36
5.3 Platoon behavior in a curve scenario with 1 second radar delay. 37
5.4 Platoon behavior at braking with varying reference velocity change 38
5.5 Platoon behavior at braking with varying radar delay .......... 39
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.6</td>
<td>Platoon behavior at braking on different road types</td>
<td>41</td>
</tr>
<tr>
<td>5.7</td>
<td>Platoon behavior at cut-in with varying velocity change</td>
<td>42</td>
</tr>
<tr>
<td>5.8</td>
<td>Platoon behavior at cut-in with varying radar delay</td>
<td>43</td>
</tr>
<tr>
<td>5.9</td>
<td>Platoon behavior at cut-in on different road types</td>
<td>44</td>
</tr>
<tr>
<td>5.10</td>
<td>CW status in velocity and relative distance plots</td>
<td>45</td>
</tr>
<tr>
<td>5.11</td>
<td>CW status on relative distance vs. relative velocity percent plot.</td>
<td>46</td>
</tr>
<tr>
<td>5.12</td>
<td>Scatter plot presenting start and end limits of CW enabled</td>
<td>46</td>
</tr>
<tr>
<td>5.13</td>
<td>Correlation representing CW status</td>
<td>47</td>
</tr>
<tr>
<td>5.14</td>
<td>Platoon behavior in a relative distance vs. relative velocity percent diagram</td>
<td>47</td>
</tr>
<tr>
<td>6.1</td>
<td>Robustness identification plot</td>
<td>48</td>
</tr>
</tbody>
</table>
Chapter 1

Background

Safety, fuel consumption, and comfort are some of the important qualities affected by the time it takes and the way a driver reacts to the environment, other vehicles, and special circumstances. Heavy-duty vehicle (HDV) manufacturers have by applying systems such as cruise control (CC), anti-lock braking system (ABS), and traction control system (TCS) enhanced control over these factors, and reduce the uncertainties of human behavior. One of the driver assistant systems which is constantly under development is the adaptive intelligent cruise control (AiCC). AiCC is a further development of the traditional cruise control.

The CC only strives to maintain a reference velocity set by the driver. Not accounting for other vehicles is a weakness of this system, causing problems when the subject vehicle has a higher reference velocity with respect to the vehicle ahead. This causes a collision if the driver does not intervene. AiCC, also known as dynamic cruise control, uses a radar to gather information regarding vehicles ahead. Utilizing information such as velocity and distance of a vehicle ahead relative subject vehicle, AiCC controls velocity of the subject vehicle to keep a predefined distance between the two vehicles. This type of cruise control paves the possibility of longitudinal vehicle platoons.

There are in particular two crucial factors which need to be taken into account when performing longitudinal vehicle platoons, the minimum and maximum distance between two following vehicles. The aim of this project is identifying disturbances affecting the adaptive cruise control and its ability to adhere to these factors. Identifying and applying control to these disturbances might make a finite longitudinal heavy-duty vehicle platoon feasible.

1.1 Platoon

To understand where the concept of platooning comes from, platoon which is the root of platooning needs to be understood. A platoon in its military context is “a subdivision of a company of soldiers, usually commanded by a subaltern or lieutenant”[1]. That is, a company of soldiers regulate their behavior and movement according to the lieutenant’s orders. Military is known for and is a symbol of discipline, order and obedience, and can therefore be regarded as a perfect role model for vehicle behavior on highways. Relating the definition of platoon to heavy-duty vehicles, the lieutenant is a vehicle moving ahead of a company of vehicles following with pre-determined distance to the vehicle ahead, as shown in figure 1.1

The idea is to determine the behavior of vehicles moving closely in a longitudinal direction, eliminating human behavior such as sudden accelerations and decelerations, in a fuel
efficient and safe manner. This is called platooning and would result in a convoy of vehicles with a rationalized inter-vehicle distance.

1.1.1 Benefits of Platooning

Transportation-cost is an important factor in the price of products, from groceries to industrial products. These products are conventionally transported using road carriers, both domestic and international. The two largest parts of the transportation-costs using this method are fuel and driver costs. Driver cost constituting 40-50% and fuel 55% of the total costs per mile[4]. These costs are reduced significantly by forming vehicle platoons through increased traffic flow and reduced aerodynamic loss.

Traffic Flow

Traffic flow is an important factor affecting transportation cost in the form of driver cost. A higher traffic flow rate decreases transportation time which is a cost reduction, also resulting in an increased comfort level for the driver. This factor is a benefit not only for road carriers, but also other drivers driving the same route. Corrosion of the road also decreases as a result of the increased flow rate.

Driving in a longitudinal platoon using adaptive cruise control increases the traffic flow rate compared to driving manually [3]. This difference is mainly caused by a lower reaction time by the automated system compared to a human driving, which causes a decreased minimum inter-vehicle distance. The comparison of traffic flow rate between a human driven and an AiCC vehicle is shown in figure 1.2. The road efficiency is increased as a result of increased flow rate as a computer controlled model is used.

Aerodynamic Loss

Drag and aerodynamic loss are interrelated with fuel consumption. Considering the vehicle model in (1.1), $F_{\text{engine}}$ is the force moving the vehicle forward, which is directly proportional to fuel consumption. $F_{\text{air drag}}(v)$ is a resisting force inhibiting the vehicles movement, and calculated as directly proportional to the drag coefficient $C_D$. Studying model in equation (1.1) and figure 1.3, it is shown that fuel consumption of a vehicle is dependent on drag coefficient. Here $F_{\text{brake}}$ is the braking force between the wheels and the ground, $F_{\text{roll}}$ is the frictional force between the wheels and the ground, and $F_{\text{gravity}}$ is the gravitational force on the vehicle.
Figure 1.2: Traffic flow rate, a comparison between automated vehicle and human controlled vehicle. [3]

Figure 1.3: Vehicle dynamics model.
\[ F_{\text{vehicle}} = F_{\text{engine}} - F_{\text{brake}} - F_{\text{airdrag}}(v) - F_{\text{roll}}(\alpha) - F_{\text{gravity}}(\alpha) \]  

A vast benefit of vehicle platooning is reducing \( C_D \), resulting in reduced fuel consumption. Drag and aerodynamic loss are directly related to inter-vehicle distance. This relationship is shown in figure 1.4.

As observed in figure 1.4, both vehicle distance in convoy and position in convoy affect the drag coefficient. A higher \( C_D \) is achieved by an increased number of vehicles ahead of the subject vehicle and lower distance between vehicles [5]. Also, having a vehicle infront results in a lower \( C_D \) compared to having one behind.

1.2 The Adaptive Cruise Control (AiCC)

AiCC is a driver assistance system similar to the basic cruise control, adjusting vehicle velocity according to predefined settings by the driver. CC has been a standard system in vehicles for many years now. It keeps the vehicle velocity at a predefined value. Using an AiCC, the distance to vehicle ahead is additionally predefined by the driver as a time gap. Time gap is a setting with five steps starting at one second, increasing 0.5 seconds per step. Figure 1.5 displays adjustment of the time gap and the time gap illustration in the Scania HDV display.

As the subject vehicle approaches a vehicle ahead with lower velocity, the AiCC reduces engine torque to decrease velocity and maintain a proper distance according to the predefined time gap. At this point, the subject vehicle adjusts its velocity to that of the vehicle ahead.
In cases where the vehicle ahead has a velocity higher than the subject vehicle or is outside its radar range, the AiCC would act as a CC. This behavior is demonstrated in figure 1.6.

Figure 1.6: AiCC enabled as vehicle ahead is in radar range, with a velocity lower than the subject vehicle’s velocity. \( v_1 \) and \( v_2 \) are velocities of vehicle ahead and subject vehicle respectively.

1.2.1 Limitations of AiCC

An automated system can have negative effects on the comfort of the vehicle. A purpose of using automated controllers is reaching reference values as fast as possible. In a vehicle, this could cause heavy acceleration and decelerations, resulting in a decreased comfort level for the passengers of the vehicle. To avoid this type of behavior, limitations have been set on the system. Maximum acceleration and deceleration limits are installed in the adaptive cruise control, set in a range suited for normal traffic situations. At extreme situations such as emergency braking, these limitations give rise to the need of other assistance systems such as the collision warning system.

1.3 Collision Warning

Collision warning is a function which alerts the driver about possibility of a collision and challenges the driver to take control over the vehicle to avoid the collision. AiCC, because of its limitations, cannot reach the deceleration needed to prevent a collision, assigning control of the vehicle to the driver. This function works parallel to the adaptive cruise control.
The collision warning has two states; true and false. The status is set to true when the system determines that the AiCC cannot prevent the collision and the driver is informed of this fact. Drivers’ reaction to this warning disengages the AiCC and the driver takes control over the vehicle. As the system determines AiCC can handle the situation, the status is set to false, and the system proceeds as usual.

1.4 Radar

The difference between CC and AiCC is the subject vehicle taking into account other vehicles ahead in regulating its velocity and behavior. Information such as relative distance and velocity of vehicles ahead are collected by a radar positioned in front of a subject vehicle. This transfer of information is one sided, the subject vehicle being the only receiver of information. Figure 1.7 is a typical radar used by AiCC systems.

![Figure 1.7: TRW Autocruise AC-20][2]

The TRW AC20 radar is a millimeter wave radar, having an advantage over other types of sensors such as optical or infrared sensors, performing equally well during day, night and in most weather conditions [6]. The International Organization of Standardization (ISO) published a standard [7] which specified performance requirements and test procedures for ACC systems, containing government requirements for vehicle radars. Different countries and continents have different allowed frequency spectrums for vehicle radars. According to this standard the common frequency to all regulation standards is 76-77 GHz, the same as the radar used in this project.

1.4.1 Radar Types

Three types of radars are usually used with AiCC systems; Frequency modulated continuous wave (FM-CW), Frequency shift keying (FSK), and Pulse modulation schemes [6]. These
radars are typically used together with the following radar antenna beam configurations, shown in figure 1.8.

- **Switched Beam** (one beam only receiving at any time)
  The system continuously switches between the overlapping transmit / receive beams.

- **Single Scanning Beam**
  A mechanical or electrically scanning antenna is used to sweep across the desired coverage.

- **Monopulse** (one transmit and two receive beams)
  Transmit a single wide beam.

![Figure 1.8: Different radar antenna beam configurations; a. Switched Beam, b. Single Scanning, c. Monopulse [6].](image)

The radar used in this project, shown in figure 1.7, is a monopulse radar operating in continuous wave mode with FSK modulation. Further specifications can be read in appendix A.

In this thesis, no effort has been put on evaluating the hardware and components. No comparison has been done between the different radar types, only an introduction of different radar types and the radar used.

### 1.4.2 Information From Radar To AiCC

The radar has the ability to gather information from four vehicles ahead as shown in figure 1.9. Information such as relative distance, speed, acceleration, azimuth angle, and if the vehicle is stationary or not is collected by the radar and sent using a CAN network to the AiCC.

The information sent by the radar are not the raw data collected, these data are computed, controlled and filtered by the radar’s circuit. Many disturbances have been managed in the radar’s signal processing unit, sending more reliable data to the vehicle. An example of disturbances managed by the radar’s circuit is ghost targets. Ghost targets are targets which are a result of radar ambiguities in phase measurements, caused for example when the vehicle drives into a tunnel.
Figure 1.9: Vehicles in the radar’s field of view
Chapter 2

Disturbances Affecting AiCC

The performance of AiCC and its reliability is dependent on management of inflicting disturbances. Even though the radar manages some disturbances, such as ghost targets, there are other disturbances outside the radar’s range of control which need to be controlled by the AiCC. For the purpose of this study these disturbances have been separated into two groups; external disturbances caused by different road and traffic situations, and internal disturbances in the vehicle.

2.1 Internal Disturbances

Internal disturbances are disturbances in a vehicle and its components, such as the vehicle’s control logic, brake system or radar. In this thesis, internal disturbances have been limited to disturbances in the radar, and two possible types of disturbances have been identified; reaction time and noise. The AiCC acts on the messages it receives, and any type of inaccuracy could cause reduced performance and security for the vehicle.

2.1.1 Reaction Time and Delays

The time it takes for the radar to send a message to the CAN network as soon as it detects an object is an important factor affecting performance of the AiCC. In a traffic situation where there are several vehicles around and in front of the subject vehicles, target identification takes a longer time. The radar needs to identify all vehicles, the lanes they are moving in, and identify the vehicles relevant to the AiCC. These calculations and computations increase reliability of the radar, but at the same time require time.

Further, the signal to noise ratio has an important positive correlation effect on the reaction time of the radar. Comparing the two scenarios in figure 2.1, the radar reaction time and delay could vary up to one second.

2.1.2 Deviation and Noise

During measurement of relative velocity and distance, the values sent to the AiCC could deviate from the true values. This could be considered as a constant error throughout the measurement, or as a noise. Existence of such an error or noise in higher amplitudes could cause uncertainty in the AiCC.
2.2 External Disturbances

External disturbances are disturbances from the road or other vehicles affecting a platoon or the AiCC. The limitations and configurations of the AiCC can cause certain traffic disturbances to be dangerous. Scenarios such as sliproad, braking and cut-in, or even topography can be understood and analyzed as disturbances.

2.2.1 Sliproad

A scenario where delays in the system could cause problems in robustness of the AiCC is at sliproads. When the vehicle ahead turns off on a sliproad to exit a high-way, the radar will continue to recognize this vehicle as a primary target if the sliproad continues parallel to the high-way. At the same time a new vehicle ahead might have a lower velocity than that of the subject vehicle. It is not clear how the system would react at the moment the new target is identified if the new vehicle ahead gets too close to the subject vehicle? This scenario is demonstrated in figure 2.2.

A delay in the system would cause a later identification of the new target, resulting in a shorter inter-vehicle distance. The short distance could enable the collision warning, which is not desired.
2.2.2 Cut-in

Another scenario which is of importance is when a vehicle cuts in between the subject vehicle and the primary target, as shown in figure 2.3. Issues that can be discussed in this scenario are the lateral movement and velocity of the cutting-in vehicle.

![Figure 2.3: Cut-in scenario](image)

Lateral movement

The AiCC does not take lateral acceleration into consideration. When a vehicle performs a cut-in, it moves laterally in front of the radar. As the lateral movement is not identified, as soon as the cutting-in vehicle moves into the radar range, AiCC will suddenly detect a new target. In the presented scenarios a new target is suddenly presented to the AiCC in a shorter target distance, and it is unclear how the AiCC of the subject vehicle manages the sudden change.

Vehicle velocity

AC-20 only detects vehicles with velocities lower than or equal to that of the subject vehicle, hence if in a cut-in where the vehicle cutting in has a higher velocity than that of the subject vehicle, the radar takes no notice of this vehicle. If for any reason, the vehicle cutting in starts braking in front of the subject vehicle, it is identified as a primary target by the AiCC.

2.2.3 Hard Braking

Hard braking is classified as when a vehicle decelerates at about 5 to 8 m/s² [8]. At a scenario where any vehicle in the platoon needs to perform a hard brake, this braking can be perceived as a disturbance for the rest of the platoon behind it. The effect of the braking could amplify through the platoon, affecting the platoon’s robustness.

2.2.4 Curve

In some road conditions, such as a curve, where every vehicle in a platoon lose their target in exactly the same position, these vehicles would change to CC-mode and accelerate because of the higher CC reference velocity. As the vehicle drives past this part of the road, its target is located and the vehicle changes back to AiCC-mode. This is repeated for every vehicle in the platoon and could have an amplifying effect through the platoon.

2.3 Disturbance Combinations

The presented disturbances will be studied, and results of these disturbances will be analyzed, but it is important to remember that in the real world each disturbance is not isolated
occurring only by itself. Disturbances can affect the system in different combinations, exerting the system to extreme conditions. During this thesis, disturbances presented in chapter 2 will be studied separately and in different combinations, analyzing their effects on a vehicle platoon. Disturbances in different combinations might amplify their isolated effects or cancel them out, effecting robustness of the platoon.
Chapter 3

Simulations

The aim of this thesis is to study robustness of the AiCC in vehicle platoons under the effect of different disturbances. These disturbances could cause the vehicles to collide, hence it would be dangerous to perform these scenarios in the field. To be able to test different hypotheses and put the vehicle in dangerous scenarios computer simulations have been used.

3.1 Software

Simulations have been performed using Simulink version 7.2 which is the Simulink version used by MATLAB R2008b. The software which the vehicle model is constructed in is Dymola (Dynamic Modeling Laboratory) version 7.2.

3.2 Single Vehicle Model

Performing simulations is an effective method for performing tests, but only reliable if the model used is accurate and validated. The model used during this thesis is a vehicle model created by Scania and validated through numerous comparisons with field tests, and is a result of collaboration between two models, the simulink model and the Dymola model.

3.2.1 Dymola Model (STARS 2)

To be able to produce reliable and realistic results, an advanced vehicle model was used, called STARS 2. This model, constructed in Dymola, contains dynamics of a heavy-duty vehicle to represent behavior and characteristics of real heavy-duty vehicles in field. The STARS 2 model has not been manipulated in any way throughout the thesis. The layout of Dymola and STARS 2 are shown in figure 3.1.

3.2.2 Simulink Model

The part of the model which has been manipulated and customized to suit the purpose of the thesis is the simulink model. This model is the part of the HDV model containing the logic. This model can be divided into three parts; inputs, the body, and outputs illustrated in figure 3.2.
Figure 3.1: STARS 2 model in Dymola environment.
**Inputs**

The inputs are information received by the body from the driver, environment, and vehicle information. Information from the driver are settings which truck drivers adjust while driving HDVs, settings such as cruise control set speed, downhill speed control and AiCC time gap settings. Change and manipulation of these settings which truck drivers change during driving can be determined before the simulations, and implemented during the simulations.

Information from the environment in this context should be regarded as road altitude and slope, and information about other vehicles on the road collected by the vehicle’s sensors. All inputs can be changed and manipulated, constructing different driving scenarios and road types.

The vehicle information can also be changed, such as using different engines and changing mass of the trailer and many other factors affecting behavior of the HDVs.

**The Body**

The body consists of the logic of the vehicle, and the STARS 2 model. STARS 2 contains all information about the HDV, its behavior and characteristics, sending these information continuously to the logic. The control logic performs required calculations, considering data from STARS 2 and other inputs presented prior, for actuator behavior, further sending information back to the dymola model.

**Outputs**

The outputs of the model are all data which the driver, and other drivers and vehicles receive from the HDV. The output data could be vehicle dynamics information such as velocity and position, engine information such as torque and fuel consumption, and even drag, braking, and acceleration.

![Figure 3.2: Illustration of process flow in the simulink model.](image)

### 3.3 Platoon Model

The aim of this thesis is analysis of robustness of a platoon of heavy duty vehicles. For this purpose, a model is needed containing more than two vehicles. In this study a platoon of five vehicles is chosen, to be able to observe change in behavior of the vehicles as the number of vehicles increase compared to a smaller platoon.
The purpose of the thesis was to study behavior of a platoon and not modeling the platoon, hence an exciting model was chosen. This was a model of two vehicles previously used for simulating the AiCC function illustrated in figure 3.3.

As shown in figure 3.3, the only connection between the two vehicles is by the AiCC radar. The information received by the radar is relative velocity ($v_{rel}$) and relative distance ($d_{rel}$), being equal to velocity difference ($v_2 - v_1$) and the distance between the two vehicles respectively.

This model needed to be manipulated to be used for simulating a five vehicle platoon. It was enlarged to a five vehicle platoon without changing the logic or structure of the model. As the only connections between a vehicle and the one ahead of it are relative distance and relative velocity, the same principle was followed in the model for all vehicles, shown in figure 3.4.

3.4 Road Profile

During the simulation tests performed, a road profile was used containing three road types; flat, uphill, and downhill, with slope of zero, two and negative two percent respectively. The road profile is illustrated in figure 3.5, and is used to be able to observe effect of different disturbances on the vehicle in a platoon in different road conditions.

3.5 Platoon Behavior With No Disturbances

Before studying the behavior of vehicles in a platoon with disturbances in the radar signals, a reference behavior is needed where the radar does not have any disturbances. In this type of system the relative distance and velocity signals of a vehicle are drawn directly to the input block of the vehicle behind as illustrated in figure 3.6.

For all simulations in this thesis, the CC reference velocity, time gap, vehicle mass, and downhill speed control (DHSC) settings are as presented in table 3.1, if not stated otherwise.
DHSC limits the deviation of vehicle speed from the reference velocity in a downhill scenario. Also, a speed limit of maximum 90 km/h is installed on the models, as this is the speed limit by law in Sweden for heavy-duty vehicles.

<table>
<thead>
<tr>
<th>Vehicle nr.</th>
<th>$v_{rel}$ (km/h)</th>
<th>Time Gap</th>
<th>Mass (kg)</th>
<th>DHSC (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80</td>
<td>-</td>
<td>40000</td>
<td>5</td>
</tr>
<tr>
<td>2-5</td>
<td>90</td>
<td>1</td>
<td>40000</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 3.1: Predetermined settings for all platoon vehicles.

A simulation of a platoon of five vehicles has been simulated. Interesting factors to study in a platoon behavior are vehicle velocity and relative distance between the vehicles, shown in figure 3.7. These factors have been plotted as a function of time to be able to compare the vehicles behavior at each moment of time.

### 3.6 Implementing Disturbances

Previously in chapter 2, different types of disturbances affecting a platoon were introduced. In this section of the report, the implementation of the disturbances will be introduced followed by change of vehicle behavior as a result of the disturbances. These implementations were performed on the input part of the simulink model, with no changes performed on the logic and dynamics of the vehicle.
Figure 3.7: Five vehicle platoon with no disturbances; vehicle velocity on top, and relative distance in bottom figure.
3.6.1 Radar Delay

One of the disturbances in measuring relative distance and velocity to the vehicle ahead is delay in the radar. It is assumed that depending on different circumstances, the signals from the radar can be delayed up to one second. Implementing this delay is done using simulink’s Transport Delay block, effecting both relative distance and relative velocity as illustrated in figure 3.8.

Figure 3.8: Model of vehicle following with radar delay, i=1,2,3,4

Result Of Radar Delay

Two simulation of five-vehicle platoons on a hill road are now performed with 0.5 and one second radar delays, and results of these simulations are observed in figures 3.9 and 3.10.

Figure 3.9: Vehicle velocity and relative distance in a platoon, with 0.5 seconds delay.
Figure 3.10: Vehicle velocity and relative distance in a platoon, with one seconds delay.

Comparing figures 3.7, 3.9, and 3.10, the effect of radar delay on vehicle behavior in a platoon can be observed. Studying the velocity plots of these three figures, an increase of overshoot (between time interval 200 to 220 seconds) is observed with increase of delay. Also, a higher settling time is required, observed at the end of the simulation. The same behavior is observed when studying the relative distance plots of these figures.

These results are strong evidence of the effect of radar delay in platooning and vehicle behavior, increasing the weight of this factor in the thesis.

3.6.2 Noise In Radar Signals

A further disturbance which could exist in the radar signal is noise. Noise in the signal could result in an unstable measurement, reducing performance of the AiCC. No information about noise in the radar signal were present, so different amplitudes of noise were used in simulations, making it possible to study its effect on vehicle behavior in a platoon.

Implementation of noise was done by adding white noise, generated by simulink’s Band-Limited White Noise block, to the original signal received from the vehicle ahead as shown in figure 3.11.

The Band-Limited White Noise settings were set up with a sampling time of 40 ms which is the update rate of the radar. The Noise powers used in the simulations are listed in table 3.2, also stating the amplitude of each noise power.

<table>
<thead>
<tr>
<th>Noise Power</th>
<th>Amplitude</th>
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<tr>
<td>0.005</td>
<td>0.7</td>
</tr>
<tr>
<td>0.05</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 3.2: Noise power with corresponding noise amplitude.
The results of the simulations performed on a hill road with the noise powers stated in table 3.2 are plotted in figures 3.12 and 3.13. Comparing these figures and figure 3.7, it can be observed that with increase of noise in the radar signals, the AiCC vehicle’s velocity reaches a higher peak value and stability time trying to stabilize to the velocity of its target. Furthermore, the relative distances have a heavy increase by the increase of noise power which is a result of the decreased rise time caused by the noise. Comparing noise powers 0.005 and 0.05, at the peak values, the relative distances have increased about 10 meters.

3.6.3 Conclusion Achieved Through Early Simulations

Studying results from simulations with disturbances in the radar, it can be concluded that disturbance in the radar cause an increased overshoot behavior, both in vehicle velocity and relative distance. The result of increased relative distance is loss in benefits of platooning in the form of decreased traffic flow rate and increased fuel consumption.

The disturbances have also caused increase in reduction of relative distance during decelerations in comparison to figure 3.7 with no radar delay, which increase probability of collision. In none of the cases simulated at this point have the vehicles been close to a collision, but this behavior is crucial when simulating traffic disturbances such as hard braking or cut-in.
Figure 3.12: Vehicle velocity and relative distance in a platoon, with 0.005 noise power.

Figure 3.13: Vehicle velocity and relative distance in a platoon, with 0.05 noise power.
Chapter 4

Field Tests

One of the possible disturbances mentioned in the previous chapter was signals from the radar. The radar signals are inputs to the AiCC, transferring behavior of vehicles ahead to the AiCC. To enable modeling a reliable platoon behavior in a simulation platform, Simulink in this case, the radar signals need to be simulated as they behave in their natural environment.

For the purpose of understanding the quality and behavior of the radar and radar signals, some field tests were performed presented in this chapter. Through the chapter, the test methods will be first discussed followed by the software used for collecting the data. Later, the methods used for analyzing the data will be presented, and finally the conclusions will be stated.

4.1 Test Method

A factor which could affect the radar signal is the road type; flat, uphill, or downhill. For the purpose of measuring the radar signals received at the different road types, two Scania trucks were driven between Södertälje and Mariefred. Information and specifications about the trucks are presented in table 4.1. In excess of the AiCC which is the main hardware used during these tests, both vehicles were equipped with GPS for registering position, altitude, and slope of the vehicle and road.

<table>
<thead>
<tr>
<th>Vehicle Name</th>
<th>Mumrik</th>
<th>Montana</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Type</td>
<td>Rigid truck</td>
<td>Tractor with semi-trailer</td>
</tr>
<tr>
<td>Position</td>
<td>Ahead</td>
<td>Tail</td>
</tr>
<tr>
<td>Velocity Control</td>
<td>CC</td>
<td>AiCC</td>
</tr>
<tr>
<td>Gearbox</td>
<td>Manual Range / Split</td>
<td>Opticruise</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>20000</td>
<td>39000</td>
</tr>
<tr>
<td>Max Power (hp)</td>
<td>420</td>
<td>620</td>
</tr>
</tbody>
</table>

Table 4.1: Test vehicle specifications.

The AiCC vehicle had a cruise control set velocity 10 km/h higher than that of the vehicle ahead, downhill speed control (DHSC) set to 5 km/h, with AiCC activated and time gap varying between 1 and 3 seconds at different test episodes.
4.2 Software

Logging of CAN messages were performed using a PC laptop connected to the vehicles CAN output, registering the vehicles CAN messages using CANalyzer version 7.1.43. CANalyzer is a software which uses CANalyzer interface connected to the vehicle’s CAN network to register messages from this network. The Layout of CANalyzer is shown in figure 4.1.

![CANalyzer Layout](image)

Figure 4.1: Layout of CANalyzer

4.3 Evaluating Collected Data

The first step in evaluating the collected data is to identify the type of road. Even though the type of road was registered at the beginning of each logging, while studying the collected data, it was observed that the road type from the GPS varied from the registered data. This difference enforced an identification of road type from the collected GPS data.

4.3.1 Identifying Road Type

The data collected from the CAN network using CANalyzer are converted to MATLAB compatible format, and after identifying slope and altitude data from the GPS, these data are plotted and studied. By studying the slope and altitude plots against each other, the road type classification is performed. Roads with a slope at approximately zero percent are classified as flat, two percent as uphill, and negative two percent as downhill. An example of plot of altitude and slope of a complete log file are displayed in figure 4.2, with the different classifications identified in these plots.
Figure 4.2: Identification of road type.
As the start and end time of the designated road type are identified, all CAN messages collected in the log file are saved in this time interval.

4.3.2 Data Deviation

The main aim of performing these tests was to identify deviation of data collected from the radar, and use this information to enable proper signal modeling in the platoon simulations. Because of the constant change of velocity and distance between the two vehicles, there is no single suitable value to account for as a proper mean value. This problem is solved by finding a polynomial fitting the designated data.

Polynomial

The polynomial fitting the designated data is calculated using MATLAB’s `polyfit` function. Using time and value measured during the tests, a third order polynomial in form of equation (4.1) is calculated.

\[
P(t) = C_1t^3 + C_2t^2 + C_3t + C_4
\]  

where \(C\) is a vector of coefficients, and \(t\) is the time. Using these data, a set of new values are calculated and used as reference for calculating the deviation. In some cases, the velocity or relative distance increased and decreased several times making it close to impossible to design a polynomial fitting the data, shown in figure 4.3. Calculating the deviation using this data and polynomial would result in misleading results.

![Figure 4.3: Polynomial Designed to fit measured data but failed.](image)

To be able to use these data, these cases are divided into shorter sequences, resulting in extraction of data suitable for analysis, demonstrated in figure 4.4.
Mean Deviation

An average deviation of the measured values is sought. This mean deviation is calculated by measuring deviation of measured data compared to the polynomial at each time instance as an absolute value, and finally a mean value is calculated. This value represents the noise in the signals received from the radar, and calculated using equation (4.2), $\Delta d$ being the mean deviation, $P$ polynomial value, $x$ measured value, and $n$ the total number of values.

$$\Delta d = \frac{1}{n} \sum_{i=1}^{n} |P_i - x_i|$$  \hspace{1cm} (4.2)

The mean deviation for relative distance and relative velocity measured have been calculated for all tests performed using equation (4.2) and presented in figure 4.5 using a chart. Studying this chart, it is observed that at highest the mean deviation in a measurement has been 0.3, and taking all test into account the average deviation has been calculated to 0.089.

4.4 Conclusion

Comparing deviations in the radar signals with the amplitude of noise presented in table 3.2, and the results in figures 3.12 and 3.13, it can be concluded that the noise in the radar signal is insignificant and does not need to be taken account to in future simulations.

A further conclusion can be drawn by studying figure 4.4, observing a periodic sinus behavior of the measured data around the polynomial result. Studying the frequency of this sinus behavior and it’s correlation with the vehicle behavior could be interesting in further development of the AiCC controllers, but as this issue is outside the aim of this thesis, no further analysis have been done regarding this issue.
Figure 4.5: Mean deviation chart, relative distance in meters and relative velocity in km/h.
Chapter 5

Traffic Behavior Simulations

At this point of the thesis the disturbances affecting the system have been presented. The platoon model has been described and simulations of disturbances in the vehicle radar have been performed. Field tests have been performed, evaluating quality of the radar signals, resulting in ignoring noise in radar signals as a disturbance.

In this chapter further simulations will be performed, taking account of the result from the previous simulations presented in chapter 3, and results from the field tests. The factors added to the simulations in this chapter compared to the simulations in chapter 3 are traffic disturbances. Different traffic scenarios were presented in chapter 1, acting as disturbances for the AiCC and platooning. The modeling of these scenarios will first be presented, and these models will be implemented on the vehicle platoon model presented in chapter 3. Finally at the end of this chapter conclusions will be presented based upon analysis of the simulation results.

5.1 Modeling Traffic Disturbances

Similar to modifications made during simulations in chapter 3, modeling of traffic disturbances is also performed in the simlink model. The traffic disturbances modeled here are hard braking scenario, cut-in scenario, and curve scenario.

5.1.1 Hard Braking

The platoon model used for these simulations is a platoon of five vehicles. For illustrating a hard brake a vehicle ahead needs to perform the braking, and this vehicle can be a motorcycle, a passenger car, or even a heavy-duty vehicle. The hard brake is performed by manipulating the set velocity of the first vehicle in the five vehicle platoon. This vehicle reacts to the changed set velocity, braking to reach the new set velocity and the other four vehicles behind react accordingly and try to avoid collision.

Manipulating Set Velocity

The reference velocity of each vehicle is presented separately and for simulating a braking by the lead vehicle, the respective reference velocity is reduced at a given point. This action results in braking by the vehicle’s brake control system (BCS). The more the set velocity
is decreased, the more set velocity change is increased, resulting in higher deceleration, presented in table 5.1.

<table>
<thead>
<tr>
<th>Reference velocity changed to (km/h)</th>
<th>Deceleration ($m/s^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>4</td>
</tr>
<tr>
<td>50</td>
<td>6</td>
</tr>
<tr>
<td>40</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 5.1: Deceleration of lead vehicle as a result of reference velocity reduction from 80 km/h.

5.1.2 Cut-in and Sliproad

Simulating a cut-in is similar to braking, performed by manipulating inputs of the first vehicle. A cut-in is when a vehicle cuts in between two vehicles, with the following vehicle’s radar measuring a sudden decrease of distance to target as a new vehicle is positioned between the radar and target. Making the assumption that a vehicle has a length of five meters and a comfortable distance to vehicle ahead during a cut-in is ten meters, the following vehicle’s radar measures a decrease of target distance of fifteen meters. The change of distance is modeled in simulink by using a step of negative fifteen as presented in figure 5.1.

![Simulink model of taget distance reduction during a cut-in.](image)

Figure 5.1: Simulink model of taget distance reduction during a cut-in.

Not all cut-ins are performed by a vehicle moving in between two other vehicles, keeping its previous velocity. In some cases the vehicle cutting in performs a braking during the cut-in process. Simulating this type of behavior is performed by combining both cut-in and braking.

From the radar’s perspective, cut-in and sliproad scenarios are similar in behavior. In both cases a new target is introduced with a lower inter-vehicle distance. Hence the results from cut-in simulations can be generalized to the sliproad scenario.

5.1.3 Curve

It has been assumed that in some roads and road conditions such as a curve, at a certain position, every vehicle will lose the target in front of them. As the radar loses its target, the AiCC is turned off and the vehicle velocity is controlled by CC. Simulation of this scenario is performed by manipulating inputs of all vehicles in the platoon which use AiCC.
Similar to the process of manipulating the set velocity, the curve scenario is modelled by changing the AiCC status from Enabled to Disabled at a certain position of the road for all vehicles.

5.2 Result of Traffic Disturbances

Different traffic disturbances have been simulated in combination with radar delay, and results of these simulations are presented in this section. An important signal observed during these simulations was the collision warning status. The collision warning continuously calculates if the AiCC can avoid a collision with the vehicle ahead. If the AiCC can avoid a collision, the status is False, and if a collision is inavoidable by the AiCC, the status is True.

5.2.1 Curve Scenario

Two simulations have been performed suited for the curve scenario, once with no radar delay and once with one second radar delay. In the the curve scenario, all vehicles lose their target at a determined position, 110 to 115 seconds after start of the simulations, and by doing so the vehicle switches to its CC set velocity which is higher than that of the first vehicle’s. Results of these simulations are displayed in figures 5.2 and 5.3. It is needed to be mentioned that as the AiCC is turned back on again in these simulations, the time gap setting is changed to 2 seconds time gap which is the setting at start up for the AiCC.

![Figure 5.2: Platoon behavior in a curve scenario without any radar delays.](image)

The purpose of the simulations in curve scenario was to observe the robustness of the AiCC when approaching a target vehicle at a close distance with higher subject velocity. Observed from figures 5.2 and 5.3, the AiCC manages to keep the desired relative distance when the AiCC is enabled again, even when applying radar delay. One especially interesting
observation was the difference between results from simulations with radar delay and without delay. The application of delay resulted in oscillations of both vehicle velocity and relative distance, and increased settling time.

Observing the relative distance, vehicle 2 is affected most at the moment it loses its target, which is because vehicle one in the lead has kept its CC velocity of 80 km/h. All other vehicles, having the same predetermined settings, have a lower decrease of relative distance because their targets have also accelerated. After the curve, vehicle 3, 4, and 5 manage to keep the relative distance at about 20 meters, both with and without delay, showing the AiCC’s ability to increase the distance to a safe range with regard to the time gap. However it is evident that delay in the radar causes higher relative distance for vehicles 4 and 5 before they stabilize at correct time gap distance.

### 5.2.2 Hard Braking

Hard braking simulations have been performed by varying different factors according to table 5.2. A list of all simulations performed with the specifications connected to each simulation are presented in appendix B.

<table>
<thead>
<tr>
<th>Manipulated Factor</th>
<th>Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road Type</td>
<td>Flat, Uphill, Downhill</td>
</tr>
<tr>
<td>Set velocity Change (km/h)</td>
<td>20, 30, 40</td>
</tr>
<tr>
<td>Radar Delay (s)</td>
<td>0, 0.5, 1</td>
</tr>
</tbody>
</table>

Table 5.2: Variables manipulated during braking simulations.

The behavior of the vehicles in the platoons, in form of relative distance and velocity,
have been observed and compared during these simulations, looking for factors affecting change of behavior in this scenario.

**Set Velocity Change**

The amount and time of deceleration is dependent on the set velocity change of the lead vehicle. To be able to observe the effect of change in set velocity, all other variables are set constant resulting in three simulations on flat road, and no radar delay. The set velocity of the lead vehicle is set to decrease from 80 to 60, 50 and 40 km/h in three simulations, resulting in figure 5.4.

![Figure 5.4](image)

**Figure 5.4:** Platoon behavior at braking on flat road, no radar delay, and 40, 30, and 20 km/h reference velocity change.

An important observation from figure 5.4 is the fact that in all three simulations all vehicles behave the same. After the braking of the first vehicle, all vehicles in the platoon reach their lowest relative distance at about 10 meters. In the third simulation this distance is a couple meters lower, but at the same time no difference is seen between any of the vehicles. After reaching this low value, the relative distances are increased to their respective time gap distance. All vehicles behaving the same show that the AiCC and platoon are robust
against hard braking, not amplifying change in relative distance and velocity through the platoon.

**Radar Delay**

In previous simulations, radar delay has shown to have a negative effect on robustness of vehicle platoons. In this part, it is chosen to observe the effect of radar delay in a braking scenario on a flat road and 30 km/h velocity decrease. Different delays have been applied and the results are displayed in figure 5.5.

Figure 5.5: Platoon behavior at braking on flat road, 30 km/h velocity difference and radar delays of 0 s, 0.5 s and 1 s.

Comparing the three simulations in figure 5.5, a clear difference is seen between them. With delay in the radar, none of the vehicles in the platoon show similar behavior with regards to their velocities. The relative distance is reduced through the platoon, hence showing evidence of loss of robustness. In the simulation with half a second delay compared to no delay, the second and third vehicles manage to keep their distance from their respective target vehicles, but the forth and fifth vehicles fail to do so, resulting in collision between
the forth and fifth vehicles. Observing the relative distance in this simulation, the value is negative close to zero. The relative distance of zero is the point where the front bumper of a subject vehicle is in contact with the rear bumper of its target vehicle. The value of zero and lower represents collision.

In the simulation with one second delay compared to no delay, the relative distances have reduced for all vehicles. Also, the relative distances have reduced through the platoon, resulting in loss of robustness in the finite platoon.

Road Type

It is hypothesised that the road type will have an effect on the platoon behavior as behavior in uphill movement could be dependent on acceleration capability while during downhill, braking has a stronger effect on the platoon behavior. For validating this hypothesis three simulations were performed on the three road types with the set velocity change set to 30 km/h and radar delay set to no delay. Results of these simulations are presented in figure 5.6.

Comparing these three simulations, all vehicles in the three simulations reach a relative distance of 10 meters after the braking, and later increasing their distance to a proper distance with regard to time gap. This behavior shows stability of the AiCC in a scenario with topography and braking disturbances.

Comparing the velocity diagrams of the uphill and downhill simulations, the vehicles in the downhill scenario have a lower settling time, which is evidence of different control strategies based on the topography in combination with gravitational force. The control strategy is more aggressive in the uphill mode, with a higher rise time, while a softer control is used in downhill mode, both resulting in satisfactory control of the vehicles.

5.2.3 Cut-in

Simulations with the same settings presented in section 5.2.2 were performed in a cut-in scenario. The results presented in figures 5.7 - 5.9 show the same platoon behavior as during braking, with the difference of increased braking time in the cut-in scenarios. Comparing vehicle number three in the cut-in scenarios with vehicle number two in the braking scenarios, the vehicle needs to decelerate for about eight seconds in cut-in, compared to three seconds in braking. The external disturbances such as topography, cut-in, and braking do not effect the robustness of the platoon, while the internal disturbance, radar delay, causes a less robust finite platoon.

5.3 Collision Warning (CW) Status

So far in the thesis, stability and robustness have been identified by collisions and stable behavior development through the finite platoon. These factors need to be predicted to be able to prevent them. A system which does this in the vehicle is the Collision Warning system introduced in section 1.3. This system calculates the possibility of AiCC avoiding a collision.

Further studying the CW system in section 1.3, CW uses the variables listed below in determining CW status.

- Vehicle velocity
- Target velocity
Figure 5.6: Platoon behavior at braking on flat, uphill, and downhill road, with no radar delay and 30 km/h velocity change.
Figure 5.7: Platoon behavior at cut-in on flat road, no radar delay, and 30 and 20 km/h velocity change.
Figure 5.8: Platoon behavior at cut-in at flat road, 30 km/h velocity difference and radar delays of 0s, 0.5s and 1s.
Figure 5.9: Platoon behavior at cut-in on flat, uphill, and downhill road, with no radar delay and 30 km/h velocity change.
• Target acceleration
• Relative distance to target
• Relative velocity to target

CW identifies possible limits of feasibility of the AiCC, and by identifying this area a guideline for adjusting size of a feasible and stable platoon could be produced. As the relative distance to target is a crucial factor regarding collision possibility, distance of zero being a collision, this variable is used in identifying a possible stable and CW approved area.

Studying the area CW is enabled in figure 5.10, it is observed that CW is enabled as a target vehicle has reduced velocity while the subject vehicle has not. This results in increased relative velocity between the two vehicles at the moment CW is enabled.

![Figure 5.10: CW status in velocity and relative distance plots, with CW enabled at the colored areas.](image)

### 5.4 Relative Velocity Percent

The significance of relative velocity can only be stated when compared to the subject vehicle velocity. A relative velocity of 20 km/h does not have the same significance if the subject velocity is 90 km/h compared to 40 km/h. In an attempt to find a correlation representing CW status, relative velocity percent was calculated using equation (5.1).

\[
v_{rel\%} = \frac{v_{rel}}{v} \times 100
\]  \hspace{1cm} (5.1)

The relative velocity percent of one of the simulations is plotted in figure 5.11 showing the areas CW is enabled for the different vehicles. As observed in this figure, CW is enabled as the relative velocity percent value is at its highest.

Observed in this chapter, CW has been enabled as the relative distance has reached its lowest values and relative velocity percent has reached at its highest values. The scatter diagram in figure 5.12 is a collection of all start and end points of the CW enabled areas for all simulations. As observed in this figure there are end values which have negative relative distance, as all start values are positioned in the positive relative distance area. This shows
that CW has been enabled before the collision, but because in these simulations the vehicles are only controlled by the AiCC, the collision has occurred. In reality, the driver would respond to the CW by increasing the deceleration to avoid the collision.

For being able to find a possible correlation between relative distance and relative velocity percent, all values with negative relative distance which are not of interest at this point, have been removed. The result is plotted in figure 5.13 and a third degree polynomial is plotted to better illustrate the correlation.

For better understanding the correlation illustrated in figure 5.13, it is compared to the relative velocity percent plot as a function of relative distance for a simulation. In this simulation vehicles 2 and 5 had CW status enabled, and this plot is presented in figure 5.14. Vehicle 2 reaches a low relative distance while vehicle 5 has both low relative distance and high relative velocity percent. Both cases result in crossing the polynomial in figure 5.13. Vehicles 3 and 4 do not cross the polynomial, hence keep a false status on CW.
Figure 5.13: Scatter plot presenting start and end limits of CW enabled in a relative distance vs. relative velocity percent diagram, with a third degree polynomial illustrating the correlation.

Figure 5.14: Platoon behavior in a relative distance vs. relative velocity percent diagram.
Chapter 6

Conclusion

The aim of this thesis was to study the effect of different disturbances on robustness of heavy-duty vehicle platoons. During this report external and internal disturbances have been identified; internal disturbance such as radar delay and external such as a cut-in traffic scenario.

The AiCC has shown it can manage external disturbances from resulting in an unstable platoon, however some disturbances in extreme worst case scenarios result in Collision warning status enabled and collisions. There external disturbances combined with radar delay, which is an internal disturbance, cause the error in relative distance to become amplified through a platoon, resulting in loss of robustness through the platoon. Radar delay has shown an amplifying effect throughout a platoon, propagating an increased reduction of the relative distance, and amplifying the increase of relative velocity. These factors put together give rise to a pattern which could in the future help calculate the size of a robust platoon, dependent on different scenarios and equipment used in the platoon.

This thesis can be summarized in figure 6.1 showing three areas; a green, a red, and a white one. The green area is the area in which the platoon is robust, and the red area is the area in which the CW status would be enabled. The white area is the uncertainty of this figure which is an undetermined error.

![Figure 6.1: Robustness identification of a platoon in a relative distance vs. relative velocity percent diagram. With all platoon vehicles in the green area the platoon is robust, and if any vehicle is in the red area the platoon loses its robustness.](image)
Results from simulations performed with radar delay show that with increase of both radar delay and position in the platoon, the relative distance versus relative velocity percent plot will grow towards the red area of figure 6.1. With all platoon vehicles in the green area the platoon is robust, and if any vehicle is in the red area the platoon loses its robustness. These results help to determine size of a robust platoon.
Chapter 7

Future Work

The results from this thesis project set up a guideline for further work on robust platoons. Radar delay has shown to have a significant effect on platoon behavior, and there are other sources of disturbance and delays in a vehicle. Similar to the introduced delay in the radar, there are delays in the braking system of a vehicle. The logic of the brake system needs time to perform its calculations and the hydraulic brake pipes cause delays dependent on their length and form. These delays have not been analyzed in this thesis, but are an important factor to study in the further improvement of platoon models.

A further factor to improve from this thesis is the error area of figure 6.1. Improvement of the error area increases the feasibility of the relationship between relative distance and relative velocity percent. With better identification of the robust area, controllers can be designed to keep the vehicles in this area.

As radar delay causes delay in communication between the vehicles, this delay could be reduced or eliminated by using vehicle to vehicle communication. By doing so, each vehicle could know how other vehicles in an area around it are behaving, and not just the vehicle in front. Further work in this area could result in improved robustness of platoons, and also reducing the inter-vehicle distances, achieving reduced fuel consumption.
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Appendices
Appendix A

TRW Autocruise AC-20

F E A T U R E S
• Adaptive Cruise Control
• Follow to stop
• Distance warning (according to customers requirements)
• Collision warning (according to customers requirements)
• Collision mitigation (according to customers requirements)
• Assisted stop and go (according to customers requirements)

S P E C I F I C A T I O N S
Length   98 mm
Height   98 mm
Width   63 mm
Weight   0.55 Kg
Frequency  76 – 77 GHz
Range   1 to 200 m
Field of view  11°
Speed resolution  0.09 kph

TRW Autocruise continues to improve its ACC systems by reducing product, size and cost, while enhancing the functional possibilities.

This product is designed for both passenger and commercial vehicle applications.

ACC / Adaptive Cruise Control

TRW Autocruise

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Autocruise SA
Avenue du Technopôle
Secteur de la Pointe du Diable
29280 Plouzané
France
Tel : 0033 (0)2 98 45 43 68
Fax : 0033 (0)2 98 49 56 55
Appendix B

Table of Simulations Performed

Figure B shows the list of simulations performed, and the vehicles which their collision warning status have become enabled during the test are marked.

<table>
<thead>
<tr>
<th>Test nr.</th>
<th>Start Velocity</th>
<th>End Velocity</th>
<th>Scenario</th>
<th>Topography</th>
<th>Radar Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80</td>
<td>80</td>
<td>Neutral</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>40</td>
<td>Braking</td>
<td>Flat</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>80</td>
<td>50</td>
<td>Braking</td>
<td>Flat</td>
<td>0</td>
</tr>
<tr>
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<td>80</td>
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<td>Braking</td>
<td>Flat</td>
<td>0</td>
</tr>
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<td>40</td>
<td>Cut-in</td>
<td>Flat</td>
<td>0</td>
</tr>
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<td>80</td>
<td>50</td>
<td>Cut-in</td>
<td>Flat</td>
<td>0</td>
</tr>
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<td>0</td>
</tr>
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<td>40</td>
<td>Braking</td>
<td>Uphill</td>
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</tr>
<tr>
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<td>Braking</td>
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<td>0</td>
</tr>
<tr>
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<td>Braking</td>
<td>Uphill</td>
<td>0</td>
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</tr>
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<td>60</td>
<td>Cut-in</td>
<td>Uphill</td>
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</tr>
<tr>
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<td>Braking</td>
<td>Downhill</td>
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<td>Braking</td>
<td>Downhill</td>
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<td>Braking</td>
<td>Downhill</td>
<td>0</td>
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<td>17</td>
<td>80</td>
<td>40</td>
<td>Cut-in</td>
<td>Downhill</td>
<td>0</td>
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<td>80</td>
<td>50</td>
<td>Cut-in</td>
<td>Downhill</td>
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<td>80</td>
<td>60</td>
<td>Cut-in</td>
<td>Downhill</td>
<td>0</td>
</tr>
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<td>80</td>
<td>80</td>
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