Proceedings of International Structural Engineering and Construction, 9(2), 2022
Achieving Technical Excellence with Data Analytics
in Materials, Structural Engineering and Construction
Edited by Vimonsatit, S., Askarinejad, H., Singh, A., and Yazdani, S.

ISSN: 2644-108X
www.doi.org/10.14455/ISEC.2022.9(2).OTH-01

TRAFFIC SIMULATION CONSISTING OF VEHICLES IN PLATOON AND OTHER VEHICLES

EISKE KIA[1], DAISUKE ISHIZAWA[1], and TATSUHIRO TAMAKI[2]

[1]*Graduate School of Informatics, Nagoya University, Nagoya, Japan*
[2]*National College of Technology Okinawa, Nago, Japan*

Recently, traffic congestion has become a serious social problem all over the world as the number of vehicles increases. Traffic congestion causes economic loss, air pollution and traffic accident. For solving this problem, study on vehicle platooning using the technology of inter-vehicle communication has been studied widely. The vehicle platoon is a technique of grouping vehicles with a short inter-vehicle distance with help of electric and mechanical control, which is expected to reduce traffic congestion, and save labor and energy. However, when realizing platooning in the real world, the adequate control algorithm of the velocity of the vehicles in the platoon is necessary. In this study, the traffic situation is assumed so that the vehicles in the platoon and the other ones are travelling on the road. The vehicles in the platoon can keep their distance short by the help of inter-vehicle communication. The purpose of this study is to control the vehicle platoon safely without causing collision between vehicles when the sudden deceleration of the general vehicle in the platoon. The simulation and the experimental results showed that the proposal algorithms could control the vehicles without collision with the other vehicles and running backwards, while maintaining control of the velocity of the vehicles in the platoon.

Keywords: Velocity control, LEGO MINDSTORMS EV3, Lead vehicle, Autonomous.

1 INTRODUCTION

In recent years, with the increase in the number of automobiles owned worldwide, the traffic volume, mileage and fuel consumption of automobiles have consistently increased. In urban areas, traffic congestion due to traffic volume concentration is a major social problem because it not only causes time loss and economic loss and also causes pollution such as air pollution and noise due to exhaust gas. For solving this situation, research on traffic congestion has been conducted in various fields such as applied mathematics and traffic engineering. Especially in the field of information science, the development of Intelligent Transportation Systems (ITS) using the technology of vehicle-to-vehicle communication has been studies widely (ITS).

As a technology using vehicle-to-vehicle communication, vehicle platooning is one of very interesting technologies. It is a traveling method that electronically connects several vehicles to form a platoon, and therefore, is expected to have energy-saving and labor-saving effects (Kita *et al.* 2014, Kita *et al.* 2016, Maiti *et al.* 2017, Kita and Yamada 2020, El-Zaher *et al.* 2021). One of the problems in platooning in the real world is that platooning vehicles that perform vehicle-to-vehicle communication and general vehicles that do not perform vehicle-to-vehicle communication coexist. Therefore, this study aims the control of the vehicle velocity when general vehicles that do not communicate with other ones are mixed in a group of platooning vehicles that travel by communicating between vehicles. First, the proposed model is simulated on a computer. Then, an actual machine experiment using LEGO MINDSTORMS EV3 will be conducted. Finally, the validity of the proposed model is quantitatively evaluated while comparing the actual machine experiment and the simulation results.

Section 2 describes the vehicle velocity control model. Section 3 describes the control model used in this study and its determination method. Section 4 shows the simulation and experimental results. Section 5 describes the conclusions and future issues.

2 VELOCITY CONTROL MODEL

2.1 Helly Model

The following model was proposed by Helly in 1959 (Helly 1959) as shown in Eq. (1):

$$\ddot{x}_n(t+\Delta t) = \alpha\big(\dot{x}_{n-1}(t) - \dot{x}_n(t)\big) + \beta\big(x_{n-1}(t) - x_n(t) - D_n(t)\big) \tag{1}$$

where $x_n(t)$ denotes the position of the n^{th} vehicle at the time t. The parameters α and β are sensitivities and Δt is the delay time. The function $D_n(t)$ is the ideal inter-vehicle distance which is given in Eq. (2):

$$D_n(t) = a + b\dot{x}_n(t) + c\ddot{x}_n(t) \tag{2}$$

where the parameters a, b and c are the parameters related to the velocity and the acceleration, respectively.

2.2 Multi-Leading Vehicles Helly Model

In this research, it is necessary to control the velocity as a vehicle formation while considering the behavior of general vehicles that interfere with the vehicle formation. In addition, when general vehicles are mixed in the formation, the leading vehicle accelerates and decelerates to create an inter-vehicle distance behind, and the following vehicle overtakes the general vehicle and enters behind the leading vehicle to return to the original vehicle formation. Therefore, it is necessary to refer not only to the velocity and inter-vehicle distance of the preceding vehicle including general vehicles, but also to the velocity of the leading vehicle in the procession. For the above reasons, in this study, the velocity of the vehicle is controlled using the multi-leading vehicles Helly model, which is an extension of the Helly model as follows (Eq. (3)).

$$\ddot{x}_n(t+\Delta t) = \alpha\big(\dot{x}_{n-1}(t) - \dot{x}_n(t)\big) + \beta\big(x_{n-1}(t) - x_n(t) - D\big) + \gamma\big(\dot{x}_1(t) - \dot{x}_n(t)\big) \tag{3}$$

where α and β are the sensitivities of the n^{th} vehicle to the $(n-1)^{\text{th}}$ vehicle, and γ is the sensitivity to the leader vehicle of the platoon. D is the desired value of the inter-vehicle distance. This model determines the acceleration according to the relative velocity with the nearest frontal vehicle, the distance between vehicles, and the relative velocity with the leading vehicle.

In the previous study (Kita *et al.* 2016), the actual traffic data were observed in Nagoya City, Japan and the term $D_n(t)$ is determined as the function of velocity $\dot{x}_n(t)$ and the acceleration $\ddot{x}_n(t)$ as shown in Eq. (4).

$$D_n(t) = 0.0029\big(\dot{x}_n(t)\big)^2 + 0.3049\ddot{x}_n(t) \tag{4}$$

Eq. (4) is different from Eq. (2). This is because Eq. (4) is determined from the actual evaluation data.

The parameter α, β and γ are estimated so that the following objective function is minimized (Eq. (5)).

$$J = w_1 T_{dv} + w_2 T_{dD} + w_3 v_{os} + w_4 D_{os} + w_5 v_{elim} + w_6 D_{elim} + w_7 S_{\Delta D} \tag{5}$$

where $T_{dv}, T_{dD}, v_{os}, D_{os}, v_{elim}, D_{elim}$ and $S_{\Delta D}$ denote the delay time for velocity, the delay time for the intervehicle distance, the overshoot for velocity, the overshoot for the intervehicle distance, the steady state deviation for velocity, the steady state deviation for the intervehicle distance and Integrated value with the target inter-vehicle distance, respectively (Table 1). The weight parameters are given as follows (Figure 1); $w_1 = w_2 = w_3 = w_4 = w_5 = w_6 = w_7 = 1$.

Figure 1. Vehicle platoon when a general vehicle is running immediately after the lead vehicle.

Table 1. Initial condition of each vehicle in deceleration experiment when a general vehicle is running immediately after the first following vehicle.

Vehicle	Position [cm]	Velocity [cm/s]	Acceleration [cm/s^2]
x_0	90	15	0
x_1	60	15	0
y	30	15	0
x_2	0	15	0

3 CONTROL ALGORITHM

This study aims the velocity control of vehicles when a general vehicle interrupts a group of platooning vehicles that perform vehicle-to-vehicle communication in the case of sudden deceleration of a general vehicle mixed in the platoon. A vehicle platoon is composed of one leader vehicle and two follower vehicles. A situation in which a general vehicle interrupts between the first and second follower vehicles are shown in Figure 1.

The initial conditions are acceleration of 0 [cm/s^2] and velocity of 15 [cm/s] for all vehicles, and the initial positions of the lead vehicle, the first follower vehicle, the general vehicle and the second follower vehicle are specified as 90, 60, 30 and 0 [cm]. Let the inter-vehicle distance of the vehicle be 10 [cm]. The reaction delay time in the vehicle following model is 0.2 [s], and the experiment is performed in 20 [s], that is, 100 steps. The general vehicle runs at a constant velocity of 15 [cm/s] between 0 [s] and 5 [s], and suddenly decelerates from 5 [s] to 7 [s]. It runs at a constant velocity of 5 [cm/s] between 7 [s] and 13 [s] and accelerates again at 13 [s] to 15 [s]. After that, it runs at a constant velocity of 15 [cm/s] between 15 [s] and 20 [s]. During that time, the leading vehicle runs at a constant velocity of 15 [cm/s], and the first follower vehicle and the second follower vehicle follow the vehicle following models. The velocity control models for all vehicles are summarized as follows shown in Eq.s (6-9):

(1) Velocity control of the leading vehicle x_0:

$$\dot{x}_0(t) = 15.0 \tag{6}$$

(2) Velocity control of the first follower vehicle x_1:

$$\ddot{x}_1(t + \Delta t) = \alpha_1\big(\dot{x}_0(t) - \dot{x}_1(t)\big) + \beta_1(x_0(t) - x_1(t) - 10) \tag{7}$$

(3) Velocity control of the general vehicle y:

$$
\begin{array}{ll}
0 < t < 5 & \dot{y}(t) = 15 \\
5 < t < 7 & \dot{y}(t) = 15 - 5(t - 5) \\
7 < t < 13 & \dot{y}(t) = 5 \\
13 < t < 15 & \dot{y}(t) = 5 + 5(t - 13) \\
15 < t < 20 & \dot{y}(t) = 15
\end{array} \tag{8}
$$

(4) Velocity control of the second follower vehicle x_2:

$$\ddot{x}_2(t + \Delta t) = \alpha_2\big(\dot{y}_0(t) - \dot{x}_2(t)\big) + \beta_2(y_0(t) - x_2(t) - 10) + \gamma_2(\dot{x}_0(t) - \dot{x}_2(t)) \tag{9}$$

The parameters in Eq. (8) and Eq. (10) are determined by minimizing Eq. (6), which are shown in Table 2.

Table 2. Parameters in velocity control models of first and second follower vehicles.

Vehicle	α	β	γ
x_1	1.00	1.00	---
x_2	1.00	0.48	0.01

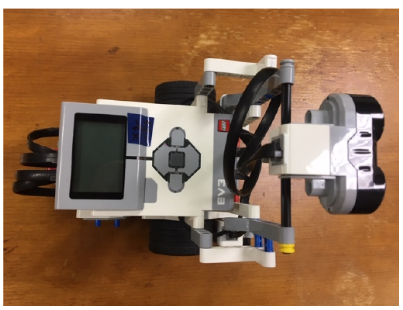

Figure 2. LEGO MINDSTORMS EV3.

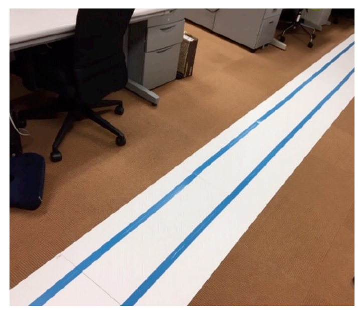

Figure 3. Experimental course.

4 EXPERIMENTAL RESULTS

4.1 Robot Vehicle

LEGO MINDSTORMS is an autonomously operating robot developed by LEGO Inc. of the United States. It is possible to combine parts such as ultrasonic sensors and motors and operate them by a program. In this research, an actual machine experiment is performed by using LEGO MINDSTORMS EV3 (Figure 2) which is programmed using "LEGO MINDSTORMS EV3 Home Edition" (TOPPERS/EV3 Platform 2019, LEGOeducation 2019). The experimental course is shown in Figure 3. The body length of LEGO MINDSTORMS EV3 is about 20 [cm]. According to the Japan Trucking Association, the total length of the semi-trailer connected vehicle is 18 [m], so the scale ratio with the actual vehicle is about 100:1. According to the actual vehicle platoon, the desired value of the inter-vehicle distance is determined as $D = 10$ [cm].

4.2 Evaluation Method

In this study, the validity of behavior and control algorithms is quantitatively evaluated using the mean absolute error and the correlation coefficient regarding the position and velocity of the vehicle in the simulation and the actual experimental results.

The mean absolute error (MAE) is defined as follows in Eq. (10):

$$MAE = \frac{1}{T}\sum_{t=1}^{T}|E_t - S_t| \tag{10}$$

where T is the total number of simulation steps, E_t is the value of the actual machine experiment in step t, and S_t is the value of the simulation in step t.

The correlation coefficient (CC) for the position of each vehicle is calculated by Eq. (11).

$$CC = \frac{\sum_{t=1}^{T}(E_t - \bar{E})(S_t - \bar{S})}{\sqrt{\sum_{t=1}^{T}(E_t - \bar{E})^2}\sqrt{\sum_{t=1}^{T}(S_t - \bar{S})^2}} \tag{11}$$

where T is the total number of steps, and $\bar{E}$ and $\bar{S}$ are the average values of E_t and S_t for all steps, respectively.

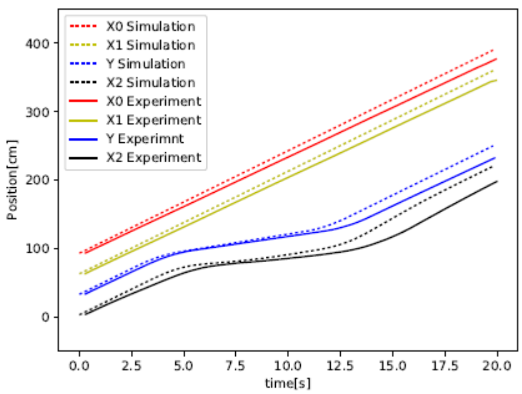

Figure 4. Comparison of position in actual machine experiment and simulation.

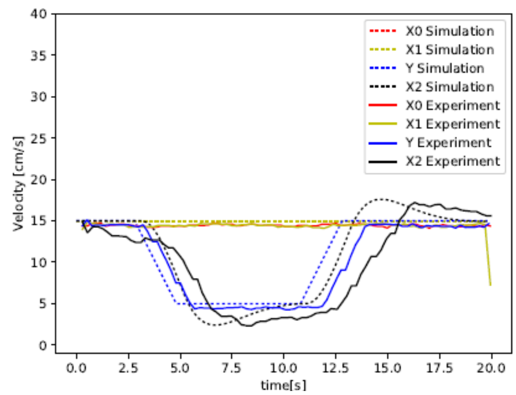

Figure 5. Comparison of velocity in actual machine experiment and simulation.

Table 3. Absolute average error regarding vehicle position and velocity.

Vehicle	MAE of position [cm]	MAE of velocity [cm/s]
x_0	9.279	0.540
x_1	9.205	0.553
y	8.175	1.303
x_2	13.678	2.421

Table 4. Correlation coefficient for vehicle position.

Vehicle	x_0	x_1	y	x_2
Correlative coefficient	0.999	0.999	0.998	0.992

4.3 Comparison of Experiment and Simulation

The simulation and the actual experimental results are shown in Figures 4 and 5. The comparison of vehicle positions is shown in Figure 4. The figure is plotted with the time as the horizontal axis and the position as the vertical axis, respectively. The solid and the dashed lines denote the experimental and simulation results, respectively. The experimental results are in good agreement with the simulation results, except for the delay. The comparison of vehicle velocities is shown in Figure 5. The figure is plotted with the time as the horizontal axis and the velocity as the vertical axis, respectively. The results of vehicle x_0 and x_1 are very similar in both simulation and experimental results. This is the matter of course because they drive at constant velocity. The results of other vehicles are also in good agreement in both simulation and experiment, except for the delay. The results show that the velocities of the vehicle x_0 and x_1 in the experiment are slightly smaller than those in the simulation. The timing of the velocity change of the vehicle y is shifted backward. Therefore, the timing of the velocity change of the vehicle x_2 is also shifted backward. This is thought to be due to the delay in the reaction time of the actual machine and the error in the motor output.

In addition, the absolute average error regarding position and velocity for each vehicle is shown in Table 3. The correlation coefficient for the position of each vehicle is shown in Table 4. Due to the reaction delay time of the actual machine, the absolute average error regarding the position and the velocity of the vehicle increases toward the rear of the vehicle platoon. On the other hand, the absolute average error regarding the position is about 14 [cm] at the maximum, which is equivalent to 3.5 [%] for the mileage of 4 [m]. In addition, the correlation coefficients are all close to 1.

From the above, it can be said that the control algorithm in this research is also effective for the actual machine.

5 CONCLUSION

This study focuses on the algorithm to control the vehicle so that it can drive safely without collision when a general vehicle that does not communicate interrupts the platoon of three vehicles that travel by communicating between vehicles in mixed traffic. The velocity control model is defined based on Helly model. The model parameters are determined by solving the optimization problem. The validity of the models with optimized parameters was discussed in simulation and experiment of LEGO MINDSOTRM EV3. The results show that the proposed algorithm can form a platoon in mixed traffic situation safely. On the other hand, it was found that the error in the actual machine experiment became larger when the number of platooning vehicles traveling behind the general vehicle increased.

Acknowledgments

This work was supported by JSPS KAKENHI Grant Number 19K04140.

References

El-Zaher, M., Dafflon, B., Gechter, F., and Contet, J.-M., *Vehicle Platoon Control with Multi-configuration Ability*, Procedia Computer Science, 9, 1503-1512, 2012.

Helly, W., *Simulation of Bottlenecks in Single-Lane Traffic Flow*, Theory of Traffic Flow, 207-238, 1959.

Kita, E., and Yamada, M., *Vehicle Velocity Control in Case of Two Vehicle Platoon Merging into One Vehicle Platoon*, International Journal of Machine Learning and Computing, 10(5), 612-617, 2020.

Kita, E., Asahina, K., Ushida, C., Wakita, Y., and Tamaki, T., *Vehicle Platoon Simulation Based on Multi-Leader Vehicle Following Model*, Proceedings of the 9th International Conference on Engineering Computational Technology, 83, 2014.

Kita, E., Takaue, H., Yamada, M., and Sakamoto, H., *Simulation of Vehicle Separated from Vehicle Platoon*, 24th International Congress of Theoretical and Applied Mechanics (ICTAM 2016), Montreal, Canada, August 22-26, 2016.

LEGOeducation, 2019. Retrieved from www.legoeducation.jp/mindstorms on March 1, 2019.

Maiti, S., Winter, S., and Kulik, L., *A Conceptualization of Vehicle Platoons and Platoon Operations*, Transportation Research Part C: Emerging Technologies, 80, 1-19, 2017.

TOPPERS/EV3 Platform, 2019. Retrieved from http://dev.toppers.jp/trac_user/ev3pf on March 1, 2019.