PLATOONING OF VEHICLES IN INTELLIGENT TRANSPORTATION SYSTEMS

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PLATOONING OF VEHICLES IN INTELLIGENT TRANSPORTATION SYSTEMS

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Submitted by **INAS BAHAA DEAIBIL**

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ABSTRACT

PLATOONING OF VEHICLES IN INTELLIGENT TRANSPORTATION SYSTEMS

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Intelligent transportation systems aim at improving the efficiency and safety of transportation. In dense traffic, vehicles are aggregated to vehicle strings that travel on thesame lane, whereby it is desired to maintain a small but safe distance between the vehicles. In the literature, this task is captured by the notion of string stability: fluctuations thatare introduced by maneuvers of the leader vehicle should be attenuated by the follower vehicles. The literature provides various methods for achieving string stability underthe assumption that a vehicle string is already formed and remains unchanged. Nevertheless, in practice, it is necessary to account for vehicles entering or leaving a platoon when performing lane changes.

The subject of this thesis is the realization of longitudinal maneuvers for safe and efficient lane changes in dense vehicle traffic. Hereby, the tasks of tight vehicle following for a high traffic throughput and opening gaps for vehicles that want to enter a string have to be considered. Both tasks have to be achieved under the requirement of safety and without a negative effect on the traffic throughput. To this end, it is proposed a control architecture that addresses the stated issues. It combines the idea of cooperative adaptive cruise control (CACC) for safe vehicle following with feedforward control for opening or closing gaps that are generated if vehicles enter or leave a string. We first show that gaps can be opened/closed safely and smoothly with our method. That is, if string stability is obtained by the CACC design, it is preserved when using our feedforward control. Second, we propose a method to schedule maneuvers of different vehicles for opening gaps at a high traffic throughput. To the best of our knowledge this is the first work on the control and scheduling of safe and efficient lane changes.

Keywords: Intelligent Transportation Systems, Cooperative Adaptive Cruise Control, String Stability, Lane Changes, Feedforward Control.

ÖZ

AKILLI ULAŞIM SİSTEMLERİNDE ARAÇLARIN TAKIMLANDIRILMASI

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Tez Yöneticisi: Doç Dr. Klaus Werner SCHMIDT
Mayıs 2015, 35 sayfa

Akıllı ulaştırma sistemlerinin amacı ulaştırmanın etkinliğinin ve emniyetinin iyileştirilmesidir. Yoğun trafikte araçlar diziler halinde aynı kulvarda ilerlerken araçların arasında küçük ancak emniyetli bir mesafe muhafaza edilmesi istenmektedir. Literatürde bu görev dizi istikrarı fikri ile yakalanmaktadır: lider araç tarafından yapılan manevralarla geliştirilen dalgalanmalar, takip eden araçlar tarafındanda takip edilmektedir. Literatürde araç dizisinin oluşturduğu ve değiştirilmeden muhafaza edileceği varsayımı iledizi istikrarının gerçekleştirilmesi için değişik yöntemler verilmektedir. Bununla birlikte, pratikte şerit değişikliği yaparken takımdan ayrılan veya takıma giren araçların açıklanması gerekmektedir.

Bu tezin konusu, yoğun araç trafiğinde şerit değişiklikleri için yapılan manevraların güvenli ve verimli bir şekilde gerçekleştirilmesidir. Böylelikle trafiğin yoğun olduğu durumlarda sıkı araç takibi ve diziye giriş yapmak isteyen araçlar için boşlukların yaratılması gibi görevlerin dikkate alınması gerekmektedir. Her iki görevin emniyet gereksinimlerini ve trafik akışını olumsuz bir şekilde etkilenmeden gerçekleşmesi gerekmektedir. Bunun için söz konusu unsurları ele alan bir kontrol yapısını önerilmektedır. Bu yapı, araçların diziye girmesi veya çıkması ile oluşturulan boşlukların açılması veya kapanması için ileriye dönük kontrol ile emniyet araç takibine yönelik uyarlanabilir seyir kontrolü (CACC) işbirliği fikrini birleştirmektedir. Öncelikle, sistemde emniyetli ve düzenli olarak açılabilen/kapatılabilen boşlukları gösterilmektedır. Bu sayede dizi istikrarı, CACC tasarımı ile elde edilen dizi kararlılığı ileri beslemeli kontrolün kullanılması ile muhafaza edilmektedir. İkinci bir husus olarak da yoğun trafik akışında boşluk açılması için farklı araçlar için manevra programı yöntemini önerilmektedır. Bu çalışma emniyetli ve etkin şerit değiştirmesi ile ilgili ilk kontrol ve programlama çalışmalarından biridir.

Anahtar Kelimeler: Akıllı Ulaştırma Sistemleri, İşbirlikçi Uyarlanabilen Seyir Kontrolü, Dizi İstikrarı, Şerit Değiştirmeleri, İleri Beslemeli Kontrol.

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ITS	Intelligent Transportation Systems
CACC	Cooperative Adaptive Cruise Control
ACC	Adaptive Cruise Control
V2V	Vehicle to Vehicle
V_i	Velocity of Vehicle i
d_i	Actual Inter-Vehicle Distance of Vehicle i
$d_{r,i}$	Desired Inter-Vehicle Distance of Vehicle i
r_i	Standstill Distance of Vehicle i
h	Time Headway
e_i	Spacing Error of Vehicle i
q_i	Rear Bumper Position of Vehicle i
L_i	Length of Vehicle i
G	Plant of Vehicle
θ	Communication Delay
ϕ	Possible Plant Delay
Γi	Complementary Sensitivity of Vehicle i
τ	Time Constant
H(s)	Spacing Policy
K_{fb}	Feedback Controller
K_{ff}	Feedforward Controller
Y_d	Desired Output Function
U_i^{ff}	Additional Exogenous Input from Feedforward Control
Δt	Difference Time Between the Maneuvers for Opening the Gap
t_{gap}	Time of Open the Gap

CHAPTER 1

INTRODUCTION

The demand for mobility in modern traffic leads to an ever-increasing traffic volume with a considerable negative impact on economy, human health and environment [1-2]. Congestion and traffic breakdown cause increased travel times, fuel consumption and emissions [3]. In addition, accidents cause a large number of fatalities and injuries [4]. Intelligent transportation systems (ITS) incorporate information, communication and control technologies into the transportation infrastructure in order to improve traffic efficiency and safety [5-6]. To this end, ITS make use of vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communication which are the basis for enabling cooperation between vehicles [7-8].

In dense traffic, vehicles do not travel independently but form *vehicle strings* [3]. Hence, an important task of ITS is to realize safe vehicle following at small inter-vehicle spacing in order to increase the traffic capacity and traffic throughput [3-9]. A promising method to achieve this task is the recently introduced Cooperative Adaptive Cruise Control (CACC) [8-10-11-12]. CACC extends adaptive cruise control (ACC) by V2V communication in order to obtain relevant signal data such as velocity and acceleration of predecessor vehicle(s) to improve vehicle following. One important objective of CACC is to guarantee driving safety by ensuring the property of *string stability*. If string stability holds, fluctuations such as velocity or acceleration changes of a vehicle are attenuated by the following vehicles, hence avoiding oscillations in the vehicle motion. The literature proposes several methods for the CACC controller design in order to achieve string stability [11-13]and it is concluded that CACC has a positive impact on string stability and the usage of CACC enables a traffic capacity increase [4-14-15].

It has to be noted that string stability is a desirable condition that aims at safe driving. Nevertheless, achieving string stability is not sufficient for obtaining a high traffic throughput in dense traffic [16-17]. In particular, it is possible that disturbances in the traffic flow are introduced for example by vehicles entering or leaving vehicle strings. Such disturbances generally have a negative effect on the traffic flow and can even lead to traffic breakdown. Accordingly, traffic breakdowns because of such disturbances must be avoided. This property is captured by the notion of *traffic flow stability* in the literature [18-19-20].

In relation to traffic flow stability, CACC has limitations since it is designed for the vehicle following on a single lane [9-13]. That is, maneuvers such as vehicles joining or leaving a lane are not supported by CACC and have to be considered as disturbances with a negative impact on traffic flow stability. Although improvements of CACC such as opening gaps for joining vehicles , no such improvements are considered in current CACC designs.

This thesis develops a new method for the realization of safe lane changes in vehicle strings based on the observation that a safe lane change requires opening gaps for vehicles that intend to enter a vehicle string or closing gaps after a vehicle leaves a vehicle string. As the first contribution of this thesis, we propose a control architecture for the longitudinal motion of vehicles in a string. This control architecture extends the existing CACC design in [21] by an additional feedforward input signal. Applying this input signal, a gap can be opened or closed smoothly if required. Since this input signal is used together with the CACC design for vehicle following, the important property of string stability is preserved. This result is supported by several simulation experiments in the thesis. As the second contribution of the thesis, we study the effect of opening gaps on the traffic flow. Analyzing different scenarios for opening multiple gaps in a vehicle string simultaneously, it is concluded that gaps should not be opened at the same time in order to avoid traffic breakdown. Hence, we propose a method to schedule the timing of maneuvers for opening gaps while keeping the traffic throughput high. To the best of our knowledge, this is the first method for the feedforward design for opening gaps and the scheduling of lane change maneuvers.

The organization of the thesis is as follows. Chapter 2 gives background information about vehicle following, adaptive cruise control, cooperative adaptive cruise control and string stability. Our control architecture for opening/closing gaps is presented in Chapter 3 and illustrated by simulation experiments in Chapter 4. In particular, Section 4.3 evaluates the effect of lane changes on the traffic flow and determines a policy for scheduling lane changes. Conclusion and ideas for future work are given in Chapter 5.

CHAPTER 2

BACKGROUND

This section provides the background on the topic of cooperative adaptive cruise control (CACC) which is the main subject of this thesis. Section 2.1 describes the concept of vehicle following and Section 2.3 explains the functionality of adaptive cruise control (ACC). CACC is introduced in Section 2.4 and two feedback control methods for CACC are outlined in Section 2.5.

2.1 Vehicle Following

The new approach of cooperative adaptive cruise control (CACC) is used for implementing vehicle following in so-called *vehicle strings* at small inter-vehicle spacings as shown in Fig. 1. In this schematic, L_i, q_i, v_i denote the length, rear bumper position and velocity of vehicle i, respectively; d_i is the gap between vehicle $i-1$ and vehicle i. Using CACC, d_i is obtained from sensor measurements (RADAR or LIDAR) by vehicle i. Additionally, signals such as the acceleration or velocity of other vehicles are received by each vehicle i via wireless vehicle-to-vehicle (V2V) communication. According to Fig. 1, the distance d_i between vehicles i and vehicle $i-1$ is evaluated as

$$d_i(t) = q_{i-1}(t) - q_i(t) - L_i. \tag{2.1}$$

When considering vehicle following, the desired distance between vehicles is denoted as the *spacing policy*. In the recent literature, the *constant headway time policy* [8-21-22-23-24] as shown in (2.2) is used.

$$d_{i,r} = r + hv_i. \tag{2.2}$$

Here, $d_{i,r}$ represents the desired spacing between vehicle $i-1$ and vehicle i. It is com-

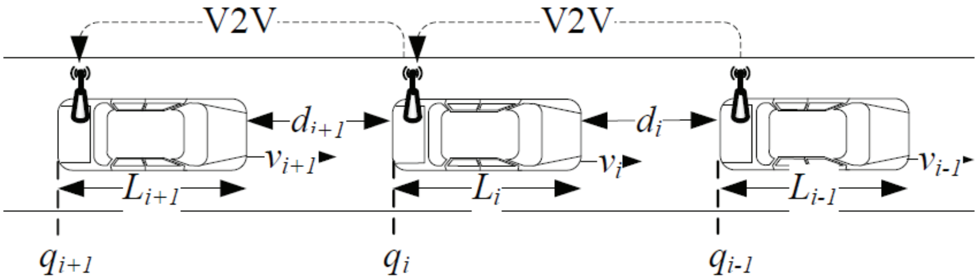

Figure 1: Vehicle string with CACC.

puted from the *distance at standstill* r_i and the *headway time* h. That is, at zero velocity, the desired distance is r_i and $d_{i,r}$ increases proportional to v_i.

Using (2.1) and (2.2), the spacing error $e_i(t)$ is

$$e_i(t) = d_i(t) - d_{i,r}(t) = (q_{i-1}(t) - q_i(t) - L_i) - (r_i + hv_i(t)), \tag{2.3}$$

2.2 String Stability

In order to realize safe and comfortable following, vehicle following must be realized such that disturbances are attenuated along a vehicle string as depicted in Fig. 1. That is, a small variation in the speed or acceleration of any vehicle i should not lead to increasing variations in the motion of its follower vehicles.

This condition is captured by the notion of *strict string stability* in the literature [8-13-21]. Assuming a linear system representation with the transfer function

$$\Gamma_i(s) = \frac{V_i(s)}{V_{i-1}(s)}. \tag{2.4}$$

between the velocities v_{i-1} and v_i, strict string stability is achieved if for all vehicles i

$$||\Gamma_i(s)||_\infty \leq 1. \tag{2.5}$$

Hereby, $V_i(s)$ denotes the Laplace transform of the signal $V_i(t)$ and $|| \bullet ||_\infty$ denotes the H_∞-norm. Hence, each controller design for vehicle following should ensure (2.5).

In order to illustrate the notion of string stability, we present two example simulations. Strict string stability is fulfilled in Fig. 2. In this simulation, the leader vehicle 1 first accelerates with up to $4\,\mathrm{m/s^2}$ and then decelerates with up to $-4\,\mathrm{m/s^2}$ (right-hand

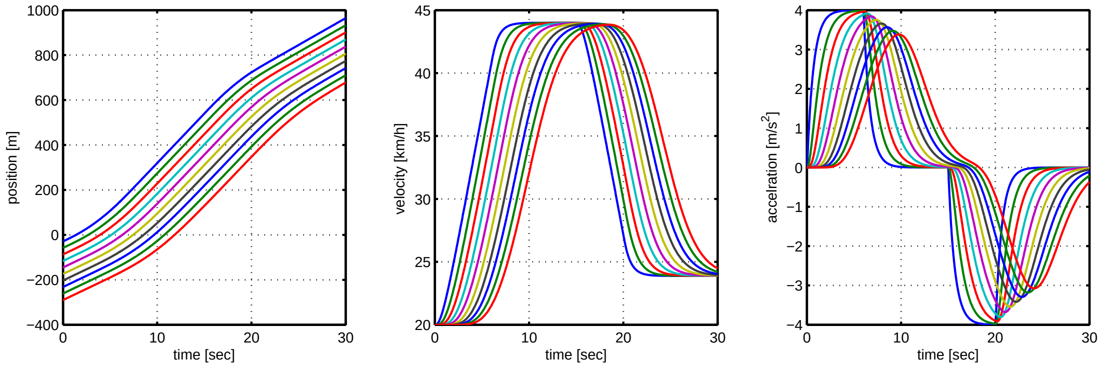

Figure 2: Vehicle string with 10 vehicles performing an acceleration/deceleration maneuver and CACC design that fulfills strict string stability. Each line represents the motion of one vehicle.

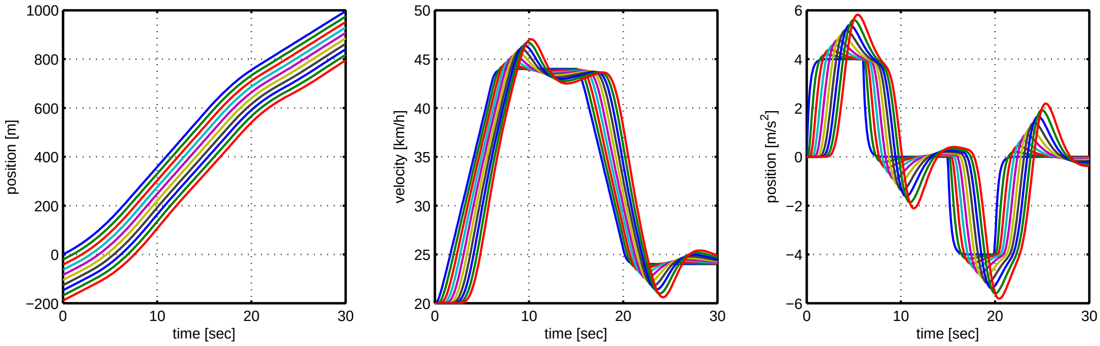

Figure 3: Vehicle string with 10 vehicles performing an acceleration/deceleration maneuver and CACC design that violates strict string stability.

plot). The follower vehicles perform the same motion with a decreased (attenuated) acceleration/deceleration. Similarly, the velocity variation (center plot) is attenuated along the vehicle string. In addition, the position plot (left-hand side) indicates that the vehicles follow each other at a safe distance. In contrast, string stability is violated in the scenario of Fig. 3. Performing the same maneuver of the leader vehicle 1, it now holds that the acceleration and velocity of the follower vehicles is amplified which is clearly undesirable.

2.3 Adaptive Cruise Control (ACC)

The first automated system for vehicle following has been realized in the form of adaptive cruise control (ACC) by several car manufacturers such as Nissan, Volkswagen, BMW, etc. ACC is based on velocity measurements and radar measurements in order to detect directly preceding vehicles and to determine the distance to directly preceding vehicles. Then, the functionality of ACC is as follows: if there is no preceding vehicle at a close distance, ACC keeps the vehicle at a constant speed that is set by the driver; if a vehicle is detected at a close distance, ACC realizes vehicle following according to the spacing policy in (2.2) [25].

The advantage of ACC is the requirements of only local measurements of each vehicle. Nevertheless, ACC has several disadvantages. First, an ACC system does not have information about vehicles that are not in the line of sight. Second, it is shown that the lags observed in a vehicle string with multiple vehicles lead to increasing spacing errors and velocity variations for vehicles at the back of the string, potentially violating the requirement of string stability. For example, in a string with three vehicles as shown in Fig. 4, a braking action of the first vehicle leads to stronger braking of the second and even stronger braking of the third vehicle. Third, in an ACC design, asymptotic stability (convergence to zero spacing errors) can only be achieved for large enough values of the headway time h around 2 s [21]. That is, close following of vehicles as required in dense traffic cannot be achieved using ACC.

Figure 4: Vehicle following using ACC.

2.4 Cooperative Adaptive Cruise Control (CACC)

Cooperative adaptive cruise control (CACC) addresses the stated disadvantages of ACC. It extends the local measurements of ACC by vehicle-to-vehicle (V2V) communication. For example, relevant information such as acceleration or engine input signals are transmitted by the preceding vehicle using wireless communication [8-21-22-23-26-27-28-29-30].

Figure 5: Vehicle platoon using (CACC)

Fig. 6 shows a block diagram of the frequently considered cas of CACC with single-vehicle lookahead.

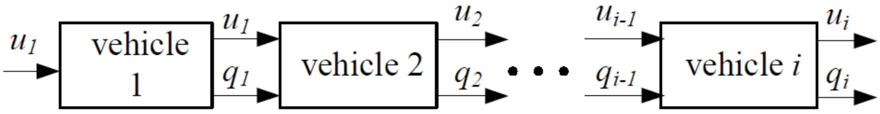

Figure 6: Vehicles with CACC in a string.

The first vehicle of a string is controlled by the exogenous input signal u_1, whereas all the other vehicles obtain the position (sensor measurement) and input signal (wireless communication) of the directly preceding vehicle. Most importantly, the additional communicated input signal aids in achieving string stability at a smaller headway time [21].

2.5 Controller Design for CACC and Simulation

In this section, we outline two controller design methods for CACC that are representative for the one vehicle lookahead policy as described before. Hereby, we consider the case of *homogeneous strings*, where all vehicles have the same dynamic properties [8-21] and model each vehicle by the plant transfer function in (2.6).

$$G(s) = \frac{e^{-\Phi s}}{(1+s\tau)s^2} = \frac{Q_i(s)}{U_i(s)}. \tag{2.6}$$

Φ is a possible plant delay and τ is the time constant of the low-level drive line dynamics and the double integration obtains the vehicle position from the acceleration.

2.5.1 Control Design for CACC Case1

Fig. 7 shows the block diagram of the CACC realization for one vehicle as used in [23]. Here, K is the controller transfer function whose input signal is the position error $q_{-i-1} - q_i - L_i - r_i - h v_i$. Hereby, the term $q_i + h v_i$ is obtained from the spacing policy transfer function $H(s)$ that is equal to

$$H(s) = hs + 1. \tag{2.7}$$

In order to maintain the open-loop transfer function KG, the additional precompensator $\frac{1}{H(s)}$ is introduced. Finally, the input signal u_{i-1} from the predecessor vehicle is obtained as an additional feedforward signal with a potential delay $D(s) = e^{-\theta s}$. In [23], K is realized as a state-feedback controller

$$K \begin{bmatrix} e_i \\ \dot{e}_i \\ \ddot{e}_i \end{bmatrix} = \begin{bmatrix} k_p & k_d & k_{dd} \end{bmatrix} \begin{bmatrix} e_i \\ \dot{e}_i \\ \ddot{e}_i \end{bmatrix}, \tag{2.8}$$

where the error e_i and its derivatives are used as states.

Since the subject of this thesis is not the feedback controller design, we do not repeat the controller design steps but rather show an example implementation for the chosen plant parameters $\tau = 0.1$, $\Phi = 0.2$ and $\theta = 0.15$. The resulting controller parameters are k_p=0.2, k_d=0.7 and k_{dd}=0.

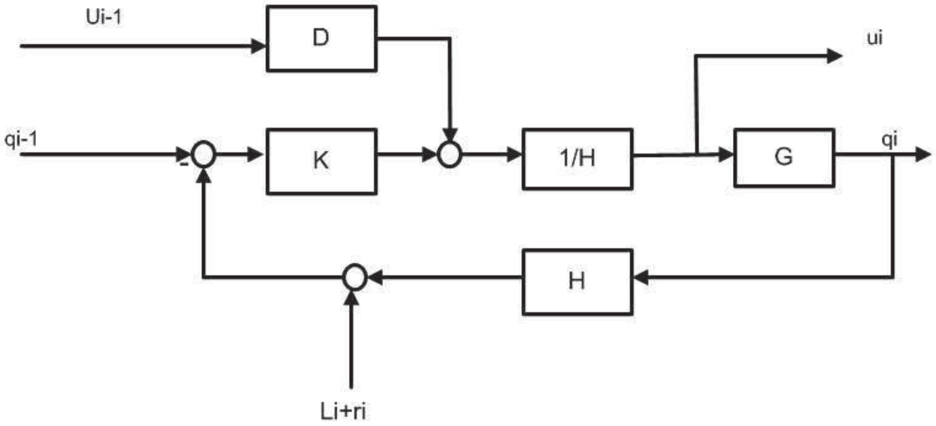

Figure 7: Block diagram case1

The CACC design in [23] is stable for values of 0.7 s of the headway distance. This can be seen in the simulation in Fig. 8. Both the velocity and acceleration variations are attenuated along a vehicle string with 10 vehicles. In this simulation, the leader vehicle receives an input step to 4 $\mathrm{m/s^2}$ at time 0, to $-4\,\mathrm{m/s^2}$ at time 4 s and to 0 $\mathrm{m/s^2}$ at time 8 s. It can be seen that the follower vehicles keep a safe distance to the leader vehicle.

Differently, if the headway is chosen too small, string stability is not preserved in this CACC design. For example, Fig. 9 shows the case of $h = 0.3$ s. Here, the system is not string stable. This can be seen by the increasing velocity and acceleration variations to the same input signal of the leader vehicle.

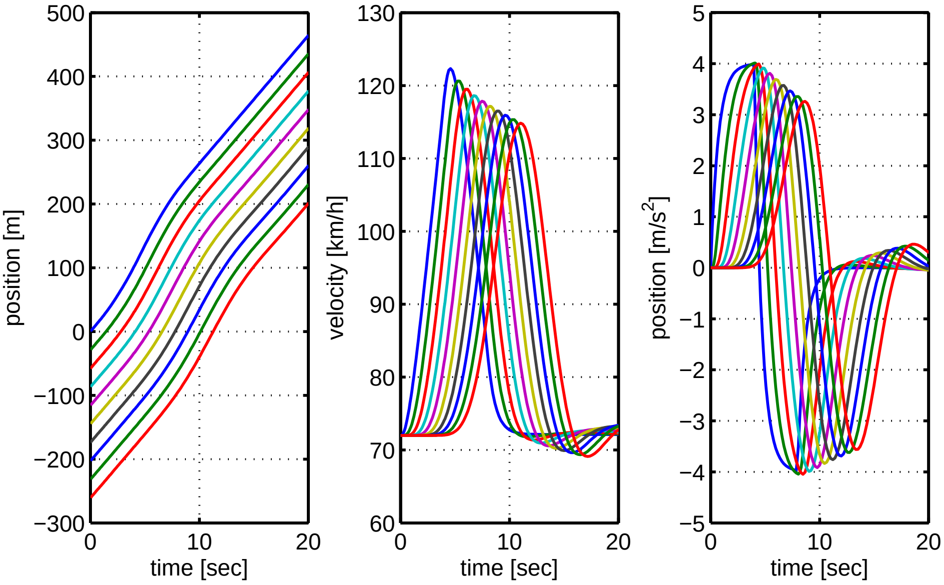

Figure 8: Behavior of ten vehicles for $h = 0.7$ s

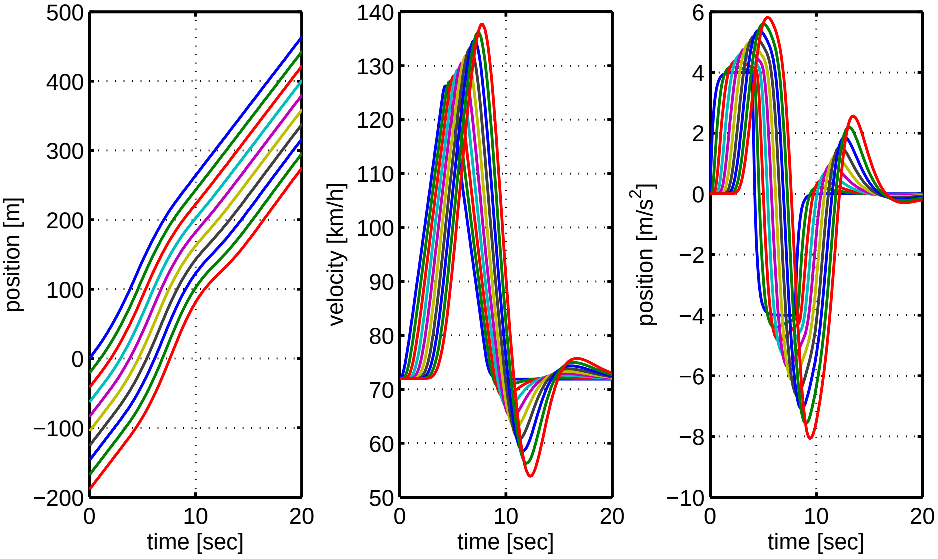

Figure 9: Behavior of ten vehicles for $h = 0.3$ s

2.5.2 Control Design for CACC Case2

Fig. 10 shows the *CACC* configuration for one vehicle look-ahead as used in [21].

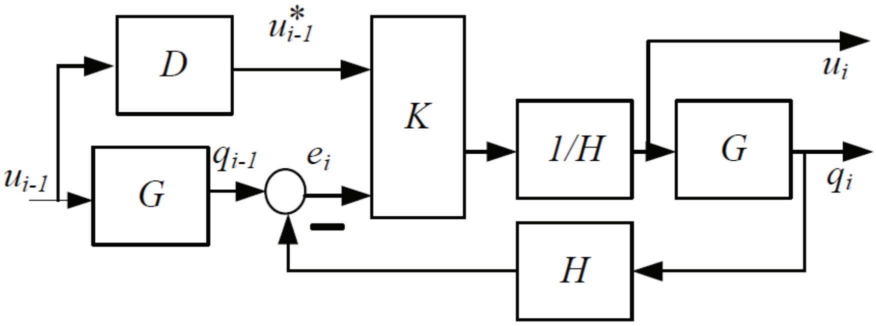

Figure 10: Block diagram for CACC

The difference of this block diagram to the previously discussed case is that has one feedback controller with the position error input and one feedforward controller using the (delayed) input signal from the predecessor vehicle. The controller transfer function can be written as

$$U_i(s) = \frac{1}{H(s)}(K_{fb}(s)E_i(s) + K_{ff}(s)U^*_{i-1}(s)). \tag{2.9}$$

Here, K_{ff} represents the feedforward controller and K_{fb} represents the feedback controller. Together, the controller transfer matrix is written as

$$K(s) = \begin{bmatrix} K_{fb}(s) & K_{ff}(s) \end{bmatrix} \tag{2.10}$$

In [21], $K(s)$ is determined using H_∞ controller synthesis. Since the feedback controller design is not the subject of this thesis, we refer to [21] for design details.

Again, we show an example implementation for the chosen plant parameters $\tau = 0.1$, $\Phi = 0.2$ and $\theta = 0.15$. The resulting controller transfer functions are

$$K_{fb} = \frac{2.6880(s+23.22)(s+10)(s+1)(s+0.3646)}{(s+24.65)(s+5.926)(s+5.049)(s+0.9947)} \tag{2.11}$$

$$K_{ff} = \frac{1.0391(s+24.1)(s+7.233)(s+4.051)(s+1)}{(s+24.65)(s+5.926)(s+5.049)(s+0.9947)} \tag{2.12}$$

We first shows the simulation of a ten vehicle string with the same input signal as in the previous section for a headway of $h = 0.7\,\text{s}$ in Fig. 11 and $h = 0.3\,\text{s}$ in Fig. 12. This simulation shows that the design in [21] achieves string stability even for the smaller headway of $h = 0.3\,\mathrm{s}$.

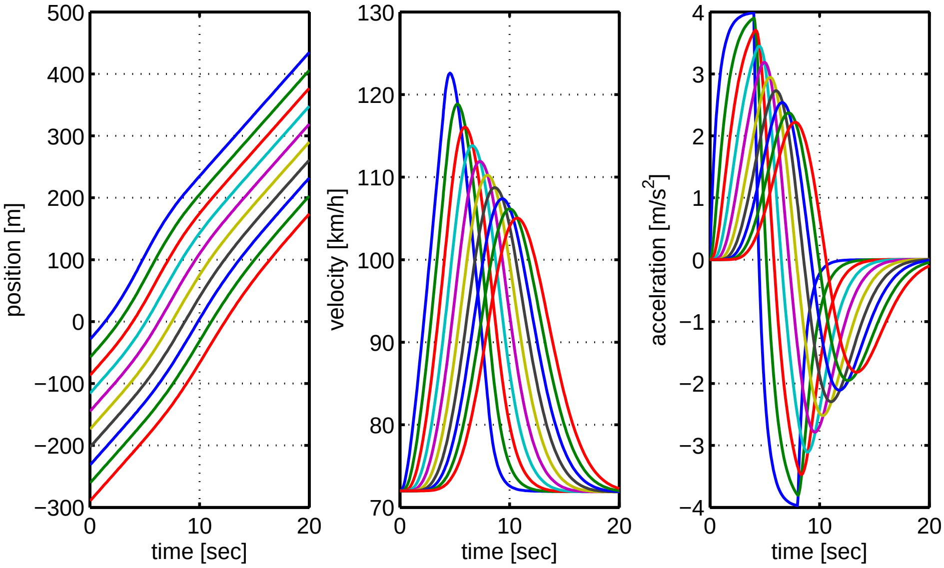

Figure 11: Behavior of ten vehicles for $h = 0.7\,\mathrm{s}$

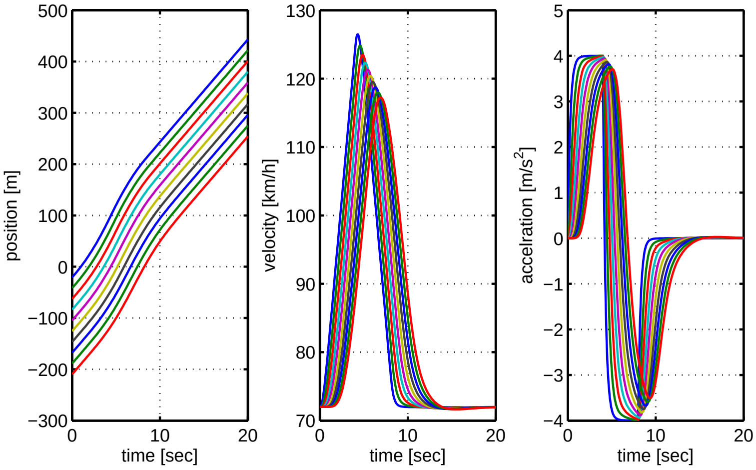

Figure 12: Behavior of ten vehicles for $h = 0.3\,\mathrm{s}$

That is, the design in [21] has the advantage of achieving string stability for smaller values of the headway time. However, the possible disadvantage of this design in practical applications is the higher controller complexity.

CHAPTER 3

MANEUVERS FOR LANE CHANGES

This chapter considers the realization of longitudinal maneuvers that are necessary for lane changes as the first main contribution of this thesis. Section 3.1 outlines the basic requirements of lane change maneuvers and Section 3.2 explains the concept of feedforward controller design. Then Section 3.3 and 3.4 propose a solution to the problem of adding a new vehicle to and removing an existing vehicle from a vehicle string, respectively. The special situation of aborting an already initiated lane change maneuver is addressed in Section 3.5. Finally, Section 3.6 briefly explains the implementation of the required functionality in a Matlab s-function.

3.1 Basic Requirements

The CACC designs in the existing literature are suitable for safe vehicle following in dense traffic as described in Chapter 2. In addition, the achievement of small inter-vehicle spacings allows a higher vehicle density on the road, hence increasing the traffic throughput [3]. Nevertheless, CACC can only be used for existing vehicle strings without any changes. In practice, it is frequently required that vehicles enter/leave a string. This happens for example when merging at an on-ramp or when performing a lane change because of an obstacle (bottleneck) on the road. Such maneuvers require additional space for vehicles that enter a string in order to ensure driving safety.

We illustrate the maneuver of a safe lane change that involves three vehicles in Fig. 13. Before the lane change (left-hand plot), the vehicles 1 and 2 on the target lane perform safe following using CACC. In order to let vehicle 3 safely move in on the target lane, vehicle 2 needs to open a sufficient gap (center plot). After that, vehicle 3 can change the lane, resulting in the modified string in the right-hand plot.

The main task in the longitudinal motion of the described lane change maneuver is

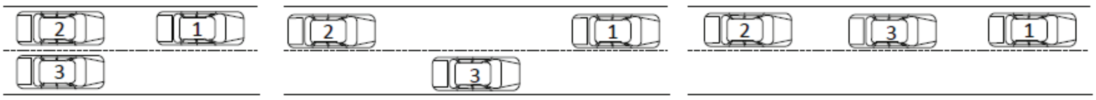

Figure 13: Lane change procedure for adding a vehicle to an existing string.

opening a sufficient gap by vehicle 2. Similarly, the case of removing a vehicle from an existing string as shown in Fig. 14 has to be considered. In this case, the procedure is as follows. Before the lane change (left-hand plot), the vehicles 1,2 and 3 on the target lane perform safe following using CACC. If vehicle 3 leaves the string, a gap appears between vehicle 1 and 2 (center plot). After that, vehicle 2 has to close the gap resulting in the modified string in the right-hand plot.

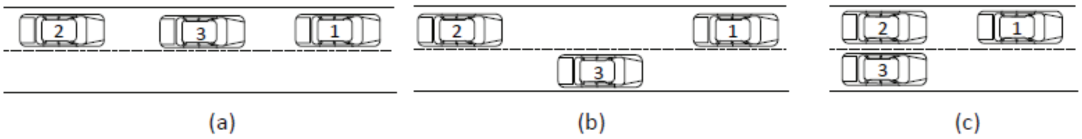

Figure 14: Lane change procedure for removing a vehicle from an existing string.

In summary, lane change maneuvers in dense traffic require longitudinal maneuvers for opening or closing gaps on the target lane. Hereby, it is important that the property of string stability that is achieved for vehicle following is not violated due to the additional longitudinal motion of the lane change maneuver. The main subject of the remainder of this chapter is the design of feedforward control laws in order to open/close gaps on the target lane while retaining the desired string stable vehicle following behavior. This is the first study on this topic in the existing literature.

3.2 Feedforward Control

The main idea in this chapter is the usage of feedforward control in order to determine an input signal u_i for vehicle i in order to smoothly open or close a gap to its preceding vehicle $i-1$. To this end, we first describe the basic concept of the feedforward controller design method used in this thesis. In particular, the method is based on the block diagram in Fig. 15 with the plant transfer function $G(s)$, the input signal u and the output signal y.

We assume that a desired output function y_d is given and we want to compute the

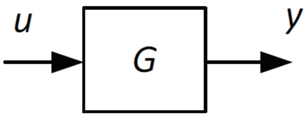

Figure 15: Feedforward block diagram.

required input signal u_d in order to achieve y_d. We consider

$$G(s) = \frac{Y(s)}{U(s)} = \frac{K}{A(s)} \tag{3.1}$$

with the denominator polynomial

$$A(s) = a_n s^n + a_{n-1} s^{n-1} + ... + a_0 \tag{3.2}$$

and the numerator K. n is the order of the transfer function.

Transforming (3.1) to the time domain, we obtain

$$K u = a_n y^{(n)} + a_{n-1} y^{(n-1)} + \cdots + a_0 y. \tag{3.3}$$

That is, knowing the output signal $y(t) = y_d(t)$, the input signal can directly be computed using y_d and n of its time derivatives. In this thesis, we represent y_d by a continuous function

$$y_d(t) = \begin{cases} y_0 & \text{for } t < 0 \\ f(t) & \text{for } 0 \leq t \leq t_f \\ y_f & \text{otherwise} \end{cases} \tag{3.4}$$

with a polynomial function $f(t)$. That is, y_d is constant until time 0, changes to the value of y_f within the time interval from 0 to t_f and remains y_f afterwards. Considering that $G(s)$ has degree n, n time derivatives of y_d have to be 0 at time 0 and at time t_f. This implies that a polynomial f of degree $l = 2n + 1$ has to be chosen [31]. Hence, we use

$$f(t) = v_0 + v_1 t + v_2 t^2 + ... + v_l t^l \tag{3.5}$$

Considering the vehicle model in Section 2.5, the relevant transfer function is

$$G(s) = \frac{1}{(1 + \tau s) s^2}. \tag{3.6}$$

That is, $n = 3$, $l = 7$, $K = 1$ and $A(s) = \tau s^2 + s^2$ and we need that

- $f(0) = 0$ and $f(t_f) = y_f$
- $f^{(i)}(0) = 0$ for $i = 1, 2, 3$
- $f^{(i)}(t_f) = 0$ for $i = 1, 2, 3$.

Using

$$
\begin{aligned}
y(t) &= v_0 + v_1 t + v_2 t^2 + v_3 t^3 + v_4 t^4 + v_5 t^5 + v_6 t^6 + v_7 t^7 && (3.7)\\
\frac{dy(t)}{dt} &= v_1 + 2v_2 t + 3v_3 t^2 + 4v_4 t^3 + 5v_5 t^4 + 6v_6 t^5 + 7v_7 t^6 && (3.8)\\
\frac{d^2y(t)}{dt^2} &= 2v_2 + 6v_3 t + 12v_4 t^2 + 20v_5 t^3 + 30v_6 t^4 + 42v_7 t^5 && (3.9)\\
\frac{dy(t)}{dt^3} &= 6v_3 + 24v_4 t + 60v_5 t^2 + 120v_6 t^3 + 210v_6 t^4, && (3.10)
\end{aligned}
$$

we arrive at the following conditions for the polynomial coefficients.

$$
\begin{aligned}
y(0) = v_0 &= y_0 && (3.11)\\
y(t_f) = v_0 + v_1 t_f + v_2 t_f^2 + v_3 t_f^3 + v_4 t_f^4 + v_5 t_f^5 + v_6 t_f^6 + v_7 t_f^7 &= y_f && (3.12)\\
\frac{dy(0)}{dt} = v_1 &= 0 && (3.13)\\
\frac{dy(t_f)}{dt^2} = 2v_2 + 6v_3 t_f + 12v_4 t_f^2 + 20v_5 t_f^3 + 30v_6 t_f^4 + 42v_7 t_f^5 &= 0 && (3.14)\\
\frac{d^2y(0)}{dt^2} = 2v_2 &= 0 && (3.15)\\
\frac{d^2y(t_f)}{dt^2} = 2v_2 + 6v_3 t_f + 12v_4 t_f^2 + 20v_5 t_f^3 + 30v_6 t_f^4 + 42v_7 t_f^5 &= 0 && (3.16)\\
\frac{d^3y(0)}{dt^3} = 6v_3 &= 0 && (3.17)\\
\frac{d^3y(t_f)}{dt^3} = 6v_3 + 24v_4 t_d + 60v_5 t_d^2 + 120v_6 t_d^3 + 210v_6 t_d^4 &= 0 && (3.18)
\end{aligned}
$$

Hence, arranging the vector $v = \begin{bmatrix} v_0 & v_1 & v_2 & v_3 & v_4 & v_5 & v_6 & v_7 \end{bmatrix}^T$, we can compute the polynomial coefficients solving the matrix equation

$$
v = A^{-1} \cdot b \tag{3.19}
$$

with the matrix

$$A = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & t_d & t_d^2 & t_d^3 & t_d^4 & t_d^5 & t_d^6 & t_d^7 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 2t_d & 3t_d^2 & 4t_d^3 & 5t_d^4 & 6t_d^5 & 7t_d^6 \\ 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 6t_d & 12t_d^2 & 20t_d^3 & 30t_d^4 & 42t_d^5 \\ 0 & 0 & 0 & 6 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 6 & 24t_d & 60t_d^2 & 120t_d^3 & 210t_d^4 \end{bmatrix} \tag{3.20}$$

and the vector

$$b = \begin{bmatrix} 0 \\ y_f \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{3.21}$$

Using the symbolic toolbox of Matlab, the solution is obtained as

$$f(t) = \frac{35\,(y_f - y_0)}{t_f^4} t^4 - \frac{84\,(y_f - y_0)}{t_f^5} t^5 + \frac{70\,(y_f - y_0)}{t_f^6} t^6 - \frac{20\,(y_f - y_0)}{t_f^7} t^7. \tag{3.22}$$

Using the output/input relationship

$$u = (\tau s^3 + s^2) Y(s) \Rightarrow u = \tau \frac{dy(t)}{dt^3} + \frac{dy(t)}{dt^2}, \tag{3.23}$$

the corresponding input signal is

$$\begin{aligned} u(t) = \quad & 140\,(y_f - y_0)/t_f^4 t^3 + (-420\,(y_f - y_0)/t_f^5 + 35\,(y_f - y_0)/t_f^4)\, t^4 \\ & +(420\,(y_f - y_0)/t_f^6 - 84\,(y_f - y_0)/t_f^5)\, t^5 \\ & +(-140\,(y_f - y_0)/t_f^7 + 70\,(y_f - y_0)/t_f^6)\, t^6 - 20\,(y_f - y_0)/t_f^7 t^7 \end{aligned} \tag{3.24}$$

Applying this input signal to the vehicle with transfer function $G(s)$, the resulting output is $y_d(t)$ as in (3.4). We note that this feedforward input computation will be used throughout this chapter for the required longitudinal maneuvers.

3.3 Adding Vehicle

The desired behavior for opening a gap between vehicle $i-1$ and i is to increase the vehicle distance from the starting value $d_{i,r} = r_i + h_i v_i$ (realized by CACC) to the distance $r_i + h_i v_i + L + r_i + h_i v_i$ in a pre-specified time t_{gap} such that an additional vehicle with the length L fits into the gap according to the constant headway spacing policy in (2.2). We solve this problem by introducing a polynomial function u_i^{ff} as an additional exogenous input (see also Fig. 16) for the distance increase of vehicle i.

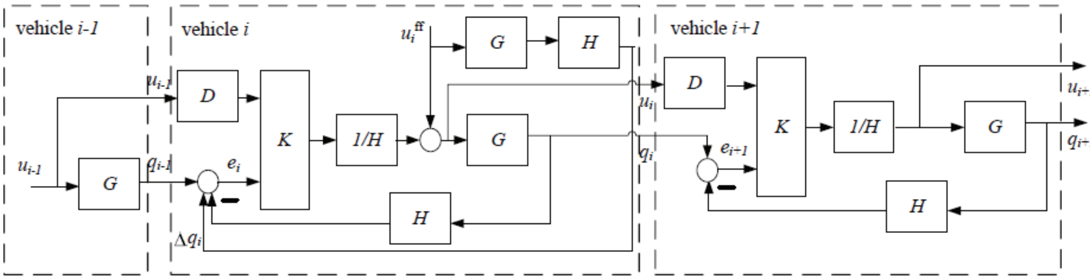

Figure 16: Block diagram of feedback loop for CACC extended by feedforward input u_i^{ff} for opening gaps.

This input signal provides a means to adjust the vehicle position for opening gaps. In order to preserve the possibility of safe following, we also introduce the path between u_i^{ff} and the error signal e_i to modify the desired distance signal according to the applied input u_i^{ff}. As a consequence, when applying u_i^{ff} for opening a gap, vehicle i keeps following vehicle $i-1$ but at an increasing distance. In particular, this measure preserves string stability as required.

Computing the input signal u_i^{ff} for opening a gap, it is only required to specify the time t_{gap} for opening the gap, the start distance $y_0 = 0$ and the final distance $y_f = L + r_i + h v_i =: \Delta_{gap}$. That is, the desired distance signal evaluates to

$$\Delta q_i(t) = \frac{35\,\Delta q_{gap}}{t_{gap}^4} t^4 - \frac{84\,\Delta q_{gap}}{t_{gap}^5} t^5 + \frac{70\,\Delta q_{gap}}{t_{gap}^6} t^6 - \frac{20\,\Delta q_{gap}}{t_{gap}^7} t^7. \tag{3.25}$$

and the desired input signal evaluates to

$$\begin{aligned} u(t) = \; & 140\,\Delta q_{gap}/t_{gap}^4 t^3 + (-420\,\Delta q_{gap}/t_{gap}^5 + 35\,\Delta q_{gap}/t_{gap}^4)\,t^4 \\ & +(420\,\Delta q_{gap}/t_{gap}^6 - 84\,\Delta q_{gap}/t_{gap}^5)\,t^5 \\ & +(-140\,\Delta q_{gap}/t_{gap}^7 + 70\,\Delta q_{gap}/t_{gap}^6)\,t^6 - 20\,\Delta q_{gap}/t_{gap}^7 t^7 \end{aligned} \tag{3.26}$$

Fig. 17 shows example trajectories for Δq_i and u_i^{ff} using $\Delta_{gap} = 29\,\text{m}$ and $t_{gap} = 10\,\text{s}$.

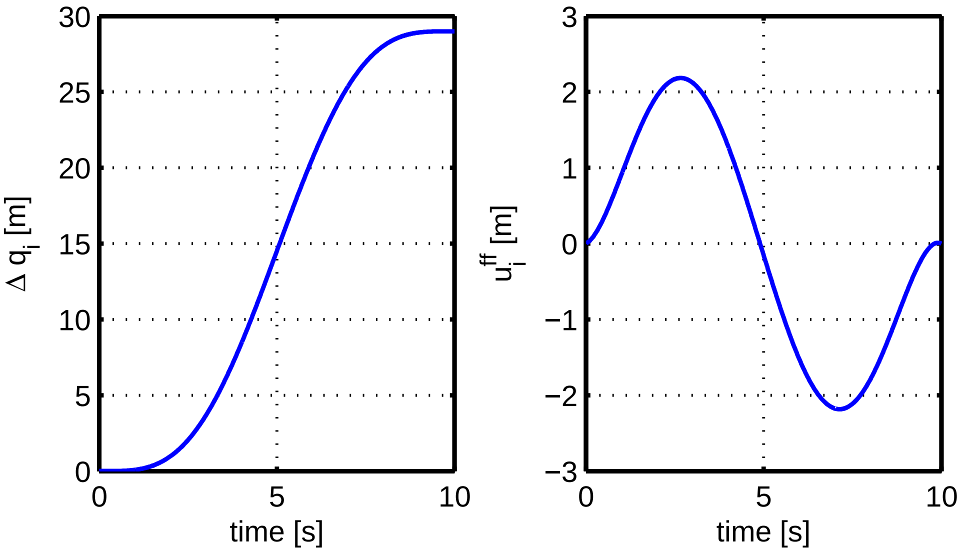

Figure 17: Polynomial trajectories for Δq_i and u_i^{ff}.

In order to illustrate the maneuver for opening a gap on the target lane, we perform a simulation with three cars. The result is shown in Fig. 18. Here, the first (leader) vehicle travels at a constant velocity of 72 km/h. The second vehicle opens a gap between time 2 s and 12 s according to the trajectory given in Fig. 17 using the feedforward control computed in (3.24). After time 12 s, a safe gap for a vehicle to enter between vehicle 1 and 2 is obtained. In turn, the third vehicle follows the second vehicle using the CACC feedback control as described in Fig. 16. That is, both smoothly opening a gap using the proposed feedforward control and safely following the respective preceding vehicle using the existing CACC design is achieved.

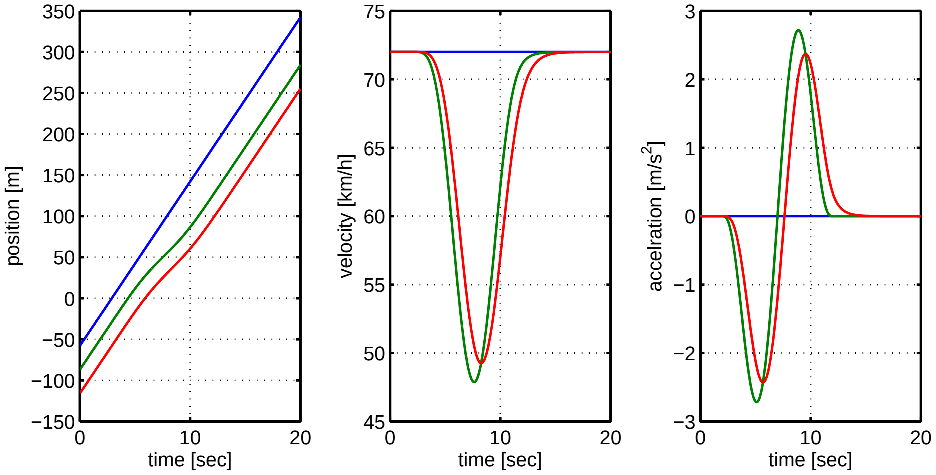

Figure 18: Opening a gap by the second vehicle in a string.

3.4 Removing a Vehicle

When a vehicle is removed from a string, it is required that the follower of that vehicle closes the gap to its predecessor. We use the same control architecture as shown in Fig. 16 and the feedforward computation in Section 3.2. Different from Fig. 17 in Section 3.3, the position now has to be decreased such that the final distance becomes $y_f = -L - r_i - hv_i = -\Delta_{gap}$. Using (3.19), the resulting distance signal evaluates to

$$\Delta q_i(t) = -\frac{35\,\Delta q_{gap}}{t_{gap}^4}t^4 + \frac{84\,\Delta q_{gap}}{t_{gap}^5}t^5 - \frac{70\,\Delta q_{gap}}{t_{gap}^6}t^6 + \frac{20\,\Delta q_{gap}}{t_{gap}^7}t^7. \tag{3.27}$$

and the desired input signal is

$$\begin{aligned} u(t) = \;& 140\,\Delta q_{gap}/t_{gap}^4\,t^3 - (-420\,\Delta q_{gap}/t_{gap}^5 - 35\,\Delta q_{gap}/t_{gap}^4)\,t^4 \\ & -(420\,\Delta q_{gap}/t_{gap}^6 + 84\,\Delta q_{gap}/t_{gap}^5)\,t^5 \\ & -(-140\,\Delta q_{gap}/t_{gap}^7 - 70\,\Delta q_{gap}/t_{gap}^6)\,t^6 + 20\,\Delta q_{gap}/t_{gap}^7\,t^7. \end{aligned} \tag{3.28}$$

The maneuver of closing a gap is illustrated in Fig. 19. Here, the trajectories of three vehicles are shown. The leader vehicle travels at a constant speed and there is a large gap between the first and the second vehicle due to a vehicle leaving the string. At time 2 s, the second vehicle starts closing the gap within 10 s. The third vehicle performs vehicle following according to the CACC design and hence keeps a safe distance to the second vehicle.

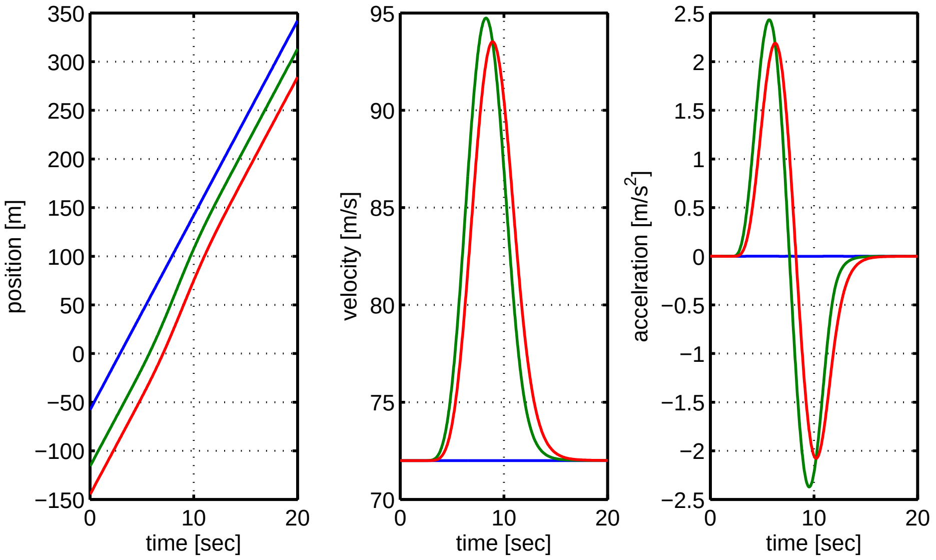

Figure 19: Removing one vehicle from a string.

3.5 Aborting a Lane Change

We finally consider the special case of a lane change that is initiated but aborted before completion. On the target lane, this means that a vehicle starts opening a gap and needs to close the already opened gap after the lane change maneuver is aborted. It is again possible to use the control architecture in Fig. 16. Nevertheless, the feedforward computation in Section 3.2 needs to be modified. Assume that the gap is opened with the trajectory $f(t)$ starting from time 0 but the maneuver is aborted at time $t_a > 0$. Then, the gap at time t_a is $f(t_a)$ and the corresponding time derivatives $\frac{d}{dt}f(t_a)$, $\frac{d^2}{dt^2}f(t_a)$, $\frac{d^3}{dt^3}f(t_a)$ are non-zero. Closing the opened gap hence starts from a non-zero initial condition. We suggest to close the gap with time t_d and compute the trajectory $f_a(t)$ for closing the gap with the conditions

- $f_a(0) = f(t_a)$,
- $f_a(t_d) = 0$,
- $\frac{d}{dt}f_a(0) = \frac{d}{dt}f(t_a)$,
- $\frac{d}{dt}f_a(t_d) = 0$,
- $\frac{d^2}{dt^2}f_a(0) = \frac{d^2}{dt^2}f(t_a)$,

- $\frac{d^2}{dt^2} f_a(t_d) = 0,$
- $\frac{d^3}{dt^3} f_a(0) = \frac{d^3}{dt^3} f(t_a),$
- $\frac{d^3}{dt^3} f_a(t_d) = 0,$

That is, we again use (3.19) but with a modified vector

$$b = \begin{bmatrix} f(t_a) \\ 0 \\ \frac{df(t_a)}{dt} \\ 0 \\ \frac{d}{dt^2} f(t_a) \\ 0 \\ \frac{d}{dt^3} f(t_a) \\ 0 \end{bmatrix} \tag{3.29}$$

We illustrate the maneuver of aborting a lane change in Fig. 20. Here, a lane change is requested at time 3 s and the second vehicle increases its distance to the first vehicle. Nevertheless, it is decided at time 10 s that the lane change should be aborted. Hence, the second vehicle closes the gap and continues following the first vehicle. The third vehicle keeps the safe distance to the second vehicle according to the CACC design.

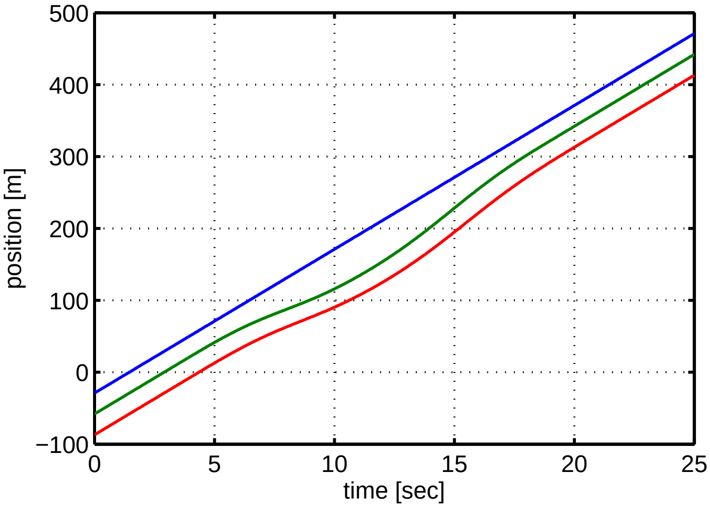

Figure 20: Aborting a lane change.

3.6 S-Function Implementation

The described functionality for opening/closing gaps of a vehicle in a vehicle string is implemented in the form of a Matlab s-function as shown in Fig. 21. This s-function is used in the simulation experiments in this thesis.

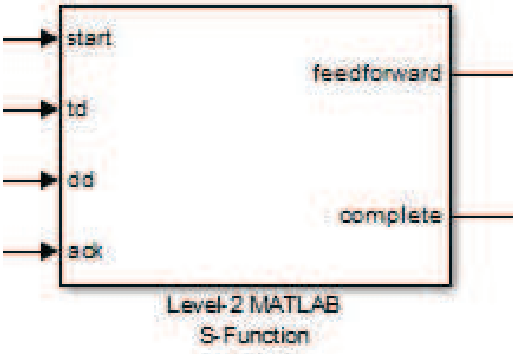

Figure 21: Block diagram of Sr function

The inputs to this s-function are

- start: this input is 0 by default; if this input is set to 1, a gap is opened; the maneuver is aborted if this input is set to -1.
- td: this input specifies the time duration for opening a gap;
- dd: this input specifies the desired distance (gap) to be opened.
- ack: this input specifies that a lane change maneuver is completed if set to 1; in that case, the internal variables of the s-function are reset.

The outputs of the s-function are

- feedforward: input and position feedforward trajectories Δu_i^{ff} and Δq_i in (3.24) and (3.22).
- complete: specifies that the maneuver is completed if set to 1.

CHAPTER 4

EXPERIMENTS

In this chapter, we perform various simulation experiments in order to support the functionality of the proposed control architecture in Chapter 3. We first consider the case of adding a single vehicle and removing a single vehicle in Section 4.1 and 4.2, respectively. Then, we address the case of multiple simultaneous lane change maneuvers in Section 4.3. As a further main contribution of the thesis, we observe the effect of multiple lane changes on the traffic flow and introduce the idea of scheduling the timing of lane changes for the first time in the literature.

4.1 Adding a Single Vehicle

We use the control architecture in Section 3.3 with a string of 10 vehicles. In this section, we intend to evaluate the simultaneous usage of feedback control (CACC) for vehicle following and feedforward control for opening gaps. To this end, the leader vehicle obtains a ”harsh” input signal with large positive and negative accelerations as shown in Fig. 22.

At the same time, we assume that a vehicle wants to enter between the first and the second vehicle at time 2 s. That is, the second vehicle has to follow the maneuver of the first vehicle and at the same open a gap starting from time 2 s.

Considering that our control architecture is general, it can be used with any CACC design. We illustrate this fact by conducting the described experiments both for the CACC design in [23] and [21] in Section 4.1.1 and 4.1.2,respectively.

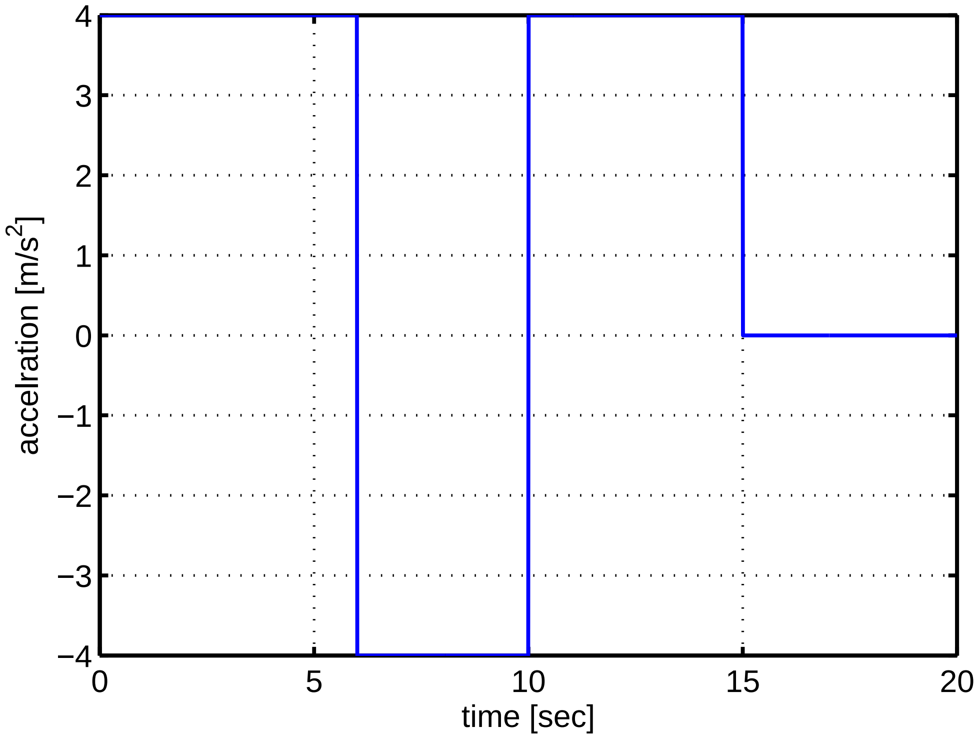

Figure 22: Input signal of the leader vehicle.

4.1.1 Adding a Single Vehicle Case1

We use the CACC controller as described in Section 2.5.1. That is, we use the parameters $k_p = 0.2$, $k_d = 0.7$ and $k_{dd} = 0$ for the feedback controller. First, we assume a large headway time of $h = 0.7$ s and a communication delay of $\theta = 0.02$ s. The simulation result is shown in Fig. 23.

It can be seen that the suggested control architecture is indeed suitable for simultaneous following and gap opening. In particular, the requested gap between vehicle 1 and vehicle 2 is available at time 12 s. In addition, a safe distance between the first and second vehicle is always obtained despite the maneuver of the first vehicle with large positive and negative accelerations. Moreover, it can be seen that both the variations in the velocity and acceleration are decreasing along the vehicle string. That is, the property of string stability is still achieved.

We now perform the same experiment for a smaller headway time of $h = 0.3$ s. The simulation result is shown in Fig. 24.

In this experiment, it can be seen that vehicle following and opening the gap is also performed. Nevertheless, the CACC design is no longer string stable such that the

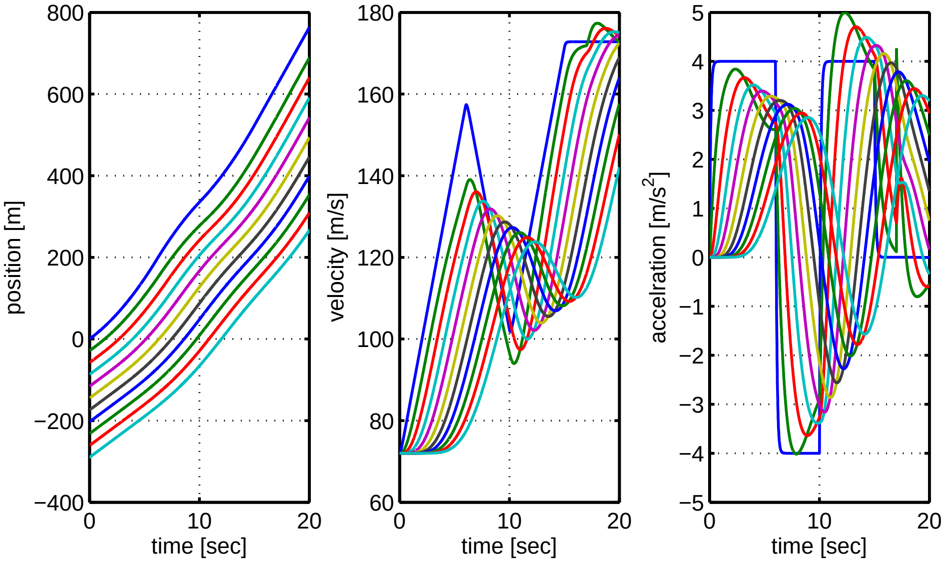

Figure 23: Simultaneous CACC following and opening a gap for $h = 0.7\,\mathrm{s}$.

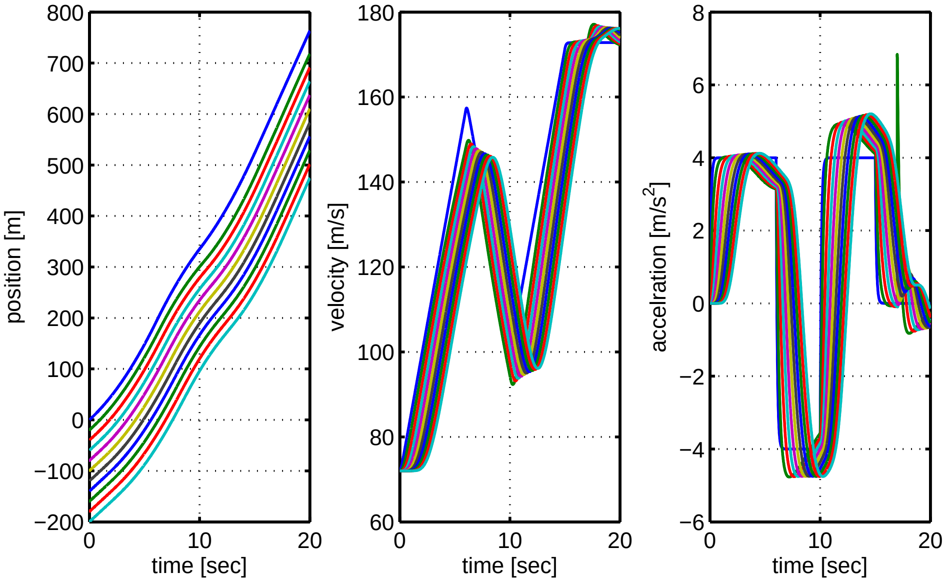

Figure 24: Simultaneous CACC following and opening a gap for $h = 0.3\,\mathrm{s}$.

variations in the velocity and acceleration now increase along the string. However, this result is not due to the additional feedforward control for opening a gap but is caused by the violation of string stability by the CACC design as already noted in Section 2.5.1.

4.1.2 Adding a Single Vehicle Case2

We now perform the same experiments as in Section 4.1.1 for the CACC design according to Section 2.5.2. The results for different headway times of $h = 0.7\,\mathrm{s}$ and $h = 0.3\,\mathrm{s}$ are shown in Fig. 25 and 26, respectively.

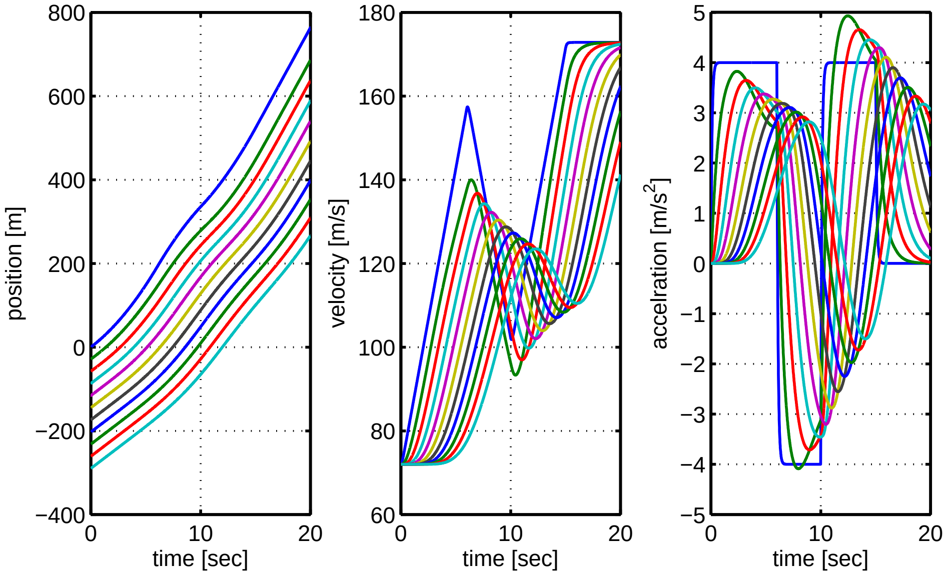

Figure 25: Simultaneous CACC following and opening a gap for $h = 0.7\,\mathrm{s}$.

As noted in Section 2.5.2, string stability is obtained in both cases at the expense of a higher CACC controller complexity.

4.1.3 Opening a Gap without Feedforward Control

The main contribution of this thesis is the usage of feedforward control for opening and closing gaps between vehicles. An alternative solution for opening a gep between two vehicles is to change the reference position of the predecessor vehicle to the desired gap distance for example by a position step. Consider two vehicles $i-1$ and i. Then, vehicle i receives the position q_{i-1} from vehicle $i-1$. A gap can be introduced by simply adding the gap distance $hv_i + L_i + r_i$ to this position. Since the controller design guarantees string stability, the position q_i of the follower vehicle i will converge to the

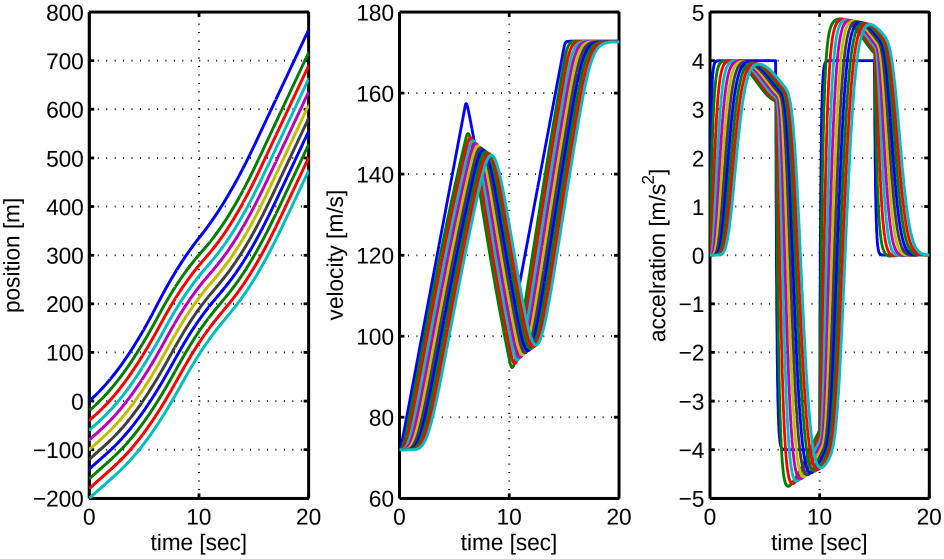

Figure 26: Simultaneous CACC following and opening a gap for $h = 0.3\,\mathrm{s}$.

desired gap distance and the follower vehicles will attenuate the motion of vehicle *i*. Fig. 27 shows the result of the same experiment as in Fig. 23 and 25 but when opening the gap using the described reference step.

It can be seen that the gap is successfully opened. Nevertheless, due to the reference step, large positive and negative accelerations are required which are both undesirable and practically not realizable. Hence, opening a gap using a reference step in the CACC design is not advisable, which demonstrates the usefulness of the proposed feedforward control.

4.2 Removing Single Vehicle

In this section, we perform the same experiment as in Section 4.1 with the difference of removing a single vehicle instead of adding a vehicle. The same input signal of the leader vehicle in Fig. 22 and the same parameter values for the CACC design are used.

4.2.1 Removing Single Vehicle Case1

We first consider closing the gap between the first and second vehicle for a headway time of $h = 0.7\,\mathrm{s}$. The simulation result is shown in Fig. 28. It can be seen that the gap between vehicle 1 and vehicle 2 is successfully closed while vehicle 2 follows the

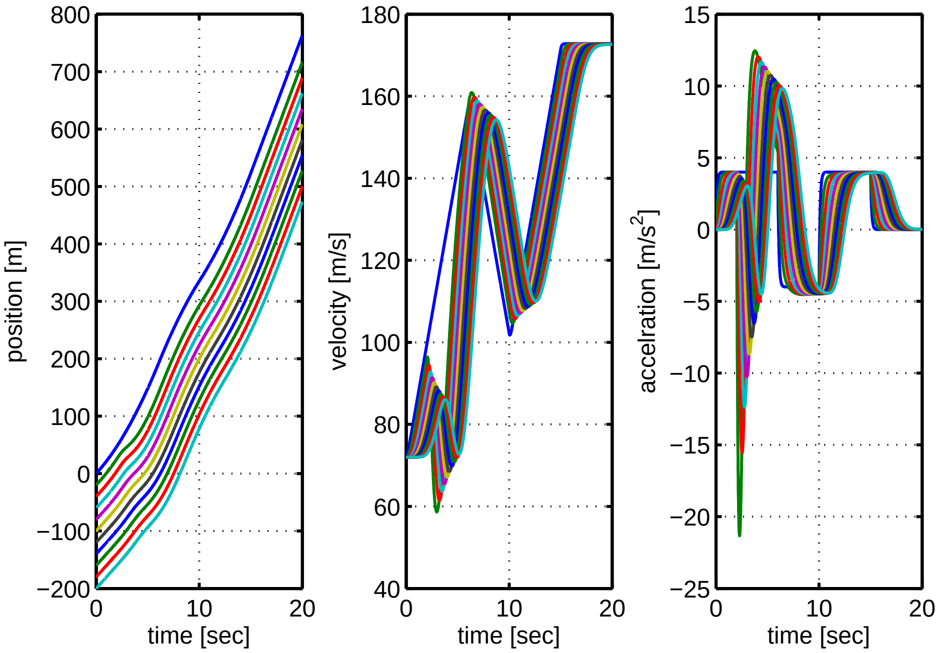

Figure 27: Simultaneous CACC following and opening a gap for $h = 0.3\,\mathrm{s}$ when applying a step for opening the gap.

maneuver of vehicle 1. In this experiment, it is interesting to note that string stability seems to be violated since the velocity fluctuations of vehicle 2 seem to be larger than those of vehicle 1. Nevertheless, this is not the case. It rather holds that a larger velocity of vehicle 2 is required in order to close the gap. As a result, vehicle 2 (and its followers) travel at a higher velocity until the gap is closed which is related to the feedforward control input. However, the fluctuations due to vehicle following (CACC) still decrease along the vehicle string, preserving string stability.

Next, we perform a simulation for $h = 0.3\,\mathrm{s}$ as shown in Fig. 29. Here, it is known from the previous sections that string stability is violated for the CACC design in [23]. This can be seen by the increasing velocity and acceleration fluctuations of the followers along the string.

4.2.2 Removing Single Vehicle Case2

We perform the same simulation experiments as in Section 4.2.1. The simulation resuls are shown in Fig. 30 and 31.

In this experiment, string stability is achieved for both values of the headway time h.

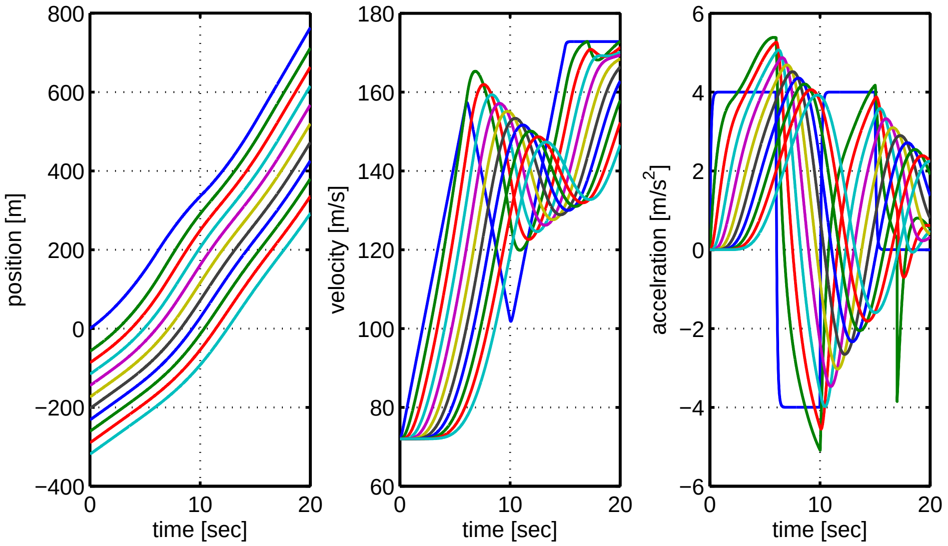

Figure 28: Simultaneous CACC following and closing a gap for $h = 0.7$ s.

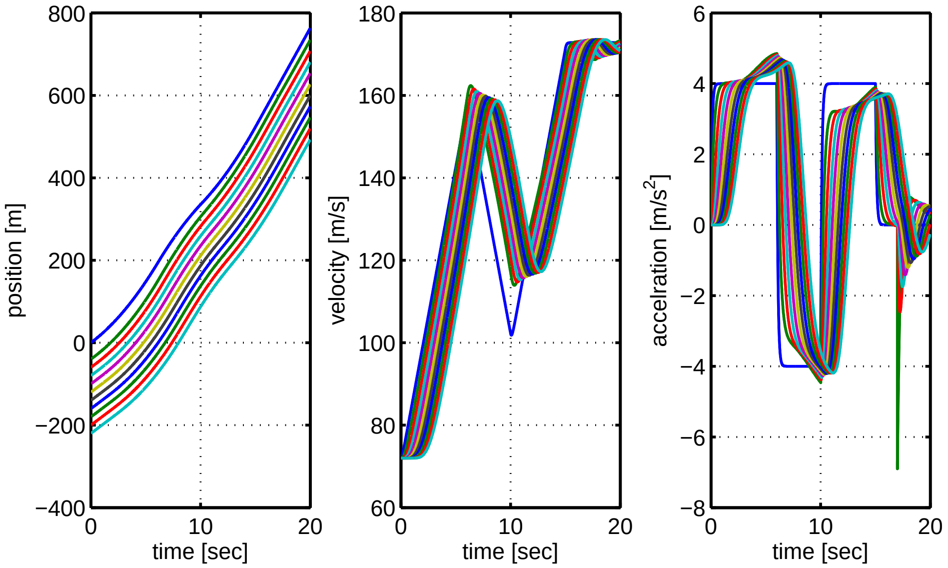

Figure 29: Simultaneous CACC following and closing a gap for $h = 0.3$ s.

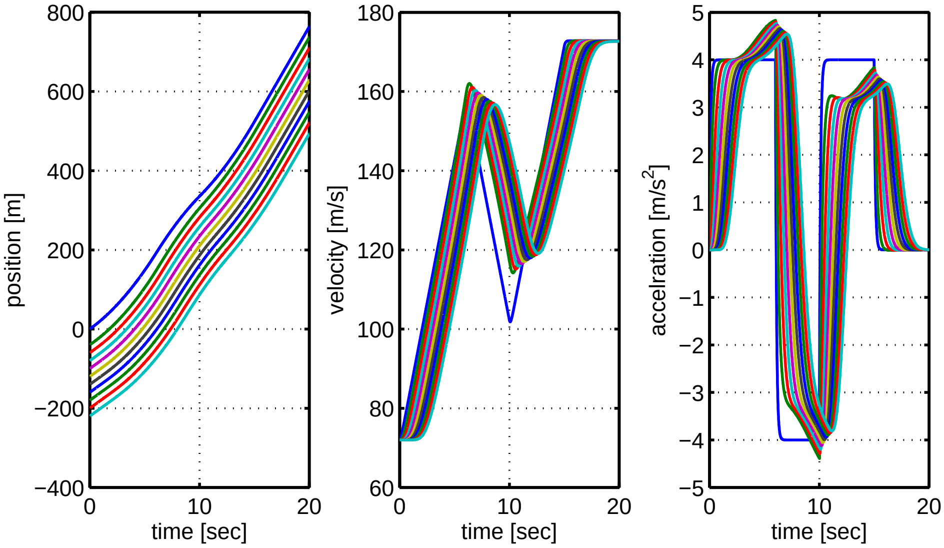

Figure 30: Simultaneous CACC following and closing a gap for $h = 0.7$ s.

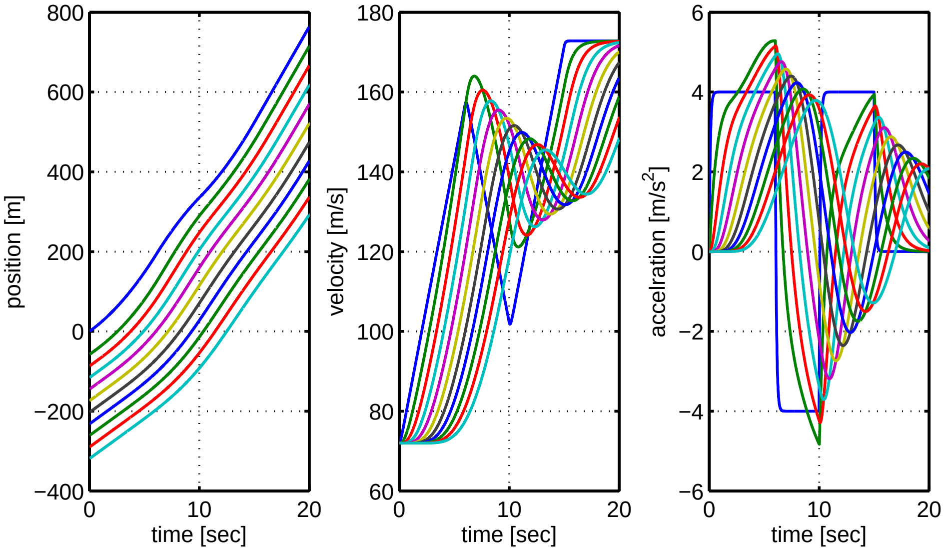

Figure 31: Simultaneous CACC following and closing a gap for $h = 0.3$ s.

4.3 Effect of Lane Changes on the Traffic Flow

In the previous sections, the case of a single vehicle entering or leaving a string was considered and it was shown that string stability is preserved under the proposed control architecture. In this section, we investigate the effect of lane change maneuvers on the overall traffic flow. Hereby, we quantify the traffic flow by looking at the velocity decrease of vehicles along a string for different maneuvers, whereby a large velocity decrease is undesired.

4.3.1 Lane Change of a Single Vehicle

We first characterize the effect of the parameter t_{gap} on the traffic flow. To this end, we perform simulations, where the second vehicle in a string opens a gap with the values $t_{gap} = 10$, $t_{gap} = 15$ and $t_{gap} = 20$. The resulting velocity profiles are shown in Fig. 32. Here, a shorter time for opening a gap leads to a larger decrease in the velocity of vehicle 2 and its follower vehicles. That is, choosing smaller values for t_{gap} has an increasingly negative effect on the traffic flow.

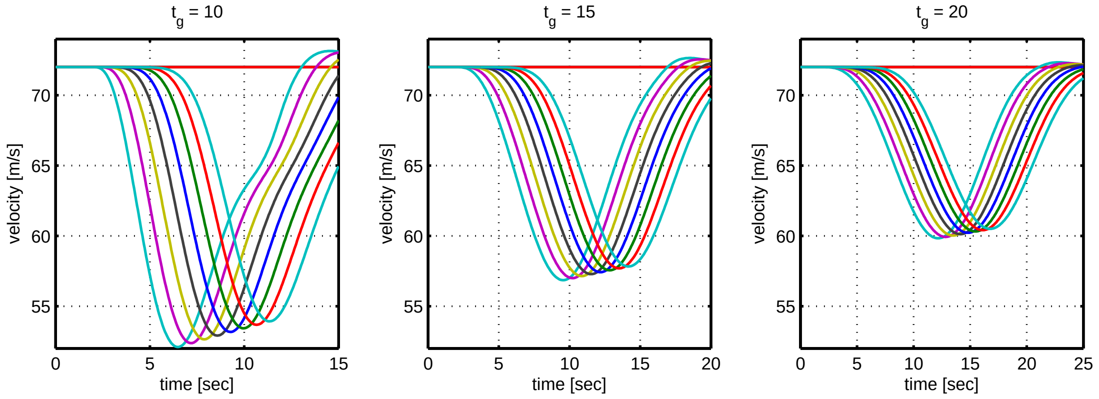

Figure 32: Velocities of different vehicles when opening a gap. Each line represents the motion of one vehicle.

4.3.2 Multiple Vehicle Merging

We next consider the practically interesting scenario where multiple vehicles have to open a gap at the same time. Such scenario for example occurs at on-ramps where multiple vehicles want to enter a vehicle string on the main road. We first conduct a simulation where vehicle 2, 3, 4 in a string open a gap at the same time. The corresponding position and velocity profiles are shown in Fig. 33. It can be seen that the velocity of the follower vehicles in the string decreases up to 20 km/h since multiple sequential vehicles perform a velocity decrease simultaneously. That is, the described situation needs to be avoided in order to prevent traffic breakdown.

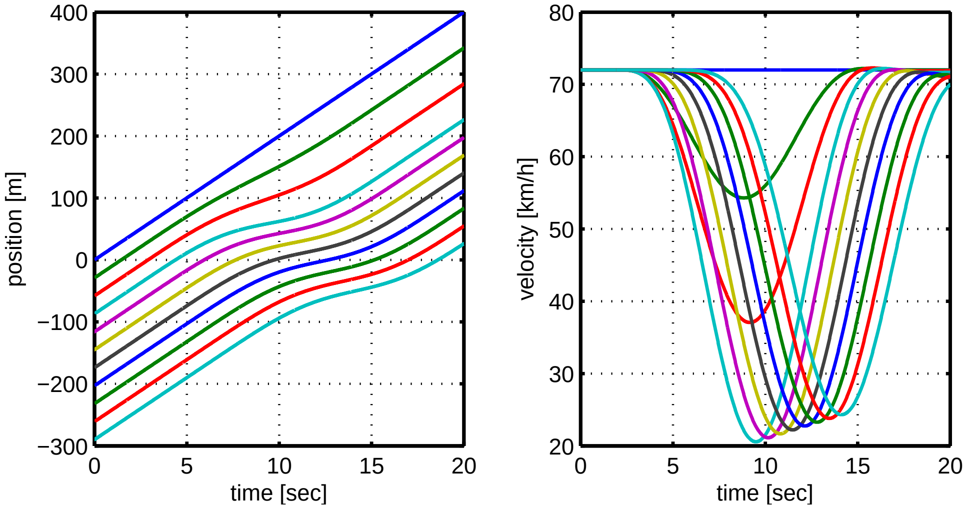

Figure 33: 3 vehicles opening a gap at the same time.

In order to open multiple gaps without causing traffic breakdown, we suggest to *schedule* the maneuvers of different vehicles such that they start opening gaps at different times. To this end, we evaluate the effect of choosing different starting times depending on the vehicle velocity v and the time t_{gap} for opening the gap. Table 1 shows our comparison for vehicle speeds of $v = 72, 108, 144$ km/h, $t_{gap} = 10, 15, 20$ s and a difference $\Delta t = 5, 8, 12$ s between the maneuvers for opening a gap of 3 vehicles. According to our evaluation, the combination of $t_{gap} = 15$ s and $\Delta t = 8$ s proved most suitable for all velocities (see rows highlighted in gray). The reason for this statement is that this parameter assignment leads to a tolerable reduction of the minimum velocity of the vehicle string while keeping the time for opening all gaps small. It can also be seen that the acceleration remains between $-2\,\text{m/s}^2$ and $2\,\text{m/s}^2$ which is suitable for practical driving scenarios.

The position, velocity and acceleration profile for the case of $t_{gap} = 15$ s, $\Delta t = 8$ s and $v = 72$km/h is shown in Fig. 34. Here, the starting times of the maneuvers for gap opening are indeed distributed such that for example the third vehicle starts opening the gap (deceleration) when the second vehicle is already accelerating again. As a result, the velocity decrease of different vehicles does not happen at the same time.

In summary, our initial experiments indicate that traffic flow stability can be achieved when appropriately scheduling the maneuvers of different vehicles.

Table 1: Choice of t_{gap}

v_0	t_{gap}	Δt	v_{max}	v_{min}	a_{max}	a_{min}	$p_{error}max$	$p_{error}min$
72	15	8	72.2	54.3	1.3	-1.29	0	-3.2
72	10	8	72.9	44.5	3.17	-3.25	0	-4.5
72	20	8	72.08	57.6	0.71	-0.706	0	-2.8
72	15	5	72.2	47.5	1.3	-1.28	0	-4.7
72	10	5	72.9	44.5	3.15	-3.1	0	-4.9
72	20	5	72.06	48	0.9	-0.9	0	-4.6
72	15	12	72.2	54.2	1.3	-1.3	0	-3.1
72	10	12	73.5.9	44.4	3.15	-3.1	0	-4.5
72	20	12	72	58.9	0.7	-0.7	0	-2.4
108	15	8	108.3	86	1.6	-1.6	0	-4
108	10	8	109	73.5	4	-4	0	-5.4
108	20	8	108.1	90.1	0.87	-0.87	0	-3.5
108	15	5	102.3	77.7	1.6	-1.6	0	-5.87
108	10	5	109	73.8	3.9	-3.8	0	-6.15
108	20	5	108.2	78.4	1.13	-1.31	0	-5.7
108	15	12	108.2	86	1.6	-1.6	0	-3.89
108	10	12	109.4	73.8	3.9	-3.8	0	-5.5
108	20	12	108	91.7	0.88	-0.88	0	-3
144	15	8	144.3	117.7	1.91	-1.91	0	-4.75
144	10	8	145	102.9	4.66	-4.83	0	-6.58
144	20	8	144.1	122.7	1.05	-1.05	0	-4.16
144	15	5	144.4	107.7	1.92	-1.92	0	-7
144	10	5	145	103	4.66	-4.83	0	-7.35
144	20	5	144	108.4	1.35	-1.34	0	-6.82
144	15	12	144.3	117.7	1.9	-1.9	0	-4.65
144	10	12	145.5	103.2	4.6	-4.6	0	-6.55
144	20	12	144	124.5	1	-1.05	0	-3.58

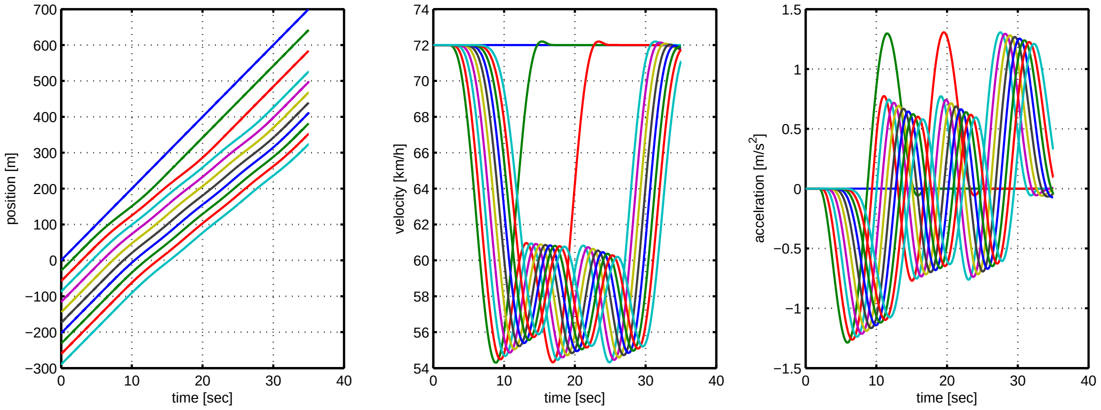

Figure 34: 3 vehicles opening gaps according to a given schedule. Each line represents the motion of one vehicle.

CHAPTER 5

CONCLUSION AND FUTURE WORK

The subject of this thesis is the realization of lane changes in dense vehicle traffic. On the one hand, it is required to perform safe *vehicle following* at small inter-vehicle distances to achieve a high traffic throughput. On the other hand, it is necessary to *open gaps* for vehicles that want to enter a vehicle string and *close gaps* after vehicles that leave a string without a negative impact on the traffic flow (such as small velocities of some vehicles). In this context, the thesis has two main contributions.

First, we propose to extend cooperative adaptive cruise control (CACC) for safe vehicle following by a feedforward control input for longitudinal maneuvers such as opening or closing gaps. Using CACC, each vehicle measures the distance to its predecessor vehicle and additionally obtains state information from its predecessor vehicles via vehicle-to-vehicle (V2V) communication in order to maintain a safe but close distance to its predecessor vehicle. In this thesis, we employ a one-vehicle lookahead policy, that is, each vehicle communicates only with its direct predecessor vehicle. In addition, the feedforward control input is used to smoothly open gaps for vehicles that enter a vehicle string and to close gaps after vehicles that leave a vehicle string. The thesis both performs the feedforward input computation and provides simulation studies of the respective maneuvers. The novelty of our control architecture is the consideration of longitudinal maneuvers different from only vehicle following.

Second, we study the effect of opening gaps for lane changes on the traffic flow. We observe that opening multiple gaps simultaneously can lead to traffic breakdown. Hence, we propose to schedule the timing of such maneuvers and experimentally evaluate appropriate timings. We show in simulation experiments that traffic breakdowns can be mitigated with our method.

In accordance with the existing literature, it is assumed throughout the thesis that the vehicles are homogeneous, that is, each vehicle has the same dynamic properties. One possible extension for future work is the consideration of lane changes of heterogeneous vehicles with different dynamic properties. We further note that a particular method for the feedforward input computation is used. The study of different methods such as optimal control for computing the feedforward control signal is also a subject of future work.

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APPENDICES A

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