ICIC Express Letters
Volume **15**, Number **3**, March **2021**

ICIC International ©2021 ISSN 1881-803X
pp. 307–318

DEVELOPING AN AUTOMATIC BRAKING SYSTEM BASED ON SENSOR FUSION

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Received July 2020; accepted September 2020

Abstract. *In some situations, an object could be a barrier for a vehicle. Objects that cross the path of, or stay in front of, a vehicle could get hit by it. A device that could help a driver to brake automatically in these situations is known as an Automatic Braking System (ABS). ABS is one of the systems that form part of the Advanced Driver Assistance Systems (ADAS). ADAS is a device to assist drivers in the driving process. This device was developed to reduce the human error that is one of the major causes of traffic accidents. This paper presents the design of ABS based on sensor fusion and simulated in hardware using an electric toy car. The inputs of fuzzy logic are the data from sensors and the speed of the vehicle, while the fuzzy output is the intensity of the braking. The sensors used in this study are a camera and two ultrasonic sensors. The results of the developed ABS test show that ABS works, according to the design.*
Keywords: Automatic braking system, Advanced driver assistance systems, Sensor fusion, Safe distance

1. **Introduction.** In the United States, a pedestrian is injured every seven minutes, or killed every two hours, because they have been struck by a vehicle [1]. Insufficient braking time is the main reason given by drivers, for their vehicle hitting the pedestrians. The sudden appearance of a pedestrian in front of a vehicle does not give enough time for vehicle to stop before hitting them. The percentage of vehicles crash into pedestrians or bikes is around 4.2% of all types of collisions. Approximately 84.6% of collisions are rear-end collisions and about 5.5% are due to 'turning into' or crossing paths [2].

Automatic braking systems were developed to help drivers brake in time and avoid collisions. These devices have been proved to reduce accidents by up to 29% [2]. ABS is an element of the Advanced Driver Assistance System (ADAS), or Intelligent Driver Assistance System (IDAS), and, currently, ABS is a mandatory feature on vehicles manufactured in the EU [3]. Other elements of ADAS are Adaptive Cruise Control (ACC) [4], Overtaking Assistance System (OAS) [5], Lane Keeping Assist System (LKAS) [6,7], and Rear-end Collision Avoidance System (RCAS) [8].

Nissan already uses an intelligent braking system, while Mercedez-Benz had equipped the S-Class car with Brake Assist Plus (BAS Plus) in 2006. Volvo and Ford collaborated to develop Collision Mitigation by Braking (CMbB) and, in 2007, the Volvo S80 and Ford S-Max were equipped with a collision warning with brake support system. In 2006, Honda used the Collision Mitigation Braking System (CMBS) on products such as the Legend Saloon and, in 2007, on the CR-V 4×4.

The algorithm and sensor are two aspects of concern to ABS researchers. Both aspects are important for the realization of reliable ABS. Researches into developing the ABS algorithm were carried out by [9-11]. In the research carried out by [9], the fuzzy logic

DOI: 10.24507/icicel.15.03.307

method is used to estimate the time it takes to hit a pedestrian. [10] develops active pedestrian safety by enhancing the ABS function, whereas, in [11], the criticality of the situation of a potential crash is estimated using a Bayesian framework. The development of ABS using a dynamic model approach was carried out in [12]. The development of ABS using ultrasonic sensors was carried out in [13,14], while the development of ABS using camera sensors was carried out in [15]. The use of multi-sensors in the development of ABS, among others, was carried out in [16].

The development of ABS mostly uses one sensor but this does not meet the reliability aspect. The weakness is that the use of one sensor limits the sensing coverage, in addition to being dangerous if the sensor becomes damaged. By using more than one type of sensor, it is expected that ABS performance will be improved, in general. This research develops ABS by using two types of sensor, namely ultrasonic and camera sensors. Both sensor output data are processed by the sensor fusion method. The reason for using sensor fusion is to make the controller have more data so the controller is going to make a better decision and could brake in time.

This paper is organized as follows: the second section describes the sensor fusion method for ABS, the third section shows experimental results, and the conclusion of this paper is given in the fourth section.

2. **Research Method.** Braking is one of the most important actions when driving. Two factors related to safe driving are how and when the intensity of braking must be done. One factor, related to driving comfort, is the intensity of the braking process that causes deceleration of the vehicle's speed. Braking suddenly can be an inconvenience for the driver as well as the passengers. In this research, driving comfort has not been considered. Fuzzy logic is going to be used for sensor fusion method to get the better safety index.

2.1. **ABS working principle.** An illustration of the working principle of ABS can be seen in Figure 1. The Following Vehicle (FV), which already has ABS, will not hit the Leading Vehicle (LV) if LV suddenly stops; ABS prevents the collision between the FV and LV. Collision avoidance is achieved by the brakes over the braking distance (b_d), so the FV stops before it hits the LV. Before the ABS automatic brake, the FV's driver would know that LV was too close to the FV at a warning distance (w_d). If the FV's driver does not apply the brake, then the vehicle is going to automatically brake at a distance of b_d.

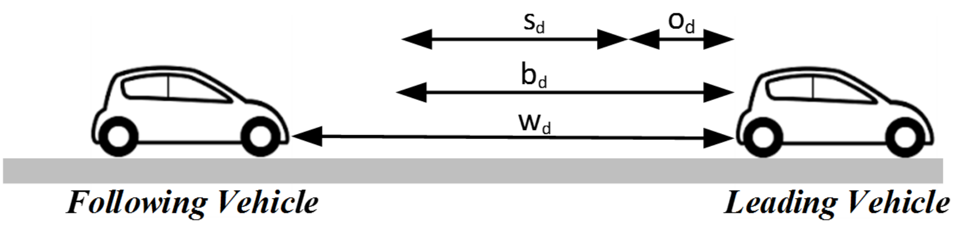

FIGURE 1. ABS illustration

In order to brake safely, the condition b_d stopping distance (s_d) must be met. The s_d value depends on the vehicle's speed and the braking intensity. In contrast, the low speed and longer distances only needed very soft braking. The main issue on ABS is how to regulate the intensity of the braking (b_r) so that a car will not hit any object at various speeds and braking distances. The distance between FV and LV, when FV has stopped, is o_d.

This issue could only be resolved by using the on-off method, already carried out by [17]. The weakness of the on-off method is when applied to the real car. The braking intensity of on-off method is less smooth and reduces driver comfort. The weaknesses of the on-off method are overcome by the fuzzy logic method, among others. Researchers have studied the development of ABS, based on fuzzy logic, including [13,18,19]. One way of improving the reliability of ABS is to use two or more sensors, with the aim of increasing sensing coverage and meeting the redundant sensor aspects.

2.2. **ABS algorithm based on sensor fusion using fuzzy logic.** There are two types of sensors used in the ABS system: one camera sensor placed in front of the car and two ultrasonic sensors placed in front of the car. The fusion of these two types of sensors is to make an ABS system more robust toward various disturbances that may cause the car hits the obstacle. Figure 2 further explains how sensor fusion in ABS works. The information coming from two type sensors are fused for the use of a control application.

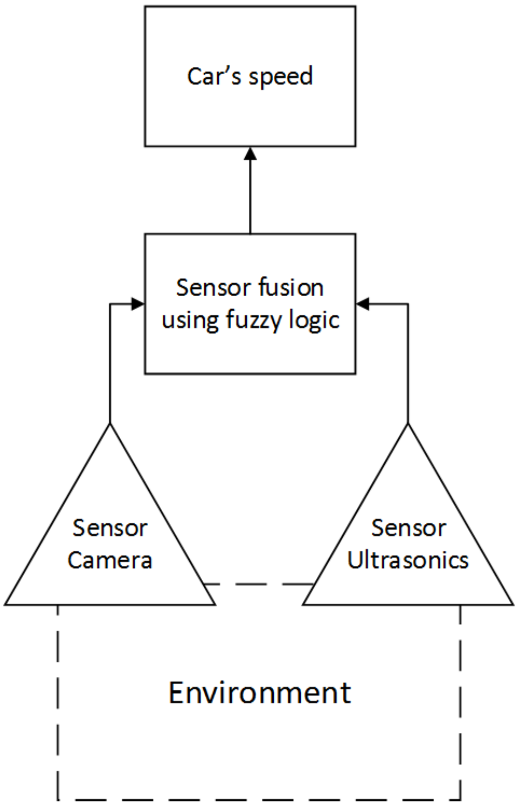

Figure 2. Sensor fusion in ABS

In Figure 3 there are 2 colours, the red and blue. Red colour represents the observation area of the ultrasonic and blue colour represents the observation area of the camera. When using sensor fusion the controller could get the information from wider area using camera and more precision using the ultrasonic at the same time. The top picture of Figure 3 shows us when the obstacle is in front of the car, and on the bottom shows us when the obstacle not really in front of the car.

Figure 4 shows the fuzzy logic for ABS, based on the sensor fusion and using Mamdani fuzzy logic. There are three inputs for ABS fuzzy logic: the vehicle's speed (VSPEED), distance from ultrasonic sensor (DU), and distance from camera sensor (DC). The vehicle's speed value is from 0-100 PWM, the distance from the ultrasonic sensor is 0-120 cm, and the distance from the camera sensor is from 0 to 640 pixels. The output of the fuzzy logic is a braking intensity with a value of 0 to 100. Brake intensity is obtained from processing VSPEED, DU, and DC using the Mamdani fuzzy inference system.

The membership function of the ABS input is based on sensor fusion using fuzzy logic, as shown in Figure 5, Figure 6, and Figure 7. The membership function of the speed consists of Low-Speed (LS), Medium-Speed (MS), and High-Speed (HS). The membership function

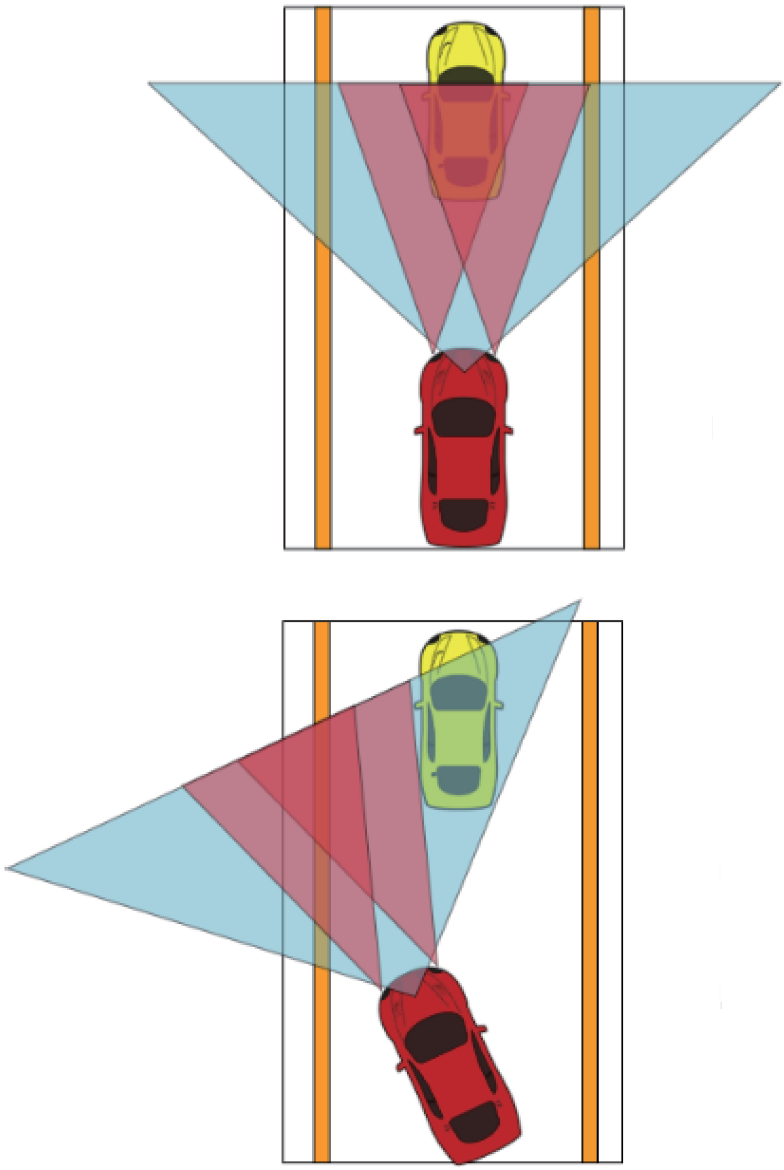

FIGURE 3. (color online) Sensor fusion using camera and ultrasonics

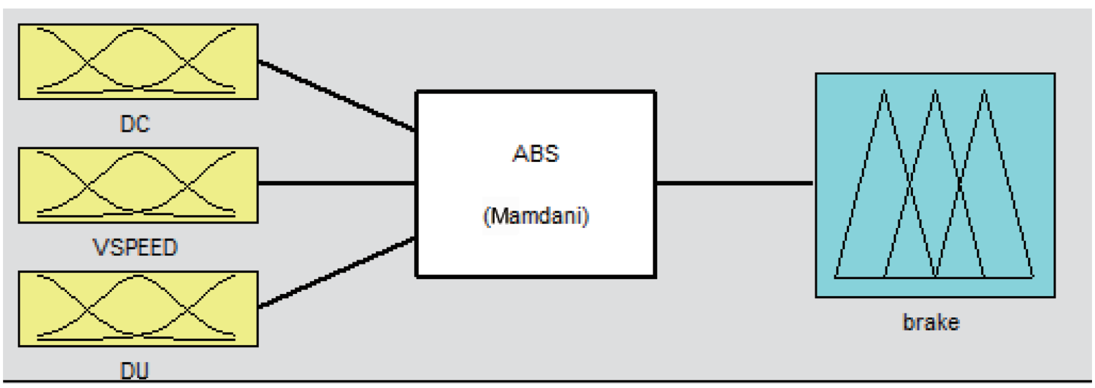

FIGURE 4. ABS sensor fusion using fuzzy logic

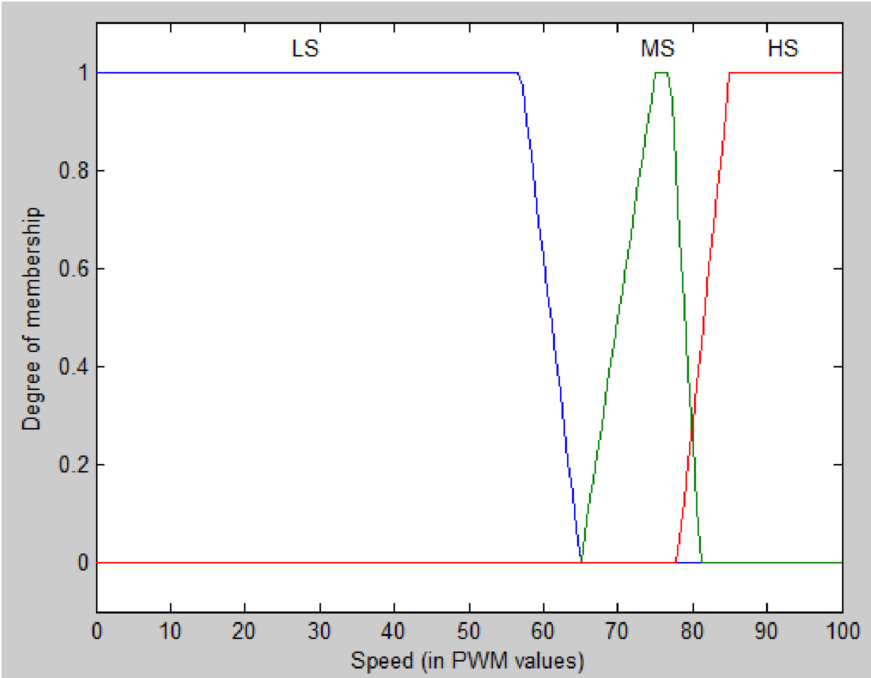

Figure 5. Membership function of vehicle speed

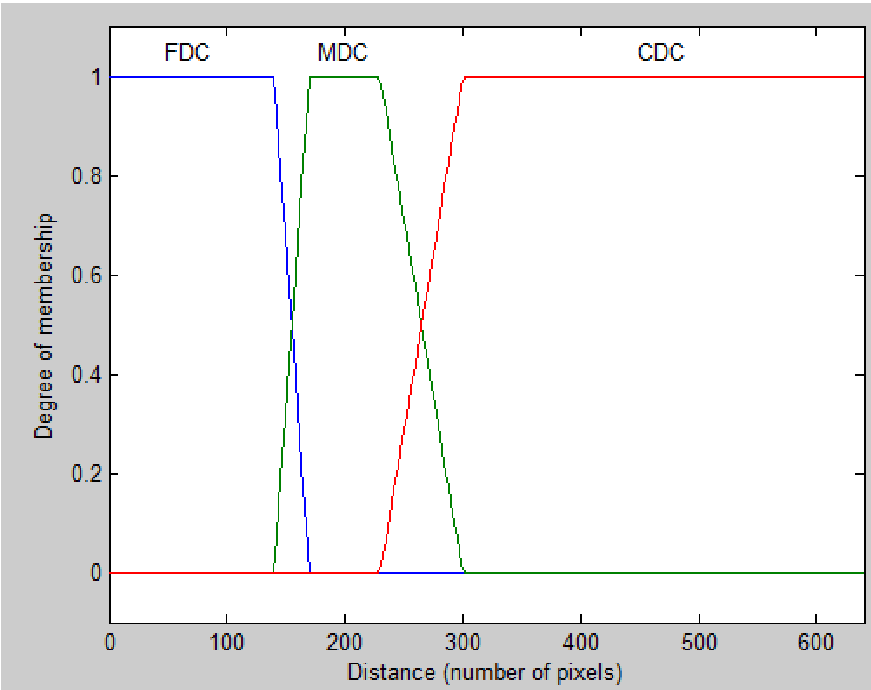

Figure 6. Membership function for distance from camera

of the distance from the camera comprises Far-Distance (FDC), Medium-Distance (MDC), and Close-Distance (CDC). The membership function of the distance from the ultrasonic sensors comprises Far-Distance (FDU), Medium-Distance (MDU), and Close-Distance (CDU).

The membership for the ABS output, based on sensor fusion using fuzzy logic, can be seen in Figure 8. The membership function of the brake intensity consists of Very-Soft-Brake (VSB), Soft-Brake (SB), Normal-Brake (NB), Hard-Brake (HB), and Very-Hard-Brake (VHB). The rules of ABS, based on sensor fusion using fuzzy logic, are shown in Table 1. There are 27 fuzzy rules from 3 membership inputs and 1 output.

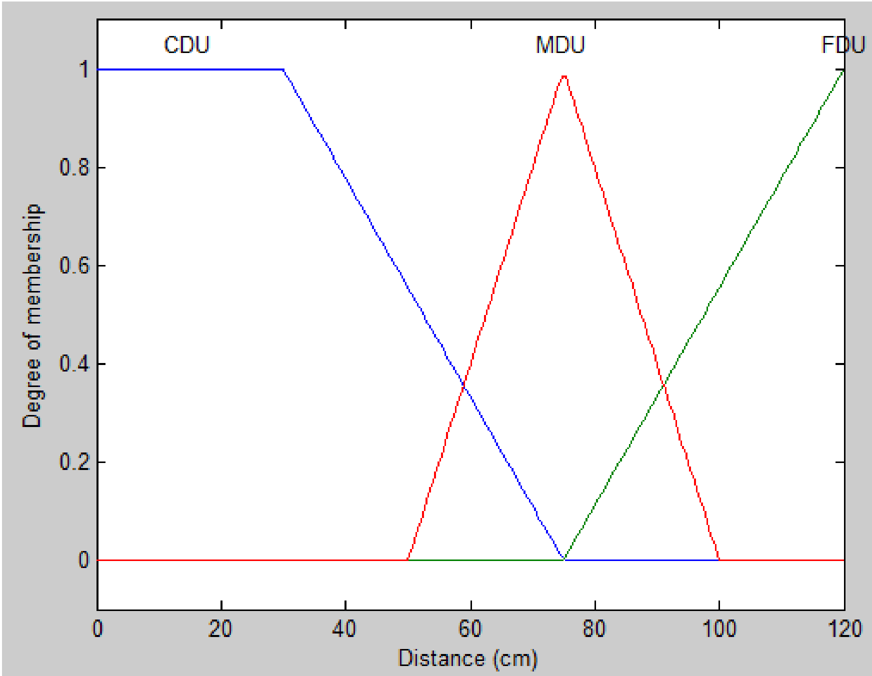

Figure 7. Membership function for distance from the ultrasonic

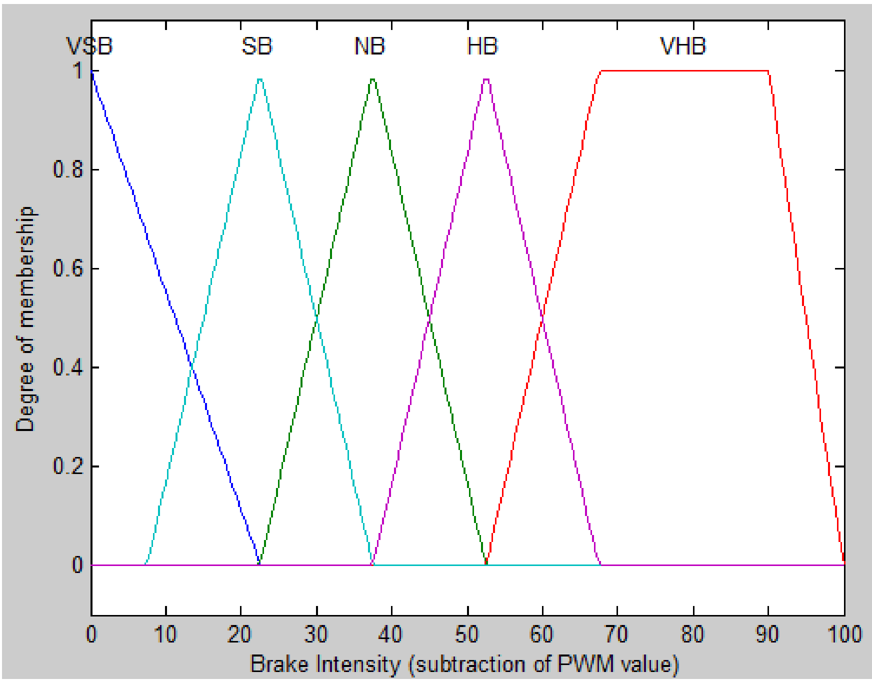

Figure 8. Membership function of brake intensity

The fuzzy surface of ABS is shown in Figure 9, Figure 10, and Figure 11. Figure 9 consists of VSPEED, DC, and brake intensity. Figure 10 consists of VSPEED, DU, and brake intensity. Figure 11 consists of DC, DU, and brake intensity.

2.3. **Hardware simulation.** The ABS hardware block diagram is shown in Figure 12. The data from camera sensor, ultrasonic sensors and vehicle speed (had been programmed) are processed in the controller, using fuzzy logic and the output is the intensity of the braking. In this simulation, the intensity of the braking is going to subtract the value of the vehicle's speed that is already programmed before.

Table 1. ABS fuzzy rules

	LS	**MS**	**HS**
FDC & FDU	VSB	SB	NB
FDC & MDU	SB	NB	HB
FDC & CDU	NB	HB	VHB
MDC & FDU	SB	NB	VHB
MDC & MDU	NB	HB	VHB
MDC & CDU	HB	VHB	VHB
CDC & FDU	NB	HB	VHB
CDC & MDU	HB	VHB	VHB
CDC & CDU	VHB	VHB	VHB

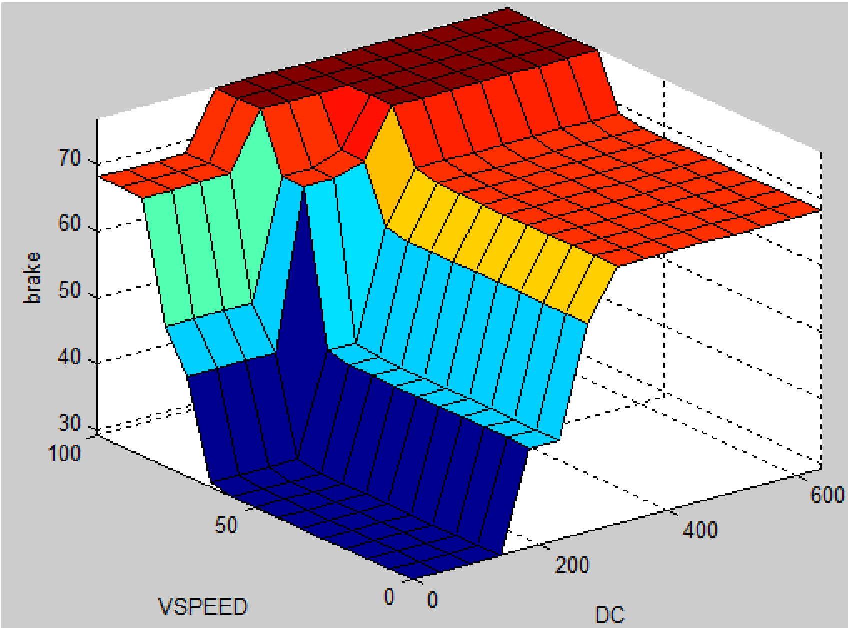

Figure 9. Fuzzy surface VSPEED, DC, and brake intensity

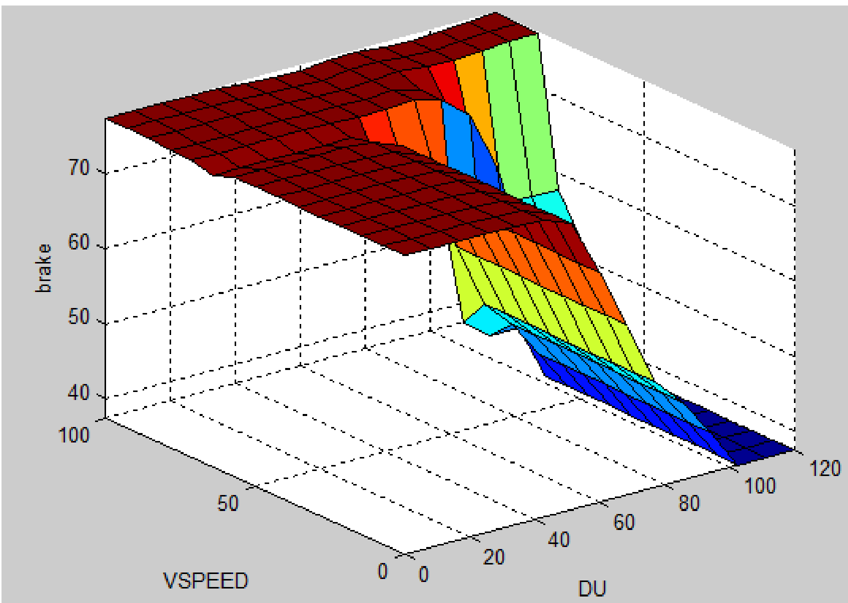

Figure 10. Fuzzy surface VSPEED, DU, and brake intensity

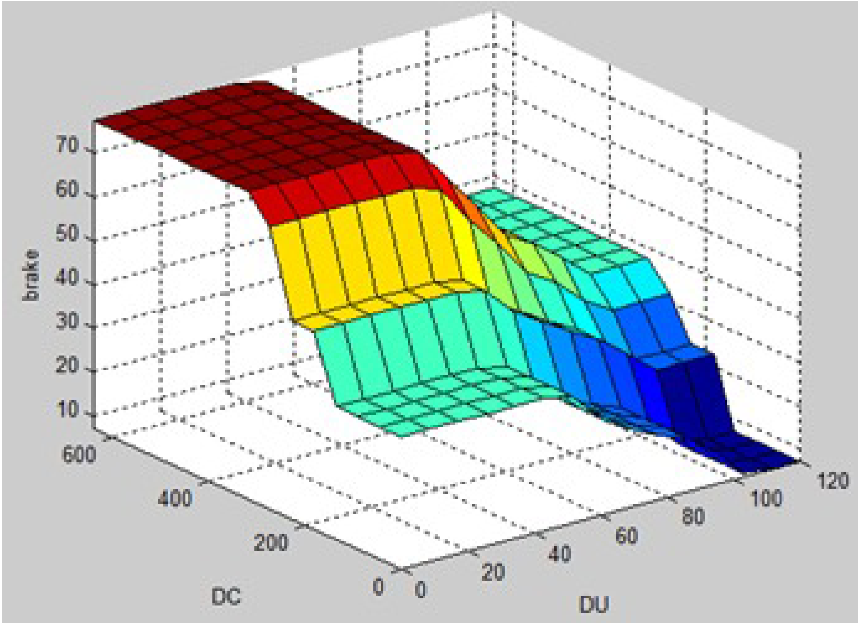

FIGURE 11. Fuzzy surface DC, DU, and brake intensity

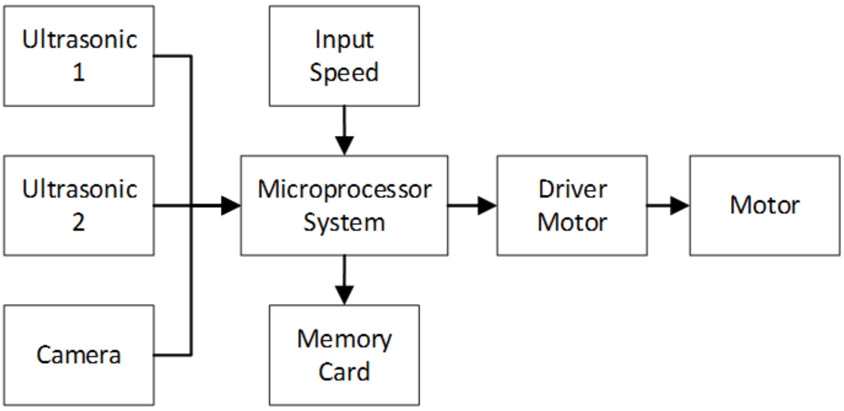

FIGURE 12. Block diagram ABS simulation

Hardware simulation was carried out using two ultrasonic sensors and a camera assembled in front of the car. The ultrasonic sensors and the camera were set up to detect the obstacle or LV. A microprocessing system processed the data from the camera, ultrasonics and vehicle's speed (already programmed), to make an ouput in PWM 0-100. A memory card was used for storing the ABS data during the test.

The camera detected the obstacle (black cardboard) in front of it by taking the picture continuously and then altering it, and changing it to 640 × 1 pixels by the microprocessor system. The camera detected more black pixels when it was closer to the obstacle and less black pixels when the camera was further from the obstacle. Changing the image from the camera into a 640 × 1 pixel row, reduce the computational load so that real-time action on ABS could be carried out in real time. The image processing of the obstacle is shown in Figure 13. The ABS hardware simulation, using an electric toy car, is shown in Figure 14.

Figure 15 shows an ABS simulation test. The vehicle started from 150 cm in front of the obstacle and then started to reduce its speed when in braking distance. The vehicle will be stopped by stopping distance in front of the obstacle before it hits the obstacle.

(a)

(b)

(c)

Figure 13. Camera image processing: (a) original image, (b) binary image, and (c) 640 × 1 pixels image

(a)

(b)

Figure 14. Electric toy car used for simulation: (a) front view, and (b) side view

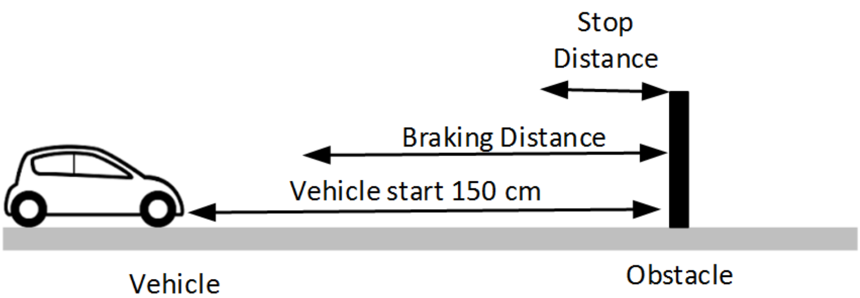

Figure 15. ABS simulation test

3. **Results and Discussion.** An ABS algorithm, based on sensor fusion using fuzzy logic, was applied to a microprocessor system and tested in three situations: low-speed, medium-speed and high-speed.

3.1. **Testing at different speeds.** Figure 16 shows the result of high-speed testing. The vehicle's output speed is directly proportional to the distance of the vehicle to the obstacle. When the distance gets closer, then the speed gets slower. The camera is

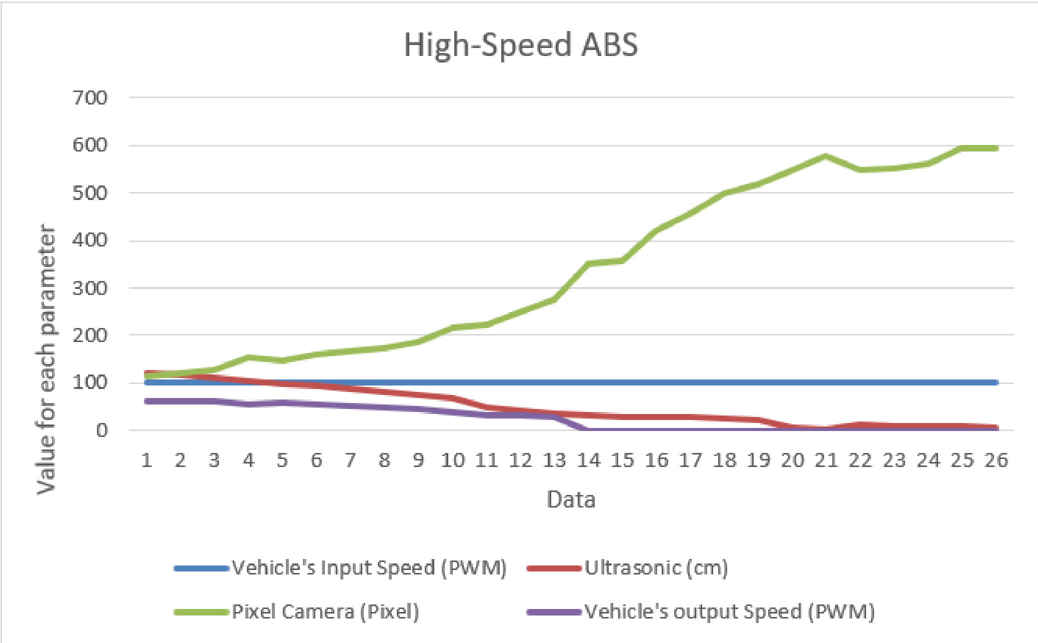

Figure 16. (color online) High-speed ABS

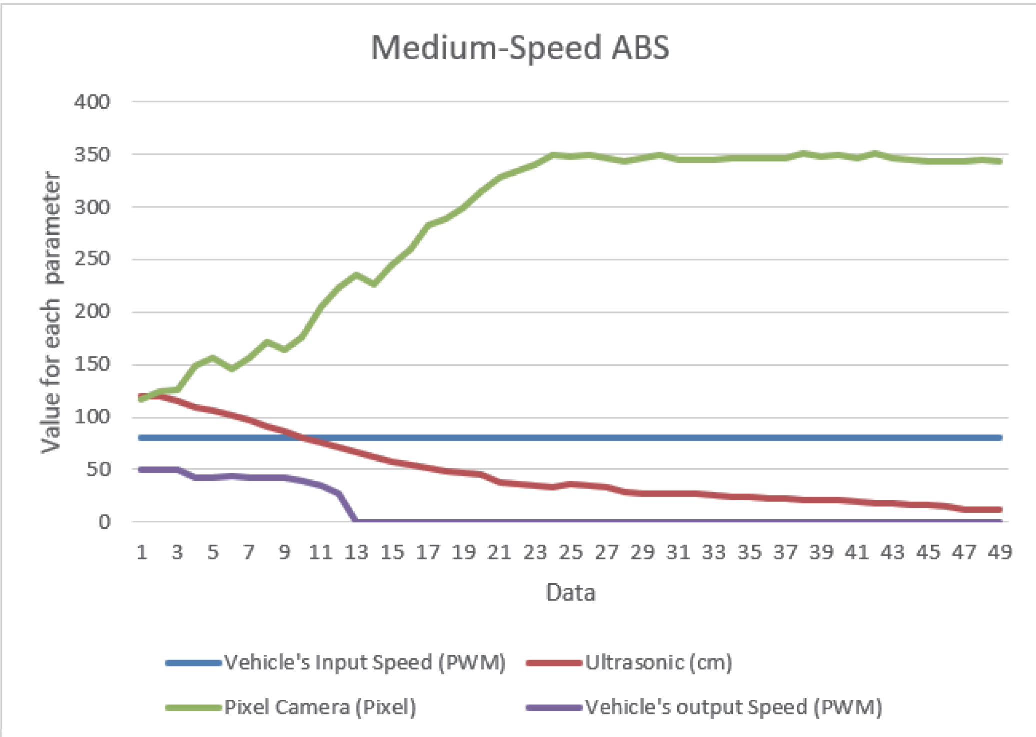

Figure 17. (color online) Medium-speed ABS

inversely proportional to the distance of the vehicle; when the black pixels of the camera are getting bigger then the distance is getting closer. At high speeds, the vehicle could stop 8.5 cm before the obstacle.

Figure 17 shows the results of medium-speed testing. The vehicle's output speed is directly proportional to the distance of the vehicle to the obstacle; when the distance gets closer then the speed gets slower. The camera is inversely proportional to the distance of the vehicle; when the black pixels of the camera are getting bigger then the distance is getting closer. At high speeds, the vehicle could stop 12 cm before the obstacle.

Figure 18 shows the results of low-speed testing. The vehicle's output speed is directly proportional to the distance of the vehicle to the obstacle; when the distance gets closer then the speed gets slower. Because the camera is inversely proportional to the distance of the vehicle, when the black pixels of the camera get bigger then the distance gets closer. At high speeds, the vehicle could stop 13.4 cm before the obstacle.

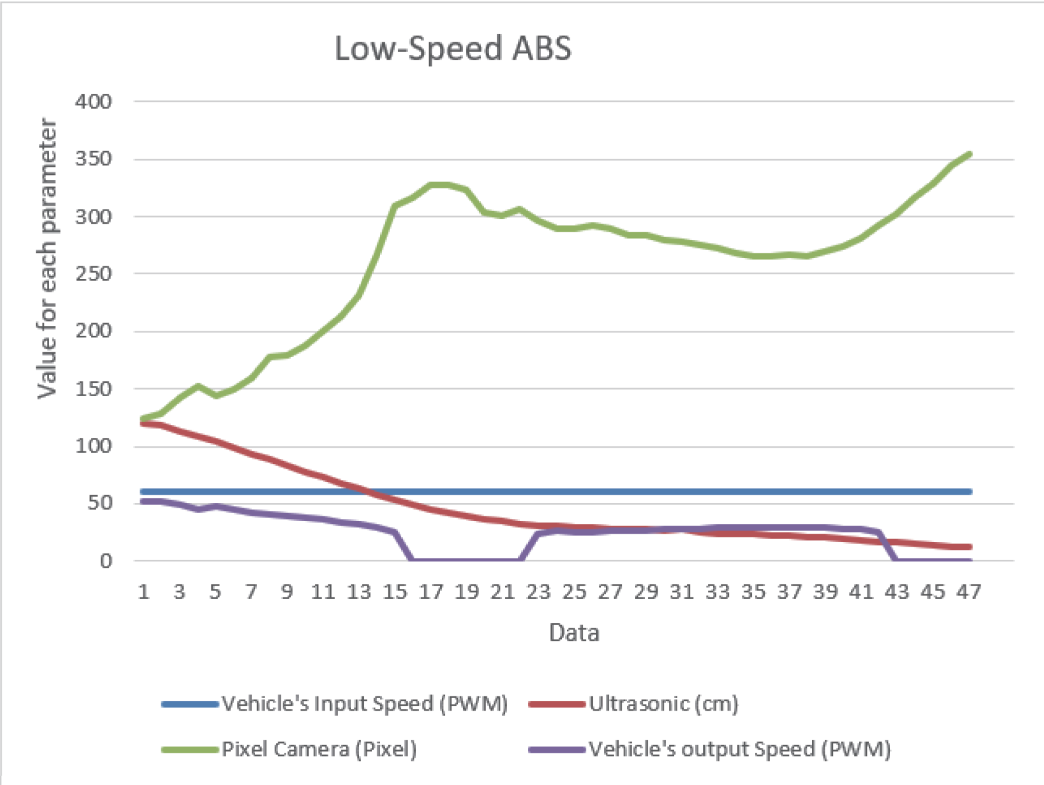

FIGURE 18. (color online) Low-speed ABS

3.2. **ABS performance.** Table 2 shows the ABS performance at high-speed, medium-speed, and low-speed. ABS was tested 20 times for each speed.

TABLE 2. ABS performance

	Successful test	Average stop distance (cm)	Safety index
High-speed	20	8.315	100%
Medium-speed	20	12.717	100%
Low-speed	20	13.315	100%

For 20 test attempts at each speed variety (low-speed, medium-speed, and high-speed), every test succeeded. The ABS could make the car stop before it hits the obstacle, so the Safety Index (SI) from this test was 100%. These test results meet ABS requirements for real conditions. In real conditions, of course some adjustments are needed, namely sensors that have a longer range, a microprocessor system with a better processing speed and adjustments in the fuzzy logic section.

4. **Conclusion.** ABS based on sensor fusion has been realized and the test results are in accordance with the design. The vehicle's output speed is directly proportional to the distance of the vehicle from the obstacle; when the distance gets closer, the speed gets

slower. The camera distance is inversely proportional to the distance of the vehicle; when the black pixels of the camera are getting bigger then the distance is getting closer. ABS based on sensor fusion has a 100% safety index for each speed variety. Sensor fusion is proven to increase the performance of ABS, especially when the obstacle not really in front of the car. Sensor fusion could increase the performance of ABS because it could get wider observation area from camera and better precision from ultrasonic at the same time. For the research topic which will be studied in the future it could use other sensor like lidar for the example.

Acknowledgements. The authors would like to thank Direktorat Riset dan Pengabdian Masyarakat for financial support through Penelitian Dasar Unggulan Perguruan Tinggi (PDUPT) with contract number 135/SP2H/AMD/LT/DRPM/2020.

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