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Effect of Vehicle-to-Vehicle Communication Latency on a Collision Avoidance Algorithm for Heavy Road Vehicles*

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Abstract— **Active safety is of utmost importance in heavy road vehicles due to the relatively higher number of fatalities encountered in their accidents. Vehicle-to-Vehicle (V2V) technology, which is seen as a future of connected vehicles, can potentially complement onboard sensing to reduce the time taken for detection, and to plan the path with the information available from road side units (RSU). This paper investigates the effect of latency in V2V communication on a collision avoidance algorithm developed for heavy road vehicles. Experiments performed on a Hardware-in-Loop (HiL) setup were used to evaluate the effect of latency for various scenarios. It was found that latency had a counterbalancing effect on vehicle spacing and relative longitudinal speed that led to insignificant changes in the final spacing. Further, a sensitivity analysis done at different host vehicle longitudinal speeds demonstrated the need of a variable time headway.**

I. Introduction

The development of Advanced Driver Assistance Systems (ADASs) to prevent accidents due to driver inattention has become important given the rising road accident fatalities. These systems are particularly important in countries such as India where the total number of road accidents was reported to be 5,01,423 in the year 2015 that resulted in 1,46,133 fatalities [1]. The percentage of accidents caused due to buses and other heavy road vehicles amounted to 28% despite their registered number being lower (5.4%). The most important cause of these accidents was drivers' fault, which was reported to be 77.1%. This situation is similar all over the world. For example, the Volvo trucks safety report showed that heavy vehicles amounted to 15% of road accidents in the European Union and 90% of them were due to human factors [2]. These numbers could be reduced by providing assistance to the driver such as collision avoidance warning systems and lane departure warning systems.

Most collision avoidance algorithms that are commercially available use on-board sensors to detect the lead vehicle (that is, the vehicle travelling ahead). It would be desirable that the information available from a vehicle be communicated to the surrounding vehicles and V2V communication is a technology that can aid in this exchange of information. This exchange of information takes place over an ad hoc network environment called Vehicular ad hoc network (VANET) where the nodes/routers are the moving vehicles. VANET consists of four major components viz., Vehicles, Devices/Sensors such as Global Positioning System (GPS) enabled devices, RSU and Traffic Management Centre (TMC) [3]. These components communicate with each other using wireless protocols. For safety applications, latency, transmission range and rate play an important role. Fast movement of vehicles/nodes poses a challenge to the data delivery and contact opportunities [4]. Dedicated Short-Range Communication (DSRC) addresses the challenges of high mobility, secure data transmission, low latency and dynamic topology for safety-related applications [5], [6]. When information is sent from one node to the other, communication latency comes into picture.

Latency is the end-to-end delay that is experienced in a network when a data packet is sent from one vehicle to the other vehicle. For vehicle safety-related applications, latency plays an important role because the lead vehicle position and speed would have changed by the time the host vehicle (that is the vehicle under focus) receives the information. A critical latency of 100 ms for a minimum transmission rate of 10 Hz was proposed for cooperative collision avoidance by National Highway Traffic Safety Administration (NHTSA) and United States Department of Transportation (USDOT), and also by European Telecommunications Standards Institute (ETSI) [8], [9]. In [10], V2V communication was used for the control of an automated emergency braking system but the effect of latency was not taken into consideration explicitly. In [11], V2V communication was used for cooperative car parking. In [12], timing of events in collision avoidance strategies was analyzed considering the effects of driver reaction time and delay in communication. From the literature survey, it was seen that the application of V2V for vehicle safety is more prevalent for passenger cars. Motivated by this gap, this research investigates the application of V2V for heavy road vehicle collision avoidance. In this paper, the Collision Avoidance Algorithm (CAA) presented in [13] was evaluated with communication latency and analyzed in a HiL setup with and without V2V communication latency. This algorithm takes into account the significant load variations that occur in heavy road vehicles and their brake actuator dynamics. The effect of latency on the final spacing and brake pressure has been studied and a sensitivity analysis was done at different speeds.

II. Collision Avoidance Algorithm with Latency

A. Vehicle Model

Schematic of a heavy road vehicle with two axle configuration indicating the forces is given in Fig. 1. Straight line braking was considered and the forces represented are the aerodynamic drag force (R_a), the rolling resistance force (R_{rf}: front, R_{rr}: rear), the braking force developed at the tires

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(F_{bf}: front, F_{br}: rear), and the weight of the vehicle (W). The mass of the vehicle are represented by M respectively. The equation for longitudinal motion of a vehicle moving on straight road is

$$Ma(t) = -R_a(t) - R_{rf}(t) - R_{rr}(t) - F_{bf}(t) - F_{br}(t). \tag{1}$$

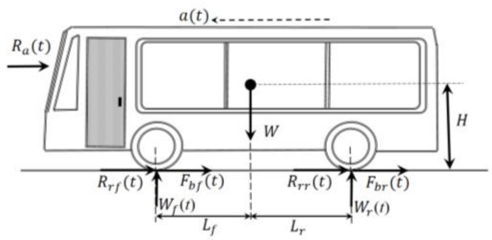

Fig. 1. Forces acting in the longitudinal direction.

B. Collision Avoidance Algorithm with Latency

The relative longitudinal speed ($v_r(t)$) and the distance between the rear of the lead vehicle and front of the host vehicle ($x_r(t)$) are used to detect the threat. The variables used in CAA are shown in Fig. 2. The absolute position from GPS, and the speed of the lead vehicle are considered to be transmitted through V2V communication. Relative distance and relative speed are then calculated and provided to the algorithm. Latency in the V2V communication is denoted by τ_c. It comes into picture when the information of the lead vehicle is sent to the host vehicle. The CAA has been evaluated to study the effect of latency. The CAA block diagram shown in Fig. 3, has two controllers. The Full State Feedback (FSF) controller was used in the outer loop and a brake controller in the inner loop to improve the brake system response. The equation for relative speed was reformulated as

$$v_r(t) = v_l(t-\tau_c) - v_h(t). \tag{2}$$

The desired safe distance (s_d) between the two vehicles that needs to be maintained is

$$s_d(t) = hv_h(t) + s_o, \tag{3}$$

where h is the time headway[1] and s_o is the headway offset (the final distance between the two vehicles when the host vehicle comes to rest). The value of h was taken as 1 s for unladen and 1.2 s for laden vehicle from the HiL analysis so that the host vehicle avoids a collision for all scenarios.

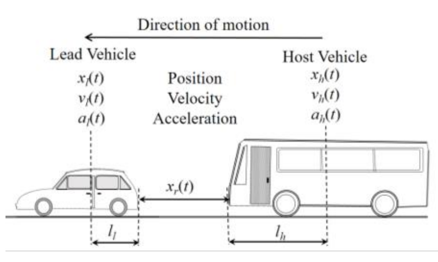

Fig. 2. Variables used in Collision Avoidance Algorithm.

[1] Time headway is defined as the time elapsed between the rear of the lead vehicle passing a point on a road to the time at which the front of the host vehicle passing the same point considering the prevailing speed of the host vehicle.

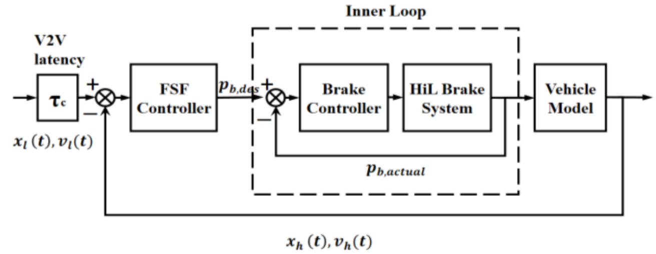

Fig. 3. Block diagram of Collision Avoidance Algorithm.

The distance between the rear of the lead vehicle to the point where a GPS device is installed on it is denoted by l_l and the distance from front of host vehicle to the point where GPS device is installed on it is denoted by l_h. The spacing between the vehicles x_r is modified as

$$x_r(t) = x_l(t-\tau_c) - x_h(t) - (l_l + l_h). \tag{4}$$

The difference between $s_d(t)$ and $x_r(t)$, denoted by $\delta(t)$, is

$$\delta(t) = x_r(t) - s_d(t). \tag{5}$$

The variable $e(t)$ as defined below was used to determine when the brakes should be applied and is given by

$$e(t) = \delta(t) + hv_r(t) = x_r(t) + hv_r(t) - s_d(t). \tag{6}$$

The system can be represented in the state-space form with $v_r(t)$ and $\delta(t)$ as the state variables. The state equation obtained was

$$\mathbf{x}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{b}_1 a_l(t-\tau_c) + \mathbf{b}_2 a_h(t). \tag{7}$$

An FSF controller was used to stabilize the system with the control input $u(t)$ being the acceleration of the host vehicle as given by

$$u(t) = a_h(t) = \mathbf{k}.\mathbf{x}(t) = k_1 v_r(t) + k_2\delta(t). \tag{8}$$

The values of the control parameters k_1 and k_2 (refer Table I) were found from the transfer function with v_r as output and v_l as input. The characteristic equation of the transfer function was

$$s^2 + (k_1 + hk_2)s + k_2 = 0. \tag{9}$$

This was equated to that of a critically damped second order system to avoid oscillations [13]. This CAA was implemented in the HiL setup with a two electro-pneumatic regulator (EPR) configuration. Latency was modeled as time delay that comes outside the loop. The results have been shown in the next section. The driver is warned when the value of $\delta(t) \leq 0$. Brakes were applied when the value of $e(t) \leq 0$. The brake force applied on the vehicle is given as

$$F_{bi,applied}(t) = \min(F_{b\max,i}(t), \mu_{\max}W_i(t), F_{bi,req}(t)), \tag{10}$$

where, i denotes (front, rear), $F_{bi,max}$ is the maximum braking capacity of the brake system, $\mu_{\max}W_i$ is the maximum longitudinal force the tire can sustain, and $F_{bi,req}$ is the braking force required to generate the desired deceleration in the vehicle. The brake system modelling along with the controller design for the available system was done in [15].

TABLE I. PARAMETERS USED IN COLLISION AVOIDANCE ALGORITHM.

	Unladen	Laden
Vehicle Weight	42732 N	152610 N
h	1 s	1.2 s
L_f	2.1 m	2.74 m
L_r	3 m	2.36 m
H	1 m	1.2 m
k_1	$1/h$	
k_2	$1/h^2$	
s_o	10 m	

III. HARDWARE-IN-LOOP EXPERIMENTAL RESULTS

HiL experiments were performed using the brake system hardware (refer to Fig. 4) and IPG/TruckMaker®, a vehicle dynamics software along with Matlab/Simulink®. The traffic scenarios, the lead and host vehicles, and the road surface with traction coefficient of 0.8 and 0.35, have been simulated using IPG/TruckMaker®. The position, speed, and acceleration of the vehicles were provided by the software. The scenarios simulated were:

1. Vehicle following: The host vehicle follows a lead vehicle (both moving at the same initial speed) and the lead vehicle starts decelerating and comes to rest.
2. Lead vehicle at rest: The host vehicle encounters a stationary lead vehicle.

Graphs have been plotted for $e(t)$, absolute brake pressure, control input, relative longitudinal speed, and spacing. Experiments were performed using the same values of k_1 and k_2 with and without latency. Tables II and III show the final spacing between the vehicles when the host vehicle has come to rest, and the time at which braking started for unladen and laden cases respectively. For example, a braking time of 2.3 s means that braking has started 2.3 s after the start of lead vehicle deceleration. It could be observed that the final spacing was not affected by latency. Also, a communication latency of 100 ms does not have effect on the time at which braking starts in the lead vehicle at rest scenario, while delays it by 20–30 ms in the vehicle following scenario. This is because, in the lead vehicle at rest scenario, the position and speed of the lead vehicle remain constant and the effect of latency was felt only at the first instant of time when the lead vehicle data are obtained.

Fig. 4. Hardware-in-Loop facility.

Figure 5 shows the profile of $e(t)$ and brakes are applied when it goes below zero. The corresponding brake pressure profiles are plotted in Fig. 6. The maximum brake force applied was limited by $\mu_{max}W$ since the weight of the unladen vehicle was lower. In the laden case, when the vehicle was moving on a dry road, the brake force was limited by the maximum braking capacity of the brake system. As the control input given was higher for the case of 100 ms latency (refer Fig. 7), brakes were applied for a longer time (about 80-100 ms).

Further, it was observed that the application of brakes was not delayed with latency by a significant amount to change the final spacing. This was because latency affected $v_r(t)$ and $x_r(t)$ in a counterbalancing manner, which can be seen in Fig. 8 and Fig. 9. From equation (6), it can be observed that $e(t)$ depends on $v_r(t)$ and $x_r(t)$. At the instant when the host vehicle started braking, the value of $x_r(t)$ was lower in the case with communication latency than without latency. But the value of $v_r(t)$ at this instant was higher with latency. Consequently, when $hv_r(t)$ and $x_r(t)$ are added, they counteract each other leading only to a 20-30 ms delay in braking with latency, which was not significant to affect the final spacing. To understand how sensitive the CAA was to different longitudinal speeds, a sensitivity analysis was performed.

IV. SENSITIVITY ANALYSIS

HiL experiments were performed at three different longitudinal speeds - 15 m/s, 20 m/s, and 25 m/s for the vehicle following and lead at rest scenarios on a dry road surface. Plots for the vehicle following laden scenario have been shown in Fig. 10. Table IV shows the final spacing with and without latency at different speeds, and the time at which braking started. It can be again inferred that the effect of latency is not significant on the final spacing (difference in the order of 10^{-2} m). From the acceleration and brake chamber pressure profiles, it was understood that at low speeds, full braking was not applied and the vehicle came to rest slowly over a period of time. This was due to the constant time headway policy. The time headway was chosen for a vehicle that moves at a speed of 20 m/s. Therefore, when the host vehicle moving at 15 m/s starts to brake, it has more distance available to come to rest. This was the reason for the mild control input given. The scenario was opposite when the speed was 25 m/s. The maximum brake force was limited and the distance within which the vehicle has to stop was also less. Hence, final spacing was less than 10 m. This analysis showed that the value of time headway needs to be adjusted based on the initial host vehicle longitudinal speed.

TABLE II. RESULTS FOR UNLADEN VEHICLE IN DIFFERENT SCENARIOS

	Unladen host vehicle						
	Initial v_l (m/s)	*Lead vehicle acceleration* a_l (m/s^2)	*Initial* v_h (m/s)	*Final Spacing* (m)		*Braking start time* (s)	
				Without latency	*With latency*	*Without latency*	*With latency*
Vehicle following:							
$\mu_{max} = 0.8$	20	-8	20	10.05	10.05	2.34	2.37
$\mu_{max} = 0.35$	10	-3.5	10	10.12	10.12	2.54	2.56
Lead vehicle at rest:							
$\mu_{max} = 0.8$	0	-	20	10.05	10.05	1.04	1.04
$\mu_{max} = 0.35$	0	-	10	10.08	10.08	1.06	1.06

TABLE III. RESULTS FOR LADEN VEHICLE IN DIFFERENT SCENARIOS

	Laden host vehicle						
	Initial v_l (m/s)	*Lead vehicle acceleration* a_l (m/s^2)	*Initial* v_h (m/s)	*Final Spacing* (m)		*Braking start time* (s)	
				Without latency	*With latency*	*Without latency*	*With latency*
Vehicle following:							
$\mu_{max} = 0.8$	20	-8	20	10.12	10.12	2.09	2.11
$\mu_{max} = 0.35$	10	-3.5	10	10.12	10.12	2.28	2.30
Lead vehicle at rest:							
$\mu_{max} = 0.8$	0	-	20	10.12	10.12	0.64	0.64
$\mu_{max} = 0.35$	0	-	10	10.12	10.12	0.64	0.64

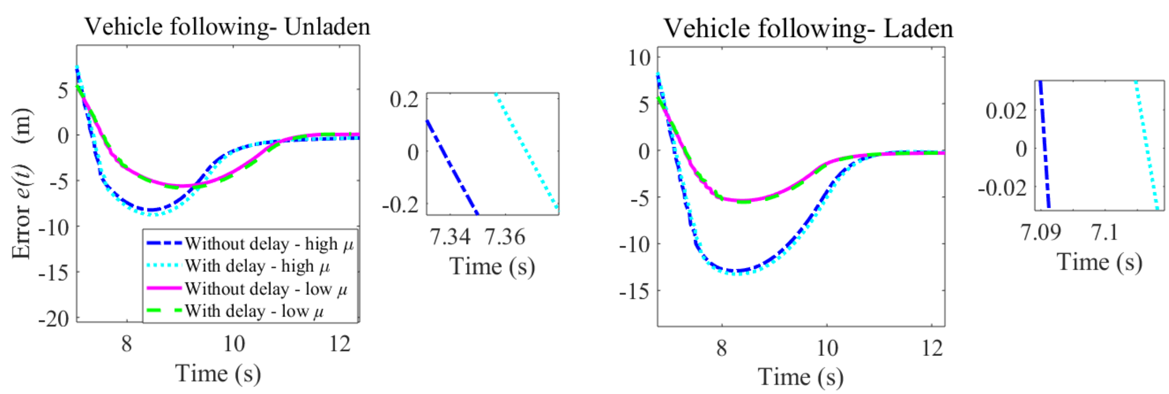

Fig. 5. Error $e(t)$ - Vehicle following.

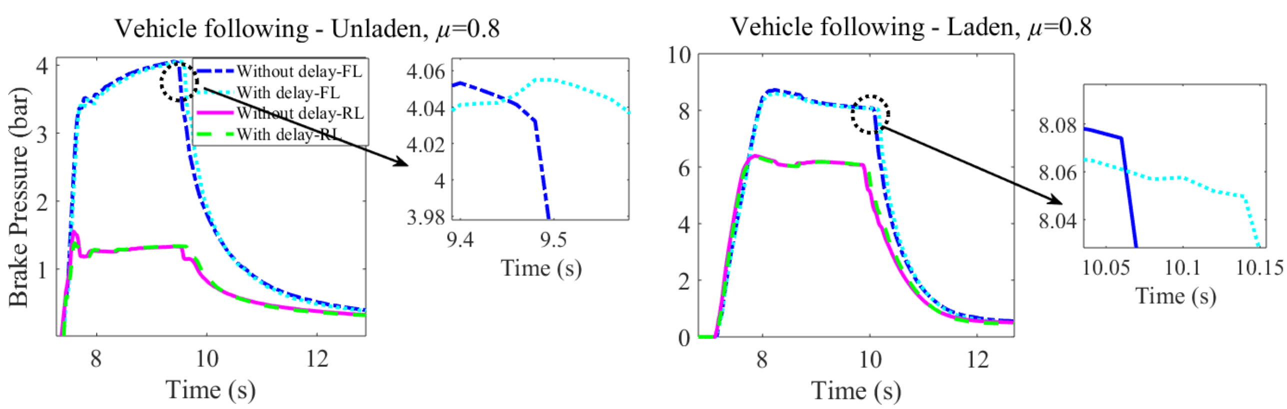

Fig. 6. Brake Chamber Pressures - Vehicle following.

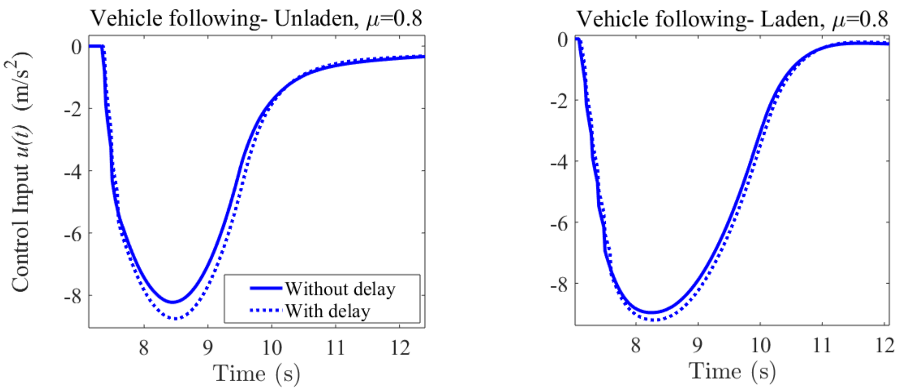

Fig. 7. Control Input $u(t)$ - Vehicle following.

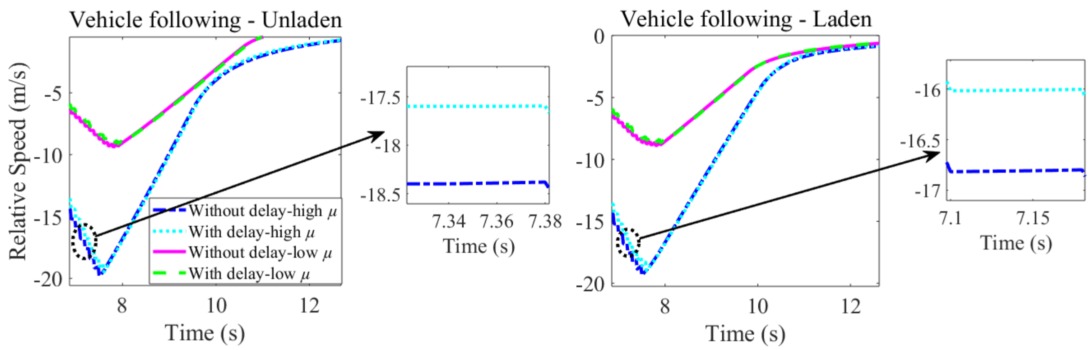

Fig. 8. Relative Speed - Vehicle following.

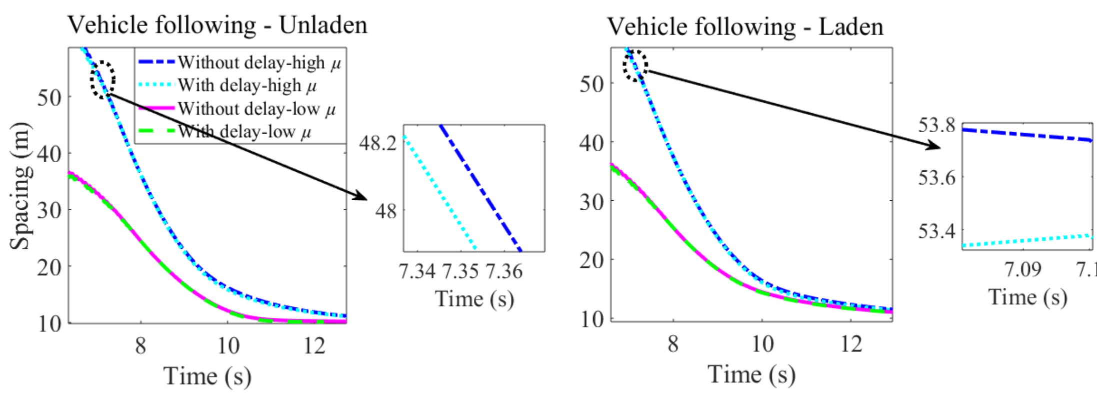

Fig. 9. Spacing between the vehicles - Vehicle following.

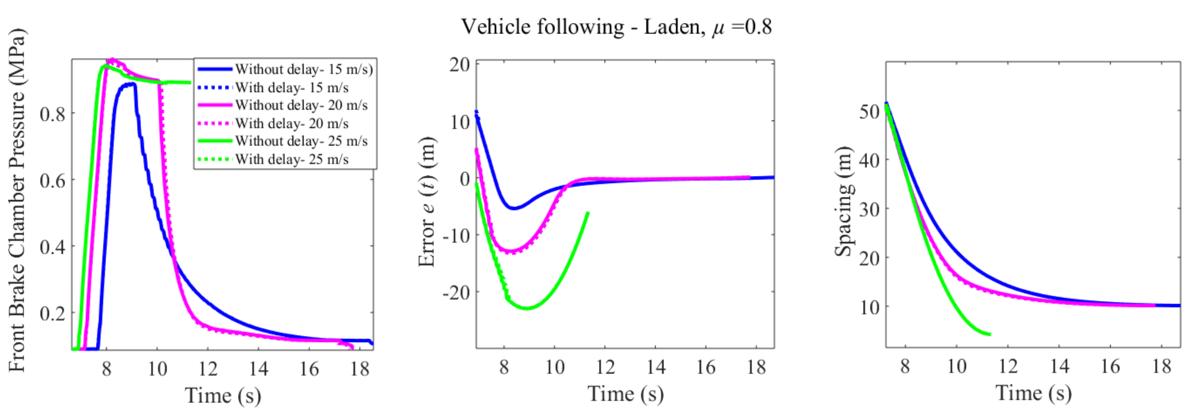

Fig. 10. Sensitivity analysis of laden vehicle following scenario at different speeds.

TABLE IV. SENSITIVITY ANALYSIS AT DIFFERENT SPEED.

	Initial speed (m/s)		**Final Spacing** (m)		**Braking Time** (s)	
	v_l	v_h	*Without latency*	*With latency*	*Without latency*	*With latency*
Vehicle following:						
Unladen	15	15	10.05	10.05	2.94	2.96
	20	20	10.05	10.05	2.34	2.37
	25	25	6.86	6.78	2.16	2.17
Laden	15	15	10.12	10.12	2.63	2.64
	20	20	10.12	10.12	2.09	2.11
	25	25	4.25	4.20	1.85	1.86
Lead vehicle at rest:						
Unladen	0	15	10.04	10.04	2.04	2.04
	0	20	10.05	10.05	1.04	1.04
	0	25	9.88	9.82	0.42	0.42
Laden	0	15	10.08	10.08	1.68	1.68
	0	20	10.12	10.12	0.64	0.64
	0	25	9.21	9.12	0.02	0.1

V. CONCLUSION

The impact of communication latency when applying V2V communication for heavy road vehicle collision avoidance was investigated. This impact was studied by conducting experiments on a HiL facility. For a latency of 100 ms and a transmission rate of 10 Hz, the effect of latency on the final spacing, and time at which braking starts was not significant assuming the successful reception of messages. It was observed that this was due to the counteracting effect of latency on the spacing and relative longitudinal speed. Analysis was done at different host vehicle longitudinal speeds and it was inferred that a variable time headway would make the CAA perform better.

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