2015 IEEE 18th International Conference on Intelligent Transportation Systems

String Stable Heterogeneous Vehicle Platoon using Cooperative Adaptive Cruise Control

Cong Wang, Henk Nijmeijer
Department of Mechanical Engineering
Eindhoven University of Technology
Eindhoven, the Netherlands
C.Wang1@tue.nl

***Abstract*—In this paper, a heterogeneous vehicle platoon equipped with Cooperative Adaptive Cruise Control (CACC) systems is studied. First, various causes of heterogeneity are reviewed. A selection of parameters is made, for which string stability is analyzed. The influence of controller parameters and headway time on string stability is studied. Numerical simulation results provide guidelines on how to choose controller parameters and headway time for different vehicles using CACC.**

Keywords—Cooperative adaptive cruise control (CACC), string stability, heterogeneous platoon, headway time.

I. INTRODUCTION

Currently, more and more vehicles are on the road, which can create severe traffic jams. To solve this problem, car manufacturers have developed advanced driver assistant systems such as Adaptive Cruise Control (ACC), which is mostly regarded as a comfort system. ACC uses a radar or a lidar to measure the relative distance and/or relative velocity of two adjacent vehicles. To maintain a desired or safe distance to the preceding vehicle, vehicles equipped with ACC are capable of accelerating and decelerating automatically. An addition to existing ACC systems is wireless communication, resulting in Cooperative Adaptive Cruise Control (CACC), which is still a topic of active research. The main objective of CACC is to improve the traffic flow. Besides that, CACC can also save energy for heavy duty vehicles [1]. Compared with ACC, CACC can keep smaller headway time, which is defined as the spacing between vehicles. In general, the headway time between vehicles equipped with CACC is smaller than one second, which can improve traffic flow dramatically. However, if this headway time is too small, traffic flow decreases due to an unstable string of vehicles. This string stability, which reflects the attenuation of disturbance along the vehicles, is the basic requirement for a vehicle platoon. If the platoon is not string stable, the disturbance will increase along the platoon and collisions may occur. A uniform definition of string stability does not exist. However, in commonly used definitions, the control input, control error, and control output are used [2].

Under the criterion of string stability, a homogeneous vehicle platoon equipped with CACC has been analyzed in [2]–[4]. The design and experimental evaluation of cooperative adaptive cruise control is realized, for instance [5]. A frequency-domain approach is used to design and validate CACC in [6]. Network-aware modelling of CACC vehicle strings is presented and network-aware string stability is analyzed in [2]. However, in reality, vehicles on the road are all different and therefore form a heterogeneous platoon. The controller synthesis and system analysis for a heterogeneous vehicle platoon are different from those for a homogeneous platoon. Two practical applications of such a heterogeneous platoon are the Grand Cooperative Driving Challenge (GCDC) competition held in the Netherlands in 2011 and its follow-up the GCDC 2016 [7]. Nine teams participated in this competition in 2011 [8]. A heterogeneous vehicle platoon with an ACC system is analyzed with a new string stability definition in [9], [10], however, CACC for this heterogeneous platoon is not analyzed. In literature, the focus is often on the analysis of a homogeneous vehicle platoon with CACC or a heterogeneous vehicle platoon with ACC. This paper, therefore, focuses on the analysis of a heterogeneous vehicle platoon with CACC. For analysis, a selection of parameters, the controller parameters and the headway time, influencing the heterogeneous vehicle platoon is taken. For this, a new feedforward controller is designed and its performance is evaluated. The aim of this study is to provide guidelines on how to choose controller parameters and headway time for different vehicles to keep string stability.

The outline of the paper is as follows. In section II, various causes for heterogeneity of a platoon are summarized. After that, the controller structure of the CACC system is presented. In order to judge the string stability of a platoon, a string stability condition is given. In section IV, numerical simulation and discussion on a heterogeneous vehicle platoon are provided. According to the simulation, some guidelines on how to choose controller parameters and headway time for different vehicles are given. Finally, conclusions and recommendations are drawn.

II. HETEROGENEOUS VEHICLE PLATOON

In order to analyze a heterogeneous vehicle platoon, it is necessary to summarize the differences firstly. In this paper a limited subset is used to analyze the behavior of a heterogeneous platoon. Below, a short summary of the causes of heterogeneity are given, an overview is given in Table I. From this table a selection on the causes of heterogeneity can be made.

The work is funded by China Scholarship Council (CSC).

978-1-4673-6596-3/15 $31.00 © 2015 IEEE
DOI 10.1109/ITSC.2015.320

A. Communication Topology and Information

Several communication topologies of CACC systems exist in literature, such as communication with the direct preceding vehicle [3], communication with the preceding vehicle and the lead vehicle [3], communication with several preceding vehicles and communication with preceding and follower vehicles [11]. In this paper, only communication with the direct preceding vehicle is considered. In this paper, it is assumed that the desired acceleration of the preceding vehicle, u_{i-1}, is communicated [3]. Taking the desired acceleration, u_{i-1}, instead of the true acceleration, a_{i-1} [4], is better, since the response time of the vehicle is shorter.

B. Spacing Policy

Different spacing policies have been proposed in the past. Three spacing policies are often found in literature, namely the constant spacing policy, the constant time spacing policy and the nonlinear spacing policy. For a platoon with a constant spacing policy is very easy to become string unstable [4]. Constant time spacing policy is most popular and it can make the platoon string stable. An example of a nonlinear spacing policy analyzed for heavy-duty vehicles is shown in [12]. However, this is still ongoing research, therefore, in this paper a constant time spacing policy is chosen.

C. Feedback Controller

Different types of feedback controllers for CACC are used in literature, for example PD controller [2]–[4], Model Predictive Controller [13], and Linear-Quadratic Regulator (LQR) [14]. With a PD controller, string stability is only achieved by a posteriori tuning the controller parameters [3]. In [13], string stability is not taken into account. The string stability requirement is not included in the LQR controller synthesis in [14]. A MPC control approach with receding horizon approach is used for designing CACC to keep a platoon string stable [15].

D. Feedforward Controller

In literature, different feedforward controllers can be found. The feedforward controllers are designed in order to minimize the distance error [2]–[4], while the feedforward controller can also be freely designed in order to realize string stability [16].

Table I. Causes of heterogeneity

Heterogeneity	1	2	3
A:Communication topology and information	One preceding	Bidirectional	Multiple preceding
B: Spacing policy	Constant spacing policy	Constant time spacing	Nonlinear spacing policy
C: Feedback controller	PD controller	H_∞	LQR
D: Feedforward controller	In order to minimize the distance error	Designed freely	
E: Error signal to be controlled	Distance error	Combination of distance error, velocity error and acceleration error	
F: Others	Communication delay time	Vehicle lag and actuator delay time	Constraints

E. Error Signals to be Controlled

Various signals can be considered as error signal. The control error can be considered as the spacing error between the relative distance of two adjacent vehicles and the desired distance [2]–[4]. The combination of the relative acceleration, speed and distance (R-ASD) can also be used as the control error [17].

F. Others

Besides those mentioned above, communication delay time, vehicle lag, actuator delay time and constraints can also be different for different vehicles in a heterogeneous platoon.

Many differences are listed, while it is rather difficult and nearly impossible to analyze all of the differences at the same time. In this paper, the main objective is to provide general guidelines on how to select the headway time and controller parameters for different vehicles using Cooperative Adaptive Cruise Control under the requirement that the heterogeneous platoon is string stable. For simplicity, only a few vehicle parameters are different. They are the feedback controller parameters, vehicle time constant, headway time and communication delay time. The purpose of focusing on these parameters is that they have great influence on string stability. The other parameters are assumed to be equal in this paper. The direct preceding vehicle communication topology is used for all vehicles. The spacing policy is the constant time spacing policy. The control structure for all vehicles is chosen as a PD controller, where the gains of these controllers vary per vehicle. A new feedforward controller is designed in this paper to minimize the spacing error and eliminate the influence of different vehicles on the string stability transfer function. The spacing error is taken as the control error for heterogeneous vehicles. The actuator delay parameters and the constraints of vehicles are not considered. Because this simplification as shown in Table I can realize the main objective of this paper, feedback controller parameters, vehicle parameter, headway time and communication delay time are only considered. A heterogeneous platoon is formed according to the above simplification, an example of such a heterogeneous platoon is shown in Fig. 1.

III. Controller Design And String Stability

One of the control objectives is to keep a desired distance with its preceding vehicle. This translates to minimization of the e_i between the relative distance d_i and the desired distance $d_{r,i}$ of two adjacent vehicles. The spacing error is given as

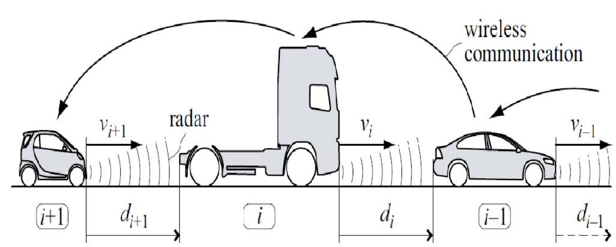

Fig. 1. A heterogeneous platoon [3]

$$e_i(t) = d_i(t) - d_{r,i}(t) \quad (1)$$

The desired distance and the relative distance are as follows

$$d_{r,i}(t) = r_i + h_i v_i(t) \quad (2)$$

$$d_i(t) = x_{i-1}(t) - x_i(t) - L_i \quad (3)$$

where r_i is the standstill distance, h_i (≥ 0) represents the headway time, $v_i(t)$ is the velocity of the host vehicle i, $x_{i-1}(t)$ and $x_i(t)$ are the positions of the host vehicle i and the preceding vehicle $i-1$ respectively, L_i is the length of vehicle i. Without loss of generality, the standstill distance and the length of vehicles are set to be zero.

The control structure of the CACC system depicted in Fig. 2 is designed based on the control structure found in [3]. However, to consider the influence of a heterogeneous vehicle platoon, a new feedforward controller is proposed.

The transfer function model from control input $U_i(s)$ to vehicle position $X_i(s)$ of vehicle i [3] is given by

$$G_i(s) = X_i(s)/U_i(s) = \frac{1}{s^2(\tau_i s + 1)} e^{-\emptyset_i s} \quad (4)$$

where $U_i(s)$ is the Laplace transformation of the signal $u_i(t)$, $X_i(s)$ is the Laplace transformation of the signal $x_i(t)$, τ_i is a time constant representing the vehicle dynamics, $\emptyset_i$ is the vehicle time delay which represents the actuator and internal communication delay time [4]. The influence of time delay of a vehicle on string stability is smaller than that of communication time delay. Thus, the time delay of vehicles is neglected in this paper.

The feedback controller is a PD controller

$$K_i(s) = k_{p,i} + k_{d,i} s \quad (5)$$

In order to improve tracking performance and string stability performance of the system, a feedforward controller is added into the system and is given as follows

$$C_{ff,i}(s) = G_{i-1}(s)/G_i(s) = \frac{\tau_i s + 1}{\tau_{i-1} s + 1} \quad (6)$$

From (6), the feedforward controller of a vehicle is closely related with its preceding vehicle. If the preceding vehicle changes, the feedforward controller should also be changed. Or else, the tracking performance and string stability will be influenced. When the vehicles dynamics of two vehicles are the same, the feedforward controller reduces to 1, which is the same to the feedforward controller found in [3].

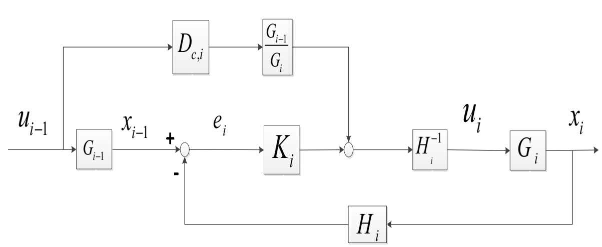

Fig. 2. Control structure of the CACC system

The Laplace transformation of the communication delay time is given by

$$D_{c,i}(s) = e^{-\theta_i s} \quad (7)$$

where θ_i is the communication delay time between vehicles.

According to the control structure in Fig. 2, the Laplace transformation of the spacing error is given by

$$E_i(s) = \frac{G_{i-1}(s)U_{i-1}(s)(1 - D_{c,i}(s))}{1 + G_i(s)K_i(s)} \quad (8)$$

where $E_i(s)$ is the Laplace transformation of the signal $e_i(t)$, $U_{i-1}(s)$ is the Laplace transformation of the signal $u_{i-1}(t)$. When the communication delay time is neglected ($D_{c,i}(s) = 1$), the spacing error is always zero according to (8), which means that the tracking performance is realized perfectly. In order to make the spacing error be zero, the feedforward controller is designed as (6).

The headway time policy transfer function is as follows

$$H_i(s) = 1 + h_i s \quad (9)$$

When the headway time changes, the system with CACC in Fig. 2 may become unstable. The purpose of adding the block H_i^{-1} in Fig. 2 is to cancel the influence of changing the headway time in the feedback loop on stability [3].

According to the control structure in Fig. 2, the string stability transfer function from A_{i-1}(s) to A_i(s) is as follows

$$A_i(s)/A_{i-1}(s) = \frac{D_{c,i}(s) + G_i(s)K_i(s)}{1 + G_i(s)K_i(s)} \frac{1}{H_i(s)} \quad (10)$$

where $A_{i-1}(s)$ and $A_i(s)$ are the Laplace transformations of the preceding vehicle's acceleration $a_{i-1}(t)$ and the host vehicle's acceleration $a_i(t)$ respectively. The string stability transfer function is only related to the parameters of the host vehicle, while it is not related to the preceding vehicle's parameters at all. The feedforward controller is selected as (6), which can make the string stability transfer function not related to the parameters of the preceding vehicle's parameters at all.

String stability is the basic requirement of CACC, the condition is given as

$$\|A_i(j\omega)/A_{i-1}(j\omega)\|_{H_\infty} \leq 1 \quad (11)$$

When the communication delay time is 0, the string stability transfer function is simplified as

$$A_i(s)/A_{i-1}(s) = 1/H_i(s) \quad (12)$$

The vehicle is always string stable for any headway time value $h_i \geq 0$, because $\|A_i(j\omega)/A_{i-1}(j\omega)\|_{H_\infty} = 1$.

Besides considering the acceleration signal in the string stability transfer function, $U_i(s)/U_{i-1}(s)$ and $E_i(s)/E_{i-1}(s)$ are also used to judge string stability [4]. For a homogeneous platoon, $A_i(s)/A_{i-1}(s)$, $U_i(s)/U_{i-1}(s)$ and $E_i(s)/E_{i-1}(s)$ are the same according to the control structure in Fig. 2. However, for a heterogeneous platoon, they are not the same. $U_i(s)/$

$U_{i-1}(s)$, $E_i(s)/E_{i-1}(s)$ and the weak string stability transfer function ($A_i(s)/A_r(s)$, $U_i(s)/U_r(s)$ and $E_i(s)/E_r(s)$ [2], where $A_r(s)$, $U_r(s)$ and $E_r(s)$ are the Laplace transformations of the acceleration, the control effort and the control error of the reference vehicle or the first vehicle in a platoon) are rather complicated for a heterogeneous platoon. They do not present much insight, because these transfer functions are closely related with vehicles' control structures. In this paper, $A_i(s)/A_{i-1}(s)$ is selected as the string stability transfer function for a heterogeneous platoon. It is also chosen as the string stability criterion in Grand Cooperative Driving Challenge (GCDC) competition [7].

Besides string stability, stability is also a necessary condition for a vehicle using CACC. Because the feedforward controller and headway time in Fig. 2 do not influence the stability, the feedback controller is only considered as to see how it influences the stability. The characteristic equation is $1+\frac{k_{p,i}+k_{d,i}s}{(\tau s+1)s^2}=0$. According to the Routh stability criterion, the system in Fig. 2 can realize stability for any value $k_{p,i}>0$, $k_{d,i}>0$, and $k_{d,i}>k_{p,i}\tau_i$.

IV. SIMULATION and DISCUSSION

The analytical results of the string stability condition and the relationship between parameters are obtained in [18]–[25]. However, the analytical results are rather difficult to be obtained because of the form of the string stability transfer function and the existence of communication delay time in the string stability transfer function in this paper. Therefore, the influence of controller parameters and headway time on string stability for a heterogeneous vehicle platoon is analyzed based on numerical simulations. From this, a guideline for choosing controller parameters and headway time is obtained.

According to the simplification for a heterogeneous vehicle platoon, there are only five different parameters considered in this paper. These are the communication delay time, vehicle time constant, headway time and the two controller parameters. The five parameters influencing string stability can be divided into two kinds of parameters: given parameters (θ and τ) and tuning parameters (h, k_p, k_d). The given parameters reflect characteristics of different vehicles. The tuning parameters are used to achieve string stability.

Firstly, it is analyzed how to tune headway time for a heterogeneous platoon to achieve string stability. In this part, how to tune headway time for different communication delay time is presented when vehicle time constant is fixed. Furthermore, how to tune the headway time for different vehicle parameters is described when communication delay time is a fixed value.

Secondly, it is analyzed how to tune the controller parameters for a heterogeneous platoon to maintain string stability. In this part a guideline on how to choose controller parameters for different vehicle parameters is given when the communication delay time is fixed. Besides this, how to select the controller parameters for different communication delay times is presented when vehicle parameters are fixed.

Finally, a method to tune the headway time for varying communication delay times and varying time constants is presented. A method to tune controller parameters for varying communication delay times and varying vehicle time constants is given.

A. Tune Headway Time

The relationship between the minimum headway time and communication delay time is obtained by taking fixed values for $k_p=k_d=0.5$ and $\tau=0.2 seconds$, as illustrated in Fig. 3. It shows that the minimum headway time should be increased with an increasing delay time to maintain string stability. As can be seen in Fig. 3, the minimum headway time is 0 when the communication delay time is 0. It corresponds with the theoretical analysis.

In Fig. 4, where fixed values for $k_p=k_d=0.5$ and $\theta=0.02\ seconds$ are taken, the relationship between the minimum headway time and vehicle time constant is obtained. The minimum headway time should be increased when the vehicle time constant increases in order to maintain string stability. It means that the minimum headway time of vehicles with slow dynamics should be selected bigger than that of vehicles with fast dynamics in a heterogeneous platoon.

B. Tune Controller Parameters

Besides increasing headway time to achieve string stability, tuning controller parameter is also a suitable method.

According to Fig. 5, taking fixed values for $h=0.5\ seconds$ and $\theta=0.02 seconds$ and taking $k_p=k_d$, the relationship between controller parameters and vehicle time constant is obtained. Controller parameters should be increased when the vehicle time constant increases in order to maintain string stability. In a heterogeneous platoon, vehicles with slow dynamics should have larger controller parameters to achieve string stability.

For example: when the vehicle time constant is 0.1 seconds, the controller parameter $k_p=0.2$ can make a platoon string stable. If vehicle parameter is 0.3 seconds, the vehicle cannot become string stable in a platoon when its controller parameter k_p is 0.2. But the vehicle becomes string stable when the controller parameter k_p increases to 0.3. Fig. 6 shows the corresponding Bode magnitude of the string stability transfer function for different vehicles and confirms the result. When the magnitude of the string stability transfer function is bigger than one, the platoon is not string stable. For all values smaller than one, it is string stable.

According to Fig. 7, taking fixed values for $h=0.5\mathrm{seconds}$ and $\tau=0.2\mathrm{seconds}$ and taking $k_p=k_d$, the controller parameters should be increased when the communication delay time increases to maintain string stability. In a heterogeneous platoon, vehicles with bigger communication delay time should have bigger controller parameters to achieve string stability. For example: when the communication delay time is 0.02seconds, a controller parameter of $k_p=0.4$ can make a platoon string stable. If the communication delay time is 0.05 seconds, the vehicle cannot achieve string stability. Increasing the controller parameter k_p

to 0.6, the vehicle can realize string stability. Fig. 8 shows the corresponding Bode magnitude of the string stability transfer function for different communication delay time and confirms the result.

C. Tune parameters for two varying given parameters

The above 2-Dimensional figures are obtained when one of two given parameters is fixed. They show the relationship between one tuning parameter and one given parameter. In reality, there are two varying given parameters (θ and τ) described above in this paper. In this part, how to tune one tuning parameter according to two varying given parameters will be analyzed. Some 3-Dimensional figures are plotted as shown in Fig. 9 and Fig. 10.

In Fig. 9, all vehicles use the same controller parameters, $k_p = k_d = 0.5$. It shows that the minimum headway time should be increased with increasing vehicle time constant and that communication delay time and headway time should be selected in the area above the surface to maintain string stability. If the headway time is selected under the surface, the heterogeneous platoon is not string stable. If the communication delay time of different vehicles is the same, vehicles with slow dynamics should have bigger headway time than those with fast dynamics, which corresponds with the results in Fig. 4. If vehicles have the same dynamics, the vehicles with bigger communication delay time should have bigger headway time, which corresponds with the results in Fig. 3. The heterogeneous platoon is always string stable no matter what value the headway time is when there is no communication delay time, which corresponds with the theoretical analysis and the simulation results in Fig. 3.

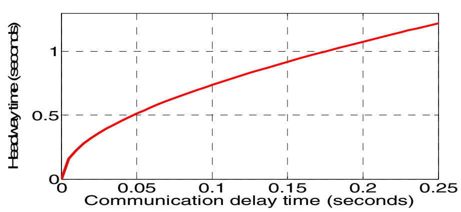

Fig. 3. Minimum headway time versus communication delay time.

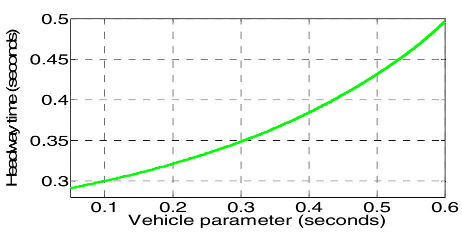

Fig. 4. Minimum headway time versus vehicle parameters.

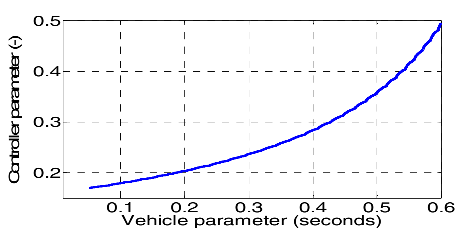

Fig. 5. Controller parameter versus vehicle parameter

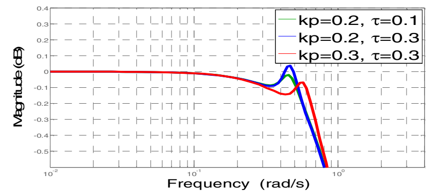

Fig. 6. String stability for different vehicles

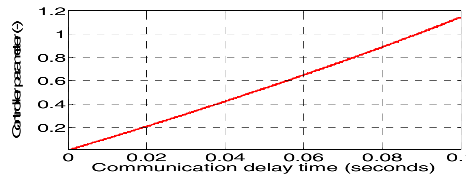

Fig. 7. Controller parameter versus communication delay

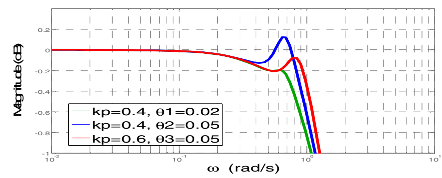

Fig. 8. String stability for different communication delay

In Fig. 10, all vehicles use the same headway time $h = 0.5$ seconds and the controller parameters are simplified as $k_p = k_d$. As can be seen, the minimum controller parameters should be increased with increasing vehicle time constant and communication delay time and controller parameter should be selected in the above area of the surface to realize string stability. If the controller parameter is selected under the surface, the heterogeneous platoon cannot maintain string stability. If the communication delay time of different vehicles is the same, vehicles with slow dynamics should have bigger controller parameters than those with fast dynamics, which corresponds with the results in Fig. 5. If vehicles have the same dynamics, the vehicles with bigger communication delay time should have bigger controller parameters, which corresponds with the results in Fig. 7.

An example is given to justify the analysis above. Three different vehicles compose a heterogeneous platoon. The vehicle time constants are 0.1 seconds, 0.3 seconds, 0.2 seconds for vehicle 1, vehicle 2 and vehicle 3 respectively. The communication delay times are 0.02 seconds and 0.03 seconds for vehicle 2 and 3 respectively. The feedback controller parameters are $k_p = k_d = 0.5$. The headway time is selected as 0.1 seconds for three vehicles. According to Fig. 9, the heterogeneous platoon cannot achieve string stability, while it is string stable if the headway time is selected as 1 second for three vehicles. This simulation is shown in Fig. 11.

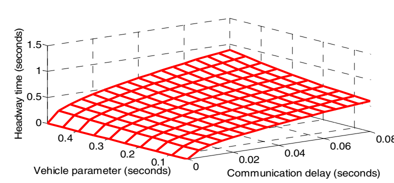

Fig. 9. Headway time versus vehicle parameters and communication delay

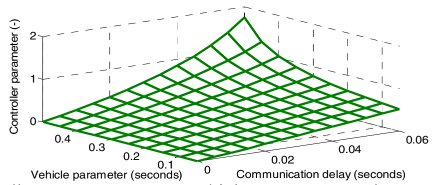

Fig. 10. Controller parameter versus vehicle parameters and communication delay

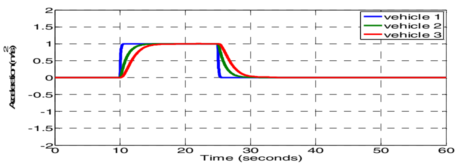

Fig. 11. String stability

V. CONCLUSIONS AND RECOMMENDATIONS

The goal of this paper is to provide guidelines on how to choose controller parameters and headway time for different vehicles with CACC systems under the condition that a heterogeneous platoon is string stable. The study on a heterogeneous vehicle platoon is simplified to the analysis on the relationship of five parameters under the condition that the heterogeneous vehicle platoon is string stable. A new feedforward controller is designed for a heterogeneous platoon with CACC systems to minimize the spacing error and eliminate the influence of the preceding vehicle parameter on the string stability transfer function.

The simulation results of a heterogeneous vehicle platoon show that string stability is influenced by the vehicle time constant and communication delay time. Choosing different controller parameters and headway time for a heterogeneous vehicle platoon can realize string stability. It is shown that controller parameters and the minimum headway time of slow dynamics vehicles should be selected bigger than those of fast dynamics vehicles. The controller parameters and the minimum headway time of vehicles with big communication delay time should be chosen bigger than those of vehicles with small communication delay time. The results could provide guidelines on how to choose controller parameters and headway time for different vehicles.

As future work, experiments on a heterogeneous vehicle platoon to verify the simulation and analysis results is suggested.

REFERENCES

[1] R. Ramakers, K. Henning, S. Gies, D. Abel, and M. Haberstroh, "Electronically coupled truck platoons on German highways," in *Conference Proceedings - IEEE International Conference on Systems, Man and Cybernetics*, 2009, pp. 2409–2414.

[2] S. Öncü, "String stability of interconnected vehicles: network-aware modelling, analysis and experiments," Ph.D. thesis, Eindhoven University of Technology, 2014.

[3] J. Ploeg, "Analysis and design of controllers for cooperative and automated driving," Ph.D. thesis, Eindhoven University of Technology, 2014.

[4] G. Naus, "Model-based control for automotive applications," Ph.D. thesis, Eindhoven University of Technology, 2010.

[5] J. Ploeg, B. T. M. Scheepers, E. Van Nunen, N. Van De Wouw, and H. Nijmeijer, "Design and experimental evaluation of cooperative adaptive cruise control," in *2011 14th International IEEE Conference on Intelligent Transportation Systems (ITSC)*, 2011, pp. 260–265.

[6] G. J. L. Naus, R. P. A. Vugts, J. Ploeg, M. (René) J. G. van de Molengraft, and M. Steinbuch, "String-stable cacc design and experimental validation: a frequency-domain approach," *IEEE Trans. Veh. Technol.*, vol. 59, no. 9, pp. 4268–4279, 2010.

[7] "Grand cooperative driving challenge." [Online]. Available: http://www.gcdc.net.

[8] E. van Nunen, M. R. J. A. E. Kwakkernaat, J. Ploeg, and B. D. Netten, "Cooperative competition for future mobility," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 3, pp. 1018–1025, 2012.

[9] E. Shaw and J. K. Hedrick, "Controller design for string stable heterogeneous vehicle strings," in *Proceedings of the IEEE Conference on Decision and Control*, 2007, pp. 2868–2875.

[10] E. Shaw and J. K. Hedrick, "String stability analysis for heterogeneous vehicle strings," in *Proceedings of the American Control Conference*, 2007, pp. 3118–3125.

[11] M. R. I. Nieuwenhuijze, "String stability analysis of bidirectional adaptive cruise control," Master's thesis, Eindhoven University of Technology, 2010.

[12] D. Yanakiev, J. Eyre, and I. Kanellakopoulos, "Analysis , design , and evaluation of AVCS for heavy-duty vehicles with actuator delays," California PATH research report, UCB-ITS-PRR-98-18, 1998.

[13] F. Bu, H.-S. Tan, and J. Huang, "Design and field testing of a cooperative adaptive cruise control system," in *Proceedings of the American Control Conference*, 2010, pp. 4616–4621.

[14] J. Mårtensson, A. Alam, S. Behere, M. A. A. Khan, J. Kjellberg, K.-Y. Liang, H. Pettersson, and D. Sundman, "The development of a cooperative heavy-duty vehicle for the GCDC 2011: Team Scoop," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 3, pp. 1033–1049, 2012.

[15] R. Kianfar, P. Falcone, and J. Fredriksson, "A receding horizon approach to string stable cooperative adaptive cruise control," in *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*, 2011, pp. 734–739.

[16] K. Lidström, K. Sjöberg, U. Holmberg, J. Andersson, F. Bergh, M. Bjäde, and S. Mak, "A modular CACC system integration and design," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 3, pp. 1050–1061, 2012.

[17] A. Ebadighajari, "Vehicle control in cooperative driving," Master's thesis, Chalmers University of Technology, 2011.

[18] C. Liang and H. Peng, "Optimal adaptive cruise control with guaranteed string stability," *Veh. Syst. Dyn.*, vol. 31, pp. 313–330, 1999.

[19] F. Morbidi, P. Colaneri, and T. Stanger, "Decentralized optimal control of a car platoon with guaranteed string stability," in *European Control Conference (ECC)*, 2013, pp. 3494–3499.

[20] J. Zhou and H. Peng, "Range policy of adaptive cruise control vehicles for improved flow stability and string stability," *IEEE Trans. Intell. Transp. Syst.*, vol. 6, no. 2, pp. 229–237, 2005.

[21] L. Xiao, S. Darbha, and F. Gao, "Stability of string of adaptive cruise control vehicles with parasitic delays and lags," in *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*, 2008, pp. 1101–1106.

[22] R. Rajamani and C. Zhu, "Semi-autonomous adaptive cruise control systems," *IEEE Trans. Veh. Technol.*, vol. 51, no. 5, pp. 1186–1192, 2002.

[23] P. Wang, Y. Wang, G. Yu, and T. Tang, "An improved cooperative adaptive cruise control (CACC) algorithm considering invalid communication," *Chinese J. Mech. Eng.*, vol. 27, no. 3, pp. 468–474, 2014.

[24] L. Xiao and F. Gao, "Effect of information delay on string stability of platoon of automated vehicles under typical information frameworks," *J. Cent. South Univ. Technol. (Engl. Ed.)*, vol. 17, pp. 1271–1278, 2010.

[25] J. Zhou and H. Peng, "String stability of adaptive cruise control systems with servo-loop dynamics," *J Automot. Saf. Energy*, vol. 1, no. 1, 2010.