Evaluation of string stability during highway platoon merge

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Automated vehicles are considered to be the future solution to reduce traffic congestion and to increase road safety. The Adaptive Cruise Control (ACC) has been introduced as Advance Driver Assistance System (ADAS) to improve road network utilization. However, complex traffic situations are still resolved by human drivers. Vehicular communication has been introduced to interconnect different nodes in the transport system for example vehicles, infrastructure, and vulnerable road users. Communication enables improved local awareness of the road users and the potential to further improve the performance is increased. In this study, a popular ACC algorithm, the notion of string stability and the concept of Cooperative Adaptive Cruise Control (CACC) are discussed. A new CACC algorithm is proposed focusing on maintaining platoon string stability during different traffic situations. The performance of the controller is compared with one of the most accepted ACC algorithms. The proposed controller was implemented in a real world cooperative highway merge scenario. The collected data was presented and appraised under three different evaluation criteria. The controller has shown low downstream error propagation in simulation and in real world experiment it successfully maintained string stability during highway platooning and merging scenarios.
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In recent years, research in the area of Intelligent transport system (ITS) has become an inevitable manner to improve the efficiency and safety of our existing transport network. We use vehicles as means of mass public transportation, merchandise transfer, home delivery service and not to mention for our personal and recreational purposes. According to US statistics [3], the number of vehicles per 1000 person in 2013 in USA was 808.6, in Canada 646.1 and in Western Europe 589.6. In Australia, an average person drives 15,530 km per year, with approximately 15.5 million drivers. This large number of transport make our lives easier in many ways but they also effectuate several negative impacts on our society. Over-use of limited fossil fuel, traffic congestion, road accidents and environment pollution are some of the major consequences.

Scientists have been investigating different ways to minimize the negative effect of this large number of vehicles. One of the popular solution is idle reduction targeted towards minimizing fuel consumption. Idle reduction is a policy where the driver of a vehicle turns off the engine when the vehicle will be stopped for more then ten seconds. Some good example of when idle occurs are waiting at traffic lights, at drive through restaurants, traffic jams or while picking up someone. According to NRCan (Natural Resources Canada), idling for more then 10 seconds uses more fuel and produce more CO$_2$ than turning off and on the engine. According to an US study [7] idle reduction saved 37.9 million Gasoline Gallon Equivalent (GGE) which is 4% of grand total savings in a year. Government in different counties are encouraging researchers and manufactures to work together to reduce idling time.

Another solution that researchers are looking into is, how can we efficiently use the existing road network in order to decrease traffic congestion and improve road safety. While keeping in mind that any improvement in vehicle behavior must not compromise the safety measures of road users.

Introducing vehicular automation is one of the possible solution to the problem. Such kind of automation can be achieved by introducing sensors and communication technologies together with vehicle control system which can be use to control the formation of vehicles on the roads. The vehicle formation strategy is called Platooning. A platoon is a series of vehicle following each other on the same lane. In a

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1 To be found at http://www.roymorgan.com/findings/australian-moterists-drive-average-15530km-201305090702 accessed on 12th August 2016
vehicle platoon, the forward most vehicle also refer to as the leading vehicle drives independently, running at a constant speed whereas the following vehicles try to follow the speed of the leading vehicle while maintaining a short but safe distance to the preceding vehicle, a general platoon is shown in Figure 1. This formation will allow more vehicle to drive on the same lane which will increase the capacity of the road. A properly designed control system for a platoon will be resilient to different means of disturbances.

![Figure 1: A general formation of a platoon.](image)

The Grand Cooperative Driving Challenge (GCDC)-2011 was a competition organized by Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (TNO) in the Netherlands where one of the first attempts to multi-brand platooning was demonstrated. The main objective of that competition was to drive several vehicles developed by different participants in a platoon on a highway equipped with wireless communication to support the exchange of information between vehicles. The competition addressed different problems in a vehicle platoon and tried to minimize the effect by applying CACC, a control strategy for connected vehicles driving in a platoon. The success of GCDC-2011 encouraged researchers to take the idea to the next level where autonomous vehicles will negotiate with each other at different scenarios in order to perform safe maneuvers on highways.
GCDC-2016 was a cooperative autonomous driving challenge. One of the main objectives of this competition was to encourage realistic implementation of heterogeneous cooperative autonomous driving in real world scenarios [4]. The project demonstrated that cooperative autonomous driving is more efficient than autonomous or manual driving. This is because of the reduced sensor perception delay and increased communication between vehicles. It also made it possible to solve more complex traffic scenarios. Another aspect was that driving in platoons is more energy and fuel efficient due to the close distance between vehicles [29]. The competition scenarios were designed in such a way that they illustrated real world problems and participants should be resilient to all kind of disturbance and anomalies. Over all, the competition aimed towards speeding up the introduction of cooperative and autonomous driving systems. The final competition was held in Helmond, Netherlands, in May 2016. There were three different scenarios:

- Merging platoons Figure 2.
- Intersecting vehicles Figure 3.
- Emergency vehicle.

The platoon merge scenario works as follows, two platoons that are driving with different speed in adjacent lanes receives a road work warning message, which means that one of the lanes is closed. The vehicles in the two platoons pair up Figure 2b and the one in the open lane creates a gap Figure 2c so that the vehicle in the closed lane can merge Figure 2c and Figure 2d. The pairing and merging is performed as fast as possible. When the platoon reaches close to the road work site, vehicles receive a road work message and starts to slows down in order to pass the road work site as safe as possible. A challenge here is to perform the merging with a relatively smooth speed. The reason for that is to use the roads as efficiently as possible, while performing the operation in a safe manner. The scenario can be split into three major parts, paring up, creating a gap and merging.
The second scenario consist of an intersection maneuver, where one vehicle is performing a left turn into a “T-intersection”. Two communicating vehicles are approaching form left and right respectively, preventing the traffic from driving too fast and thereby allows the turning vehicle to turn into the road. There are only three vehicles involved in the actual scenario. Figure 3 visualizes the intersection scenario.
The third scenario is the emergency scenario where an emergency vehicle is approaching two platoons driving in two adjacent lanes on a motorway. The ambulance sends out an emergency vehicle approaching message that tells the other vehicles to make way. The vehicles move to the side so that the emergency vehicle can pass. This scenario was only for demonstration purpose, which is why it is not discussed on in this thesis.

Figure 3: The intersection scenario.
Introduction

1.2 Problem Definition

When driving vehicles in a platoon, one of the major challenges is *string stability*, or rather string instability. In a platoon, the ego vehicles aim is to maintain a constant inter vehicular distance to the preceding vehicle by using distance measurement sensor such as RADAR. Any sudden changes in acceleration or deceleration of the leading or preceding vehicle will generate a transient resulting in an inter vehicular spacing error which will increase along the string. This behavior is known as string instability. One example of string instability is when a traffic jam occurs for no obvious reason on a high way, due to breaking and accelerations of drivers. The irrational behavior creates waves that force the following vehicles to slowdown, or standstill, and limits the throughput. From an economical and environmental point of view, this is very undesirable.

1.3 Problem Statement

The research question investigated in this thesis is how string stability can be maintained while performing highway merge operations between two vehicle platoons. The two questions that this thesis aims to answer are:

- How is the string stability affected when a vehicle is merging in front of the ego vehicle?
- How will string stability be affected when the ego vehicle is merging into another platoon in the adjacent lane?

1.4 Purpose and Aim

The purpose is to design a controller that can maintain string stability when performing platoon operations. The overall goal of this thesis is to design a system that maintain the string stability during the merge scenario in GCDC-2016.

1.5 Contribution

Evaluation of a new approach to solve the string stability problem in cooperative driving during cooperative highway merge. The proposed system is validated using real world data during a full scale demonstration at the GCDC-2016.
Driver assist and automated systems are two means of creating more efficient, safe and comfortable vehicles. This chapter summarizes the current state of art in the field of ADAS from a platoon perspective i.e focusing on ACC and CACC.

2.1 CRUISE CONTROL

In a Cruise Control (CC) system, a reference or desired speed is set by the driver, the CC system maintains the reference speed by compensating all external disturbance such as road slopes or wind and send acceleration or break signals to the engine.

2.2 ADAPTIVE CRUISE CONTROL

The history of research in vehicle following strategies goes back until 1960’s [10]. However the commercial deployment started in late 2000’s when industry grade Electronic Control Unit (ECU) and sophisticated electronic sensors came to market. ACC is a modern ADAS that assists the driver to maintain primarily longitudinal control of the vehicle. A formal definition of ACC can be found in [9] and reads:

"An adaptive cruise control speed limiting consistent with sensor and system limitations ensures an adaptive cruise control source vehicle operates in adaptively controllable speed ranges including speed ranges corresponding to following distances within the sensor range and excluding speed ranges at which preceding targets are not reliably distinguishable by the sensing system."

During a motorway driving, an ACC performs longitudinal control of the vehicle while the lateral maneuver remains the drivers’ responsibility. While driving in ACC mode, it is mandatory for the driver to monitor the situation at all times and prepare to take over control at any unanticipated event. A primitive ACC equipped vehicular system is illustrated in Figure 4.

2.2.1 Adaptive cruise control strategy

ACC is an extension of the CC system. In an ACC system the driver specifies a desired distance from the vehicle in front and a maximum speed which the system should not exceed. The control algorithm of
the ACC maintains the distance to the preceding vehicle measured typically by a RADAR and sends acceleration or deceleration signals to the engine system.

The core of an ACC system relies on the selection of an inter vehicle spacing policy. Among different vehicle following speed control methods proposed over the years [24] only a handful of them have been proven for real world application. The most popular gap regulation strategies are [25]:

- **Constant Clearance or Constant Distance Gap (CDG)**
  - In this strategy the distance between vehicles (measured in meters) remains constant regardless of change in speed. Achieving constant clearance requires an ideal platoon formation and noise free sensor measurements. According to studies, it is very likely that a CDG platoon will be prone to string instability [12]. Constant clear policy is not favorable for non-interconnected platoons in general [34].

- **Constant Time Gap (CTG) or Constant Time Headway (CTH)**
  - The CTG policy proposed a linear relation between inter vehicle space and vehicle speed [34]. This resembles to how human drivers behave on a motorway. In CTH, inter vehicle distance increase when the speed of the ego vehicle is increasing and vice versa, which appears to be very convenient and safe to the driver. The space between two vehicle is expressed in terms of time which is also known as time headway. The formal definition of time headway is the time between, when the front bumper of the leading vehicle and the front bumper of following vehicle, pass a fixed point on the road (measured in seconds). CTH is the most common strategy in the research of ACC. Mathematically desired distance in CTH for the $i^{th}$ vehicle is calculated by

$$D_{i,des}(t) = D_{min} + h_i \cdot v_i(t)$$

(1)
where
\[ D_i,des(t) \] desired distance (m)
\[ D_{min} \] desired standstill distance (m)
\[ h_i \] time headway (s)
\[ v_i(t) \] vehicle speed \((m/s^2)\)

In [28] researcher have monitored real world traffic and found that about 50% of the drivers maintained a time headway between 1s and 2s. There were less than 20% which was driving with a headway time below 1s.

- Constant Safety-Factor Criterion (CSFC)
  - This policy defined an concept which is different from CTH. In this strategy inter vehicle spacing has a non linear relation to the vehicle speed [21]. The CSFC calculates inter vehicle space which is proportional to the square of the cruising speed [25]. However this method is still under development.

Generally, the structure of an ACC system is consists of a two layer control system namely high level or supervisory level and low level control or servo level [11] [21] [30]. The supervisory level controller measures the range to the preceding vehicle, if it is out of range or not present at all, the CC controller is activated to drive at the desired speed. In the scenario where the preceding vehicle is in range, the supervisory level controller switches to ACC mode, measures range and range rate and calculates all the kinematics required to maintain the inter vehicle gap set by driver. The low level or servo level control is identical for an ACC and a CC system. It translates the speed or acceleration input from the supervisory level into an engine signal for acceleration or deceleration. The overall diagram of an ACC system with selection criteria between ACC and CC has demonstrated in Figure 5. An ACC system should ensure road safety and driver comfort, any change in the environment should be dealt with in a rational way so that it does not amplify any disturbances. According to (ISO 15622,2010) for any ACC system it is recommended not to exceed an average automatic acceleration of 2m/s^2 and deceleration of 3.5m/s^2.
2.2.2 ACC control algorithm

Different ACC control algorithms have been discussed in [33] and considered CTH spacing policy. Most of the algorithms are designed focusing on acceleration as output. One exception is found [5], where the authors proposed a controller with velocity output. In this thesis, a Sliding Mode control algorithm has been chosen where the desired acceleration is obtained as output.

Figure 5: Controller structure of ACC and selection between ACC and CC.

Figure 6: Two vehicles driving in ACC mode.
Let us define the actual distance $d_i$ between the $i$th and the $(i-1)$th vehicle as shown in Figure 6

$$d_i = x_{i-1} - x_i - l_{i-1}$$  \hspace{1cm} (2)

where

- $x_{i-1}$ position of vehicle $(i-1)$
- $x_i$ position of vehicle $i$
- $l_{i-1}$ length of vehicle $(i-1)$

The spacing error $\delta_i$ for the ACC controller is the difference between the desired distance and the actual distance which is

$$\delta_i = d_i(t) - h_i \cdot v_i(t) - D_{\text{min}}$$  \hspace{1cm} (3)

Sliding surface $S_i$ for the $i$th vehicle is defined as

$$S_i \equiv \delta_i = d_i(t) - h_i \cdot v_i(t) - D_{\text{min}}$$  \hspace{1cm} (4)

In order for to reduce the spacing error asymptotically converging towards zero we impose the condition

$$\dot{S}_i = \delta_i = -k_i \cdot S_i$$  \hspace{1cm} (5)

According to [34], the control algorithm for vehicle $i$ is then

- **Mainloop**: $a_{i,\text{des}} = \frac{k_i}{h_i} \cdot \delta_i + \frac{1}{h_i} \cdot \dot{d}_i$  \hspace{1cm} (6)
- **Subloop**: $a_{i,\text{des}} = \tau_i \cdot \dot{a}_i + a_i$  \hspace{1cm} (7)

where

- $a_{i,\text{des}}$ acceleration command
- $a_i$ actual acceleration of the vehicle
- $K_i$ controller gain for the $i$th vehicle
- $\dot{d}_i$ velocity error
- $\tau_i$ vehicle response time

In practical systems there exist different time delays such as sensor data acquisition, communication between different modules, external disturbance and noise. To compensate these delays a cumulative time delay $\Delta$ is introduced for vehicle $(i-1)$. Equation 6 with time delay at any time $t$ is rewritten
Mainloop: \( a_{i,\text{des}}(t - \Delta_i) = \frac{k_i}{h_i} \cdot \delta_i(t - \Delta_i) + \frac{1}{h_i} \cdot \dot{d}_i(t - \Delta_i) \) \hspace{1cm} (8)

From Equation 7 and Equation 8 we obtain

\[
\tau_i \cdot a_i(t) + a_i(t) = \frac{k_i}{h_i} \cdot \delta_i(t - \Delta_i) + \frac{1}{h_i} \cdot \dot{d}_i(t - \Delta_i)
\]

(9)

Differentiating both sides of Equation 9 and taking Laplace transform we obtain velocity error dynamic model \( G_i(s) \) for two successive vehicles

\[
G_i(s) = \frac{v_i(s)}{v_{i-1}(s)}
\]

\[
= \frac{(s + k_i) \cdot e^{-\Delta_i s}}{h_i \tau_i s^3 + h_i s^2 + (1 + h_i k_i) s e^{-\Delta_i s} + k_i e^{-\Delta_i s}}
\]  

(10)

The relationship between the spacing error and velocity of the vehicles \( i \) and \( (i+1) \) can be formulated by taking the differentiation and Laplace transformation of the Equation 3

\[
s \delta_i(s) = (1 - (1 + h_i s) G_i(s)) v_{i-1}(s)
\]

(11)

\[
s \delta_{i-1}(s) = \left( \frac{1}{G_{i-1}(s)} - (1 + h_{i-1} s) \right) v_{i-1}(s)
\]

(12)

The spacing error for the dynamic model \( H_i(s) \) is formulated from Equation 11 and Equation 12

\[
\frac{\delta_i(s)}{\delta_{i-1}(s)} = \frac{(h_i \tau_i s + h_i - h_i e^{-\Delta_i s})(s + k_{i-1}) e^{-\Delta_i s}}{(h_{i-1} \tau_{i-1} s + h_{i-1} - h_{i-1} e^{-\Delta_{i-1} s})(h_i \tau_i s^3 + h_i s^2 + (1 + h_i k_i) s e^{-\Delta_i s} + k_i e^{-\Delta_i s})}
\]

\[
= \frac{h_i}{h_{i-1} M_i(s) G_i(s)}
\]

(13)

where,

\[
M_i(s) = \frac{(\tau_i s + 1 - e^{-\Delta_i s})(s + k_{i-1}) e^{-\Delta_i s}}{(\tau_{i-1} s + 1 - e^{-\Delta_{i-1} s})(s + k_i) e^{-\Delta_i s}}
\]

(14)

As a safety precaution an ACC system can only be activated when the vehicle is running above a certain speed which is not feasible for e.g. a congested area. Stop and Go cruise control is an extension of the ACC system which enables the vehicle to accelerate, decelerate and
break automatically in city traffic. Stop and Go cruise control requires more complex sensory analysis, due to the presence of pedestrians, bikers and buildings. Some automakers have already introduced this functionality in their vehicles but the functionality needs further development.

2.3 STRING STABILITY

The notion of string stability in automated vehicular platoon has been introduced in 1977 [1]. A platoon of vehicles on the road is refereed to as a vehicle string. A string of vehicles is said to be “string stable” if the range error does not amplify as it propagates along the string but rather decrease towards zero. In general a platoon is string stable if any change in the speed of a lead vehicle will not result in a fluctuation in the space error for the following vehicles. Mathematically string stability is defined as, if the transfer function from the range error of a vehicle to that of its following vehicle has a magnitude less than or equal to 1 [26]. The motion of the leading vehicle is measured by several sensors. The delays in sensor data acquisition is incorporated with the control system response time. For an ACC equipped vehicle, if the accumulated time delay from sensor data acquisition, processioning, controller and dynamics is 1.5s, it will take 4.5s for the 4th vehicle in the platoon to sense the change in motion of the lead vehicle [25]. California PATH project demonstrated that, in a platoon if the leading vehicle decelerates at 0.1m/s^2, the declaration will amplify and when it 4th reacts the deceleration will peak to 0.3m/s^2 [17]. A platoon with string stable behavior is illustrated in Figure 7.

![Figure 7: A string stable platoon behavior.](image)

An approximate effect of string instability is illustrated in Figure 8.

![Figure 8: A string unstable platoon behavior.](image)
2.4 CONDITION FOR STRING STABILITY

The study of string stability is done for two different platoon namely homogeneous and heterogeneous platoon.

2.4.1 String stability for homogeneous platoon

The string stability for homogeneous platoon has been studied extensively [2] [6] [26]. In a homogeneous platoon all the vehicles are equipped with identical controller, dynamic characteristics are the same and they follow the same inter vehicle spacing policy. According to the concept, for two consecutive vehicles in a platoon sensor perception delay $\Delta_{i-1} = \Delta_i$, engine constant $\tau_{i-1} = \tau_i$, controller gain $\lambda_{i-1} = \lambda_i$ and time headway $h_{i-1} = h_i$. So from Equation 14 for homogeneous platoon $M_i(s) = 1$. As a result the velocity dynamic model and spacing error dynamic model become identical

$$H_i(s) = G_i(s) = \frac{\delta_i(s)}{\delta_{i-1}(s)} = \frac{v_i(s)}{v_{i-1}(s)}$$

according to the definition of string stability, the system will be string stable only if

$$|H_i(j\omega)| < 1, \quad \forall \ \omega > 0$$  \hspace{1cm} (16)

where $s$ is substituted by $s = j\omega$ in Equation 15. Since $H_i(s) = G_i(s)$, the condition for string stability for vehicle dynamic model is also $|G_i(j\omega)| < 1$. It is also to be noted that, in order to avoid any sudden accident the response time $\tau$ and process lag $\Delta$ should follow the condition [32].

$$h_i > \tau_i$$

$$h_i > \Delta_i$$

The condition $|H_i(s)| = |G_i(s)| < 1$ is satisfied for $\forall \ \omega > 0$ if

$$h_i > 2(\Delta_i + \tau_i)$$

where control gain $\lambda_i$ is chosen such that,

$$0 < \lambda_i < \frac{h_i - 2(\Delta_i + \tau_i)}{2(h_i(\Delta_i + \tau_i) - \Delta_i\tau_i)}$$

Further proof of this condition is showed in [32].
2.4.2 String stability for heterogeneous platoon

The concept of homogeneous platoon does not hold in real world traffic situations. Vehicles are designed by different automakers, and as a result, each vehicle has different dynamics, engine response, sensors and their ACC implementation policy is typically not identical. Hence, a string stability analysis for a heterogeneous vehicle platoon is necessary.

In a heterogeneous platoon, for two consecutive vehicles, $\Delta_i-1 \neq \Delta_i$, $\tau_{i-1} \neq \tau_i$, $\lambda_{i-1} \neq \lambda_i$ and $h_{i-1} \neq h_i$. As a result, unlike homogeneous platoon, in a heterogeneous platoon $H_i(s) \neq G_i(s)$. In order to achieve string stability both the vehicle velocity error dynamic model and the spacing error dynamic model has to be satisfied simultaneously.

\[
|H_i(j\omega)| < 1, \quad \forall \ \omega > 0 \quad (17)
\]
\[
|G_i(j\omega)| < 1, \quad \forall \ \omega > 0 \quad (18)
\]

In a platoon, each driver can choose different $\text{CTH}$. The longer the $\text{CTH}$ is selected, the higher probability of data loss and the data acquisition time increases due to external disturbance which leads to higher spacing error. For two constitutive vehicle in a platoon, if $h_i > h_{i-1}$ then they are driving safely even though the spacing error $\delta_i > \delta_{i-1}$ because of $D_i > D_{i-1}$. In the opposite scenario when $h_i < h_{i-1}$, the vehicles are driving with a potential risk of accident even though $\delta_i < \delta_{i-1}$ [32]. From this analysis the condition for string stability in heterogeneous platoon is reformulated as

\[
|H_i(j\omega)| < \frac{h_i}{h_i-1}, \quad \forall \ \omega > 0 \quad (19)
\]
\[
|G_i(j\omega)| < 1, \quad \forall \ \omega > 0 \quad (20)
\]

As proved in [32] string stability for Equation 19 and Equation 20 is guaranteed if

\[
h_i > 2(\Delta_i + \tau_i) \quad (21)
\]

holds where control gain $\lambda_i$ is chosen such that,

\[
0 < \lambda_i < \frac{h_i - 2(\Delta_i + \tau_i)}{2(h_i(\Delta_i + \tau_i) - \Delta_i\tau_i)} \quad (22)
\]

2.5 COOPERATIVE ADAPTIVE CRUISE CONTROL

CACC is an automated speed maneuver strategy where vehicles are interconnected via Vehicle to Vehicle ($\text{V2V}$) and/or Vehicle to Infrastructure ($\text{V2I}$). CACC is an extension of ACC, where vehicles exploit on
board sensors as well as cooperative information to adapt a platoon speed profile. V2V communication contains information about neighboring vehicles’ current position, speed, acceleration, intended behavior whereas V2I massages conveys information about maximum road speed, proposed road speed, traffic updates, warnings about road accident and road works. A CACC system can be implemented using both V2V and V2I or only V2V or V2I [25].

![Figure 9: Illustration of the Cooperative driving concept.](image)

ACC equipped vehicles have been on market for a decade. Studies have demonstrated that ACC system assist drivers in controlling vehicle speed effectively [31] and improved traffic flow by maintaining string stability [8]. But recent research illustrated that an ACC system has a negative impact on traffic flow, in comparison with human drivers an ACC system may amplify the disturbances more than the human drivers [17] [15].

The motivation behind introducing CACC is to use traffic networks more efficiently and reduce fuel consumption [25] [22]. Integrating V2V information with an ACC system brings two major contribution on the traffic flow systems [16]

1. String stability
2. Tighter inter vehicle gap

The mean CTG can be reduced from 1.6s when driving manually to 0.6s when using an CACC system [20]. The shorter CTG can increase lane capacity from 2200 vehicles to around 4000 vehicles per hour [23].
CACC systems utilize V2I communication also to improve highway capacity and stay updated about the current traffic situation. The two most discussed implementation of V2I are

1. Variable speed limits for bottleneck capacity increase [13] where infrastructure will advice vehicle to drive at a speed, determined by the traffic condition.

2. Arterial coordinated start [25] where vehicle waiting on a traffic signal will be instructed to start the vehicle and accelerate when the light turns green.
Chapter 3 explains the methodology and development strategy of the control system. A vehicle model is first developed and that was used to evaluate the controller. An introduction to the different approaches to vehicle following controllers is also presented. To evaluate the system we also introduce three evaluation criteria.

3.1 Vehicle Model Identification

The model used to simulate a vehicle is derived from the plot in Figure 10. The procedure is to estimate the behavior of the system and then find the parameters for this transfer function. After several trials, the system could be characterized as a first-order system with a time delay and a dead time Equation (23). The dead time is when a system gives no reaction during a time T. The time constant τ effects how fast the system reacts to an input. The system input and output are both accelerations. The parameters are set based on the measured data. The dead time was selected to \( T = 0.3 \) and the time constant \( \tau = 0.3 \).

\[
G(s) = \frac{e^{-Ts}}{\tau s + 1}
\]
However the objective is to control the speed instead of the acceleration. This is achieved by adding an integration to the plant. In the frequency domain an integration is described with the transfer function $\frac{1}{s}$. The new plant is found by multiplying the integration with the plant $G(s)$ which is showed in Equation 24. The input to the plant is acceleration, while the output is speed.

$$G(s) = \frac{e^{-Ts}}{Ts + 1} \ast \frac{1}{s} = \frac{e^{-Ts}}{s(Ts + 1)}$$  \hspace{1cm} (24)

### 3.2 Speed Controller Design

The control structure for the speed controller is showed in Figure 11.
The evaluation of the speed controller is done individually for an ideal and real system respectively.

### 3.2.1 Speed controller design with an ideal system

Initially it is assumed that the system does not have any dead time T. So the plant model is Equation 25.

\[ G(s) = \frac{1}{s(\tau s + 1)} \]  

(25)

The relation between the input speed \( V_{\text{des}}(s) \) and the output speed \( V(s) \) is described by the closed loop transfer function Equation 26.

\[ F(s) = \frac{V(s)}{V_{\text{des}}} = \frac{C(s)G(s)}{1 + C(s)G(s)} = \frac{C(s)}{\tau s^2 + s + C(s)} \]  

(26)

The simplest way to design a control system is to have a proportional controller. To determine the behavior of such a controller, the final value theorem can be used [27]. It describes how the system behaves after infinite time Equation 27.

\[ \lim_{t \to \infty} f(t) = \lim_{s \to 0} sF(s) = \lim_{s \to 0} s \frac{C(s)}{\tau s^2 + s + C(s)} \]  

(27)

In Equation 27 \( C(s) \) is replaced with a proportional controller \( k_p \) in order to reduce the steady state error to zero Equation 28.

\[ \lim_{s \to 0} sF(s) = \lim_{s \to 0} s \frac{k_p}{\tau s^2 + s + k_p} = 0 \]  

(28)

To determine a proper value of the gain \( k_p \), a root locus analysis was performed, see Figure 12a. The gain is selected so that the raise time of the system is as fast as possible, without overshoot. In Figure 12b the performance of the controller for different \( k_p \) values are plotted to show the behavior of the system when the gain is changed. When the gain is high there is a short rise time but an overshoot is introduced. A lower gain results in longer rise time. For the controller gain is chosen \( k_p = 0.872 \).

![Root locus analysis](image1.png)

(a) Root locus analysis

![Step Response](image2.png)

(b) Step Response

Figure 12: Speed controller analysis for ideal system.
3.2.2 Speed controller design with a real system

Previously it was assumed that the system does not have any dead time, however the behavior analysis of the real car revealed that that the system have an average dead time of 0.3 seconds. In order to improve the response time lead compensate is introduced according to Equation 29.

\[
C_l(s) = k_l \frac{s + 2.5}{s + 10}
\]  

(29)

The performance of the CC controller is shown in Figure 13.

![Figure 13: Speed controller analysis for system with dead time.](image)

3.3 Adaptive cruise control design

The control structure for the ACC system is shown in Figure 14.

![Figure 14: The design approach of the distance controller.](image)
The plant model for the **ACC** system is reformulated from the speed controller. The closed loop speed controller plant model is given in **Equation 30**.

\[
G(s) = \frac{4.8s + 12}{0.3s^3 + 4s^2 + 14.8s + 12}
\]

The input to the new plant is desired speed. The desired speed is determined by **Equation 31**.

\[
v_{i, \text{des}}(t) = \lambda_2 \delta_i(t) + v_{i-1}(t) - v_i(t)
\]

The gain $\lambda_2$ is designed to remove any steady state error from the system according to **Equation 32**.

\[
\lambda_2 = \lambda_3 \delta_i(t) + \lambda_4 \int_0^t \delta_i(t) \, dt
\]

$\lambda_3$ and $\lambda_4$ are chosen experimentally and by validation.

The preceding vehicles’ acceleration is feed forwarded to the controller with a proportional gain $\lambda_5$ to get a faster reaction with change in acceleration. The desired speed is reformulated to **Equation 33**.

\[
v_{i, \text{des}}(t) = \lambda_2 \delta_i(t) + v_{i-1}(t) - v_i(t) + \lambda_5 a_{i-1}(t)
\]

### 3.3.1 Obstacle Avoidance

In [19] the Obstacle Avoidance (OA) is used to create the gap when a vehicle intends to perform a merge and also to increase the safety of the operation. The general idea is to create a negative acceleration that grows exponentially (but limited) when a target comes closer. The further away the target is the less effect does the OA have, and at some distance no effect at all. In **Equation 34** the formula is given of how the controller functions. $\delta$ is the distance to the obstacle/target. $\beta$ is the gain factor that maximize the effect and $\alpha$ decides how the effect of the OA should be reduced. In **Figure 15** the effect of different parameters is showed.

\[
u_{\text{OA},i} = -\beta (\alpha \delta_i^o + 1)e^{-\alpha \delta_i^p} + u_{\text{obstacle}}
\]
In HCS the OA is used as a safety feature and to improve the ACC, so it keeps the desired distance when the preceding vehicle is decelerating. The feature is only active when the preceding vehicle is decelerating. The OA used is described by Equation 35. The OA is feed forward directly to the vehicle. The parameters is selected from experimentation.

\[
u_{OA,i} = -\beta (\alpha \delta_i + 1)e^{-\alpha \delta_i} \quad (a_{i-1} < 0)
\] (35)

3.4 EVALUATION CRITERIA

Different ACC evaluation criteria is discussed in [14]. For this work, the performance evaluates to what extent the system is capable of keeping the desired distance to the preceding vehicle. The safety criteria evaluates if the distance becomes smaller than the desired distance. The final criteria is comfort and is evaluated by analyzing the vehicle jerk. The performance is most important because that it considers if the platoon is string stable or not. The performance criteria also determent how the system keeps the desired distance, which is important when it comes to saving fuel due to the reduced wind resistance.

3.4.1 Performance

The performance evaluation is performed individually for the ACC and the CACC systems. The ACC system is evaluated by checking how the acceleration and speed profiles, considering two vehicles only (based on [18]). The mean value and variance is used to evaluate this condition. The CACC system is evaluated in two steps, both for homogeneous and heterogeneous platoons. For the homogeneous platoon the condition described by equation Equation 16, saying that a platoon is string stable if the spacing error does not amplify through the platoon is used for evaluation. For the heterogeneous platoon the
3.4.2 Safety

Safety is evaluated by monitoring the distance measurement from the vehicle in front. The system is considered as safe if the actual distance is larger or equal to the desired distance.

\[
\begin{align*}
    &d_i \geq D_{i,\text{des}} \quad \text{safe} \\
    &d_i < D_{i,\text{des}} \quad \text{unsafe} \\
    &d_i < D_{\text{min}} \quad \text{severe risk of collision}
\end{align*}
\]

3.4.3 Comfort

The comfort of the controller is measured by the jerk effect. The goal is to archive zero jerk from the system.

\[
\ddot{a}(t) = 0
\]

We analyze the minimum and maximum jerk value and the variance during the ACC maneuver.

3.5 Experimental Platform

The vehicle used in GCDC is a Volvo S60 equipped with a dSpace MicroAutobox II, a communication device (Alix board), differential GPS, a general purpose laptop, network router, inverter for 220V equipment, UPS as backup power supply and interconnection equipment. The MicroAutobox performs the control-loop and have an interface to the car through the CAN-bus. The Laptop is executing several JAVA applications that are communicating using Lightweight Communications and Marshalling (LCM). The LCM application have a built in logger that was used to log data in the GCDC. Figure 16 shows the setup in the vehicle.
Figure 16: The physical setup in the vehicle during GCDC.
In Chapter 4 the results of this thesis are presented. Simulation results showing the evaluation of the ACC and CACC are presented in both homogeneous and heterogeneous platoon setups. Finally experimental results from the GCDC-2016 are presented.

4.1 SIMULATION

The performance of the proposed HCS controller is evaluated by comparing it with a SMA controller for both homogeneous and heterogeneous system. The two controllers are designed to follow the speed of the preceding vehicle with a time headway \( h = 1 \). The lead vehicle started with a speed \( 0\text{m/s} \), at \( 20\text{s} \) the lead vehicle started to accelerate with \( 2\text{m/s}^2 \) until it reached the speed \( 20\text{m/s} \). The goal was to evaluate the ACC and CACC performance of HCS and SMA controller. The three evaluation criteria described in Section 3.4 were used to evaluate the performance.

4.1.1 ACC evaluation

Distance following performance on both homogeneous and heterogeneous system are shown in Figure 17a and Figure 17b.

![Figure 17: Distance following on homogeneous and heterogeneous systems.](image)

The speed error for both the homogeneous and the heterogeneous systems are shown in Figure 18a and Figure 18b. The speed error was always zero except between time 20s to 35s when the lead vehicle was accelerating.
Figure 18: Speed error for the homogeneous and the heterogeneous systems.

Figure 19a and Figure 19b shows the distance error propagation. During lead vehicles acceleration, a peak in the distance error occurred which went towards zero in 5 seconds.

Figure 19: Distance error for the homogeneous and the heterogeneous systems.

Table 1 shows the mean and variance of the speed and acceleration error. The measurement was performed from the time when the preceding vehicle started accelerating until the error was stabled around zero. The data is for an ideal system (no dead time) with a communication delay of 100ms. The desired speed of the first vehicle was set to 20m/s.

<table>
<thead>
<tr>
<th>Value (Unit)</th>
<th>Mean</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>SpeedErrorHomogeneous (m/s)</td>
<td>1.3745</td>
<td>0.6778</td>
</tr>
<tr>
<td>SpeedErrorHeterogeneous (m/s)</td>
<td>0.1160</td>
<td>0.1898</td>
</tr>
<tr>
<td>AccelerationErrorHomogeneous (m/s$^2$)</td>
<td>0.0625</td>
<td>0.1655</td>
</tr>
<tr>
<td>AccelerationErrorHeterogeneous (m/s$^2$)</td>
<td>0.0162</td>
<td>0.0313</td>
</tr>
</tbody>
</table>

Table 1: The mean and variance value of the speed and acceleration errors, when simulating two vehicles.

4.1.2 Evaluation of CACC performance on homogeneous platoon

A homogeneous platoon consist of eight vehicles were designed to simulate vehicles of the same kind driving in a platoon. The parameters of the controllers are found in Table 2.
<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>CAR 1</th>
<th>CAR 2</th>
<th>CAR 3</th>
<th>CAR 4</th>
<th>CAR 5</th>
<th>CAR 6</th>
<th>CAR 7</th>
<th>CAR 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Headwaytime ($h_i$)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>engine ($\tau_i$)</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>delay ($\Delta_i$)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 2: The parameters set to simulate a homogeneous platoon.

In Figure 20 and Figure 21, the actual distance between each vehicle is shown where distance 1 is the distance between the leading vehicle and 2\textsuperscript{nd} vehicle in the platoon and so on along the platoon. From the figures it is evident that both controllers were able to maintain a smooth distance from the preceding vehicle and the maximum distance was 25m.

Figure 20: Actual distance between vehicles in a homogeneous platoon using HCS.

Figure 21: Actual distance between vehicles in a homogeneous platoon using SMA.

Figure 22 and Figure 23 shows the distance error propagation along the platoon. According to Equation 16 both controllers maintained string stability i.e. $H(s) < 1$ and the error propagated downstream.
along the platoon. The main difference between HCS and SMA was the maximum amplitude of distance error. The maximum distance error for HCS was 0.12m where as for SMA amplitude was 0.40m.

Figure 22: Distance error propagation along the homogeneous platoon using HCS.

Figure 23: Distance error propagation along the homogeneous platoon using SMA.

Speed error propagation along the platoons using the HCS and SMA controllers are shown in Figure 24 and Figure 25 respectively. Both controllers have a downward error propagation along the platoon
Figure 24: Speed error propagation along the homogeneous platoon using HCS.

Figure 25: Speed error propagation along the homogeneous platoon using SMA.

The homogeneous platoon is string stable according to equation Equation 16.

4.1.3 Evaluation of CACC performance on heterogeneous platoon

The concept of homogeneous platoon does not apply to real road traffic. In a real traffic scenario, all the vehicles have different controllers and dynamics. In order to simulate the performance of the controllers in a heterogeneous system, a platoon that consists of eight vehicle is designed with the parameters shown in Table 3.
Table 3: The parameters used to simulate a platoon. $h$ is the headway time, $\tau$ is the time constant of the engine, $\Delta$ the communication delay and $\lambda$ gain of proportional controller.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Car 1</th>
<th>Car 2</th>
<th>Car 3</th>
<th>Car 4</th>
<th>Car 5</th>
<th>Car 6</th>
<th>Car 7</th>
<th>Car 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Headwaytime ($h$)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Engine ($\tau$)</td>
<td>0.3</td>
<td>0.5</td>
<td>0.3</td>
<td>0.4</td>
<td>0.2</td>
<td>0.5</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>Delay ($\Delta$)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Gain ($\lambda$)</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Figure 26 and Figure 27 show that for the HCS and the SMA controllers, the maximum distance between vehicles in the platoon is 25m.

Figure 26: Actual distance between vehicles in a heterogeneous platoon using HCS.

Figure 27: Actual distance between vehicles in a heterogeneous platoon using SMA.

The major difference between HCS and SMA is how the distance error propagate along the string when vehicles do not satisfy the
string stability condition Equation 21. In Figure 29 for SMA the distance error propagation does not propagates towards zero. For HCS the distance error propagates downstream in Figure 28. In Figure 28 and Figure 30 it is shown that both the speed error and the distance error are bounded. The magnitude of the first distance error is approximately 0.1 meters.

![Distance error propagation along platoon using HCS.](image)

Figure 28: Distance error propagation along the heterogeneous platoon using HCS.

![Distance error propagation along platoon using SMA.](image)

Figure 29: Distance error propagation along the heterogeneous platoon using SMA.

The speed error in Figure 30 and Figure 31 show that the speed error propagation is smoother in the HCS than in the SMA.
Figure 30: Speed error propagation along the heterogeneous platoon using HCS.

Figure 31: Speed error propagation along the heterogeneous platoon using SMA.

4.2 GCDC DATA EVALUATION

A set of data from the merging scenario in GCDC 2016 has been presented here where the ego vehicle was the second vehicle in the platoon. In the GCDC competition, the preceding vehicle is denoted as mio (most important object). Each vehicle had their unique id. In this scenario the lead vehicle had id 3, merging vehicle id 2. The platoon formation before and after merging is shown Figure 32.
Figure 32: Platoon formation before and after merging scenario.

Figure 33 shows the speed of the ego and the mio vehicles. Initially the mio vehicle was id 3. At 475s the merging scenario started. The ego vehicle decelerated in order to create a gap to allow the the vehicle in the left lane to merge. At 500s the merging is completed and the ego vehicle started to follow a new mio, now the vehicle with id 2.
The speed error between the ego and the mio vehicles is shown in Figure 34. During platooning the speed error variation was less than 1 m/s. After merging the speed error between the vehicles id 3, id 2 and ego and mio was stable.

The acceleration profiles of the ego and the mio vehicles are shown in Figure 35. From the graph it is evident that ego vehicle followed the acceleration profile of the mio almost identically.
The desired distance form mio vs actual distance of ego vehicle from mio is shown in Figure 36. In all the situation the real distance was slightly larger than the desired distance. During the entire scenario, the ego vehicle maintained a steady distance from the mio. In time stamp 500 the mio changed from id 3 to id 2, which resulted in an abrupt change in distance. The mio was still in the left lane and performed the merge at time stamp 540-620 approximately. During this period the ego vehicle maintained a steady distance from the mio. This behavior verifies that the controller maintains the string stability.

The jerk effect of the controller is shown in Figure 37. The jerk value was $-0.3 < a_i(t) < 0.3$. 
In order to summarize the overall performance of the ego vehicle, mean and variance of the speed, acceleration and jerk is provided in Table 4.

<table>
<thead>
<tr>
<th>VALUE (UNIT)</th>
<th>MEAN</th>
<th>VARIANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SpeedError (m/s)</td>
<td>−0.0017</td>
<td>0.0965</td>
</tr>
<tr>
<td>AccelerationError (m/s^2)</td>
<td>0.084</td>
<td>0.025</td>
</tr>
<tr>
<td>Jerk (m/s^3)</td>
<td>−2.89e−06</td>
<td>0.0024</td>
</tr>
</tbody>
</table>

Table 4: The mean and variance value of system from GCDC Competition.
CONCLUSION AND FUTURE WORK

The goal of this thesis was to develop an CACC control system capable of performing smooth longitudinal maneuvers, handling platoon merging scenarios and at all times maintaining string stability while driving in a cooperative automated highway platoon. The traditional ACC solution can maintain string stability only if vehicles satisfy conditions that are hard to guarantee in a real world traffic situation i.e. the vehicle dynamics and controller design are unknown for vehicles of other brands. In this work, a control system was implemented that could handle all the situations and yet, resilient to string instability. The performance of the proposed system showed that the ACC system was able to follow the speed profile of a preceding vehicle almost identically. The merging scenario was handled without creating any major disturbances. Due to the heterogeneity of the highway platoon in GCDC-2016, vehicles could ensure its own string stability. The distance graph showed that the ego vehicle maintained a constant distance from the preceding vehicle and that any abrupt change in distance are absent.

The two research questions that this thesis tries to answer are as follows:

- How is the string stability affected when a vehicle is merging in front of the ego vehicle?
- How will string stability be affected when the ego vehicle is merging into another platoon in the adjacent lane?

From simulations we can see that the developed system can maintain the string stability for both a homogeneous and a heterogeneous platoon. But due to the dynamic environment and heterogeneity of a platoon, in cooperative driving, is it harder to keep string stability when a vehicle is merging in front, than in a normal situation where the preceding vehicle is just accelerating or decelerating. During GCDC-2016, the ego vehicle is only responsible for its own string stability. From the merging scenario data, it is shown that ego vehicle maintained a steady distance to the merging vehicle (i.e. vehicle id 2).

Future work include investigating the effect of using intended acceleration of the preceding vehicle instead of actual acceleration as a feed forward in the control strategy. The $h^{-1}$ (where the spacing error and speed error have a gain of $h^{-1}$) approach in also something that should be studied.


23] Steven Shladover, Dongyan Su, and Xiao-Yun Lu. Impacts of cooperative adaptive cruise control on freeway traffic flow. *Transport-


DECLARATION

Halmstad, September 2016

Golam Shahanoor, October 9, 2016

Oscar Uddman Jansson, October 9, 2016