COMPARISON OF COOPERATIVE ADAPTIVE CRUISE CONTROL METHODS IN IDEALISTIC AND REALISTIC SCENARIOS

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ABSTRACT

COMPARISON OF COOPERATIVE ADAPTIVE CRUISE CONTROL METHODS IN IDEALISTIC AND REALISTIC SCENARIOS

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Intelligent transportation systems (ITS) aim at improving the efficiency and safety of transportation. In dense traffic, vehicles are aggregated to vehicle strings that travel on the same lane, whereby it is desired to maintain a small but safe distance between the vehicles in order to ensure driving comfort and safety. Cooperative adaptive cruise control (CACC) is a technology that is developed to address this issue. Hereby, the condition of string stability is highly relevant since it ensures the attenuation of disturbances along a vehicle string.

When designing controllers for CACC, it is required to select a signal with respect to which string stability should be fulfilled. In the literature, the most common signals for this purpose are the distance error signal and the acceleration signal. Although various design and analysis methods for string stability based on these signals are available, it is not clear which of these signals is more suitable for fulfilling string stability in practice. To this end, this thesis compares different methods from the existing literature regarding their suitability for the realization of CACC in practice. As the main outcome, it is shown that, although methods that are based on the error signal are functional in case of ideal conditions such as negligible delays, they are clearly outperformed by methods that use the acceleration signals in realistic scenarios with both actuator and communication delays.

Keywords: Cooperative Adaptive Cruise Control, String Stability, Homogeneous Vehicle Strings, Comparison

ÖZ

İDEAL VE GERÇEKÇİ KOŞULLARDA KOOPERATİF ADAPTİF SEYİR KONTROLÜ YÖNTEMLERİNİN KARŞILAŞTIRILMASI

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Akıllı Ulaşım Sistemleri (AUS), ulaşımın verimliliğini ve güvenliğini artırmayı amaçlar. Yoğun trafikte, tek bir şeritte seyahat eden araç zincirinde sürüş konforu ve güvenliğini sağlamak için araçlar arasında küçük ama güvenli bir mesafenin korunması gerekmektedir. Kooperatif Adaptif Seyir Kontrolü (KASK), bu sorunu çözmek için geliştirilmiş bir teknolojidir. Bu vesileyle, zincir stabilizesinin durumu, seyir esnasındaki bozulmaların araç dizisi boyunca azaltılmasını sağladığı için oldukça önemlidir.

KASK için kontrolör tasarlarken, zincir stabilizesi sağlamak için incelenecek bir sinyal seçmek gerekir. Literatürde bu amaç için kullanılan en yaygın sinyaller, mesafe hata sinyali ile ivme sinyalidir. Bu sinyallere dayalı zincir stabilizesi için çeşitli tasarım ve analiz yöntemleri mevcut olmasına rağmen, bu sinyallerden hangisinin zincir stabilizesini yerine getirmek için pratikte daha uygun olduğu açık değildir. Bu tez çalışması, literatürde mevcut farklı yöntemleri pratikte KASK gerçekleştirilmesi için uygunluklarına göre karşılaştırmaktadır. Buna göre, hata sinyaline dayalı yöntemlerin ihmal edilebilir gecikmeler gibi ideal koşullar durumunda işlevsel olmasına rağmen hem aktüatör hem de iletişim gecikmelerinin bulunduğu gerçekçi senaryolarda ivme

sinyallerini kullanan yöntemlerin açıkça daha iyi performans sunduğu gösterilmiştir.

Anahtar Kelimeler: Kooperatif Adaptif Hız Kontrolü, Zincir-Stabilite, Homojen Araç Zincirleri, Karşılaştırma

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LIST OF ABBREVIATIONS

CC	Cruise Control
ACC	Adaptive Cruise Control
CACC	Coopertative Adaptive Cruise Control
CTHP	Constant Time Headway Policy
SS	String Stability
PI	Proportional-Integral
PD	Proportional-Derivative
PID	Proportional-Integral-Derivative
AF	Acceleration Feedforward
PAF	Predicted Acceleration Feedforward
ISF	Input Signal Feedforward

LIST OF VARIABLES

x	Position
v	Velocity
a	Acceleration
L	Vehicle length
d	Intervehicle distance
r	Intervehicle distance at standstill
h	Headway time
ϕ	Actuator time delay
τ	Driveline dynamics
θ	Communication delay
G	Plant transfer function
C	Feedback controller transfer function
K_p	Proportional gain
K_d	Derivative gain
F	Feedforward filter transfer function
H	Constant time-gap transfer function
D	Communication delay transfer function
Γ	Closed loop transfer function between vehicles

CHAPTER 1

INTRODUCTION

Autonomous vehicles have been one of the most popular topics for the past years. With the introduction of vehicles from Tesla and others, the interest is high in the public level. Moreover, with the significant autonomous driving trials from Google's Waymo and others, there is as well an increasing interest in the industry. However, there is still a considerable amount of work that needs to be done before fully autonomous vehicles can participate in traffic safely and efficiently. In particular, the limitations and issues faced in the field show the necessity of the work both in control area and interdisciplinary areas such as communication.

The problems can be dealt with in multiple ways. Hereby, one of the major problems, namely control of the longitudinal motion has been the focus of many research efforts thanks to the fact that the longitudinal motion, which is speeding up or down, can be automated based on a limited number of sensors. Therefore, it has been studied rigorously. At this point, it is clear to the researchers [1] and [2] that vehicle following distances have significant implications on driving safety and comfort. It is desired to have a safe but small following distance to achieve higher traffic throughput so that transportation takes less time for all travelers and passengers. It is expected that traffic throughput increases for the time headway that is significantly less than one second [3, 4]. In this context, Cooperative Adaptive Cruise Control (CACC) is a recently developed technique for automating the longitudinal vehicle motion [1, 5–8]. For a quick review, one can look at Darbha and his colleagues [7] work. On the other hand, experimental results are clearly shown in [4]. In addition, a CACC implementation has been used in the Grand Cooperative Driving Challenge by Bayezit et al. in [9]. In order to see the utilization CACC, engineers from major car manufacturers conducted a study [10] recently.

Analogous to Adaptive Cruise Control (ACC) [11, 12], CACC allows to travel at a desired vehicle speed and inter-vehicle spacing, hence maintaining a safe distance to predecessor vehicles based on the distance measurements (RADAR or LIDAR). Commonly, a velocity-dependent spacing policy with a constant headway time (time to reach the position of the predecessor vehicle) is chosen. As an extension to ACC, CACC also uses state information of the predecessor vehicles such as acceleration or velocity that is provided via vehicle-to-vehicle (V2V) communication [5, 13–16]. Accordingly, CACC enables small inter-vehicle distances which is a pre-requisite for high levels of traffic throughput [17].

CACC is particularly important in dense traffic, where vehicles follow their respective predecessor vehicle at small distances in the form of so-called *vehicle strings*. However, as any control system, there is one key discussion that needs to be made and that is the stability of the operation. While there exist various stability conditions such as Bounded Input Bounded Output(BIBO) or Input to State Stability (ISS), these definitions are not enough to cover the stability of the vehicle string. Even if the vehicles are stable in the vehicle string, the string still might exhibit undesired behavior such as oscillations. There should be a stability condition that connects the vehicles along the string and that is where the next definition is important. Here, it is desired that fluctuations in the vehicle string are attenuated by the follower vehicles which is captured by the formal condition of *string stability* [1].

When designing controllers for CACC, it is required to select a signal with respect to which string stability should be fulfilled. However, this stability condition can be satisfied in multiple ways. In the literature, the most common signals for this purpose are the distance error signal [2, 7, 18] and the acceleration signal [1, 4–6, 8, 9, 19, 20]. Although various design and analysis methods for string stability based on these signals are available, it is not clear which of these signals is more suitable for fulfilling string stability in practice.

Accordingly, this thesis compares different methods from the existing literature regarding their suitability for the realization of CACC in practice. Since the majority of the research on string stability considers the case of homogeneous vehicles with identical vehicles [1, 2, 5, 6, 9, 19, 21, 22], this thesis also focuses on this case. On the one hand, [7] provides a methodology for realizing controllers with multi (r-) vehicle look-ahead (RVLA). Hereby, the distance error signal is chosen as the signal for achieving string stability. On the other hand, [8] provides several methods such as input signal feedworward (IF) and acceleration signal feedforward (AF) for realizing string stability based on the acceleration signal. The first outcome of the thesis is a comparison of these methods in the ideal case, where the vehicle plant does not encounter actuator delay and the communication between vehicles is instantaneous. In this case, it turns out that all methods provide reasonable results. Nevertheless, as the second main outcome, the thesis shows that the methods with RVLA are not robust to actuator and communication delays, which strongly impairs their use in practice. Differently, the methods with IF and AF can tolerate actuator and communication delays, while ensuring string stability and small inter-vehicle distances for tight vehicle following.

This thesis is organized as follows. Chapter 2 provides background information. In Chapter 3, the CACC control methods used in the thesis are described and Chapter 4 contains comprehensive simulation experiments for the comparison of the selected methods. Chapter 5 gives conclusion and directions for future work.

CHAPTER 2

BACKGROUND

2.1 Cooperative Adaptive Cruise Control

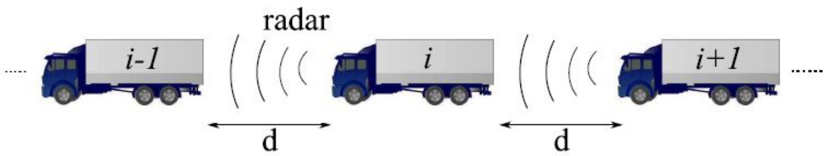

Figure 2.1: ACC with on board sensors

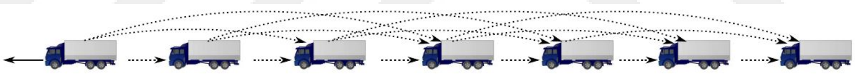

Figure 2.2: CACC Vehicle String Structure

To form the basis, let us first introduce Cruise Control(CC). CC is the most commonly used and widely known automation procedure in cars today. By setting the cruise speed, the vehicle aims to follow the given cruise speed by speeding up the vehicle when vehicle slows down or slowing down the vehicle when the vehicle speeds up. These control actions occur when traveling uphill or downhill for example. However, the driver is still in full control and should slow down for upcoming traffic.

The adaptive cruise control(ACC) is a step forward from CC and, as the name suggests, adapts to the preceding vehicles' speed changes. ACC can achieve this by using on board sensors like radar. An example vehicle string can be seen in Figure 2.1. Use of ACC also allows for control of vehicle strings as a platoon, a string of vehicles, and optimize their controllers for desired responses. To name a few, the optimization can be done for better ride comfort with low accelerations, for better passenger safety with long following distances, or for better traffic density with low following distances.

The next step is Cooperative Adaptive Cruise Control (CACC) and as the name suggests, CACC is an ACC network that not only relies on adapting to the first preceding vehicle but also adapts to further preceding vehicles by communicating information. The information set commonly used in the literature and will be discussed in this work consists of a subset of acceleration, speed, and position of preceding vehicles but mainly all three. With more information available, the optimization can be enhanced further. For instance, with vehicles stationary in front of a traffic light turning to green from red, the vehicles that start speeding up only when the preceding vehicle starts moving can be an example to ACC. In a similar situation, the set of vehicles that start moving at the same time can be an example to CACC. As one might imagine this harmonious movement is thanks to CACC. An example CACC vehicle string can be seen in Figure 2.2 where dashed lines denote the flow of information. Here, the vehicle collects information from 3 preceding vehicles. This kind of information transfer configuration is referred as three vehicle look ahead as the vehicle in question takes information from three vehicles.

These vehicle strings, named platoons, aim to achieve a harmonious longitudinal motion. As the platoon achieves this behaviour, it obeys certain following distancing, i.e. spacing, policies between vehicles. A common policy is the Constant Time Headway Policy (CTHP). Headway is the spacing between vehicles and the platoons that obey CTHP consists of vehicles that follow each other with distances such that the duration to cover the distance between vehicles is constant duration.

Assuming a constant distance between all vehicles along the string at standstill,referred as standstill distance, the aim of CACC is to maximize the number of vehicles travelling, that is increasing the traffic throughput. In the ideal case, with a platoon consisting of the same vehicles, the string of vehicles would have acted same, applying the acceleration profiles of their predecessors instantaneously yielding zero velocity tracking error thus keeping their spacing gaps unchanged. Hence, in the ideal case presented, the inter-vehicle distance would be zero and traffic throughput would be maximum with vehicles traveling bumper-to-bumper at highway speeds. However, there are limiting factors in reality. In the order of our ideal example, the different and changing vehicles in platoons, communication protocols and delays, data loss in communication, actuator delays and signal bounds, unexpected disturbances are some of the limiting factors we can list. Thus, the inter-vehicle distance, i.e headway time, and acceleration responses of vehicles be trade off areas for robustness and safety.

In predecessor-follower type CACC application, the plant is the platoon, the string of vehicles In CACC, every vehicle other than the leading vehicle should response to the changes, in longitudinal motion, it receives from its predecessor treating the information of preceding vehicle's signals as a reference signal. This response can be characterized with a transient behavior and it is sought to show stability. This stability is referred as string stability. Therefore, the string stable CACC will be achieved if and only if all follower vehicles are controlled string stably and meet certain conditions.

CACC problems study only on the longitudinal motion. The platoon can consists of any number of vehicles. If the vehicles that form the platoon are all same, the platoon is referred as a homogeneous platoon and the CACC problem is a homogeneous CACC problem. Otherwise, that is to say platoon has vehicles that have different characteristics than each other, the platoon is referred as a heterogeneous platoon. For practical purposes, the homogeneous platoons are assumed to be formed with identical vehicles that has the exact same vehicle dynamics. Unlike homogeneous platoons, heterogeneous platoons use different models for vehicles which has to be communicated and the following vehicles have to include the preceeding vehicles' dynamics' effects.

Referring to Figure 2.1, we can discuss parametrization on the platoon. The vehicles are named with increasing indexes, i, starting from leading vehicle to last vehicle. Then, each parameter can be defined for each vehicle with the subscript i. The distance between the vehicle $i-1$ and the vehicle i is defined as d_i. Finally, the rear bumper position of the i^{th} vehicle is defined as x_i, and following this, the velocity and acceleration of the i^{th} vehicle is v_i and a_i respectively while the length of the vehicle is defined as L_i.

Let r_i denote the distance between the i^{th} and $i-1^{th}$ vehicles at standstill and h_i

denote the headway time between vehicle i and $i-1$. The constant time gap spacing policy and hence the desired distance is defined in Equation (2.1).

$$d_{i,ref} = r_i + h_i v_i. \tag{2.1}$$

where $i = 2, 3, 4, ..., n$. It is easy to observe that as vehicle velocity,v_i, becomes zero, the following distance $d_{i,ref}$ reduces down to r_i. However, during the transient responses, the instantaneous distance between the vehicles will be defined as presented in Equation (2.2).

$$d_i = x_{i-1} - x_i - L_i. \tag{2.2}$$

Then, the error can be defined as the difference between the actual distance signal and the reference distance value, shown in Equation (2.3).

$$e_i = d_i - d_{i,ref} = (x_{i-1} - x_i - L_i) - (r_i + h_i v_i). \tag{2.3}$$

This positional error will be taken as a controller measurement and used in CACC in a way that guarantees safe drive under any acceleration or deceleration behavior within the operation region.

It is also worth noting that the constant time gap policy can be expressed in s-domain as

$$H_i(s) = h_i s + 1. \tag{2.4}$$

where s is the Laplace transform parameter. This form of constant time gap policy will be used in s-domain analysis of the closed loop transfer function. In fact, we can define error signal in s-domain as

$$E_i(s) = X_{i-1}(s) - H_i(s)X_i(s). \tag{2.5}$$

where $E_i(s)$ denote the Laplace transform of $e_i(t)$. Note that the capital letters will be used as the Laplace transform of the corresponding time function unless otherwise noted in the following parts. To describe the vehicle transfer function, let us define u_i as the acceleration input to the vehicle i and the position, x_i, as the output. Note that u_1, the acceleration input to first vehicle in the string will be used as the disturbance signal to the platoon during the simulations in the following chapters. The transfer function in Equation (2.6) is validated for a wide range of driving scenarios [23] and its usefulness is acknowledged in the recent academic works [24], [5], [19].

$$G_i(s) = \frac{Y_i(s)}{U_i(s)} = \frac{X_i(s)}{U_i(s)} = \frac{e^{-\phi_i s}}{(1 + s\tau_i)} \frac{1}{s^2} \tag{2.6}$$

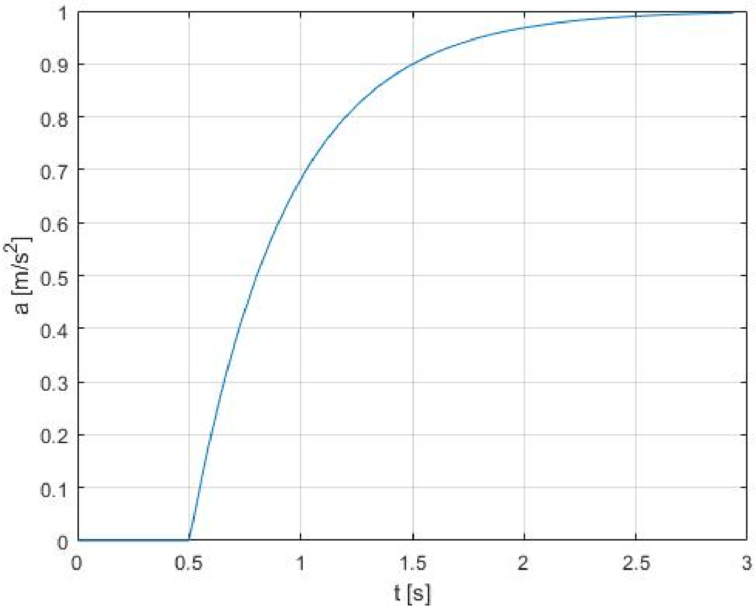

Figure 2.3: Vehicle acceleration response to unit step acceleration input.

Here in this equation, in the first fraction, τ_i stands for the drive line dynamics of the respective vehicle, ϕ_i represents the delay between the control input being generated and the time of actuator realization. The first fraction term describes a simple First Order Plus Dead Time (FOPDT) model for the nonlinear transfer function from the input acceleration to the vehicle acceleration. How this FOPDT model behaves can be seen in Figure 2.3, which shows a vehicle acceleration response to unit step acceleration. The vehicle in the Figure 2.3 has $\phi = 0.5s$ and $\tau = 0.4s$. It can be seen that vehicle acceleration stays constant at $0m/s^2$ for $0.5s$, hence the term dead time, and then tracks the step input with a first order time constant of $0.4s$, hence the term first-order plus dead time. This model is the first fraction in the Equation (2.6). The squared s term (double integrator) describes the transformation from the vehicle acceleration to vehicle position. Thus, we obtain the transfer function from input acceleration to position for a vehicle.

2.2 String Stability

The string stability can be expressed as the stability of the string of vehicles formed with CACC in this discussion. In control theory, there are different definitions for stability for a system. To name a few, we can think of input to output stability in the from of Bounded Input Bounded Output (BIBO) stabilty. Alternatively, there is also Lyapunov stability that deals with initial condition, i.e. zero-input stability. The examples can be increased with input to state stability (ISS), closed loop stabilty etc. However, in the discussion of CACC, the stability of a single vehicle, for example the fact that vehicles are BIBO stable, does not ensure collision free platoons. String stability is then defined as the attenuation of the response signal of interest as we move along the string of vehicles from leading vehicle to following vehicles. The signal of interest can be error signals, acceleration signals, velocity signals. Without loss of generality, if we consider velocity signals as our signal of interest, the stability will be that the follower vehicles' velocity signals should be bounded by the preceding vehicles' velocity. Thus, there should be no overshoot or undershoot. Similar definition can be done for the acceleration signal. In CACC, safety of the travellers is one of the top priorities that has to be ensured. The measure of relative safety however can be defined mathematically using various string stability definitions. Although these definitions can guarantee safety theoretically, the disturbances and imperfections that are not part of the models have considerable effects. Therefore, these definitions and designs based on these definitions should be tested thoroughly.

The literature has various approaches to define and satisfy string stability. One of the most common type of string stability definition is that norm of the each successive vehicles' signal of interest should be smaller than the preceding vehicle. Let $\mathcal{L}_p$ be the norm of a signal x is defined as

$$||x||_{\mathcal{L}_p} = \Big(\int_0^\infty ||x(\tau)||^p d\tau\Big)^{1/p}. \tag{2.7}$$

Using this definition and a suitable output signal y_i within the CACC system (such as acceleration a_i or distance error e_i), we say that the system is L_2 string stable if it holds for any consecutive vehicles $i-1$ and i that

$$||y_i||_{\mathcal{L}_2} \leq ||y_{i-1}|_{\mathcal{L}_2} \tag{2.8}$$

That is, the 2-norm of the selected output signal decreases along the string. We say that the system is L_∞ string stable if it holds that

$$||y_i||_{\mathcal{L}_\infty} \leq ||y_{i-1}|_{\mathcal{L}_\infty} \tag{2.9}$$

That is, the ∞-norm (maximum absolute value) of the selected output value decreases along the string.

CHAPTER 3

CONTROL METHODS IN COOPERATIVE ADAPTIVE CRUISE CONTROLLERS

3.1 Objectives

When applying CACC, it is desired to achieve string stability. On the one hand, it is important to decide on the definition of string stability to be used. On the other hand, it needs to be decided which signal should be used for string stability. The classical signals used in the literature are the error signal e_i and the acceleration signal a_i. The main aim of this thesis is to determine which of these signals is more practical when designing controllers for CACC. Because of this reason, we next consider two recent methods from the literature for a comparative evaluation.

3.2 Method in the publication "Benefits of V2V communication for Autonomous and Connected Vehicles"

The first publication we will be discussing the control method is the one presented by Darbha et al. In the study, a platoon of homogeneous vehicles which are represented as point masses are considered. With the presence of parasitic lags, the vehicle model is described in Equation (3.1) and (3.2).

$$\ddot{x}_i = a_i, \tag{3.1}$$

$$\tau \dot{a}_i + a_i = u_i. \tag{3.2}$$

where $x_i(t)$, $a_i(t)$ and $u_i(t)$, respectively, are the position, acceleration and control input of the i^{th} vehicle at time t. The parasitic lag τ is usually unknown but may be bounded between [0, τ_0] where $\tau = 0$ would be instantaneous actuation and τ_0 as the maximum. The Equation (3.2) represents a first-order linear model for actuation response and is same between the vehicles thanks to homogeneous vehicle string. This model is commonly used in the literature. In the study, in order to evaluate the performance of the method, the spacing error is used. Let r and h denote the standstill distance and headway time between vehicles respectively. With the consideration of the constant time headway policy (CTHP), the spacing error can be defined as presented in Equation (3.3).

$$e_i = x_i - x_{i_1} + r + hv_i \tag{3.3}$$

The study uses CTHP and a modified Proportional-Integral-Derivative (PID) control law. In its most general form, the control law is presented in Equation (3.4). Recall that u_1 will be used as the disturbance signal during the simulation of platoons. Thus, it will not be controlled with the control law that is presented in Equation (3.4).

$$u_i(t) = \sum_{l=1}^{r}[k_{al}a_{i-l} - k_{vl}(v_i - v_{i-l}) - k_{pl}(x_i - x_{i-l} + r_l + lhv_i)] \tag{3.4}$$

where k_{al}, k_{vl}, k_{pl} are the gains associated with acceleration, velocity and position information associated with the l^{th} predecessors, r_l is the standstill distance between the i_{th} vehicle and the l^{th} predecessor. Notice that this controller is a r vehicle look ahead controller, whereby each vehicle can have different gains. However, in [7], it is assumed that gains and standstill distances are constant between vehicles. That is, the study uses the control law in Equation (3.5).

$$u_i(t) = \sum_{l=1}^{r}[k_a a_{i-l} - k_v(v_i - v_{i-l}) - k_p(x_i - x_{i-l} + lr + lhv_i)] \tag{3.5}$$

Darbha and his colleagues then a reach minimum employable headway times for various information and communication types. The most important ones to our discussion are given in Equation (3.6), (3.7), and (3.8).

$$h_{min} = \frac{2\tau_0}{1 + k_a}, \tag{3.6}$$

$$h_{min} = \frac{4\tau_0}{(1 + R)(1 + Rk_a)}, \tag{3.7}$$

$$h_{min} = \frac{4\tau_0}{(1 + R)(1 + 2k_a)}. \tag{3.8}$$

where Equation (3.6) is the minimum employable headway time for immediate predecessor with its acceleration, velocity and position information, i.e. one vehicle look ahead (OVLA), Equation (3.7) is the minimum employable headway time for r vehicle look ahead RVLA, and Equation (3.8) is the minimum employable headway time for 1RVLA. Notice that RVLA and 1RVLA minimum headway times are same. Darbha and his colleagues note that this is important as the same level of performance can be achieved while decreasing the information load.

Then, [7] introduces a specific notion of string stability that is targeted towards the usage of RVLA. Specifically, the following conditions is used for string stability:

$$\sum_{l=1}^{r} ||H_l(j\omega)||_\infty \leq 1. \tag{3.9}$$

Here, H_l is the transfer function between the error signals E_{l-1} and E_l in the Laplace domain. Verbally, this conditions means that the infinity norms of the transfer functions between the error signals involved in the RVLA have to add up to a number less than 1. In the case of one-vehicle look-ahead (OVLA), this condition becomes strict $\mathcal{L}_2$ string stability.

3.3 CACC Control Structure

The CACC design is an extension of standard Adaptive Cruise Control (ACC), feeding additional data by wireless communication to allow short-distance automatic vehicle following. The control objective in this chapter is, as in the literature, only for the case of homogeneous strings, where all vehicles have the same dynamic properties [19, 20]. The most recent approaches [7, 8] use the spacing policy in (2.1) and model each vehicle by the plant transfer function as in (2.6). This model is obtained from a nonlinear model of the driveline dynamics based on feedback linearization and low-level control [23, 25]. The low-level control loop ensures that τ_i is constant over a wide range of normal driving situations [14, 26] which are predominant for CACC [5].

Using the plant model in (2.6) and PF, we employ the control architecture in Fig. 3.1. Here, the spacing error of vehicle i is

$$e_i = d_i - d_{r,i} = q_{i-1} - q_i - L_i - r_i - h_i\, v_i \tag{3.10}$$

and (3.10) is realized by the transfer function $H_i(s) = 1 + h_i\, s$. $K_{\text{fb},i}$ is a feedback controller and $K_{\text{ff},i}$ is a feedforward filter that receives the signal c_i from vehicle $i-1$ via V2V communication. $D_i(s) = e^{-s\,\theta_i}$ represents a communication delay between vehicle $i-1$ and vehicle i. In agreement with the recent literature on PF, we investigate *input signal feedforward* (ISF) with $c_{i-1} = u_{i-1}$ and $C_i(s) = 1$ as well as *acceleration feedforward* (AF) with $c_{i-1} = a_{i-1}$ and $C_i(s) = \frac{e^{-s\,\phi_{i-1}}}{1+s\,\tau_{i-1}}$.

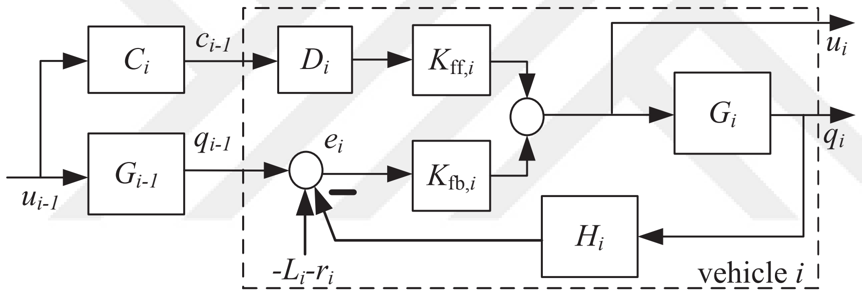

Figure 3.1: Feedback loop for CACC.

AF is for example employed in [9, 14, 19, 21] and ISF is assumed in [1, 5, 19]. PAF is first used in [24] as a special case of ISF where $C_i(s) = \dfrac{1}{1 + s\,\tau_{i-1}}$ is realized as a part of the filter transfer function $K_{\texttt{ff},i}$ on vehicle i. We note that such implementation requires updating $K_{\texttt{ff},i}$ depending on the predecessor vehicle time constant τ_{i-1} during run-time, which is generally undesired. Instead, we suggest to implement $C_i(s) = \dfrac{1}{1 + s\,\tau_{i-1}}$ on vehicle $i-1$ itself such that the communicated signal is $a_{i-1}(t + \phi_{i-1})$. We finally note that most of the existing literature focuses on the case of homogeneous vehicles with identical vehicle models.

The literature provides various controller realizations for guaranteeing string stability in the control architecture in Fig. 3.1 [1, 5, 14, 19, 24]. In this thesis, we adopt the PD controller designs from [1] (ISF) and [14] (AF).

In the case of ISF, we use [1]

$$K_{\mathrm{ff},i}(s) = \frac{1}{1 + h_i\, s} \text{ and } K_{\mathrm{fb},i}(s) = \frac{K_{\mathrm{P},i} + K_{\mathrm{D},i}\, s}{1 + h_i\, s} \tag{3.11}$$

That is, the PD-parameters $K_{\mathrm{P},i}$ and $K_{\mathrm{D},i}$ as well as the headway time h_i need to be selected in the design.

In the case of AF, we use [14]

$$K_{\mathrm{ff},i}(s) = \frac{1 + s\,\tau_i}{1 + s\,h_i} \text{ and } K_{\mathrm{fb,i}}(s) = \omega_{K,i}\,(\omega_{K,i} + s). \tag{3.12}$$

Here, the parameters $\omega_{K,i}$ and h_i are needed for the design.

We note that all the controller designed in this thesis are designed manually with the aim of achieving $\mathcal{L}_\infty$ string stability and reducing the headway time as much as possible.

3.4 Simulation Example For Homogeneous Vehicles

Our simulation platform is based on MATLAB/SIMULINK to evaluate the performance of CACC for homogeneous vehicle strings. An example experiment is accomplished for 11 vehicles as shown in Figure 3.2. In order to quantify values of τ_i, we

Figure 3.2: Vehicle string with 11 vehicles.

refer to practical experiments in [5], where a value of $\tau \approx 0.4 seconds$ is obtained. That is, we choose $\tau_i = 0.4s$ for each vehicle and design $K_{\mathrm{ff},i}$ and $K_{\mathrm{fb},i}$ according to (3.11). In our simulation, the leader vehicle is provided with the input signal u_1 in Figure 3.3. That is, sharp accelerations of $4\,\mathrm{m/s^2}$ and $-4\,\mathrm{m/s^2}$ are given in order to study a difficult vehicle following scenario. The simulation result is shown in Figure. 3.4. It can be seen from the vehicle positions that each vehicle follows its predecessor at a safe distance. In addition, the velocity and acceleration plot suggest

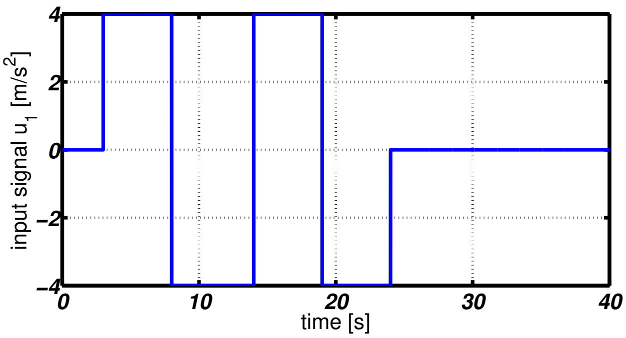

Figure 3.3: Input signal u_1 of the leader vehicle.

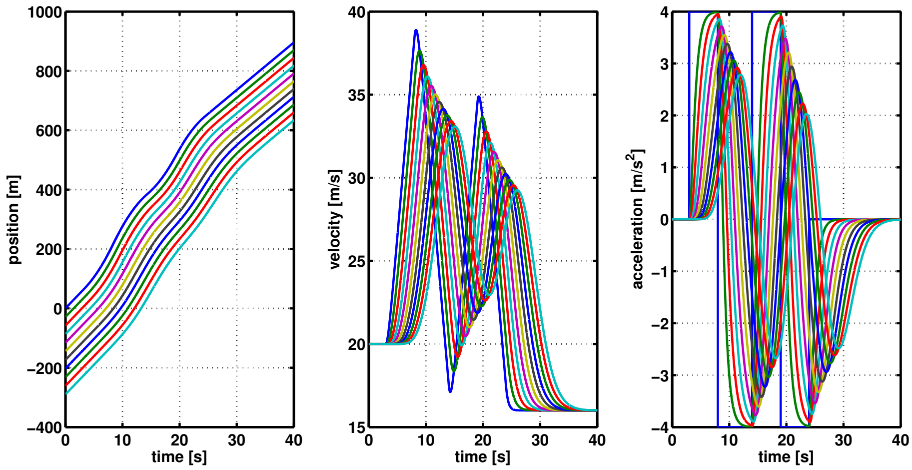

Figure 3.4: CACC design for string stability: simulation with homogeneous vehicles.

that the disturbance provided by the input signal is attenuated along the string (the respective signal amplitudes decrease along the string). That is, strict string stability is confirmed.

CHAPTER 4

COMPARISON OF CACC METHODS WITH DIFFERENT OBJECTIVES

This chapter contains the main contributions of the thesis. It is intended to evaluate and compare the different methods presented in Chapter 3. The main aim here is the study of realistic parameter values in order to assess the practicability of the different methods.

4.1 Discussion and Comparison Methodology

The methods described in Chapter 3 have different objectives and are evaluated with different parameter choices in their respective papers. As before, we denote these methods as IF (input feedforward), AF (acceleration feedforward), 1VLA (one-vehicle-lookahead), 2VLA (two-vehicle-lookahead) and 3VLA (three-vehicle-lookahead). In this thesis, we want to evaluate all the methods with realistic parameter values and driving conditions. It has to be noted that the relevant parameters are the driveline constant τ_i and the actuator delay Φ_i of each vehicle and the communication delay θ_i. The driving conditions are given by the input signal $u_1(t)$ provided to the first vehicle of a string.

Regarding the parameter values, we consider the value $\tau_i = 0.5[s]$ (Case 1), which is in line with the simulation experiments in [7]. In addition, we refer to [8], which provides a comprehensive collection of parameter combinations for vehicle models and communication delays. In this thesis, we choose the parameter combinations in Table 4.1 that are taken from real vehicle experiments. From the Table 4.1, it can be noted that Case 4 would correspond to a string with comparably fast driveline dynamics such as an automobile platoon while Case 3 would correspond to a platoon of vehicles with slow driveline dynamics such as a truck platoon, and Case 2 would be considering platoons with driveline dynamics that are in the middle in terms of vehicle responsiveness compared to the other cases. The comparisons are done within each case, then the discussion and comparisons are done on the next case and so on. By comparing the methods in multiple cases, we decrease the effect of parameter values on the comparisons and make the comparison more robust.

Table 4.1: Parameter values for τ_i, ϕ_i and θ_i.

	$\tau_i[s]$	$\phi_i[s]$	$\theta_i[s]$
Case 2 [14]	$0.38, \leq 1.0$	0.18	0.06
Case 3 [9]	0.8	0.02	0.2
Case 4 [4, 5]	0.1	$0.18, 0.2$	0.02

Since the work in [7] only takes into account the case without actuator and communication delays, we perform an initial evaluation without these delays. This evaluation is carried out in Section 4.2 and 4.3. As the input signals to the first vehicle, we use two different signals. The first signal consists of one period of the sinusoidal signal

$$u_1(t) = \sin(\pi/3 \cdot t). \tag{4.1}$$

This signal has a period of 6 s and can be considered as a driver performing a smooth speed-up and slow-down maneuver. Such maneuver is also considered in [7]. The second maneuver is a harsh speed-up/slow-down maneuver. First, an acceleration step from 0 to 3 m/s^2 is applied and then a deceleration step from 3 m/s^2 to 0 is applied. The chosen values comply with values in the literature that consider accelerations above 3 m/s^2 as uncomfortable for human drivers and passengers [27–30].

In our evaluation, we want to look at the following performance metrics

- $||e_i||_\infty$: the maximum absolute value of the distance error signal. This signal shows how well driving safety is addressed.
- $||e_i||_2$: the 2-norm of the distance error signal. This signal shows how much error is accumulated during the respective driving maneuver. Since the proposed

driving maneuvers are (sinusoidal and rectangular) pulse signals, it is the case that the error signal always converges to zero after the maneuver. Because of this reason, computing the 2-norm is meaningful.

- $||a_i||_\infty$: the maximum absolute value of the acceleration signal. This signal gives an idea about driving comfort.

It is also good to point out that the above signals are the relevant signals for the string stability definitions in the papers considered in this thesis. The string stability definition in [7] is based on the distance error signal and the string stability definition in [5] uses the acceleration signal.

After the initial evaluation, we perform a further more realistic evaluation with actuator and communication in Section 4.4.

4.2 Sinusoidal Disturbance Signals without Actuator and Communication Delays

In this section, we use the parameters in Table 4.1 by setting both the actuator and communication delay to zero.

4.2.1 Case 1

We assume that $\tau_i = 0.5$ for all vehicles and apply the sinusoidal disturbance input in 4.1. The controller parameters for the different methods in this case are as follows:

- IF: $K_P = 0.3$, $K_D = 1$, $h = 0.3$,
- AF: $\omega_K = 3.5$; $h = 0.4$,
- 1VLA: $k_a = 0.7$, $k_p = 5$, $k_v = 0.8$, $h = 0.8$,
- 2VLA: $k_a = 0.2$, $k_p = 20$, $k_v = 10$, $h = 0.75$,
- 3VLA: $k_a = 0.25$, $k_p = 1$, $k_v = 2$, $h = 0.7$,

It can be seen that IF and AF enable smaller headway times. The simulation results for the different methods are shown in Figure 4.1 to 4.5.

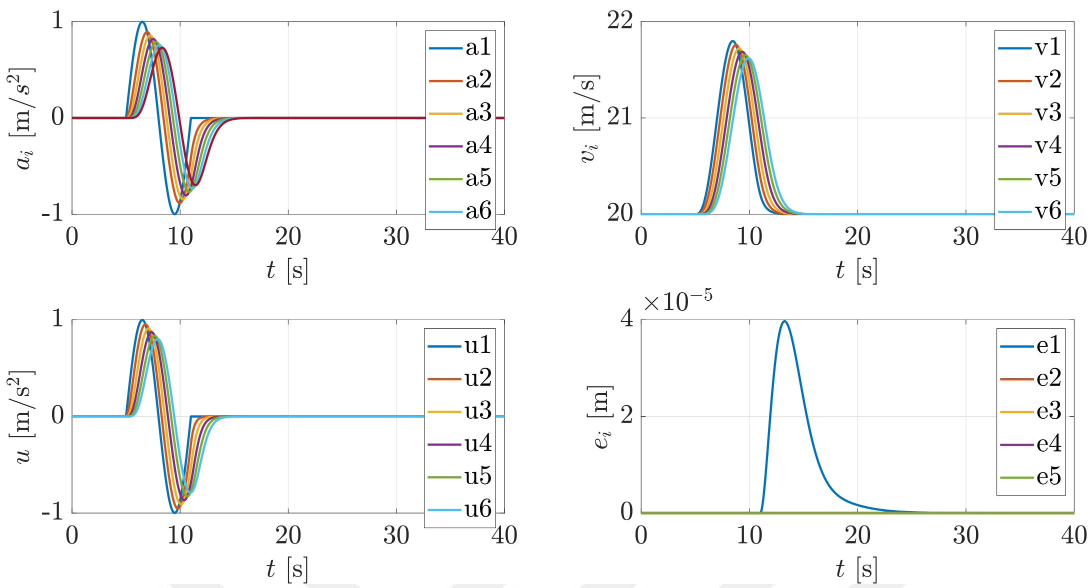

Figure 4.1: Case 1 with sinusoidal disturbance input and IF

It can be seen that especially IF leads to very small error signals. This is expected for the case of zero delays [14]. It is further interesting to note that increasing errors occur when more vehicles are used for the look-ahead (2VLA and 3VLA).

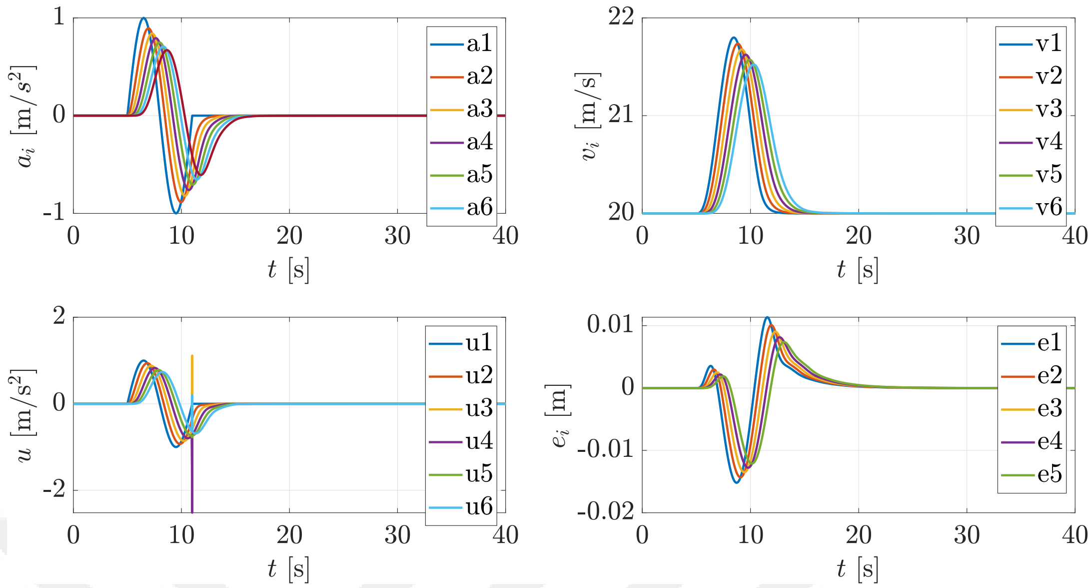

Figure 4.2: Case 1 with sinusoidal disturbance input and AF

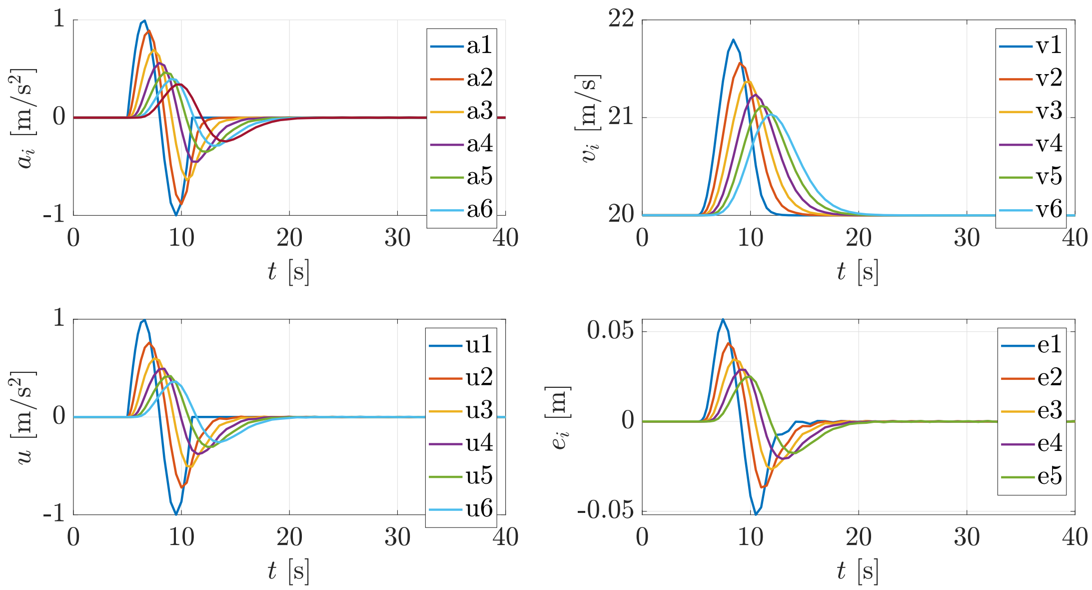

Figure 4.3: Case 1 with sinusoidal disturbance input and 1VLA

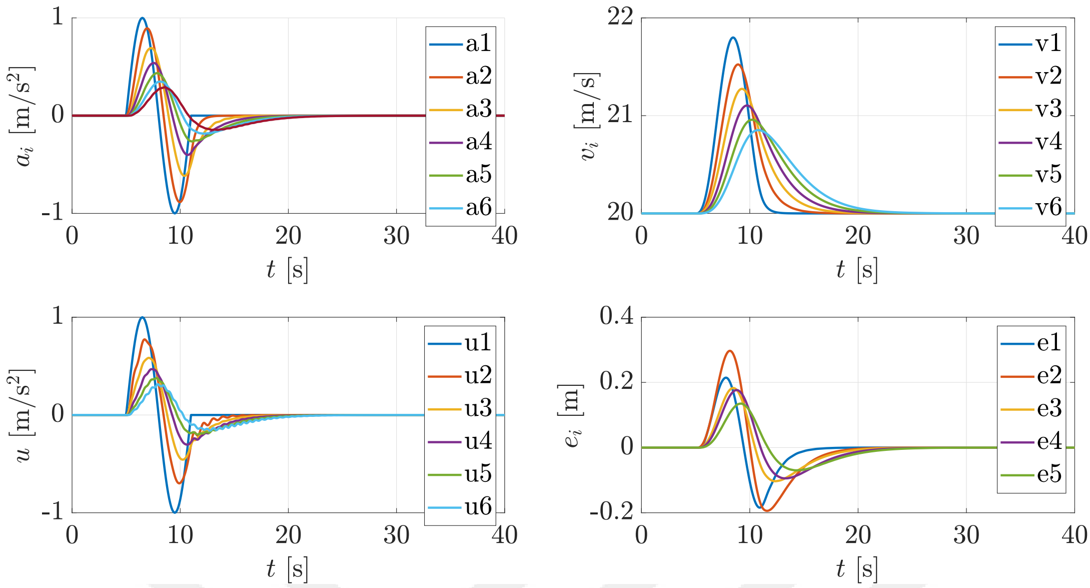

Figure 4.4: Case 1 with sinusoidal disturbance input and 2VLA

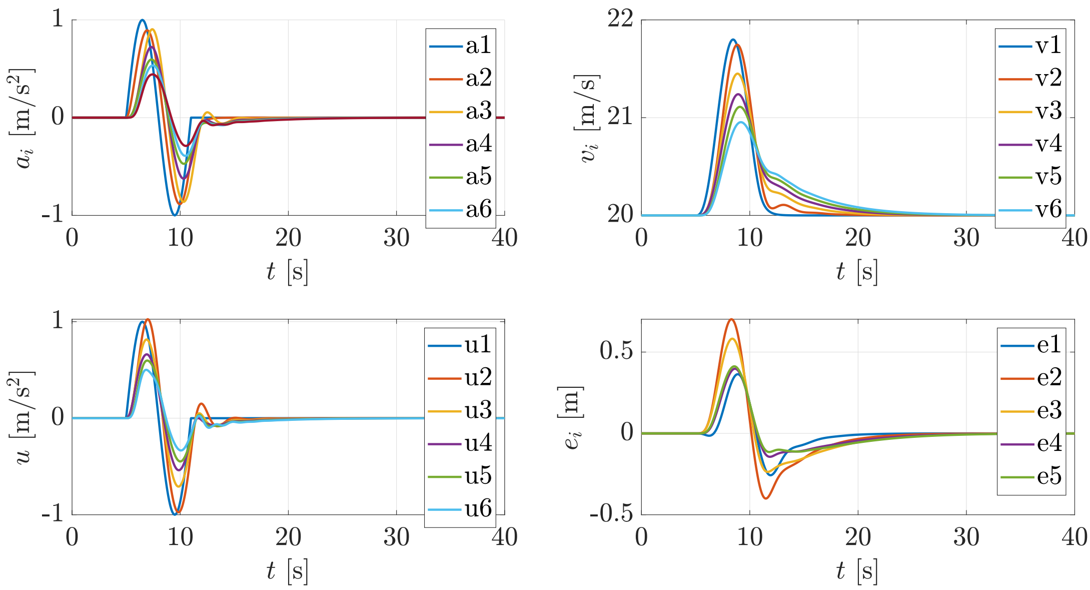

Figure 4.5: Case 1 with sinusoidal disturbance input and 3VLA

4.2.2 Case 2

We assume that $\tau_i = 0.38$ for all vehicles and apply the sinusoidal disturbance input in 4.1. The controller parameters for the different methods in this case are as follows:

- IF: $K_P = 9$, $K_D = 3$, $h = 0.3$,
- AF: $\omega_K = 2.5$; $h = 0.4$,
- 1VLA: $k_a = 0.25$, $k_p = 45$, $k_v = 0.8$, $h = 0.8$,
- 2VLA: $k_a = 0.25$, $k_p = 45$, $k_v = 0.8$, $h = 0.44$,
- 3VLA: $k_a = 0.25$, $k_p = 45$, $k_v = 0.8$, $h = 0.28$,

Again, it is generally the case that IF and AF lead to a smaller headway. Nevertheless, it can be stated that small headways can also be achieved for 2VLA and 3VLA. This seems to be related to the small driveline constant of this case.

The related simulation results are shown in Figure 4.6 to 4.10.

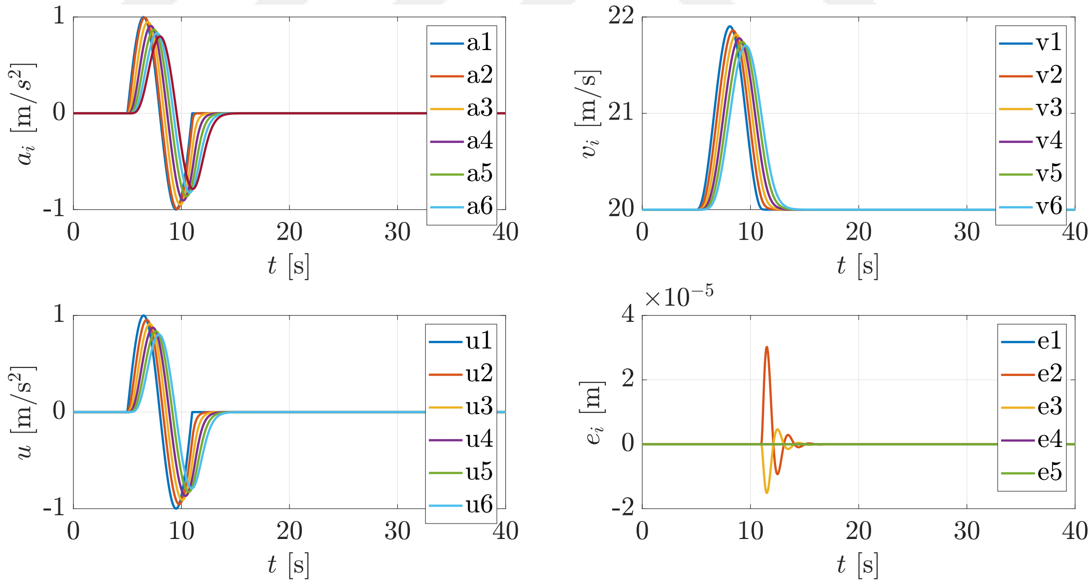

Figure 4.6: Case 2 with sinusoidal disturbance input and IF

In this case, the observed errors are smaller compared to the previous case since $\tau_i = 0.38$. In addition, it can be seen that the error generally converges to zero faster when using IF and AF.

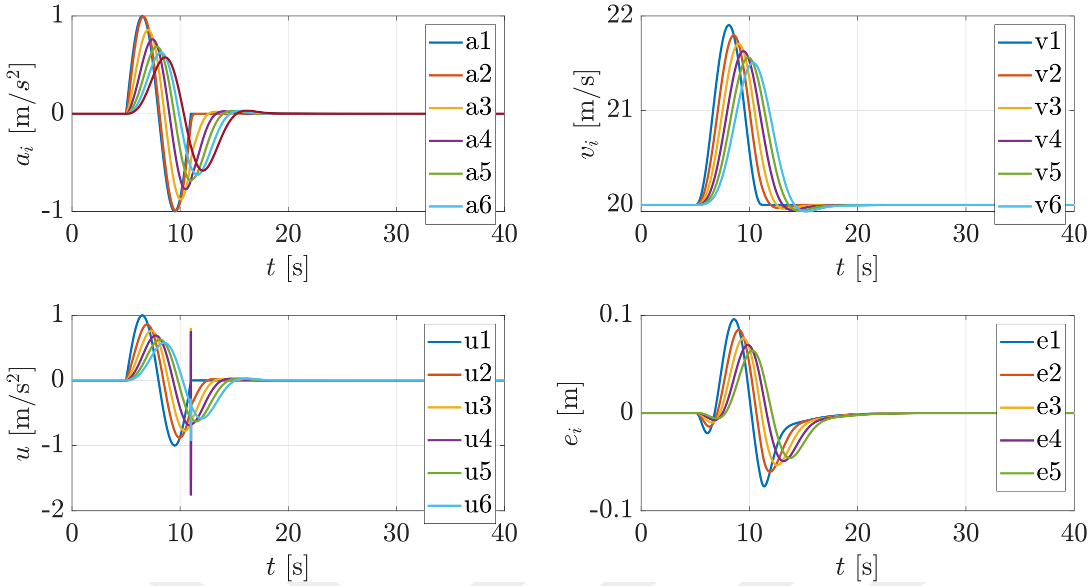

Figure 4.7: Case 2 with sinusoidal disturbance input and AF

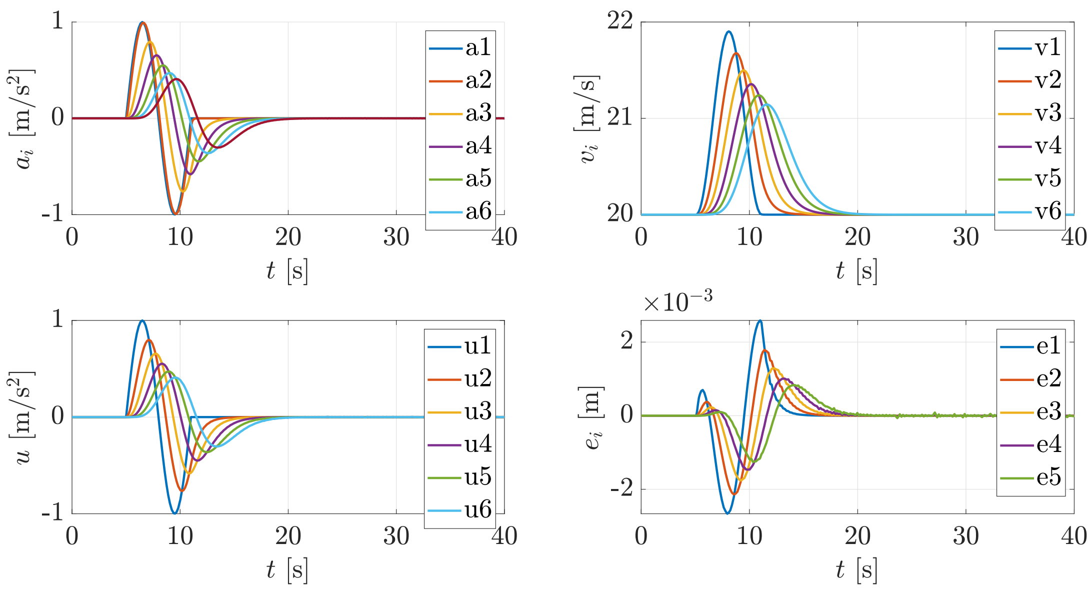

Figure 4.8: Case 2 with sinusoidal disturbance input and 1VLA

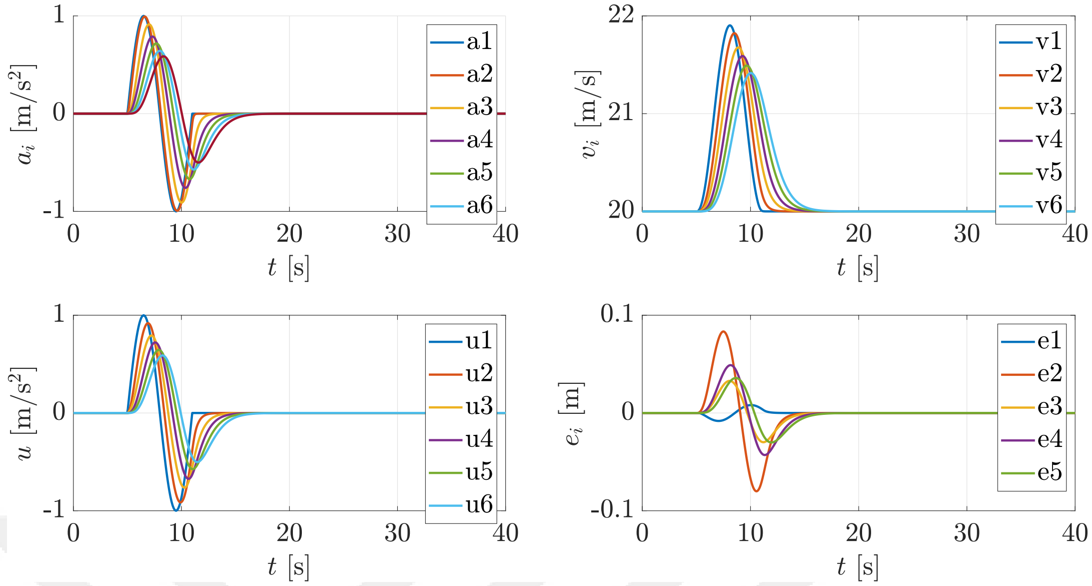

Figure 4.9: Case 2 with sinusoidal disturbance input and 2VLA

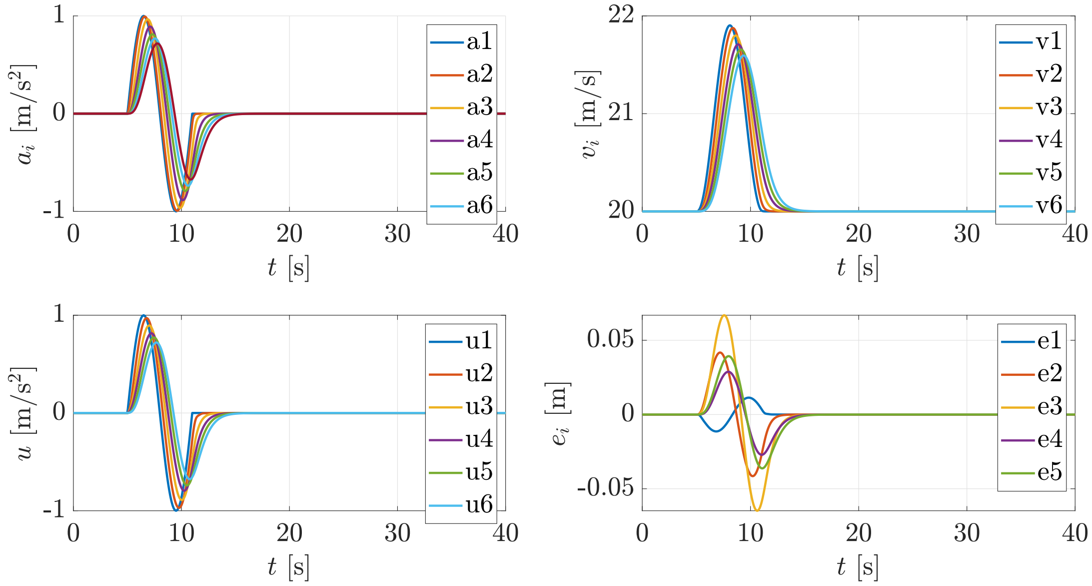

Figure 4.10: Case 2 with sinusoidal disturbance input and 3VLA

4.2.3 Case 3

We assume that $\tau_i = 0.8$ for all vehicles and apply the sinusoidal disturbance input in 4.1. The controller parameters for the different methods in this case are as follows:

- IF: $K_P = 0.3$, $K_D = 1$, $h = 0.3$,
- AF: $\omega_K = 2.5$; $h = 0.4$,
- 1VLA: $k_a = 0.5$, $k_p = 5$, $k_v = 2$, $h = 0.8$,
- 2VLA: $k_a = 0.25$, $k_p = 3$, $k_v = 1$, $h = 0.6$,
- 3VLA: $k_a = 0.4$, $k_p = 5$, $k_v = 3$, $h = 0.6$,

Again, the headway times for IF and AF are smaller. The simulation results are shown in Figure 4.11 to 4.15.

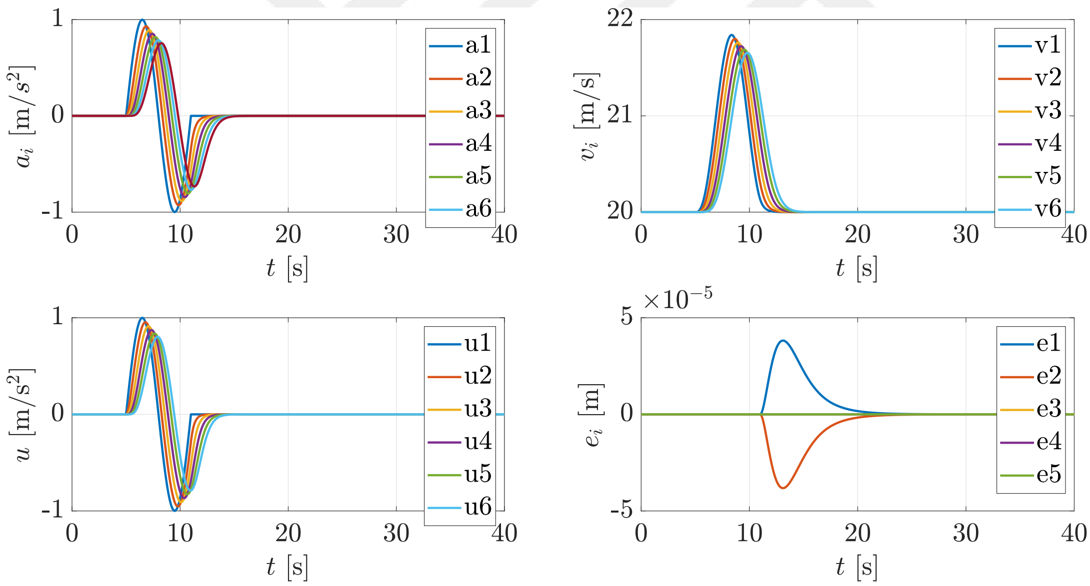

Figure 4.11: Case 3 with sinusoidal disturbance input and IF

As before, the simulations show that smaller error values can be achieved with IF and AF.

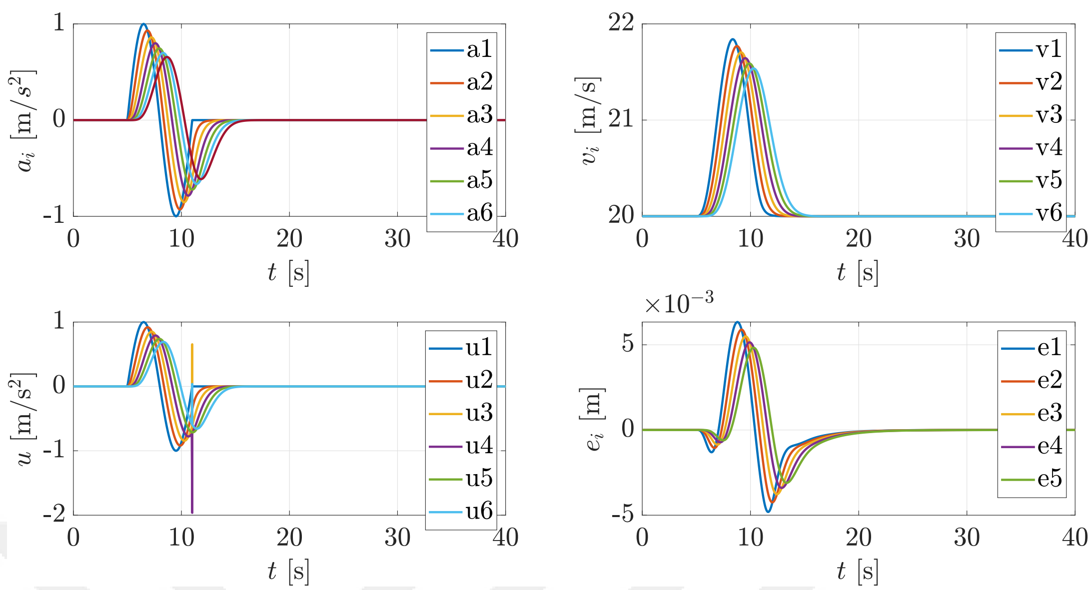

Figure 4.12: Case 3 with sinusoidal disturbance input and AF

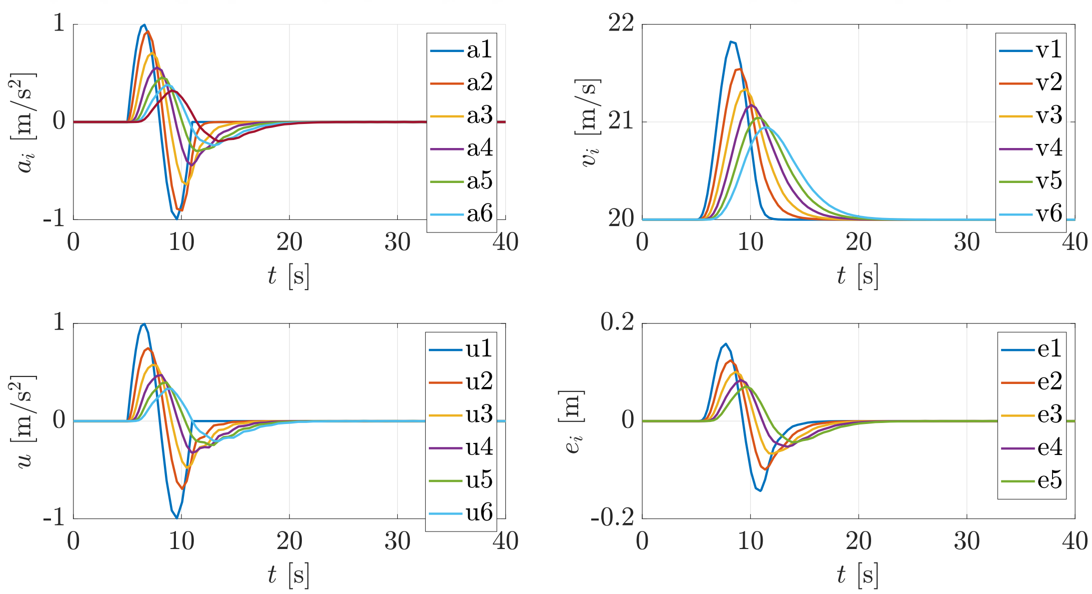

Figure 4.13: Case 3 with sinusoidal disturbance input and 1VLA

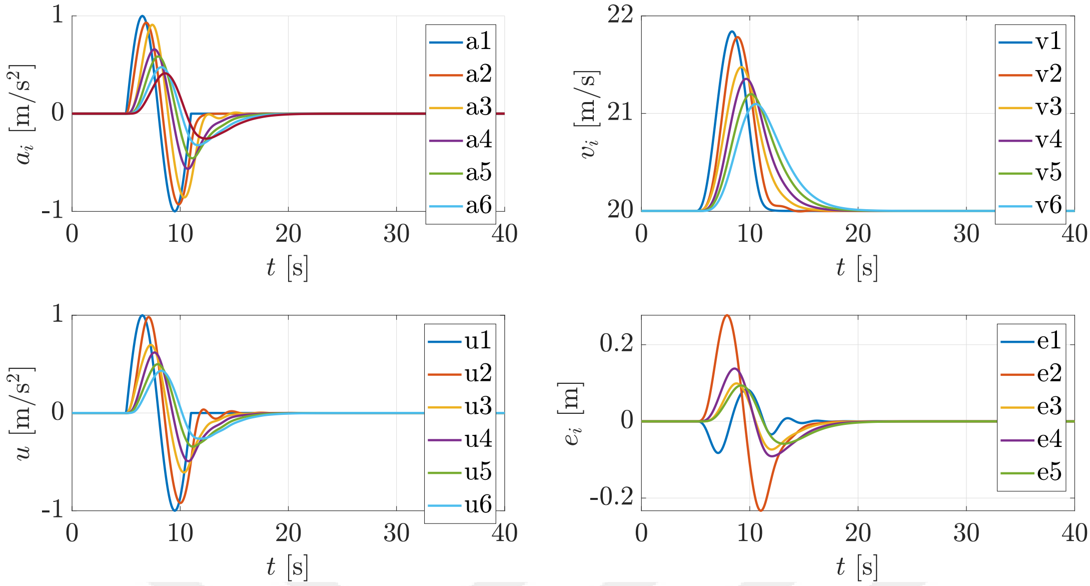

Figure 4.14: Case 3 with sinusoidal disturbance input and 2VLA

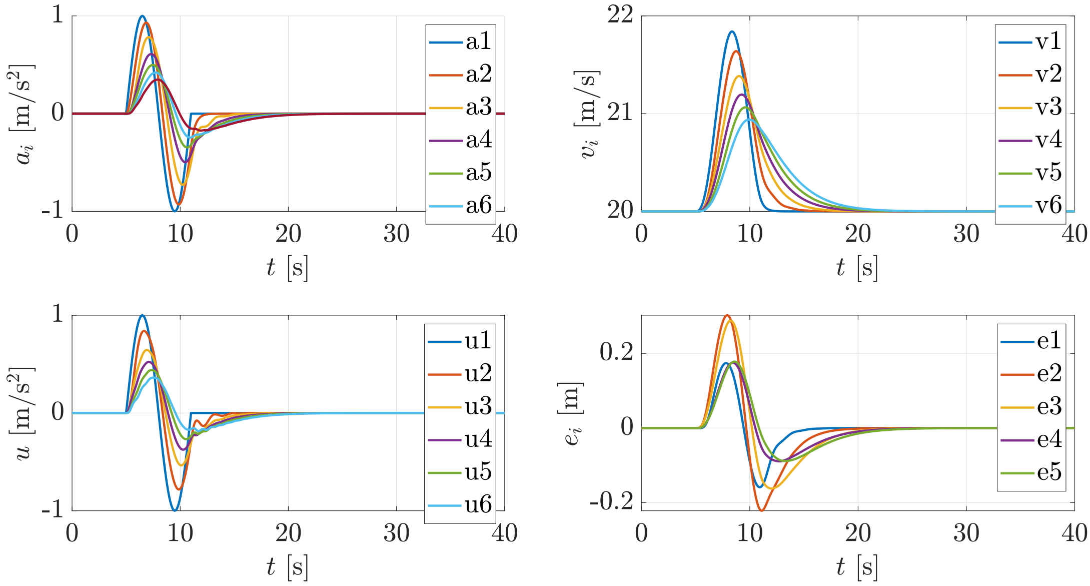

Figure 4.15: Case 3 with sinusoidal disturbance input and 3VLA

4.2.4 Case 4

We assume that $\tau_i = 0.1$ for all vehicles and apply the sinusoidal disturbance input in 4.1. The controller parameters for the different methods in this case are as follows:

- IF: $K_P = 0.1$, $K_D = 2$, $h = 0.3$,
- AF: $\omega_K = 5.5$; $h = 0.3$,
- 1VLA: $k_a = 0.75$, $k_p = 0.8$, $k_v = 0.5$, $h = 1.2$,
- 2VLA: $k_a = 0.4$, $k_p = 0.8$, $k_v = 0.8$, $h = 1.1$,
- 3VLA: $k_a = 0.25$, $k_p = 0.8$, $k_v = 0.8$, $h = 1$,

Again, the headway time for 1VLA, 2VLA and 3VLA is larger and the simulations in Figure 4.16 to 4.20 show that the errors for IF and AF are smaller.

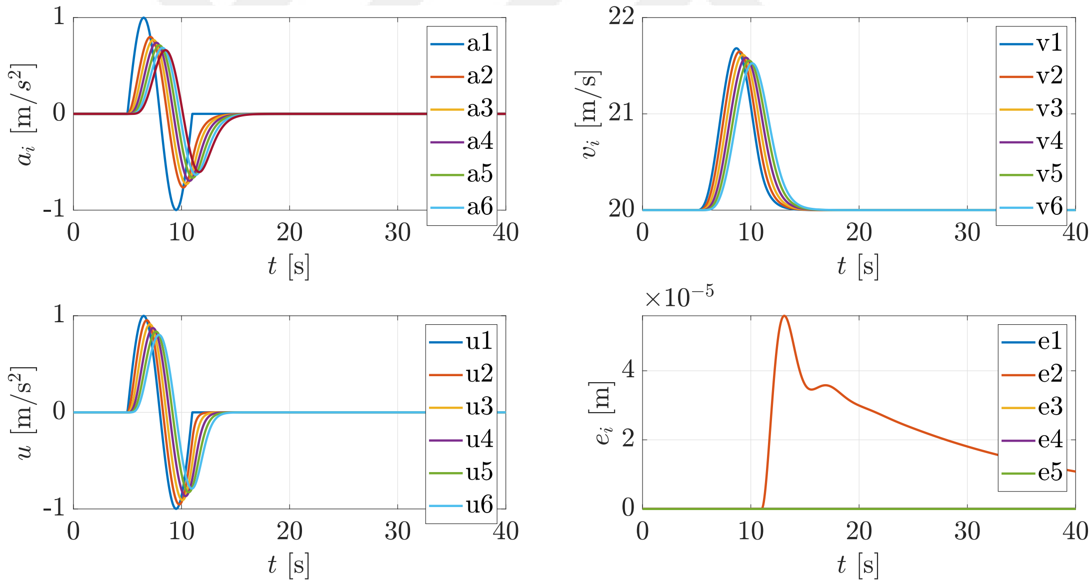

Figure 4.16: Case 4 with sinusoidal disturbance input and IF

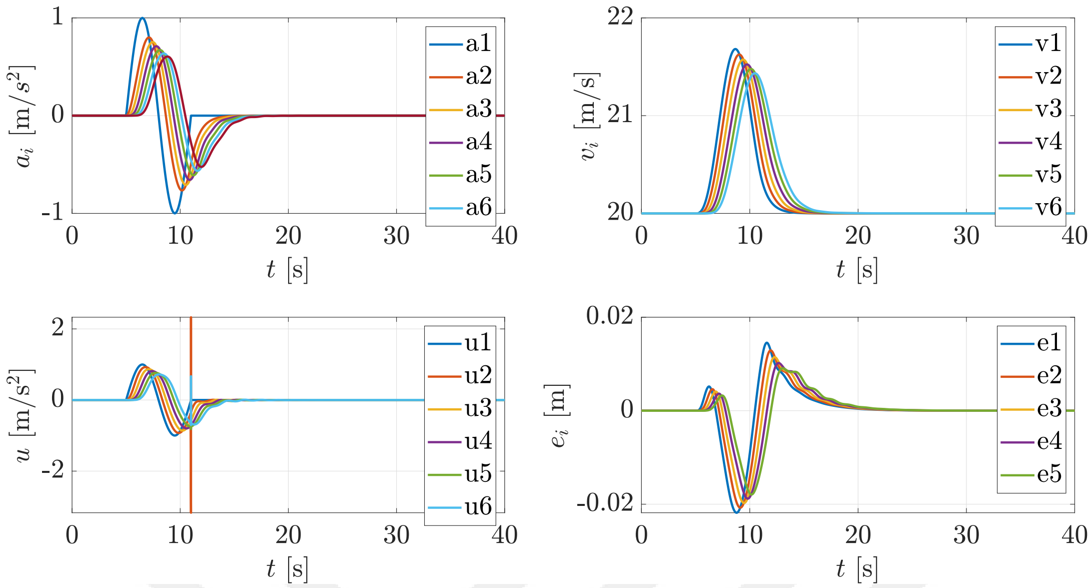

Figure 4.17: Case 4 with sinusoidal disturbance input and AF

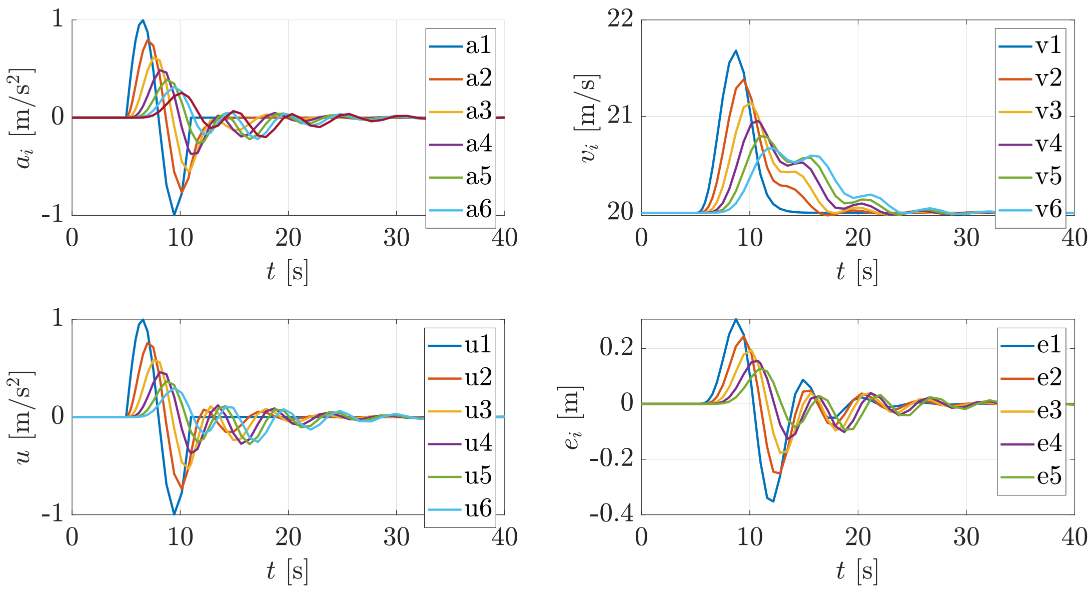

Figure 4.18: Case 4 with sinusoidal disturbance input and 1VLA

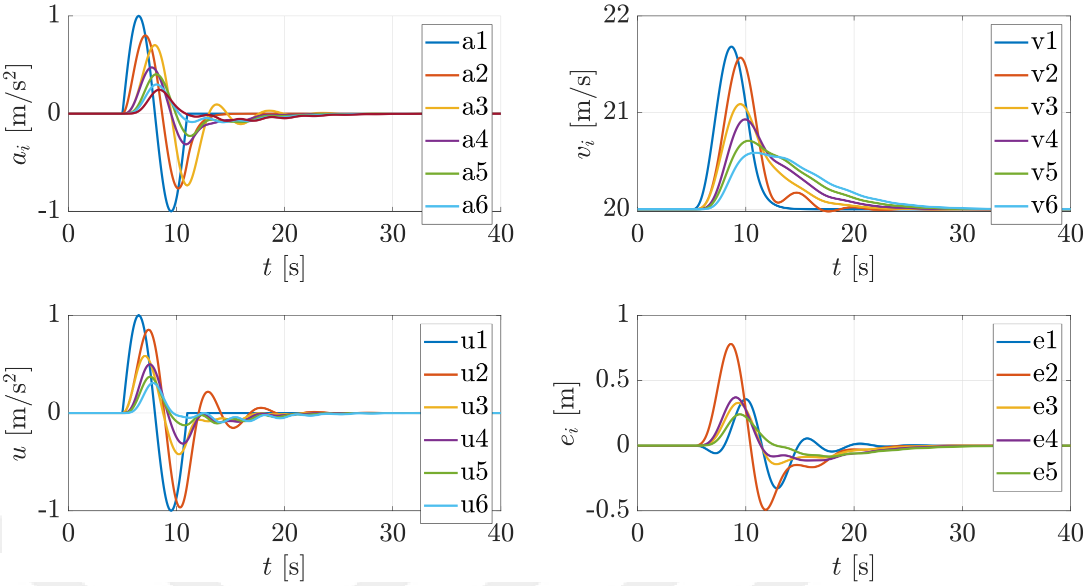

Figure 4.19: Case 4 with sinusoidal disturbance input and 2VLA

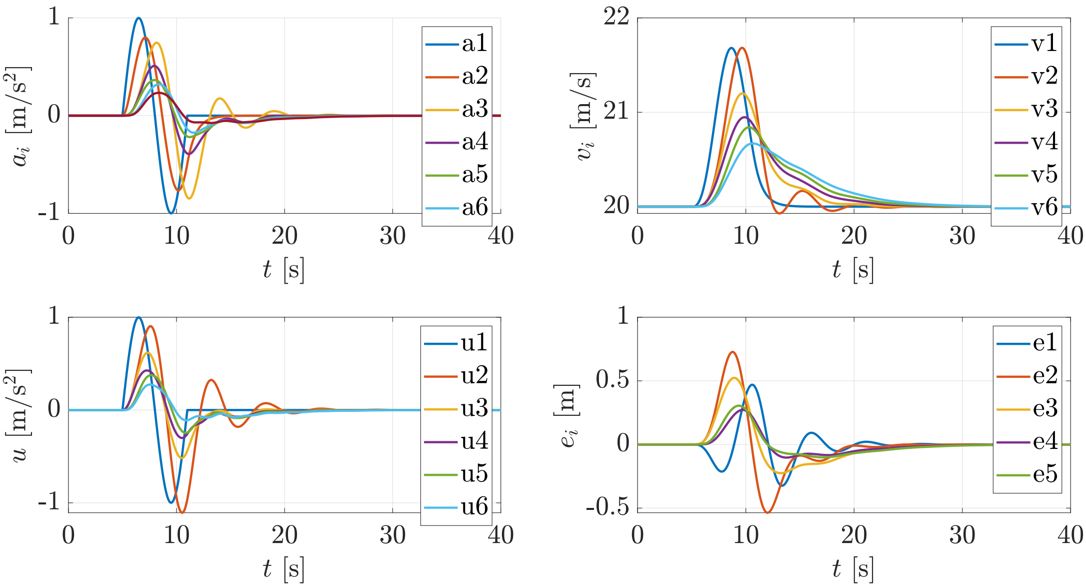

Figure 4.20: Case 4 with sinusoidal disturbance input and 3VLA

4.2.5 Comparison Tables

In summary, the following important observations can be made:

- IF and AF enable smaller headway times. This is important for driving in vehicle strings, where it is desired to achieve a small inter-vehicle spacing
- The error magnitudes are generally smaller when using IF and AF. This is an interesting result, since 1VLA, 2VLA and 3VLA address a condition on the error signal.
- The error magnitude generally increases from 1VLA to 3VLA. This is an expected result since the controller parameters of each predecessor vehicle used for the look-ahead are the same. Choosing different controller parameters for different predecessor vehicles can mitigate this problem.
- The distance error converges to zero faster when using IF and AF.

Furthermore, it is possible to make additional observations from Table 4.2 to 4.4. Table 4.2 summarizes the results regarding the infinity-norm of the error and conforms the previous analysis. Moreover, Table 4.3 shows that the 2-norm of the error signal is usually high for 2VLA and 3VLA. Table 4.4 illustrates that the maximum acceleration values commonly decrease along the vehicle string. Overall, it can be said that CACC with IF provides the best results in the case of sine inputs and without actuator and communication delays.

Table 4.2: Maximum error with sinusoidal input and without delays

	Case 1				
	$\|\|e_1\|\|_\infty$	$\|\|e_2\|\|_\infty$	$\|\|e_3\|\|_\infty$	$\|\|e_4\|\|_\infty$	$\|\|e_5\|\|_\infty$
IF	0.0004	0.0	0.0	0.0	0.0
AF	0.015	0.014	0.013	0.012	0.012
1VLA	0.057	0.044	0.035	0.029	0.025
2VLA	0.215	0.297	0.183	0.177	0.135
3VLA	0.363	0.702	0.582	0.398	0.412
	Case 2				
	$\|\|e_1\|\|_\infty$	$\|\|e_2\|\|_\infty$	$\|\|e_3\|\|_\infty$	$\|\|e_4\|\|_\infty$	$\|\|e_5\|\|_\infty$
IF	0.0	0.0	0.0	0.0	0.0
AF	0.10	0.09	0.08	0.07	0.07
1VLA	0.003	0.002	0.002	0.002	0.001
2VLA	0.008	0.08	0.03	0.05	0.04
3VLA	0.01	0.04	0.07	0.03	0.04
	Case 3				
	$\|\|e_1\|\|_\infty$	$\|\|e_2\|\|_\infty$	$\|\|e_3\|\|_\infty$	$\|\|e_4\|\|_\infty$	$\|\|e_5\|\|_\infty$
IF	0.0	0.0	0.0	0.0	0.0
AF	0.006	0.006	0.006	0.005	0.005
1VLA	0.16	0.12	0.10	0.08	0.07
2VLA	0.08	0.28	0.10	0.14	0.09
3VLA	0.17	0.30	0.29	0.18	0.18
	Case 4				
	$\|\|e_1\|\|_\infty$	$\|\|e_2\|\|_\infty$	$\|\|e_3\|\|_\infty$	$\|\|e_4\|\|_\infty$	$\|\|e_5\|\|_\infty$
IF	0.0	0.0	0.0	0.0	0.0
AF	0.021	0.021	0.020	0.019	0.018
1VLA	0.35	0.25	0.19	0.16	0.13
2VLA	0.36	0.78	0.33	0.37	0.24
3VLA	0.47	0.73	0.53	0.27	0.30

Table 4.3: 2-norm of the error with sinusoidal input and without delays

	Case 1				
	$\|\|e_1\|\|_2$	$\|\|e_2\|\|_2$	$\|\|e_3\|\|_2$	$\|\|e_4\|\|_2$	$\|\|e_5\|\|_2$
IF	0.002	0.0	0.0	0.0	0.0
AF	1.08	1.02	0.96	0.91	0.87
1VLA	0.16	0.13	0.09	0.08	0.07
2VLA	11.8	16.5	10.2	10.1	8.02
3VLA	18.7	36.1	29.8	20.1	20.9
	Case 2				
	$\|\|e_1\|\|_2$	$\|\|e_2\|\|_2$	$\|\|e_3\|\|_2$	$\|\|e_4\|\|_2$	$\|\|e_5\|\|_2$
IF	0.0	0.007	0.004	0.0	0.0
AF	6.81	6.15	5.67	5.29	4.99
1VLA	0.012	0.009	0.008	0.007	0.006
2VLA	0.44	4.66	1.86	2.78	2.06
3VLA	0.624	2.31	3.75	1.63	2.23
	Case 3				
	$\|\|e_1\|\|_2$	$\|\|e_2\|\|_2$	$\|\|e_3\|\|_2$	$\|\|e_4\|\|_2$	$\|\|e_5\|\|_2$
IF	0.002	0.002	0.0	0.0	0.0
AF	0.45	0.42	0.39	0.37	0.35
1VLA	0.49	0.37	0.28	0.26	0.20
2VLA	4.46	15.0	5.43	7.69	5.37
3VLA	9.58	16.6	15.9	9.71	10.1
	Case 4				
	$\|\|e_1\|\|_2$	$\|\|e_2\|\|_2$	$\|\|e_3\|\|_2$	$\|\|e_4\|\|_2$	$\|\|e_5\|\|_2$
IF	0.0	0.005	0.0	0.0	0.0
AF	1.54	1.46	1.39	1.32	1.27
1VLA	0.86	0.60	0.50	0.44	0.37
2VLA	19.6	41.1	17.4	19.0	13.0
3VLA	23.7	39.6	29.1	15.1	16.1

Table 4.4: Maximum acceleration with sinusoidal input and without delays

	Case 1					
	$\|\|a_1\|\|_\infty$	$\|\|a_2\|\|_\infty$	$\|\|a_3\|\|_\infty$	$\|\|a_4\|\|_\infty$	$\|\|a_5\|\|_\infty$	$\|\|a_6\|\|_\infty$
IF	0.89	0.86	0.82	0.79	0.76	0.73
AF	0.89	0.84	0.79	0.74	0.70	0.67
1VLA	0.89	0.69	0.56	0.47	0.40	0.344
2VLA	0.89	0.69	0.54	0.43	0.35	0.29
3VLA	0.89	0.90	0.72	0.59	0.53	0.44
	Case 2					
	$\|\|a_1\|\|_\infty$	$\|\|a_2\|\|_\infty$	$\|\|a_3\|\|_\infty$	$\|\|a_4\|\|_\infty$	$\|\|a_5\|\|_\infty$	$\|\|a_6\|\|_\infty$
IF	0.99	0.95	0.91	0.87	0.83	0.80
AF	0.99	0.88	0.77	0.69	0.63	0.58
1VLA	0.99	0.79	0.66	0.55	0.47	0.41
2VLA	0.99	0.91	0.79	0.72	0.64	0.59
3VLA	0.99	0.97	0.89	0.81	0.77	0.72
	Case 3					
	$\|\|a_1\|\|_\infty$	$\|\|a_2\|\|_\infty$	$\|\|a_3\|\|_\infty$	$\|\|a_4\|\|_\infty$	$\|\|a_5\|\|_\infty$	$\|\|a_6\|\|_\infty$
IF	0.93	0.89	0.85	0.82	0.79	0.76
AF	0.93	0.86	0.80	0.74	0.70	0.66
1VLA	0.93	0.71	0.56	0.46	0.38	0.32
2VLA	0.93	0.91	0.66	0.59	0.48	0.41
3VLA	0.93	0.78	0.61	0.50	0.42	0.35
	Case 4					
	$\|\|a_1\|\|_\infty$	$\|\|a_2\|\|_\infty$	$\|\|a_3\|\|_\infty$	$\|\|a_4\|\|_\infty$	$\|\|a_5\|\|_\infty$	$\|\|a_6\|\|_\infty$
IF	0.80	0.77	0.74	0.71	0.69	0.66
AF	0.80	0.75	0.71	0.67	0.63	0.60
1VLA	0.79	0.61	0.49	0.39	0.32	0.25
2VLA	0.80	0.73	0.47	0.40	0.30	0.24
3VLA	0.80	0.85	0.51	0.36	0.32	0.23

4.3 Step Disturbance Signals without Actuator and Communication Delays

For brevity, we restrict ourselves to $\tau_i = 0.5$ when applying step inputs. The controller parameters for the different methods are the same as in the previous section. The simulation results in Figure 4.21 to 4.25 are mostly in line with the results in the previous section. It can be emphasized that the distance errors observed for 2VLA and 3VLA are significant and oscillations are observed for this method. The reason for this is again the choice of the same controller parameters for different predecessor vehicles. The related Tables 4.5 to 4.7 confirm that CACC with IF is best suited when there is no actuator and communiation delay.

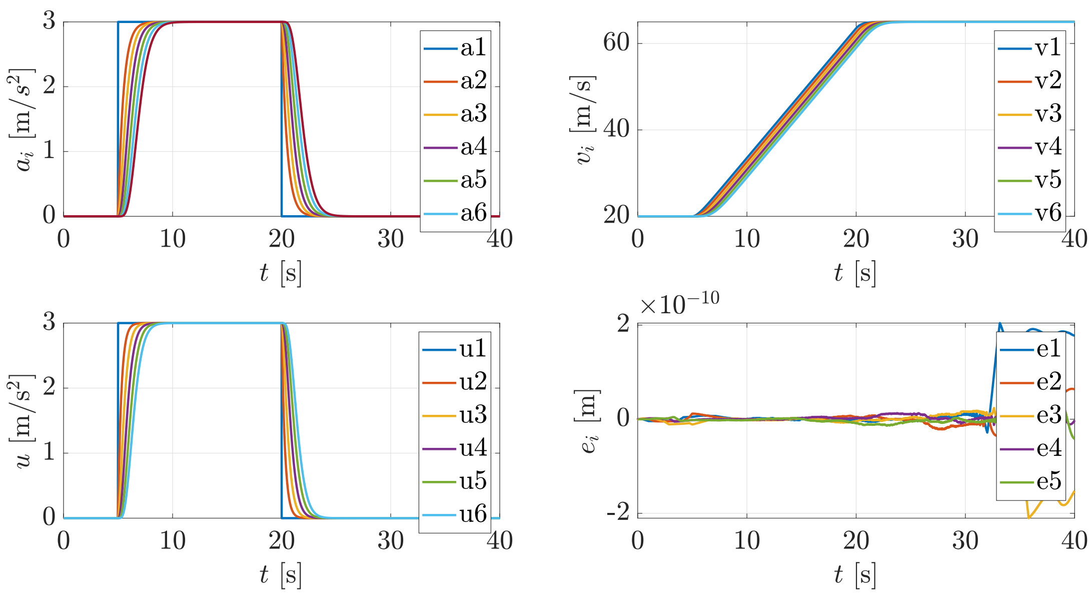

Figure 4.21: Case 1 with step input and IF

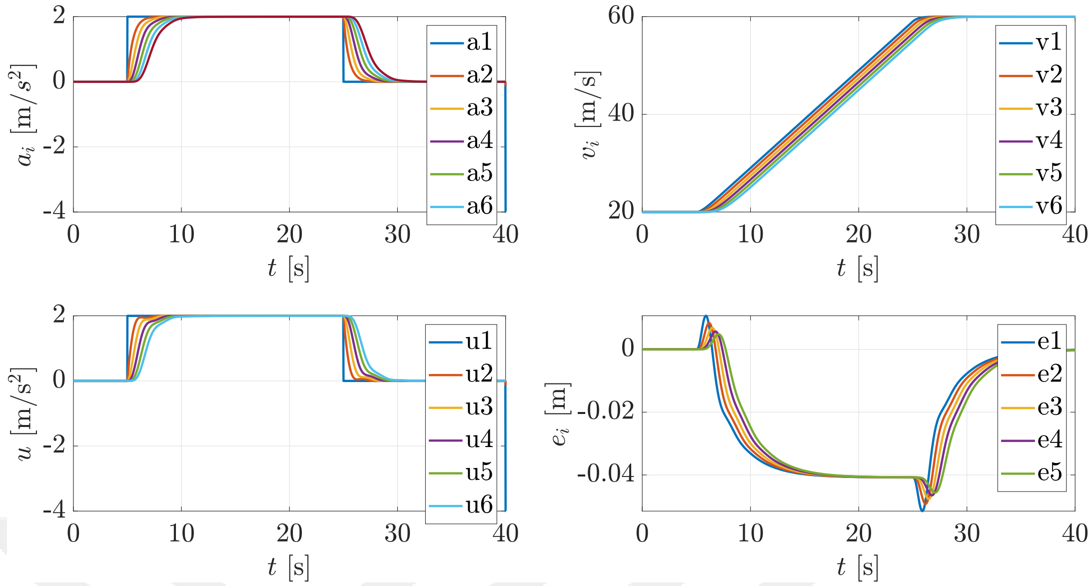

Figure 4.22: Case 1 with step input and AF

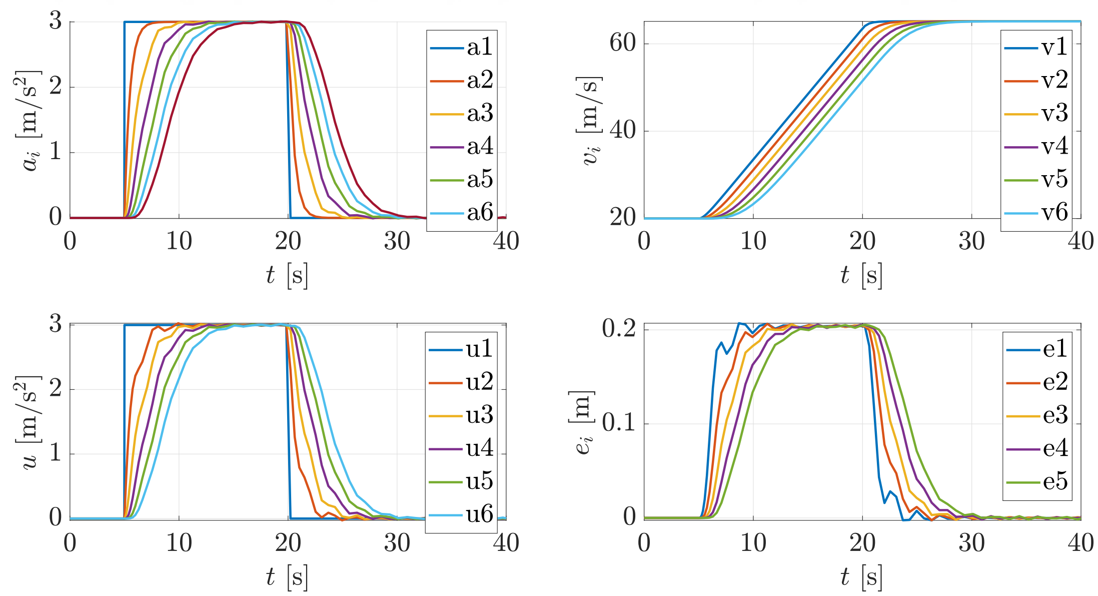

Figure 4.23: Case 1 with step input and 1VLA

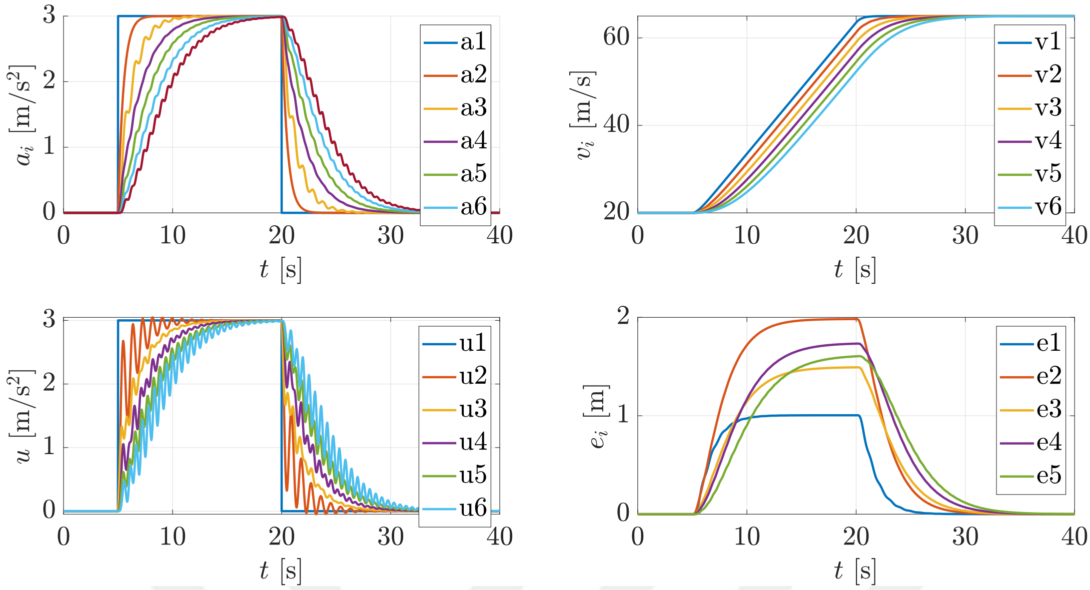

Figure 4.24: Case 1 with step input and 2VLA

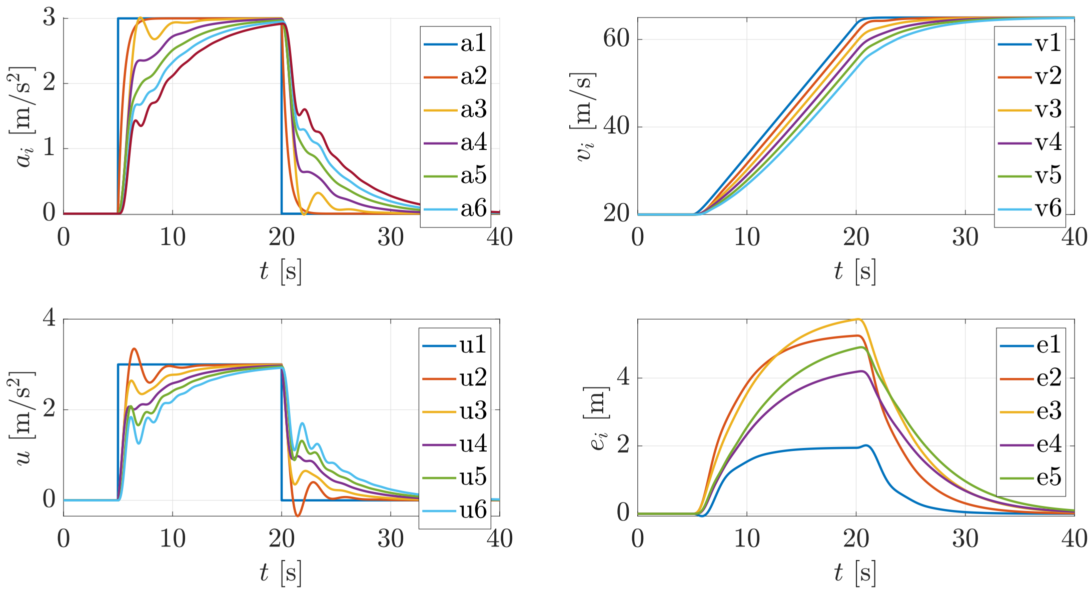

Figure 4.25: Case 1 with step input and 3VLA

Table 4.5: Maximum error with step input and without delays

	Case 1				
	$\|\|e_1\|\|_\infty$	$\|\|e_2\|\|_\infty$	$\|\|e_3\|\|_\infty$	$\|\|e_4\|\|_\infty$	$\|\|e_5\|\|_\infty$
IF	0.0	0.0	0.0	0.0	0.0
AF	0.077	0.074	0.071	0.070	0.068
1VLA	0.21	0.21	0.21	0.21	0.21
2VLA	1.00	1.98	1.49	1.73	1.61
3VLA	2.02	5.25	5.74	4.20	4.91

Table 4.6: 2-norm of the error with step input and without delays

	Case 1				
	$\|\|e_1\|\|_2$	$\|\|e_2\|\|_2$	$\|\|e_3\|\|_2$	$\|\|e_4\|\|_2$	$\|\|e_5\|\|_2$
IF	0.0	0.0	0.0	0.0	0.0
AF	9.94	9.89	9.86	9.83	9.80
1VLA	0.96	0.93	0.92	0.91	0.91
2VLA	117.4	225.0	166.5	191.1	175.0
3VLA	220.3	575.4	615.5	448.6	522.4

Table 4.7: Maximum acceleration with step input and without delays

	Case 1					
	$\|\|a_1\|\|_\infty$	$\|\|a_2\|\|_\infty$	$\|\|a_3\|\|_\infty$	$\|\|a_4\|\|_\infty$	$\|\|a_5\|\|_\infty$	$\|\|a_6\|\|_\infty$
IF	3.0	3.0	3.0	3.0	3.0	3.0
AF	3.0	3.0	3.0	3.0	3.0	3.0
1VLA	3.0	3.0	3.0	3.0	3.0	3.0
2VLA	3.00	3.00	3.00	3.00	2.99	2,99
3VLA	3.00	3.00	3.01	2.97	2.95	2.91

4.4 Realistic Case with Actuator and Communication Delays

The previous sections assumed the absence of actuator and communication delays in line with the design and evaluation in [7]. Nevertheless, in practice, actuator and communication delays are present, which is also confirmed by the practical studies in [4,5,9,14]. This section will evaluate the described methods (IF, AF, 1VLA, 2VLA, 3VLA) with realistic parameters. Since $\tau_i = 0.5$ (Case 1) was not measured in any practical setup, we only focus on the Cases 2, 3, 4, which are also shown in Table 4.1.

4.4.1 Case 2

We assume that $\tau_i = 0.38$ for all vehicles and apply the sinusoidal disturbance input in 4.1. The controller parameters for the different methods in this case are as follows:

- IF: $K_P = 1$, $K_D = 2$, $h = 0.7$,
- AF: $\omega_K = 1.32$; $h = 0.7$,
- 1VLA: $k_a = 0.5$, $k_p = 0.2$, $k_v = 0.8$, $h = 1$,
- 2VLA: $k_a = 0.3$, $k_p = 0.3$, $k_v = 0.6$, $h = 1.1$,
- 3VLA: $k_a = 0.2$, $k_p = 0.05$, $k_v = 0.7$, $h = 1.1$,

As in the case without delays, it holds that IF and AF allow for smaller headway times. Furthermore, Figure 4.26 to Figure 4.30 highlight that 1VLA, 2VLA and 3VLA lead to very large distance errors that are not tolerable in practice. Especially, it has to be emphasized that IF and AF seem to be more robust to delays compared to 1VLA, 2VLA and 3VLA.

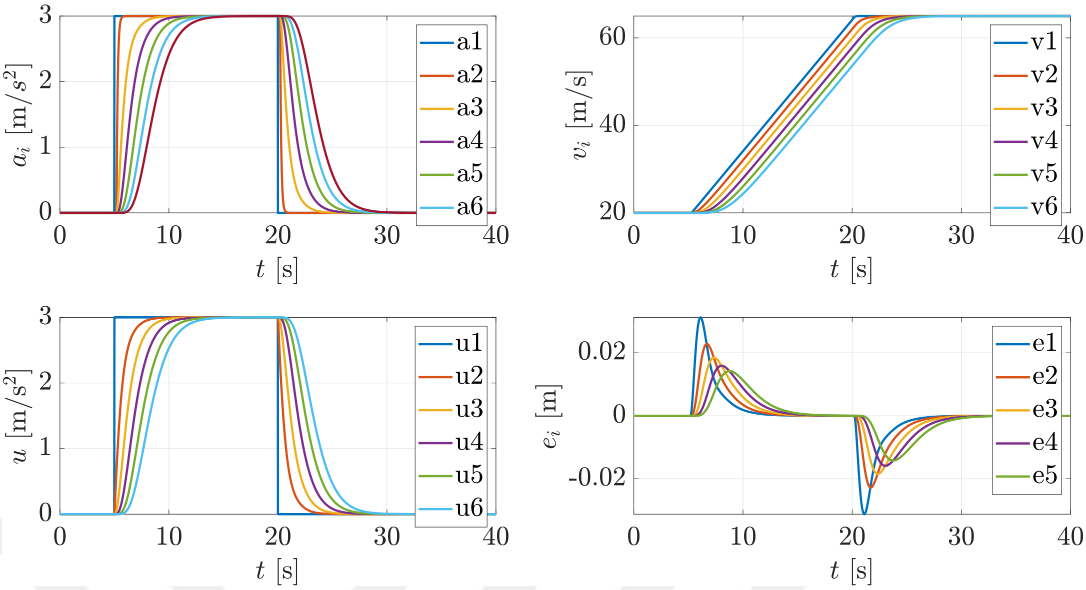

Figure 4.26: Case 2 with actuator and communication delay for 2F

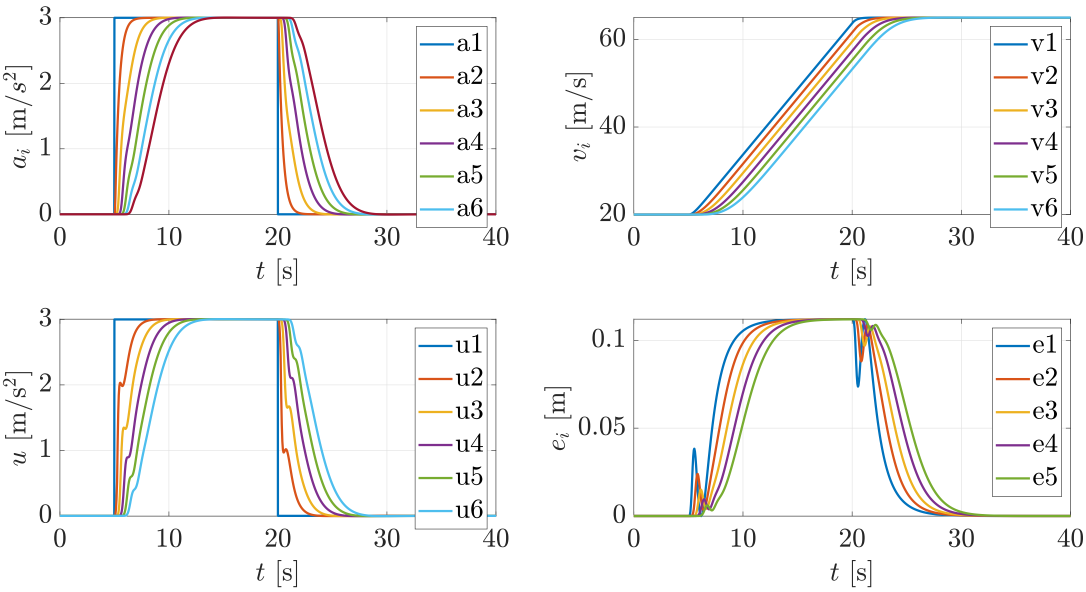

Figure 4.27: Case 2 with actuator and communication delay for AF

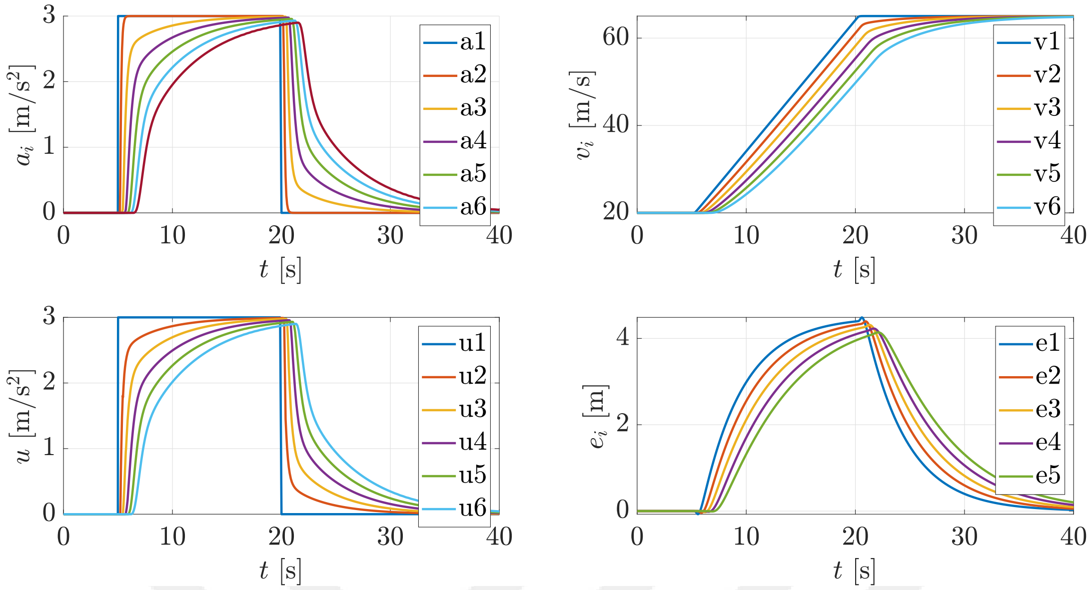

Figure 4.28: Case 2 with actuator and communication delay for 1VLA

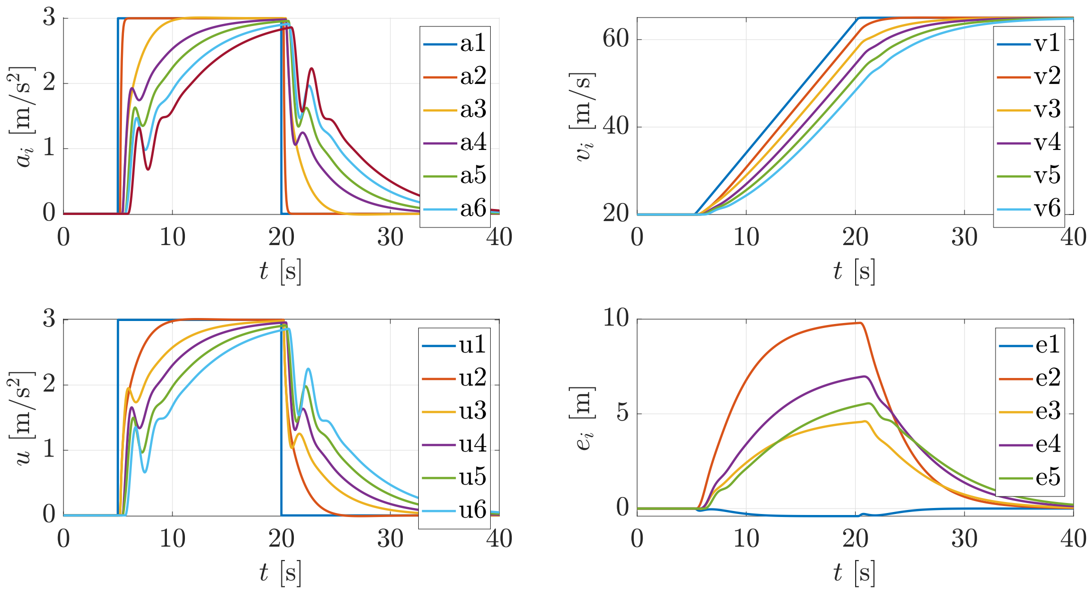

Figure 4.29: Case 2 with actuator and communication delay for 2VLA

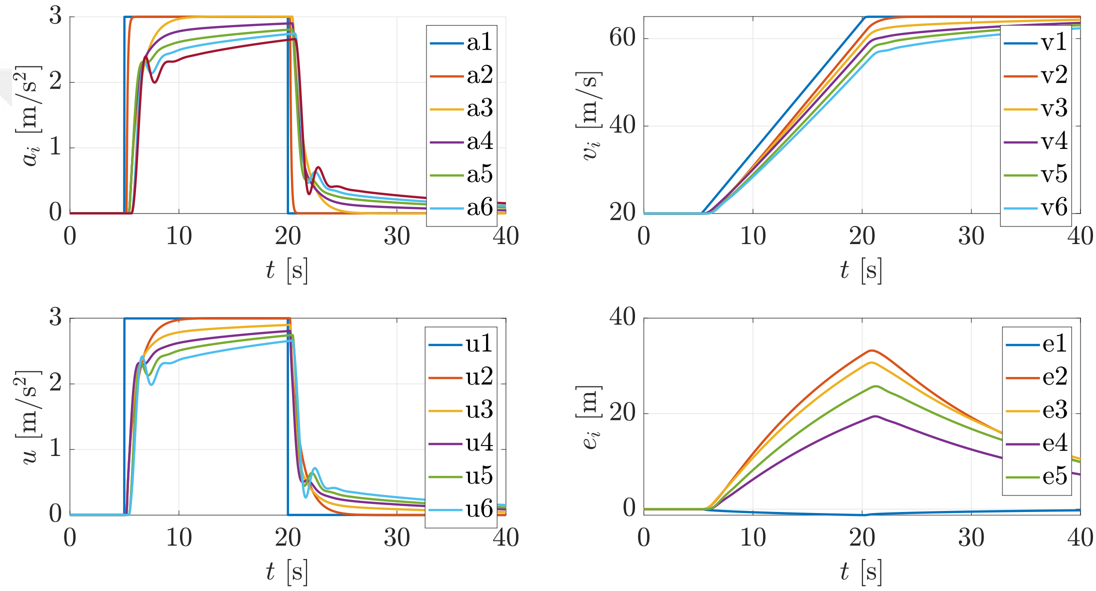

Figure 4.30: Case 2 with actuator and communication delay for 3VLA

4.4.2 Case 3

The results in the previous section are confirmed by the next simulation experiment for $\tau_i = 0.8$ in Figure 4.31 to 4.35. The controller parameters for the different methods in this case are as follows:

- IF: $K_P = 5$, $K_D = 1.5$, $h = 0.7$,
- AF: $\omega_K = 3.5$; $h = 0.7$,
- 1VLA: $k_a = 0.3$, $k_p = 0.25$, $k_v = 0.5$, $h = 1.25$,
- 2VLA: $k_a = 0.2$, $k_p = 0.6$, $k_v = 0.5$, $h = 1.25$,
- 3VLA: $k_a = 0.15$, $k_p = 1$, $k_v = 0.8$, $h = 1.25$,

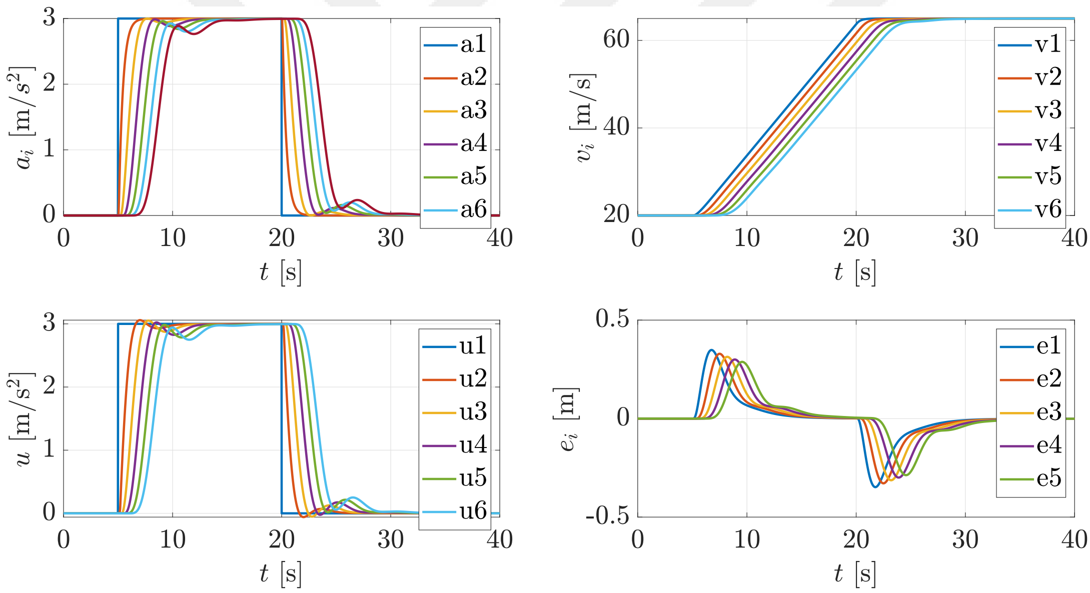

Figure 4.31: Case 3 with actuator and communication delay for IF

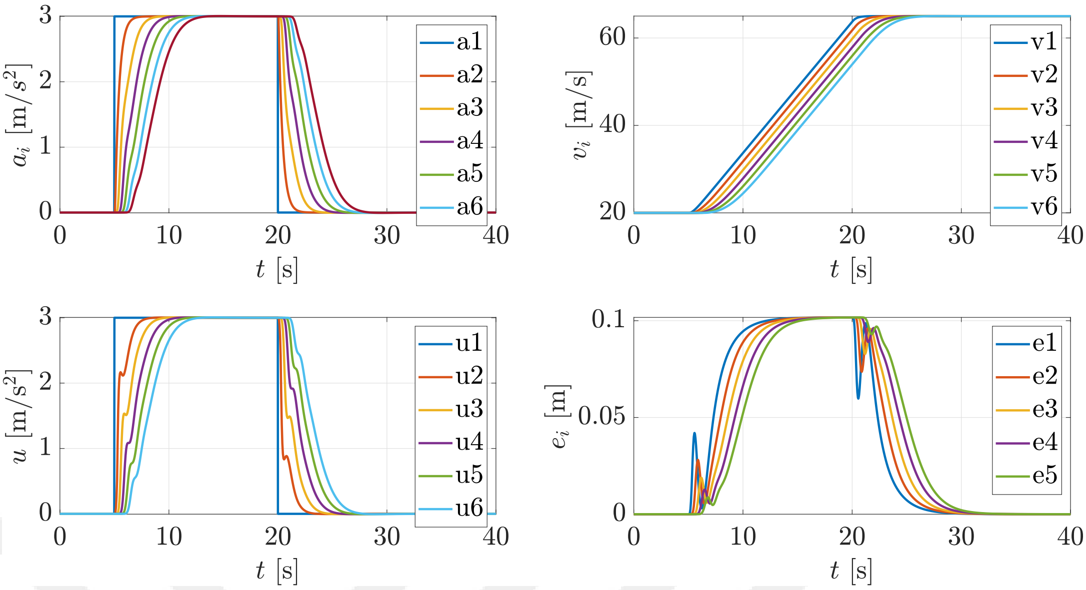

Figure 4.32: Case 3 with actuator and communication delay for AF

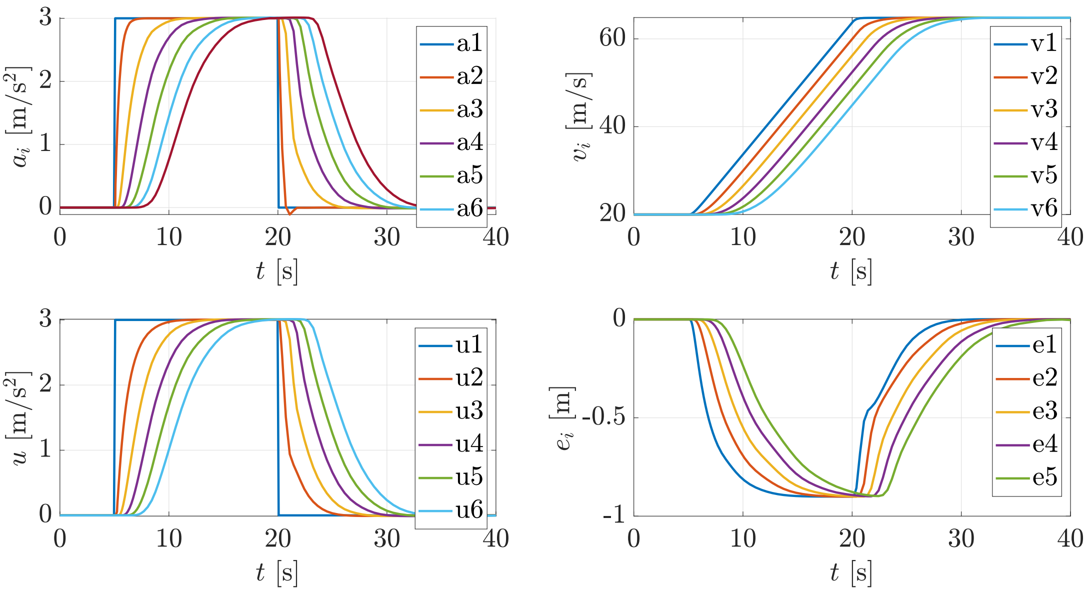

Figure 4.33: Case 3 with actuator and communication delay for 1VLA

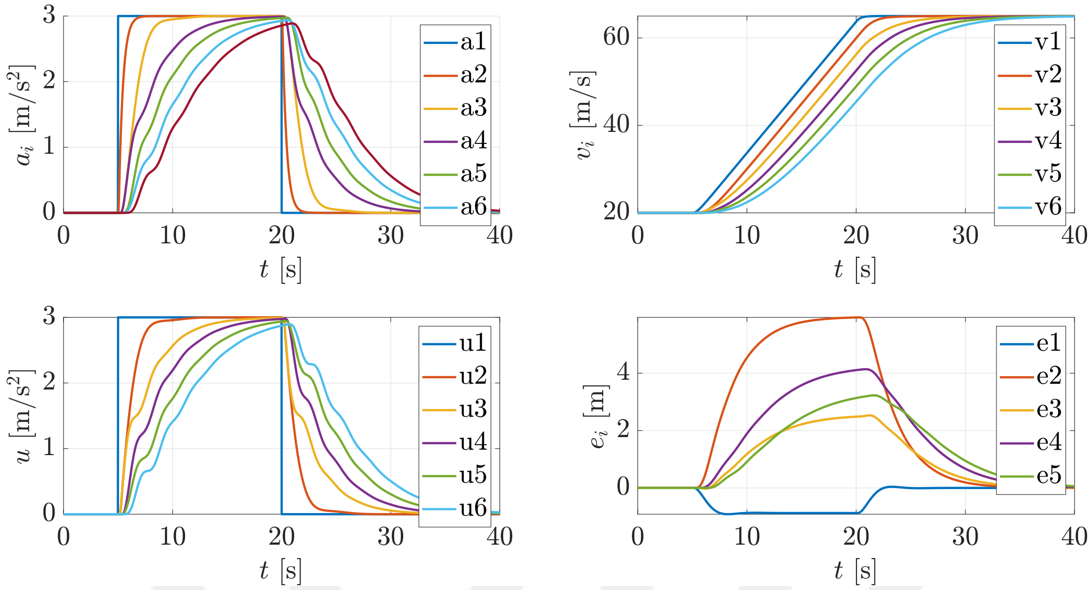

Figure 4.34: Case 3 with actuator and communication delay for 2VLA

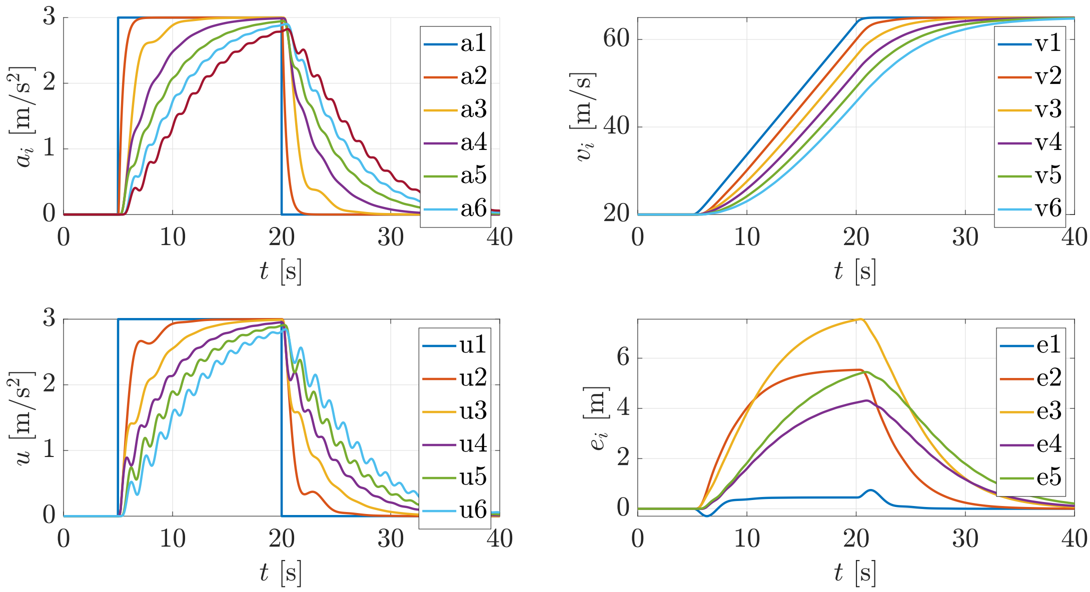

Figure 4.35: Case 3 with actuator and communication delay for 3VLA

4.4.3 Case 4

We finally use $\tau_i = 0.1$ for all vehicles and apply the same step input as before. The controller parameters for the different methods in this case are as follows:

- IF: $K_P = 0.1$, $K_D = 3$, $h = 1.2$,
- AF: $\omega_K = 3.5$; $h = 0.65$,
- 1VLA: $k_a = 0.75$, $k_p = 0.01$, $k_v = 0.2$, $h = 1.4$,
- 2VLA: $k_a = 0.12$, $k_p = 1$, $k_v = 1.1$, $h = 1.4$,
- 3VLA: $k_a = 0.2$, $k_p = 0.8$, $k_v = 1$, $h = 1.4$,

Here, it interesting to note that the smallest headway time is found for AF, which also leads to the smallest distance errors in Figure 4.36 to 4.40. Again, the distance errors for 1VLA, 2VLA and 3VLA are not suitable for practical applications.

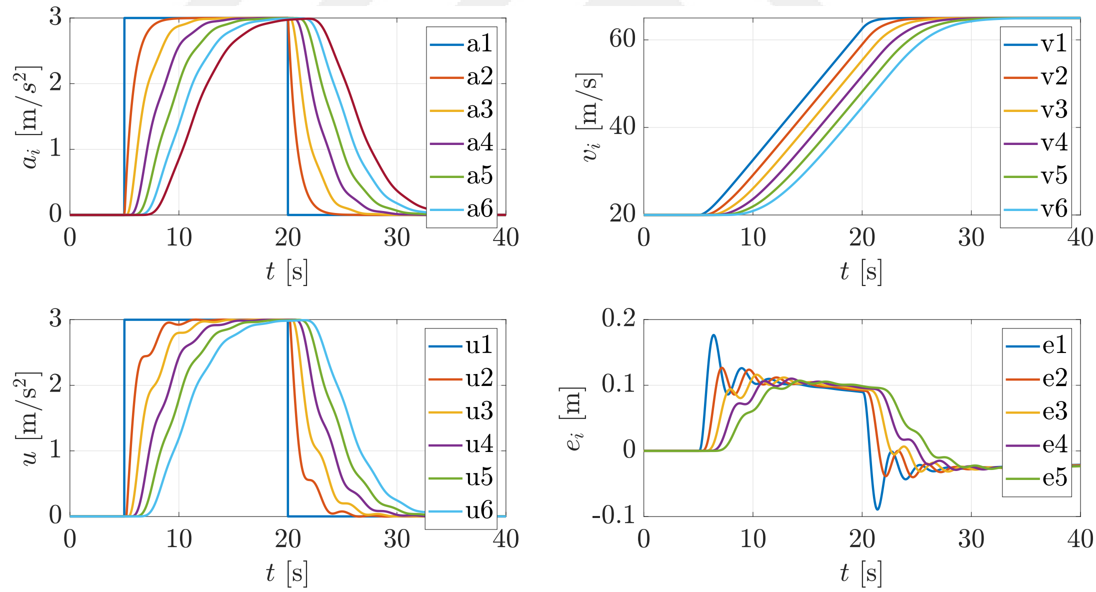

Figure 4.36: Case 4 with actuator and communication delay for IF

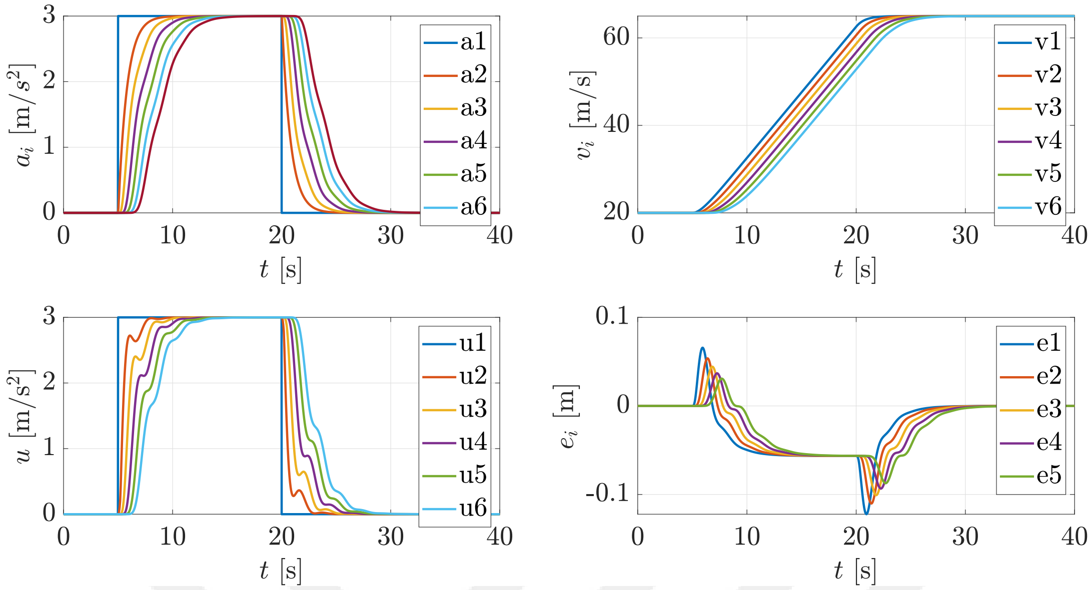

Figure 4.37: Case 4 with actuator and communication delay for AF

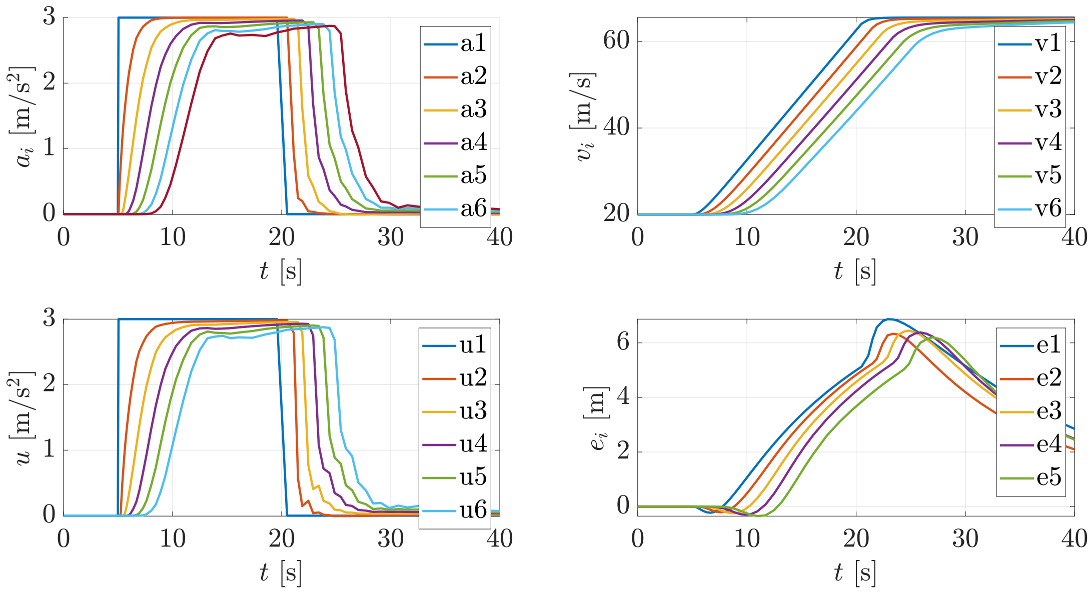

Figure 4.38: Case 4 with actuator and communication delay for 1VLA

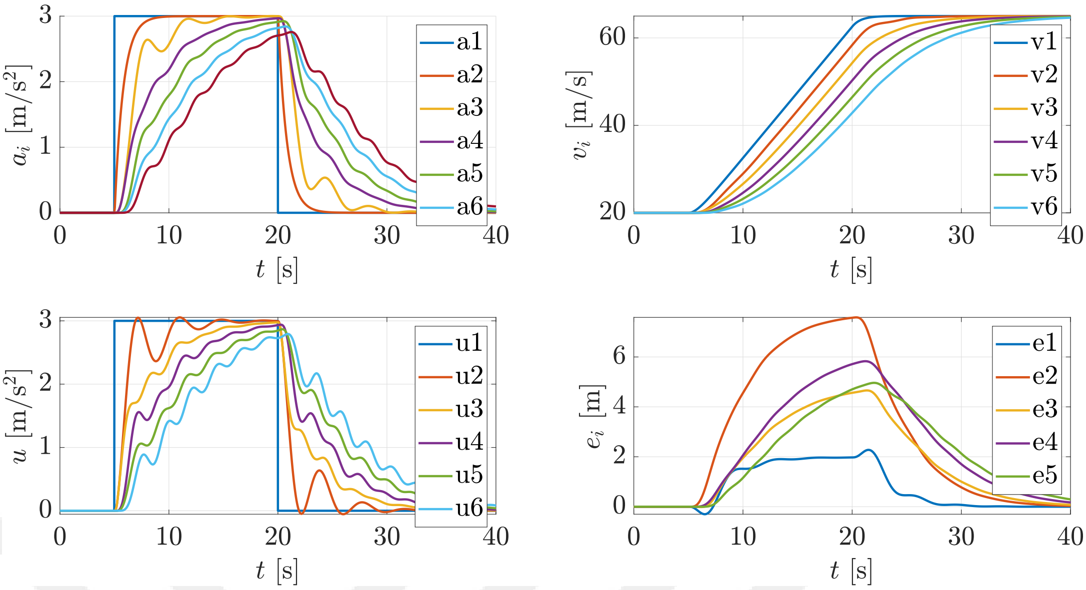

Figure 4.39: Case 4 with actuator and communication delay for 2VLA

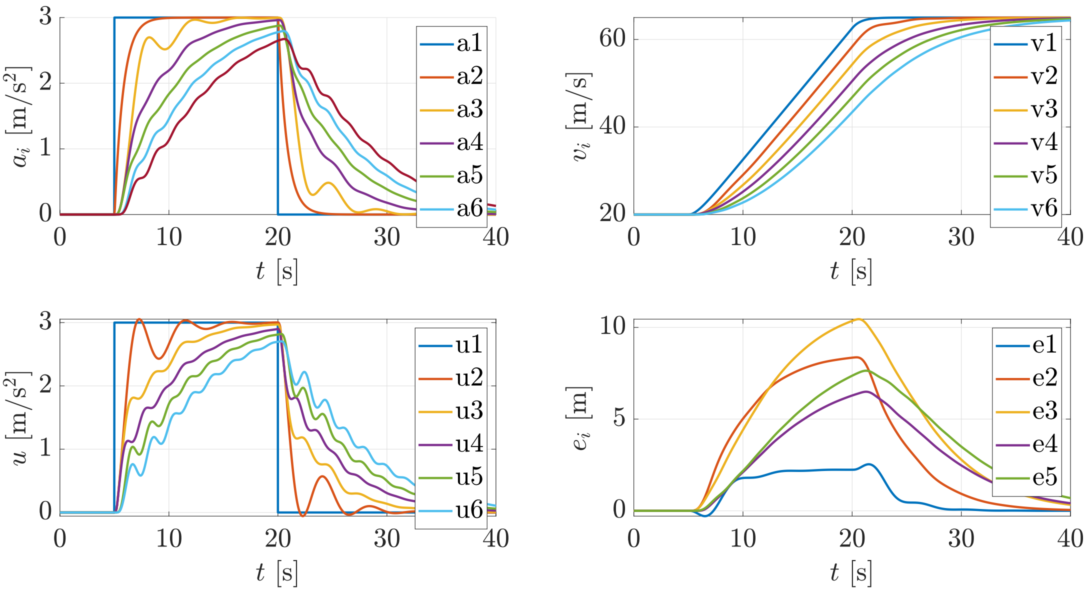

Figure 4.40: Case4 with actuator and communication delay for 3VLA

4.4.4 Comparison Tables

In summary, the following important points have to be highlighted for the case with actuator and communication delays:

- Very large headway times are required in order to achieve string stability for the methods in [7] (1VLA, 2VLA, 3VLA),
- Very large distance errors are observed for the methods in [7]
- Both IF and AF lead to satisfactory results regarding headway time and distance errors,
- AF outperforms the other methods especially for larger driveline time constants.

The same observations can as well be made in Table 4.8 to 4.10.

Table 4.8: Maximum error with actuator and communication delay

	Case 2				
	$\|\|e_1\|\|_\infty$	$\|\|e_2\|\|_\infty$	$\|\|e_3\|\|_\infty$	$\|\|e_4\|\|_\infty$	$\|\|e_5\|\|_\infty$
IF	0.031	0.021	0.016	0.014	0.012
AF	0.031	0.023	0.019	0.016	0.014
1VLA	4.49	4.40	4.31	4.23	4.14
2VLA	0.4	9.8	4.6	6.9	5.6
3VLA	1.26	33.2	30.7	19.4	25.7
	Case 3				
	$\|\|e_1\|\|_\infty$	$\|\|e_2\|\|_\infty$	$\|\|e_3\|\|_\infty$	$\|\|e_4\|\|_\infty$	$\|\|e_5\|\|_\infty$
IF	0.35	0.33	0.32	0.30	0.29
AF	0.10	0.10	0.10	0.10	0.10
1VLA	0.9	0.9	0.9	0.9	0.9
2VLA	0.92	5.94	2.53	4.14	3.22
3VLA	0.74	5.54	7.56	4.31	5.44
	Case 4				
	$\|\|e_1\|\|_\infty$	$\|\|e_2\|\|_\infty$	$\|\|e_3\|\|_\infty$	$\|\|e_4\|\|_\infty$	$\|\|e_5\|\|_\infty$
IF	0.18	0.13	0.12	0.11	0.11
AF	0.12	0.11	0.10	0.09	0.08
1VLA	6.87	6.33	6.44	6.38	6.20
2VLA	2.27	7.59	4.66	5.83	4.96
3VLA	2.54	8.37	10.45	6.59	7.64

Table 4.9: 2-norm of the error with actuator and communication delay

	Case 2				
	$\|\|e_1\|\|_2$	$\|\|e_2\|\|_2$	$\|\|e_3\|\|_2$	$\|\|e_4\|\|_2$	$\|\|e_5\|\|_2$
IF	1.51	1.27	1.15	1.07	1.01
AF	1.51	1.31	1.21	1.13	1.08
1VLA	34.7	34.3	33.8	33.2	32.6
2VLA	44.0	1070	488	741	589
3VLA	140	4004	3804	2442	3263
	Case 3				
	$\|\|e_1\|\|_2$	$\|\|e_2\|\|_2$	$\|\|e_3\|\|_2$	$\|\|e_4\|\|_2$	$\|\|e_5\|\|_2$
IF	21.5	20.8	20.2	19.7	19.3
AF	16.6	16.5	16.4	16.3	16.2
1VLA	5.0	4.7	4.7	4.6	4.6
2VLA	105.1	662.4	270.7	443.9	344.6
3VLA	56.9	610.5	807.5	459.5	585.9
	Case 4				
	$\|\|e_1\|\|_2$	$\|\|e_2\|\|_2$	$\|\|e_3\|\|_2$	$\|\|e_4\|\|_2$	$\|\|e_5\|\|_2$
IF	14.0	13.3	12.9	12.6	12.3
AF	10.6	10.3	10.1	9.9	9.8
1VLA	31.5	27.4	28.2	27.5	25.9
2VLA	228.7	819.6	495.5	623.8	535.9
3VLA	259.1	9.2.6	1119	701.4	841.9

Table 4.10: Maximum acceleration with actuator and communication delay

	Case 2					
	$\|\|a_1\|\|_\infty$	$\|\|a_2\|\|_\infty$	$\|\|a_3\|\|_\infty$	$\|\|a_4\|\|_\infty$	$\|\|a_5\|\|_\infty$	$\|\|a_6\|\|_\infty$
IF	3.0	3.0	3.0	3.0	2.99	2.99
AF	3.0	3.0	3.0	3.0	3.0	2.99
1VLA	3.0	2.99	2.98	2.96	2.93	2.90
2VLA	3.0	3.01	2.98	2.96	2.91	2.86
3VLA	3.0	3.0	2.9	2.8	2.7	2.7
	Case 3					
	$\|\|a_1\|\|_\infty$	$\|\|a_2\|\|_\infty$	$\|\|a_3\|\|_\infty$	$\|\|a_4\|\|_\infty$	$\|\|a_5\|\|_\infty$	$\|\|a_6\|\|_\infty$
IF	3.0	2.99	2.99	2.99	2.99	2.99
AF	3.0	3.0	3.0	3.0	3.0	2.99
1VLA	3.0	3.005	3.008	3.009	3.011	3.011
2VLA	3.0	3.0	2.99	2.98	2.94	2.89
3VLA	3.0	2.99	2.99	2,95	2.90	2.82
	Case 4					
	$\|\|a_1\|\|_\infty$	$\|\|a_2\|\|_\infty$	$\|\|a_3\|\|_\infty$	$\|\|a_4\|\|_\infty$	$\|\|a_5\|\|_\infty$	$\|\|a_6\|\|_\infty$
IF	3.0	3.0	3.0	2.99	2.99	2.99
AF	3.0	3.0	3.0	3.0	2.99	2.99
1VLA	3.0	2.98	2.96	2.92	2.90	2.87
2VLA	3.0	3.001	2.97	2.92	2.84	2.76
3VLA	3.0	3.004	2.9	2.8	2.74	2.66

CHAPTER 5

CONCLUSION

Cooperative Adaptive Cruise Control (CACC) is a technique for automating the longitudinal vehicle motion based on distance measurements and communicated state information from predecessor vehicles. The main aim of CACC is to achieve safe and comfortable vehicle following at small inter-vehicle distances in vehicle strings. An important condition to be fulfilled for this purpose is string stability, which ensures that attenuation of disturbances along a vehicle string. When designing controllers for string stability, it is required to select a signal such as the vehicle acceleration or distance error with respect to which string stability should be fulfilled.

The main focus of the thesis is the question about which of these signals is most suitable for fulfilling string stability in practice. To this end, the thesis compares different methods from the existing literature regarding their suitability for the realization of CACC in practice. As the main outcome, it is shown that, although methods that are based on the error signal are functional in case of ideal conditions such as negligible delays, they are clearly outperformed by methods that use the acceleration signals in realistic scenarios with both actuator and communication delays. To emphasize, it is shown on the Section 4.2 that Input Feedforward (IF) and Acceleration Feedforward (AF) methods, which are based on acceleration based string stability definitions enable smaller headway times. This is especially important since smaller inter-vehicle distances enables higher traffic throughput. It is also shown that error magnitudes are generally smaller for both of these acceleration based methods compared to r vehicle look ahead controllers (RVLA) that are based on string stability condition using distance error signals. Furthermore, it is observed that errors increase as we increase look ahead controllers from 1VLA to 3VLA. As discussed, this is due to the fact that using 2VLA and 3VLA controllers are used on the second and third vehicles which only have 1 and 2 vehicles they can look ahead respectively. It is also shown that IF and AF enable faster converging distance errors. Thus, the point at which vehicles do not receive any disturbance is closer to the leading vehicle for IF and AF methods. Although all the methods have shown satisfactory results for a CACC implementation, it can be concluded that IF performed best with the cases without actuation and communication delays in Section 4.2. When the realistic scenarios with delays are considered in Section 4.4, the control methods using string stability using acceleration signals outperform control methods with error based string stability definitions. In the Section 4.4, it is shown that very large headway times are required to achieve string stability for RVLA methods. Moreover, RVLA controllers also showed very large distance errors. In contrast, IF and AF methods have both shown satisfactory result regarding headway times and distance errors. Overall, AF method has been shown to outperform other methods especially for larger driveline time constants which correspond to slower driveline dynamics. To sum up, it is shown that, although methods that are based on the error signal are functional in case of ideal conditions such as negligible delays, they are clearly outperformed by methods that use the acceleration signals in realistic scenarios with both actuator and communication delays.

One possible direction for future work is the development of control methods for string stability based on the distance error signal that are robust to actuator and communication delays.

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