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Modelling, testing and validation of an innovative AEB control logic on a Hardware-in-the-loop test bench

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Abstract. AEB, autonomous emergency braking, is an active safety system designed to prevent vehicle frontal collision. The most diffused AEB systems are based on simple $Bang\ Bang$ control logic, which could often avoid, or at least mitigate collision effects, but their effectiveness can still be improved by increasing system repeatability. The aim of this study is to model and test an innovative AEB control logic that will increase system reliability by compensating for the non-immediate response of the braking system to braking requests. Using a hardware-in-the-loop test bench with two different braking systems implemented, the new controller was tested simulating the $CCRs$ and $CCRm$ scenarios, used by Euro NCAP for AEB system assessment. By compensating for the delay introduced by the response of two different braking systems, the innovative control logic stops the VUT, Vehicle Under Test, at the desired safety distance from the GVT, Global Vehicle Target.

1. Introduction

The main task of the AEB, Autonomous Emergency Braking, system is to reduce the severity of front collision by lowering the speed of the striking vehicle if it can't completely avoid the incident. This system is usually paired with the FCW, Forward Collision Warning, which task is to warn the driver of the imminent danger through auditory warning, blinking optical display and sometimes using haptic devices as tactors. It is demonstrated by many studies that the Autonomous Emergency Braking System offers high reductions in crash avoidance and mitigation of impact's consequences. Fildes et al. [6] analyses data from 6 different country in which vehicles equipped with AEB system and vehicle without impact the rear of another vehicle. The conclusion shows a 38% overall reduction in rear-end crash both for urban ($\leq$ 60 km/h) and rural ($>$ 60 km/h) speed zones. J.Cicchino [16] Studied the different effect of the FCW, the EB and their combination. Rear-end striking crash result reduced by 27%, 43% and 56% respectively for FCW only, EB only and their combination.

Typical AEB control logics base their decisional process on the data collected from the camera and multi-target Radar [18] mounted on the front of the vehicle. Once critical conditions are detected, from the Radar sensor can be extrapolated two important data that are: relative distance d_{rel}, and relative velocity v_{rel} between the VUT and the GVT. From these two quantities many parameters, that aid to understand the severity of the situation, can be calculated.

There are essentially two ways to determine the start of the FCW and AEB intervention and their behaviour during the braking phase.

- Time based principle: Control logic choices are based on: HWT, TTC, ETTC, Driver estimated reaction time and system response time.
- Acceleration based principle: Control logic choices are based on the calculation of longitudinal acceleration required to avoid collision.

The use of classical $Bang\ Bang$ control logic results in low repetitiveness of stopping distances between the two vehicles. This is due to the difficult characterization of the response of the braking system, which depends on many uncontrollable parameters such as ambient temperature or the time of use of brake fluid due to his hygroscopic properties. Therefore, in this paper is proposed a deceleration based controller that does not need precise characterization of the braking system but corrects the level of deceleration by monitoring the relative distance trend. AEB controller has been tested in two rear-end collision test scenarios: *Car-to-Car Rear stationary CCRs* and *Car-to-Car Rear moving CCRm* which are used by Euro NCAP as part of the Safety Assist assessment [11]. The validation of AEB controller has been carried out on a commercial available brake-by-wire system unit (BSU) and the Corner brake actuator (CBA) developed by Meccanica 42. Both braking systems has been integrated in a hardware-in-the-loop test bench. The two different scenarios has been simulated using a static simulator provided by Meccanica 42 in which the two different braking system were integrated with Hardware in the loop technique.

2. AEB control logic

The AEB controller is modelled with a state machine in Stateflow. The state machine allows for quick and easy modelling as it is sufficient to specify actions and transition conditions for each state. It is also very easy to make changes and add new features such as brake pre-fill or brake jerk in the future, or pass from two to three deceleration thresholds. Two types of intervention are supported by the controller, a classical one in which the requested deceleration remains constant throughout the simulation and a "$Corrected$" one in which the deceleration is updated every simulation time step. The state machine is composed by four states:

- *OFF*: This is the default state, in which no action is determined by the AEB. Each of the next states can return to the OFF state when $v_{vut} < v_{gvt}$ or $v_{vut} = 0$.
- *FCW - Forward Collision Warning*: Actuates driver warning strategies and pre-condition the vehicle. To these actions can be added the Jerk function if activated.
- *PB - Partial Braking state*: This is the first state that determines a braking intervention to avoid the collision. In the $Bang\ Bang$ mode PB requires a constant deceleration equal to a_{pb}, while in $Corrected$ mode the DR_{out} is updated at each time-step allowing to compensate brake system delay.
- *FB - Full Braking*: When the intervention of the Partial Braking state is not sufficient to avoid the collision the control logic switches to the last state with the full braking request. As in the PB state the requested deceleration remains constant in $Bang\ Bang$ mode and is updated in $Corrected$ mode.

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The controller continuously monitors the relative distance and the relative velocity between the two vehicles which are measured by the radar sensor. During the event the controller computes three different stopping distances, these are calculated considering three different deceleration thresholds which are set to $a_{fcw} = -2m/s^2$, $a_{pb} = -4m/s^2$, $a_{fb=-8}m/s^2$. The stopping distances are then compared to a safety margin SM_d, when the following condition is true

$$DR(t) = d_{rel} - SD_x < SM_d \tag{1}$$

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the corresponding state is activated. A scheme of the process is represented in figure 1, in which the FCW status should be activated.

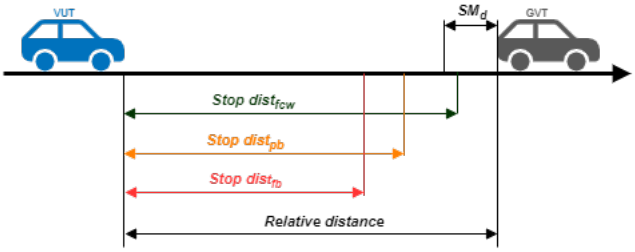

Figure 1. Stopping distances scheme

The deceleration requested to stop the vehicle at the distance SM_d from the target vehicle for both the $CCRs$ and the $CCRm$ scenario is calculated with the following formula:

$$DR_{ccrsm}(t) = \frac{v_{vut}(t)^2}{2d_{rel}(t) - SM_d} \tag{2}$$

In figure 2 is reported the required deceleration to stop the VUT at the SM_d distance from the target during a $CCRs$ or $CCRm$ scenario, splitting the plot zones corresponding to states of the state machine.

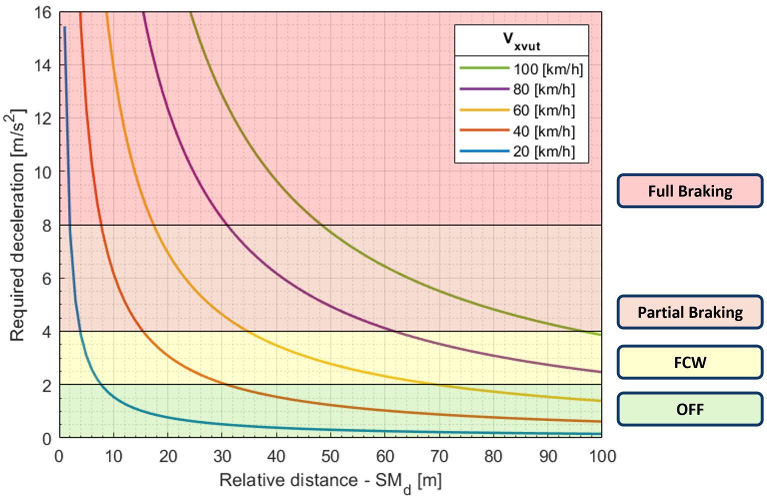

Figure 2. Deceleration required to stop the VUT vehicle at the SM_d distance

In table 1 the transition conditions and the action of each state of the state machine are shown.

3. Real-time simulator

Figure 3 shows the Hardware-in-the-loop static simulator provided by Meccanica 42 s.r.l used to test the AEB control logic with the two different braking systems. The simulator is composed by a Real-time computer which executes the simulation and manages the communication lines providing via CAN the signals needed to feed the EPS and braking units ECU, and via EtherCAT the signals necessary to control

Table 1. AEB logic steps

Transition Conditions	AEB Status
$v_{vut} > v_{gvt}$; $SD_{fcw} > d_{rel} - SM_d$	FCW
$v_{vut} > v_{gvt}$; $SD_{pb} > d_{rel} - SM_d$	Partial braking
$v_{vut} > v_{gvt}$; $SD_{fb} > d_{rel} - SM_d$	Full braking

the EPS test bench actuators, as schematized in Figure 4. The entire steering system is integrated into the simulator and the dynamic forces on the tie rods are applied by two torque motors by means of a rocker, to accurately reproduce the steering feel. The rockers are necessary to properly replicate tie-rods motion during wheel travel. Also, the complete braking system is integrated in the simulator. In fact, the commercial brake-by-wire unit is connected to brake lines with real length and diameter, that are connected to four brake callipers acting on a non-rotating brake disk. To include the CBA system in the simulation loop, as shown in Figure 5, a Micro Auto Box is added to feed the CBA ECU with the pressure request at each vehicle corner. The CBAs included in the simulation loop are the two already integrated into the experimental vehicle provided by Meccanica 42 S.r.l, hence the brake actuators pressurizes the brake line and the caliper of the vehicle acting on his brake disks.

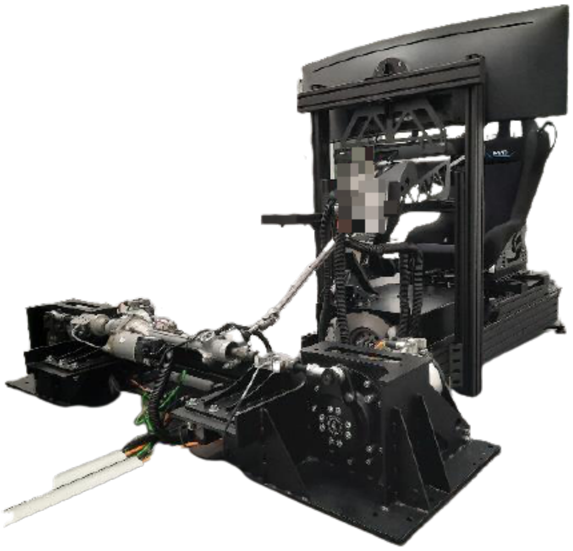

Figure 3. Static simulator provided by Meccanica 42 S.r.l

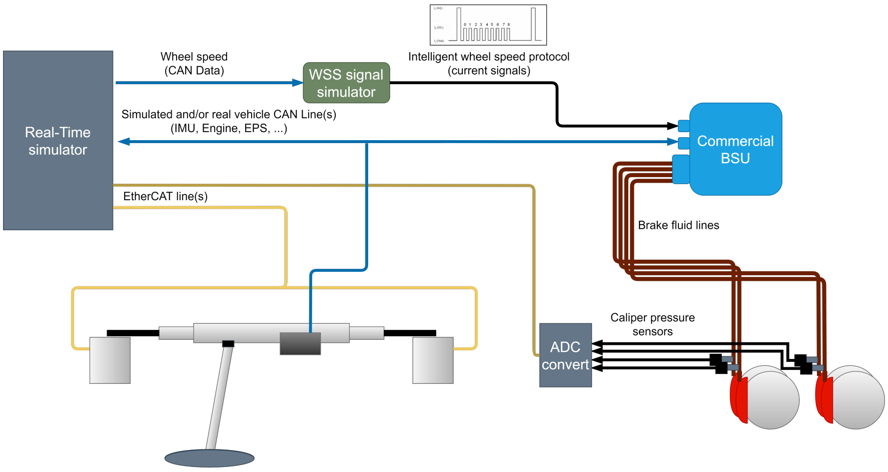

Figure 4. Static simulator layout

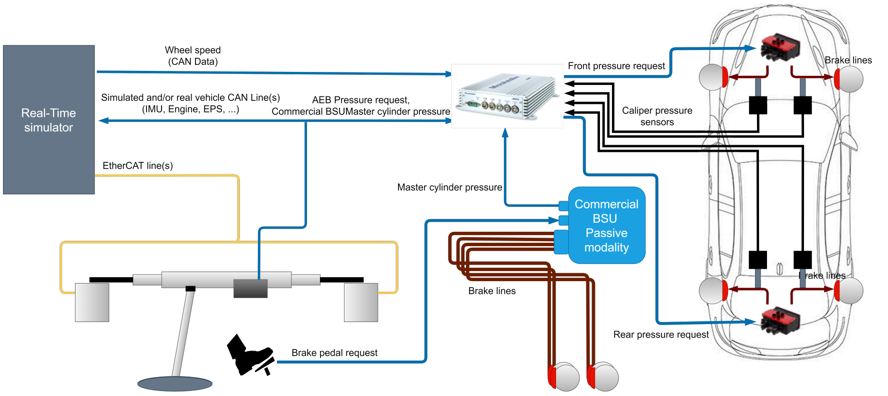

Figure 5. CBA in the loop simulator layout

4. Methodology

Once the AEB controller functioning has been debugged on offline simulation, the AEB assessment scenario has been reproduced online with the use of the driving simulator. As indicated by Euro NCAP in *Test protocol - AEB Car-to-Car systems* [11], the AEB controller has been tested on two different scenarios:

4.1. CCRs Car-to-Car rear stationary

CCRs is the simplest scenario in which the Global Vehicle Target (GVT) is stationary and the Vehicle Under Test (VUT) is moving toward the GVT at constant velocity. In table 2 can be found the test VUT velocities.

Table 2. CCRs scenario

Scenario	AEB + FCW combined		AEB only	FCW only
	AEB	FCW		
AEB CCRs	10-50 km/h	30-80 km/h	10-80 km/h	30-80 km/h

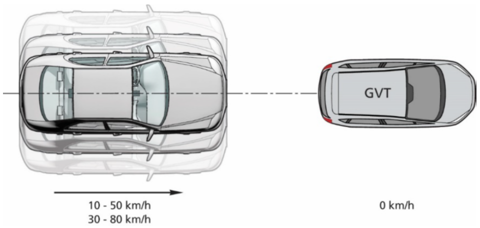

Figure 6. CCRs scenario [11]

4.2. *Car-to-Car Rear moving*

In this scenario the GVT proceed at constant velocity and the VUT is moving toward the GVT at a higher constant velocity. In table 3 can be found the test VUT velocities. In this case the controller aims to turn a rear-end collision scenario into a car-following scenario. The VUT will be decelerated so that it follows the GVT at a SM_d distance with $v_{vut} = v_{gvt}$.

Table 3. CCRm scenario

Scenario	AEB + FCW combined		AEB only	FCW only
	AEB	FCW		
AEB CCRs	30-80 km/h	50-80 km/h	30-80 km/h	50-80 km/h

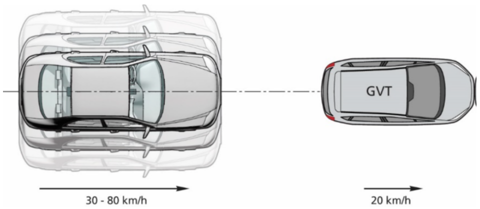

Figure 7. CCRm scenario [11]

5. Results

The AEB controller avoids car collision both in CCRs and CCRm scenarios using $Bang\ Bang$ and $Corrected$ control logic. In figure 8, and figure 9 the intervention of the two controller is compared with both braking systems in a CCRs scenario with a VUT constant velocity of 40 km/h. In the pressure curve, it can be noticed how the response of the two braking systems is different. In fact, the CBA presents a much shorter rise time to reach the target pressure compared to the commercial BSU. In addition, it can be observed that the CBA exhibits more oscillatory behaviour after reaching the target pressure value unlike the commercial BSU, which therefore exhibits a shorter stabilization time. The same kind of behaviour can be seen for both the first and second pressure demand steps. The image shows how the intervention of a classic AEB control logic requires two level of constant deceleration ignoring the system response, while the $Corrected$ control logic after requesting the first deceleration threshold, increases its request to compensate for the delay in pressure build up which is evident in the first plot. Once the detachment from the ideal condition has been recovered, the required deceleration returns to values equal to those of the first threshold. As a result the stopping distance of the VUT from the vehicle GVT in the $Corrected$ case is 0.98 m while in the $Bang\ Bang$ case it is 0.76 m.

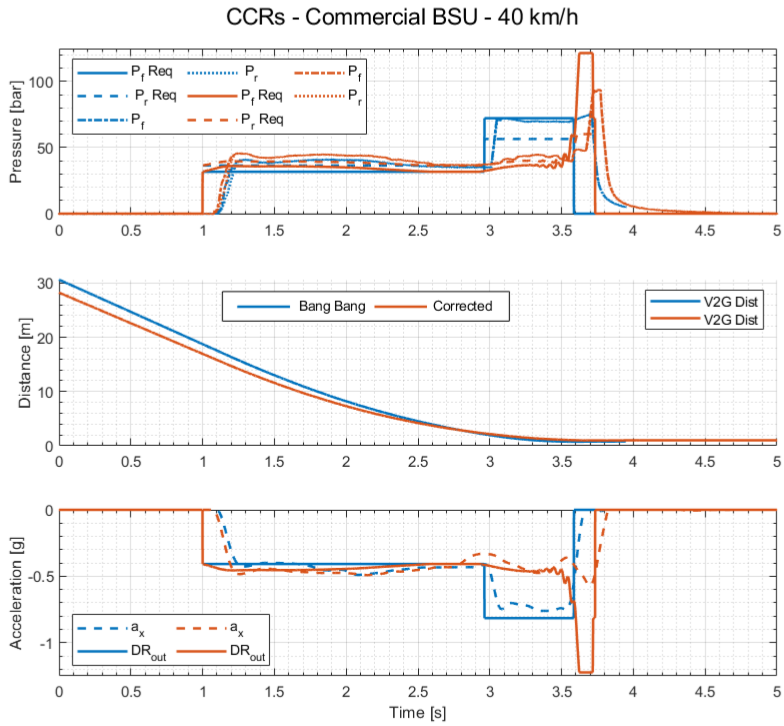

Figure 8. Comparison between *Bang Bang* and *Corrected* controller on commercial BSU

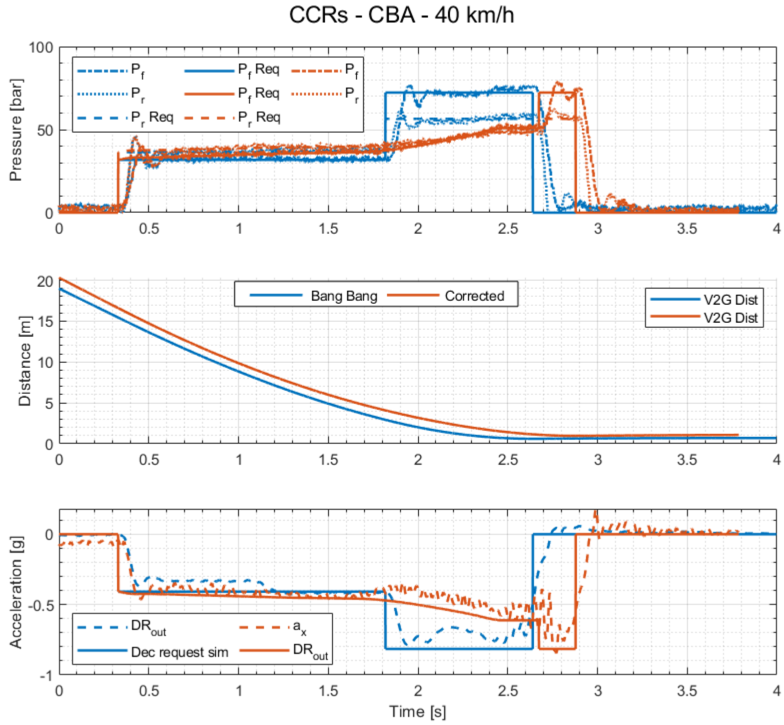

Figure 9. Comparison between *Bang Bang* and *Corrected* controller on CBA

6. Conclusion

The control logic proposed in this study made it possible to avoid crashes in all 20 simulated cases whether implemented with delay correction or not. Despite this, the correction of the system response allows to obtain more repeatable results and to stop the vehicle more safely by requiring lower average accelerations and keeping the vehicle in a more stable condition. The dispersion of stopping distances with the classic $Bang\ Bang$ logic is very high, while the $Corrected$ control logic allows very similar results to be obtained even though it is implemented on different hardware; in fact, its purpose is to cancel the effects of system delay in an adaptive manner. Figure 10 and figure 11 show the stop distance for the CCRs and CCRm scenarios highlighting the improved accuracy for the $Corrected$ controller. Another advantage demonstrated by this type of algorithm is that it does not require any time-consuming calibration work. In fact, there are no tuning parameters, only parameters which affect the operating mode and the aggressiveness of the intervention. Since there is no anticipation of the intervention which takes into account the response of the braking system and vehicle and the driver's reaction time, the interventions controlled by this type of control logic are much less invasive.

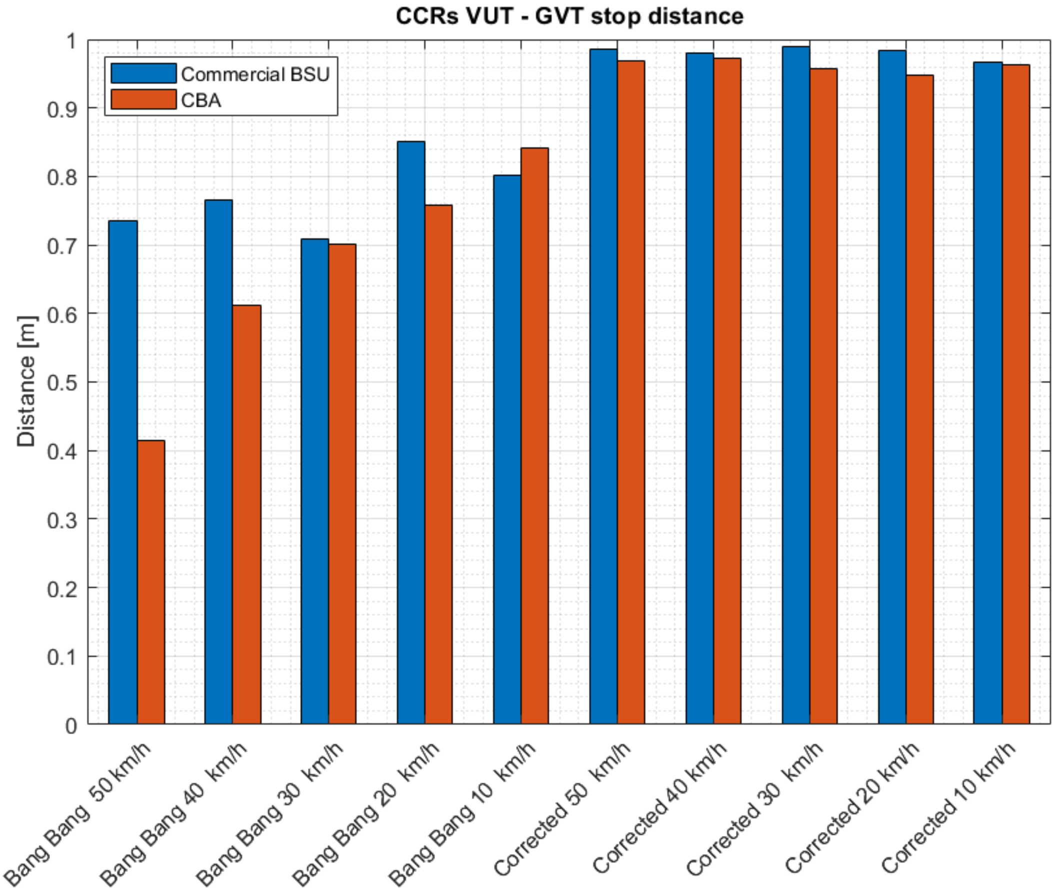

Figure 10. CCRs final distances using $Bang\ Bang$ and $Corrected$ control logic

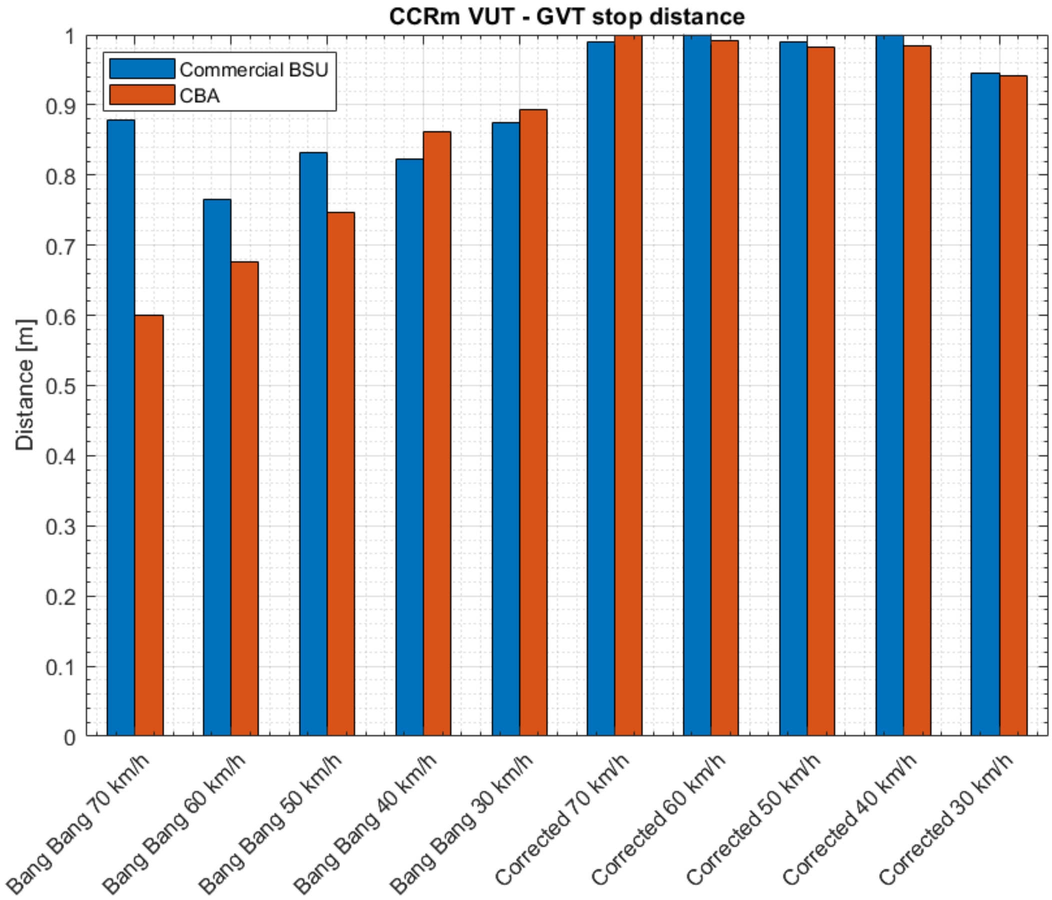

Figure 11. CCRm final distances using $Bang\ Bang$ and $Corrected$ control logic

Nomenclature

AEB	Autonomous emergency braking
BSU	Braking system unit
CBA	Corner brake actuator
$CCRm$	Car to car rear end collision moving
$CCRs$	Car to car rear end collision stationary
DR	Deceleration request for CCRs and CCRm event
$ETTC$	Enhanced Time To Collision
$Euro\ NCAP$	European New Car Assessment Programme
FCW	Forward Collision Warning
GVT	Global Vehicle target
HWT	Headway Time
SD	Stopping distance
SM_d	Safety margin distance
TTC	Time To Collision
VUT	Vehicle under test

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