Designing Fuzzy VSPID Controller for Vehicle Speed Control

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Abstract

A new method for adjusting PID parameters in a variable-structure fashion, based on fuzzy logic, is presented in this paper. In this method, the PD control mode is being used for a faster response when large errors are present, and the PI control mode has been used in order to eliminate the steady-state errors. The control mode of VSPID is being changed during transient state of the system. The proposed controller is applied to vehicle velocity-control problem. The simulation results show a better performance for the proposed fuzzy variable-structure PID controller.

Keywords: fuzzy control; variable-structure control; PID control; velocity control

1-INTRODUCTION

The PID controller has been extensively used in control applications. This is mainly due to the fact that despite the simple structure and ease of design of this controller, it still has some degree of robustness. In PID control method, three parameters, namely proportional, integral, and derivative, are being determined in such a way that the response of the system is satisfactory. The proportional part of the PID controller has an important role in determining the overshoot and the rise time, while the integral part reduces the steady-state error, and the derivative portion of the controller is mainly responsible for the stability of the closed-loop system and the smoothness of the response. But the major limitation of PID controller is that its response is only acceptable if the system is working around the operating point, especially when the nonlinearity of the system is complicated. Hence, there is need for more sophisticated control method [1]. Several methods have been proposed in the literature to overcome the weaknesses of the PID controller. Among these methods, there are Zeigler-Nichols PID [10], fuzzy PID [9], and P-fuzzy + conventional ID [4]. In the proposed method in this paper, first the PID coefficients are determined using Zeigler-Nichols method, which guarantee the stability of the system. Then, the coefficients are fine-tuned using fuzzy logic method. Finally, the PID parameters are being adjusted during the operation of the system, using Variable-Structure PID (VSPID) control method. In the VSPID controller, the PD state is being used to increase the speed of the response and the PI state is for reduction of the steady-state errors. The structure of this controller changes according to the instantaneous error signals, based on a predefined algorithm [1]. In the case of fuzzy VSPID (FVSPID), these changes are performed using fuzzy logic method. Also, The fuzzy rules for the proposed FVSPID controller have been generated intuitively. For the first time, Dimler Company performed the velocity control of vehicles on Mercedes. Since the performance of the conventional nonlinear control methods was not satisfactory and because of the ability of fuzzy logic in modeling, identifying, and controlling highly nonlinear systems with uncertainty in their parameters, Dimler Company started to use fuzzy logic for velocity control of vehicles [5]. Since the velocity control of vehicles with changes in the environment is a difficult task, the proposed FVSPID control method is tested with this problem and the results are compared with Zeigler-Nichols PID (ZNPID) and Fuzzy PID (FPID).

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2-PID CONTROLLERS

2.1. Zeigler-Nichols PID Controller

The proper performance of the PID controller depends on defining the correct coefficients. Zeigler and Nichols [10] have proposed a method for adjusting the control gains, in which, first the integral and the derivative gains are set to zero, then the proportional gain is increased until the system starts to oscillate. This is called the critical point and it is characterized with T_{critical} and $K_{p_{\text{critical}}}$. Zeigler and Nichols suggest the following PID gains for the gain margin equal to 2:

$$
\begin{aligned}
K_p &= 0.6\, K_{p_{\text{critical}}} \\
K_I &= \frac{2\, K_p}{T_{\text{critical}}} \qquad (1) \\
K_D &= 0.12\, K_{p_{\text{critical}}}
\end{aligned}
$$

2.2. Variable-Structure PID

Two important aspects in VSPID design are: 1) the static precision (e.g. the steady-state error) and 2) the dynamic sensitivity (e.g. the speed of the response). The VSPID controller has a flexible structure in which the changes between different control modes (i.e. from PI to PID and then to PD and vise versa) are defined continuously using a predefined procedure. The structure of this controller is based on the instantaneous value of the error. Chen and Chang [1] have proposed the following control signal:

$$
\begin{aligned}
u(t) = c_1 + k_p(t)\, e(t) + \alpha\, k_d(t) \frac{de(t)}{dt} \\
+ (1-\alpha)\, k_i(t) \int_0^t e(\tau)\, d\tau
\end{aligned} \qquad (2)
$$

where c_1 is a constant, and $\alpha \in [0,1]$ is a continuous function of error

$$
\begin{aligned}
\alpha(t) &= \tanh\left(\tau\, \beta(t)\right) \\
\beta(t) &= \begin{cases} |e(t)| - \varepsilon & \text{if } |e(t)| \geq \varepsilon > 0 \\ 0 & \text{if } |e(t)| \leq \varepsilon \end{cases}
\end{aligned} \qquad (3)
$$

in which ε is a predefined positive constant. According to Eqs. (3), for very large and very small errors we may write

$$
\alpha(t) = \begin{cases} 1 & \text{if } |e(t)| \quad \varepsilon \\ 0 & \text{if } |e(t)| \quad \varepsilon \end{cases} \qquad (4)
$$

That is, for $\alpha = 0$ the controller acts as a PI controller, for $\alpha = 1$ it is a PD controller, and for α between 0 and 1 it behaves like a PID controller. The value of τ in Eqs. (3) defines the slope of change of α between 0 and 1.

2.3. Fuzzy Variable-Structure PID

In the proposed controller in this paper, the variable-structure PID coefficients are defined using fuzzy logic. Fig. 1 shows the block diagram of the proposed Fuzzy Variable-Structure PID (FVSPID) controller.

The fuzzy system composes of three fuzzy subsystems, each with two inputs (the error e and the derivative of that $\dot{e}$) and one output, which adjust the value of K_p, K_d, and K_i at each step of the time. There are 4 membership functions for every input to the fuzzy system. Hence, there are 16 fuzzy IF-THEN rules for each fuzzy subsystem. These rules, that is found intuitively for K_p, K_d, and K_i, are shown in Tables 1, 2, and 3, respectively. The membership functions for all variables in fuzzy system are shown in Figs. 2, 3, 4, and 5. In these Figs.

$$
\begin{aligned}
b &= \gamma\, a \\
c &= \delta\, a \qquad (5) \\
d &= \lambda\, a
\end{aligned}
$$

where the positive contestants γ, δ, and λ have been introduced to adjust the maximum value of the universe of discourse for K_p, K_d, and K_i, relative to the universe of discourse of e and $\dot{e}$ for different plants. These constants can be found by having some experience about the system under study and a few trial and errors.

3. SIMULATION RESULTS

The simulation example is the velocity control of vehicle, which is a highly nonlinear system with differential equations of order 6. The dynamic equations usually include the engine, clutch, gearbox, and differential. These equations, along with the chosen parameters for the vehicle, are given in the appendix. In order to show the performance of the proposed FVSPID, the simulation results have been compared with ZNPID and FPID. The PID coefficients for ZNPID controller have been found as

$$
\begin{aligned}
K_p &= 13.2 \\
K_I &= 66 \\
K_D &= 1
\end{aligned}
$$

and the constants in Eq. (5) for FVSPID are

$$
\begin{aligned}
a &= 10, \quad \gamma = 5 \\
\delta &= 2, \quad \lambda = 10
\end{aligned}
$$

The simulations have been performed in two parts. In the first case, the vehicle is following a reference velocity, while in the second case the vehicle is following a second vehicle, which changes its velocity at different time instances. Variations in road conditions and changes in wind velocity have also been considered. Fig. 6 shows the step response of the system for the final velocity of 10 m/sec, when the vehicle is moving on a leveled road and there is no wind. As this Fig. shows, all three controllers have very small steady-state errors, but the FVSPID has much smaller overshoot and undershoot as compared to other controllers. Then, at $t = 2$ sec some changes takes place in the environment conditions. That is, the vehicle enters a downhill with a slope of 30° while the road friction coefficient changes from $K_r = 0.6$ (dry road) to 0.2 (snowy road) and wind is blowing towards the moving direction of the vehicle with a velocity of 4 m/sec. The results have been shown in Fig. 7. In the second part of the simulations, the vehicle is following another vehicle with a changing velocity profile. It is assumed that there is a safely clearance between two vehicles, which depends on the speed of the pursuing vehicle. Both vehicles are moving on a leveled road with no wind. Then, at time 1 second the front vehicle changes its speed from 10 m/s to 15 m/s, followed by another change in its speed from 15 m/s back to 10 m/s at time 2 second. Fig. 8 shows the simulation results. It is obvious that the FVSPID performs much better than the FPID and ZNPID. Next, at the time of deceleration (i.e. at $t = 2$ sec), both vehicles come to a snowy road, where it is assumed that the front vehicle can accelerate and decelerate much like on a dry road (e.g. it has snow tires), while the controlled vehicle is not equipped with snow tires. As the plots in Fig. 9 show, the FVSPID outperforms the other PID controllers. In all the cases up to this point, all controllers are able to keep the safety distance from the front vehicle. In the next two cases, the limits of the ZNPID FPID will be tested. Fig. 10 shows a case where the front vehicle changes its speed from 20 m/s to 30 m/s at $t = 1$ sec and again from 30 m/s back to 10 m/s at $t = 2$ sec . In addition, both vehicles come to a snowy road at the time of deceleration. In this condition, the distance form the front vehicle for ZNPID and FPID becomes negative, which corresponds to a collision, while the FVSPID can still keep some distance from the front vehicle.

4. CONCLUSION

The fuzzy variable-structure PID control method was presented in this paper. In this method, first the PID coefficients have been determined using Zeigler-Nichols method, which guaranties the stability of the system. Then, the PID coefficients are fine-tuned using a fuzzy system. Finally, the PID parameters have been adjusted during the operation of the system, using Variable-Structure PID (VSPID) control method. The simulation results for the velocity control of a vehicle show a much better performance of the proposed method as compared to the Zeigler-Nichols PID controllers and fuzzy PID controllers.

5. REFERENCES

[1] Chen, C.L. and Y.F. Chang (1996). Design and analysis of neural/fuzzy variable structural PID control systems. *IEE Proceedings-Control Theory Applications*, **Vol. 143**, **No. 2**, pp 200-208.

[2] Fritz, H. (1996). Model-based neural distance control for autonomous road vehicles. *IEEE Intelligent Vehicle Symposium*, pp. 29-34.

[3] Kang, J.M. and J.W. Grizzle (1999). Nonlinear control for joint air and fuel management in a SI engine. *American Control Conference*, **Vol. 2**, pp. 1040-1045.

[4] Li, W. (1998). Design of a hybrid fuzzy logic proportional plus conventional integral-derivative controller. *IEEE Transactions on Fuzzy Systems*, **Vol. 6**, **No. 4**, pp. 449-463.

[5] Muller, R. and G. Nocker (1990). Intelligent cruise control with fuzzy logic. *Symposium on Intelligent Vehicles*, pp.173-178.

[6] Puskorius, G.V. and L.A. Feldkamp (1994). Truncated backpropagation through time and Kalman filter training for neurocontrol. *IEEE International Conference on Computational Intelligence*, pp. 2488-2492.

[7] Trebi-Ollennu, A. and J.M. Dolan (1999). Adaptive fuzzy throttle control for a terrain vehicle. *Institute for Complex Engineered Systems, Carnegie Mellon University, Internal Report.*

[8] Vachtsevanos, G.J., S.S. Farinwata, and D.K. Pirovolou (1993). Fuzzy logic control of an automotive engine. *IEEE Control System Magazine*, **Vol. 13**, **No. 3**, pp. 62-68.

[9] Wang, L.X. (1997). *A Course in Fuzzy Systems and Control*, Prentice Hall, New Jersy.

[10] Zeigler, J.G. and N.B. Nichols (1942). Optimum setting for automatic controllers. *Trans. Assoc. Soc. Mech. Eng.*, **Vol. 8**, pp. 759-768.

6. APPENDIX

The dynamic model is composed of two parts: 1) engine model and 2) vehicle model.

6.1. The Engine Model

The engine of a vehicle consists of different parts like manifolds, throttle valve, cylinders, pistons, and crankshaft. The state equation for the air mass inside fuel throttle can be written using the mass conservation law as follows [6]:

$$\dot{m}_a = \dot{m}_{ai} - \dot{m}_{ao}$$

where $\dot{m}_{ai}$ and $\dot{m}_{ao}$ are the inlet and outlet air flow rates, respectively, which can be calculated using the following equations:

$$\dot{m}_{ai} = (1 + .907\theta + .0998\theta^2)g(P)$$

$$\dot{m}_{ao} = -0.057N - 0.133P + 0.059NP + 0.001NP^2$$

$$m_{ao} = \dot{m}_{ao}(t-\tau), \qquad \tau = \frac{45}{N}$$

where θ is the valve-valve angle, P is the manifold pressure, N is the engine velocity, and $g(P)$ is function of manifold pressure, which can be obtained using following equation:

$$g(P) = \begin{cases} 1 & P < 50.66 \\ 0.0197(101.325P - P^2) & P \geq 50.66 \end{cases}$$

The manifold pressure rate can also be defined as

$$\dot{P} = K_P(\dot{m}_{ai} - \dot{m}_{ao}), \qquad K_p = 42.4$$

The ignition and torque-generating model is the same as Dubner proposed model with minor modifications. The advance spark parameter has been defined in [3] as follows:

$$SA = \delta = -37.44 + 0.041\omega_e - 0.001\omega_e^2$$

$$\omega_e = \frac{2\pi}{60}N$$

The generation of torque, according to Vachtsevanos et al. [8] is

$$T_i = -39.22 + \frac{325024}{120N}m_{ao} - 0.01\delta^2 + 0.06\delta\frac{2\pi}{60}N + 0.63\delta + 0.021N\frac{2\pi}{60} - 0.001\left(\frac{2\pi}{60}\right)^2 N^2$$

Also, the engine acceleration can be defined as

$$\dot{N} = K_N(T_i - T_L), \qquad K_N = 54.26$$

where T_L is load torque.

6.2. The Vehicle Model

The vehicle model consists of three parts 1) transmission, 2) differential, and 3) tires. The automatic transmission contains of torque converter and automatic gearbox. According to Fritz (1996)

$$\dot{\omega}_e = \frac{T_e - 0.6T_t}{J_e}$$

And in [7]

$$\dot{\omega}_e = \frac{T_e - T_f - T_L}{J_e}, \quad T_f = d_1N + d_2, \quad T_e = KT_i$$

In the above equations, T_e is the driving torque after clutch, T_t is the driving torque applied to the wheels, J_e is the engine moment of inertia, and d_1 and d_2 are constants. In [2] the longitudinal motion of the vehicle is described as

$$\dot{\omega} = \frac{T_t i_g i_d \eta_g \eta_d - T_{ex}}{J_e i_d^2 \eta_d + J_d + 4J + mr^2}$$

where i_d and i_g are the gear ratios in automatic transmission and rear-axle differential, respectively, and η_d and η_g are the efficiency coefficients in automatic transmission and rear-axle differential, respectively. Also, J_d, J_g, and J are the moment of inertia of transmission, differential, and wheels, respectively, m is the mass of the wheels, and r is the radius of the tires. Table 4 shows the chosen parameters for simulations in section 3. The external torque applied to the vehicle T_{ex} can be calculated as

$$T_{ex} = T_w + T_r + T_c$$

where T_w is the aerodynamic resistance of the air, T_r is the rolling of the road, and T_c is the torque due to the slope of the road. These quantities can be calculated using the following equations:

$$T_r = K_r mg\cos(\alpha_s)r$$

$$T_c = mg\sin(\alpha_s)r$$

$$T_w = c(v - v_w)^2$$

where c is the aerodynamic coefficient of the air, v and v_w are the velocity of the vehicle and the wind, respectively, α_s is the slope of the road, r is the radius of the tires, K_r is the friction coefficient of the road, and g is the gravity acceleration. If the vehicle is equipped with anti-skid braking system, then, according to the following equations, the tire skids can be assumed zero:

$$v = r\omega, \quad i = 1 - \frac{v}{r\omega}$$

where ω is the angular velocity of the tires, v is the longitudinal velocity of the vehicle and i is the skid of the tires.

Table 4: Chosen parameters for simulations

i_g	5	J	5 Kgm^2
i_d	4	J_g	2.5 Kgm^2
η_g	60	J_d	1 Kgm^2
η_d	80	K	0.8
r	0.3 m	d_1	10
m	20 Kg	d_2	20

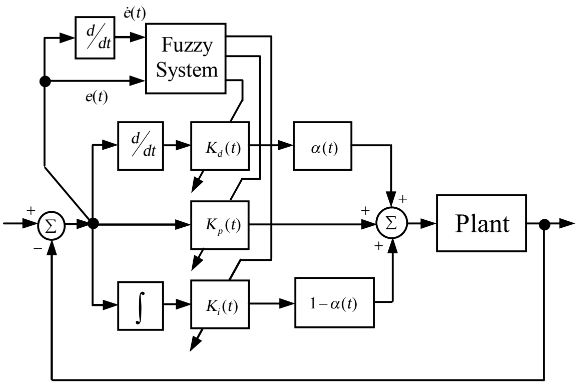

Fig. 1. The control system structure of fuzzy variable-structure PID

Table 1: The fuzzy rules for the proportional part of the VSPID controller

$\dot{e}$ \ e	S	M	L	VL
S	S	S	S	S
M	S	M	M	M
L	M	M	L	L
VL	VL	VL	VL	VL

Table 2: The fuzzy rules for the derivative part of the VSPID controller

$\dot{e}$ \ e	S	M	L	VL
S	VL	VL	VL	VL
M	L	L	M	M
L	VL	M	L	L
VL	S	S	S	S

Table 3: The fuzzy rules for the integral part of the VSPID controller

$\dot{e}$ \ e	S	M	L	VL
S	S	M	L	VL
M	S	M	M	M
L	M	M	L	L
VL	VL	VL	VL	VL

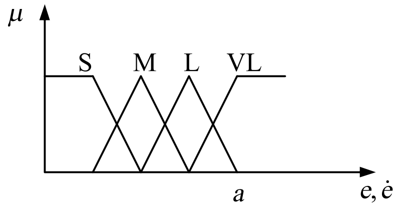

Fig. 2. Membership functions for the error and its derivative

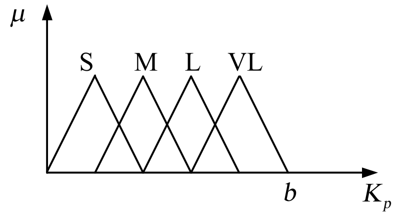

Fig. 3. Membership functions for the proportional part of the PID controller

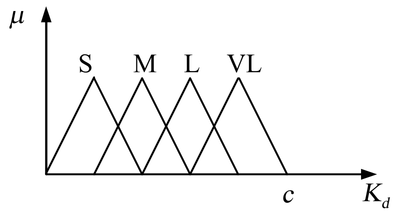

Fig. 4. Membership functions for the derivative part of the PID controller

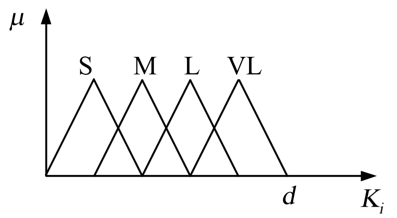

Fig. 5. Membership functions for the integral part of the PID controller

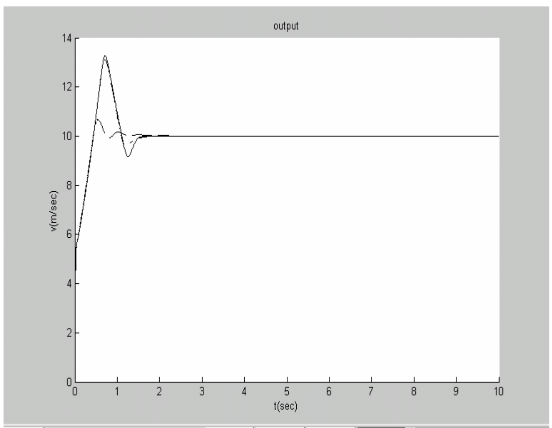

Fig. 6: Step response of ZNPID (—), FVSPID (--), and (·—) FPID.

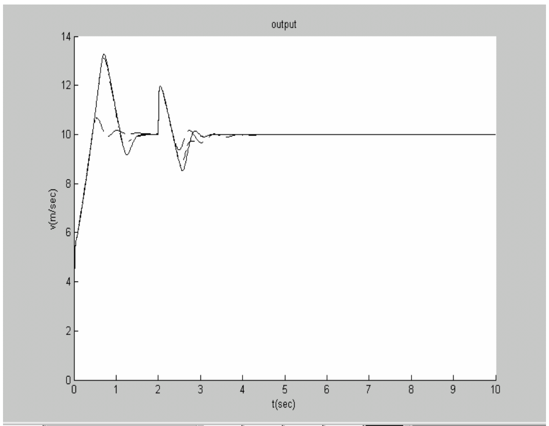

Fig. 7: Same as in Fig. 6, but when the environment conditions change at $t = 2$ sec .

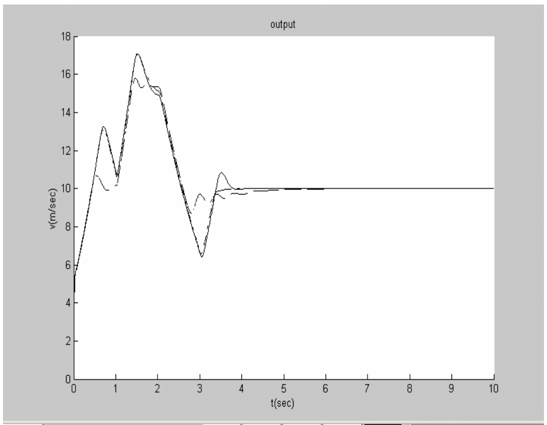

Fig. 8: The comparison of the control methods, when the vehicle is following a second vehicle with velocity profile shown in Fig. 11.

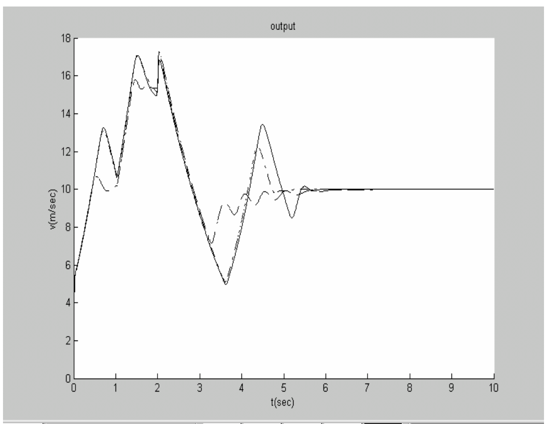

Fig. 9: Same as in Fig. 8, but when the road condition changes during deceleration of the front vehicle (i.e. at $t = 2$ sec).

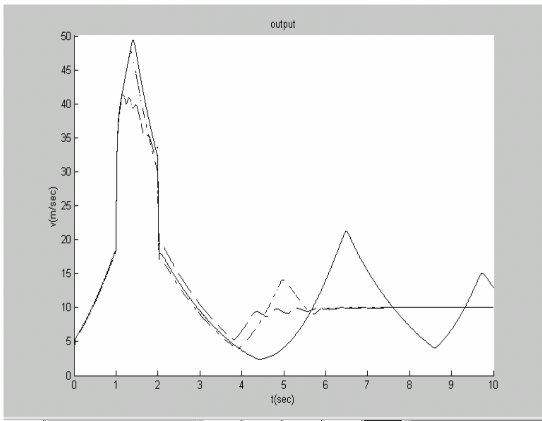

Fig. 10: Same as in Fig.9, but with the velocity profile of the front vehicle shown in Fig. 12. The Zeigler-Nichols PID and the FPID end up with negative distance from the front vehicle, which corresponds to a collision.

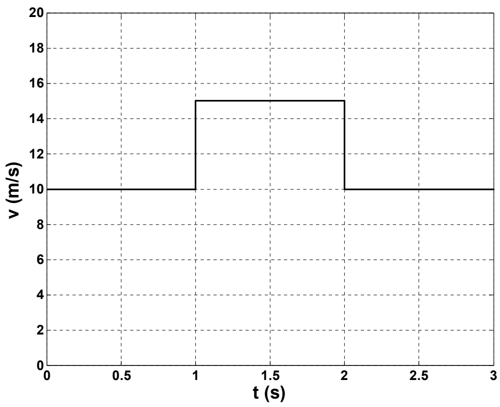

Fig. 11: The velocity profile of the front vehicle for the first scenario (Figs. 8 and 9).

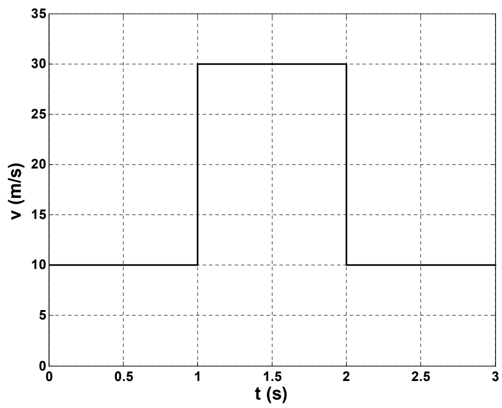

Fig. 12: The velocity profile of the front vehicle for the second scenario (Fig. 10).