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Vehicle Assessment Using Integrated Crash Avoidance and Crashworthiness Pedestrian Safety Test Procedures

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16. Abstract

The objective of this study was to test a set of vehicles using both pedestrian automatic emergency braking (PAEB) and crashworthiness (CW) test protocols to evaluate ways in which the results of each test condition can be used to inform and, if necessary, refine, the test conditions and/or performance requirements of the other. PAEB test track results were used to determine CW head and leg impact speeds and locations, and CW test results were used to help understand minimum speed reduction requirements for PAEB tests. Secondary goals of this study were to explore a method for evaluating contact-induced safety features (i.e., deployable hood systems) and provide an improved overall picture of a vehicle's expected real-world performance.

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Introduction

Background

Pedestrian injuries and fatalities have increased in the United States over the past several years (NCSA, 2022). To address this safety problem, NHTSA conducted research that looked at both crash avoidance and crashworthiness (CW) test methods that assess how effectively vehicle safety systems can reduce the risk posed to pedestrians in the event of a vehicle-pedestrian interaction. Pedestrian automatic emergency braking (PAEB) is a pre-crash countermeasure becoming more prevalent in U.S. vehicles (Haus et al., 2019). PAEB is intended to first detect a pedestrian projected to be in the vehicle's forward path and quickly respond by automatically applying the brakes to avoid or mitigate the potential collision. NHTSA recently published a New Car Assessment Program (NCAP) request for comment (RFC) (NHTSA, 2022) that proposes to add PAEB as a recommended technology to the consumer information program. Additionally, NHTSA has published a notice for proposed rulemaking for automatic emergency braking systems on light vehicles (NHTSA, 2023) which includes PAEB on all new vehicles sold in the United States. On the CW side, test procedures following the global technical regulation (GTR) no. 9 (pedestrian safety) have been developed through international coordination, and test procedures following the European New Car Assessment Programme (Euro NCAP) have been used in Europe for consumer information purposes for several years. Per the NCAP roadmap (NHTSA, 2022), NHTSA has requested comment on adding pedestrian CW tests to NCAP. NHTSA has also indicated intent to propose new regulatory requirements to protect pedestrian heads impacting vehicle hoods (Office of Information and Regulatory Affairs, 2022). These regulatory and consumer information actions are steps toward addressing the increasing pedestrian safety problem in the United States.

Recently, PAEB systems, which formerly have been available in largely luxury class platforms, have begun to appear in other vehicle classes. This trend has made it possible to identify high-sales-volume vehicles that can be tested with both PAEB and CW procedures. In a real-world crash, both PAEB (active) and CW (passive) countermeasures can influence the injury outcome for a pedestrian. The increasing prevalence of PAEB systems provides the opportunity to experimentally attempt to capture the projected combined safety benefit of pre- and post-crash systems.

Objective

The objective of this study was to test a set of vehicles using both PAEB and CW protocols to evaluate ways in which the PAEB test-track results can be used to inform CW test protocols. PAEB test track results were used to determine CW head and leg impact speeds and locations. Secondary goals of this study were to explore a method for evaluating contact-induced safety features (i.e., deployable hood systems) and provide an improved overall picture of a vehicle's real-world performance.

Subject Vehicles

Four subject vehicles (SVs) equipped with PAEB systems were tested during this study, with two of those vehicles chosen specifically because they also were equipped with active hood systems. Active hood systems lift the rear of the hood upon contact with a pedestrian to provide more clearance to engine components and provide a more "cushioned" impact.

2016 Chevrolet Malibu

The 2016 Chevrolet Malibu Premier shown in Figure 1 is equipped with Chevrolet's "Front Pedestrian Braking" PAEB system, which warns the driver and enhances or applies the brakes if an imminent collision with a pedestrian has been detected. According to the vehicle's owner's manual, the Front Pedestrian Braking system uses a forward-facing camera system and is active in the 5-50 mph (8-80 kph) range (Chevrolet, 2016).

Figure 1. The 2016 Chevrolet Malibu

2020 Subaru Outback

The 2020 Subaru Outback Premium shown in Figure 2 is equipped with Subaru's EyeSight technology, which is a stereo camera driver assistance system that can detect obstacles in the forward path of the vehicle. The pre-collision braking system provides both audible and visual alerts to the driver when a collision is imminent and applies the brakes to either avoid or decrease the impact speed with a pedestrian. According to the owner's manual, the PAEB system is active in the 7-100 mph (10-160 kph) range (Subaru, 2020).

Figure 2. The 2020 Subaru Outback

2018 Buick Regal

The 2018 Buick Regal Essence shown in Figure 3 is equipped with Buick's "Front Pedestrian Braking" PAEB system, which warns the driver and enhances or applies the brakes if an imminent collision with a pedestrian has been detected. The Front Pedestrian Braking system includes both a forward camera and radar system. According to the owner's manual, the PAEB system is active in the 5-50 mph (8-80 kph) range (GM, 2018). Additionally, the Buick is equipped with an active hood system which lifts the rear of the hood to create additional cushion for a pedestrian impacted in the 16-30 mph (25-48 kph) range (GM, 2018). During PAEB testing the active hood system was disabled following manufacturer-provided instructions.

Figure 3. The 2018 Buick Regal

2021 Volkswagen Arteon

The 2021 Volkswagen Arteon SEL Premium R-Line shown in Figure 4 is equipped with both "Front Assist" and "Pedestrian Monitoring," which are radar-based systems capable of detecting crossing pedestrians and pedestrians that are moving in the same direction as the vehicle. According to the owner's manual, for the scenarios tested in this research, the PAEB system is active in the 3-40 mph (5-65 kph) range (Volkswagen, 2021). The vehicle is also equipped with an active hood system which raises the hood from the rear a few inches to protect a pedestrian when sensors in the front bumper are triggered at 25-55 kph (15-34 mph) (Volkswagen, 2021). During PAEB testing the active hood system was disabled per the manufacturer-provided instructions.

Figure 4. The 2021 Volkswagen Arteon

Methods

Crash Avoidance PAEB Testing

Tests were performed following the NHTSA *Pedestrian Automatic Emergency Braking System Confirmation Test* draft test procedures (NHTSA, 2019), which provides methods and specifications for collecting performance data in the most frequent vehicle-to-pedestrian collision scenarios in the United States (Yanagisawa et al., 2017). This study focused on the results in the nearside adult walking S1 scenarios (S1a, S1b, and S1c). These scenarios were designed to evaluate PAEB response to an adult pedestrian mannequin crossing into the path of the vehicle from the passenger side, as demonstrated in Figure 5 (NHTSA, 2019).

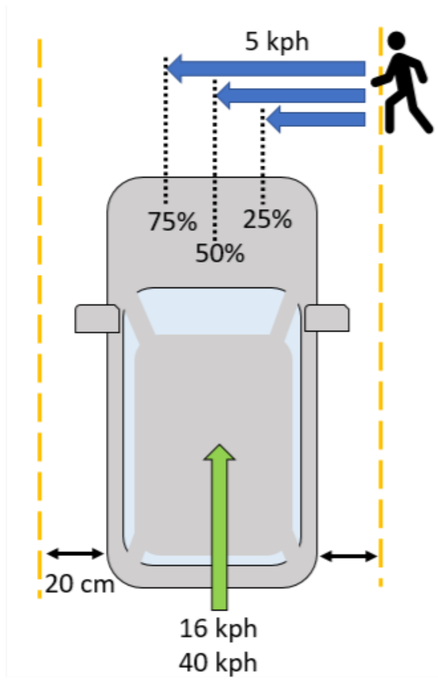

Figure 5. PAEB test scenarios S1a (25%), S1b (50%), and S1c (75%)

The three scenarios differ only in their specified impact overlap. The impact overlap defines the point along the front of the vehicle at which the collision with the mannequin would occur if there were no PAEB intervention. The overlap is defined as a percentage of vehicle width measured from the passenger side of the vehicle. The overlap positions for S1a, S1b, and S1c are 25 percent, 50 percent, and 75 percent, respectively. The nominal speed of the pedestrian test mannequin is 5 kph, and the acceleration distance for the mannequin is specified as 0.5 m. The test was performed at two subject vehicle (SV) speeds of 16 kph and 40 kph. The S1 test scenarios are summarized in Table 1.

Table 1. PAEB test scenarios S1a (25%), S1b (50%), and S1c (75%)

Test Scenario Designation	Test Condition	Mannequin Speed/Acceleration Distance	Mannequin Initial Position	Overlap (%)	SV Speeds (kph)
S1a	Nearside Adult Walk	5 kph, Accel. in 0.5 meters	Passenger Side, 3.5 m from center	25	16, 40
S1b	Nearside Adult Walk	5 kph, Accel. in 0.5 meters	Passenger Side, 3.5 m from center	50	16, 40
S1c	Nearside Adult Walk	5 kph, Accel. in 0.5 meters	Passenger Side, 3.5 m from center	75	16, 40

For all tests resulting in an impact between the vehicle and pedestrian, the vehicle speed at impact was recorded. These reduced impact speeds were later used in the crashworthiness pedestrian headform testing.

Crashworthiness Pedestrian Headform Testing

All headform tests in this study were performed according to the procedures outlined in the European New Car Assessment Programme (Euro NCAP) Pedestrian Testing Protocol (Version 8.3, December 2016). Certified child and adult headforms that conform to Euro NCAP requirements (mass, diameter, moment of inertia, and instrumentation position) were used in this study. Headforms were launched into the hoods of the test vehicles at two speeds: the 40 kph impact speed as specified by the Euro NCAP procedures and a reduced speed obtained from the PAEB test results. Headform impacts were performed near the 25-percent and 50-percent (centerline) overlap to coincide with the S1a and S1b PAEB test scenarios. For the purposes of conducting the impact tests, the 75-percent overlap impact location associated with the S1c PAEB test scenario was omitted, as symmetry was assumed for the vehicle between the 25-percent and 75-percent overlap impact locations. Three headform impact locations along each of the overlaps were targeted for a total of six impact locations per vehicle. The three impact points along each overlap line simulate three different pedestrian heights. In terms of placing headform impact points directly on the overlap line where initial contact occurs, factors such as pre-contact braking, vehicle speed, and pedestrian crossing speed would all be expected to influence the lateral difference between initial front-end contact with the pedestrian's and location of the head impact in a real-world vehicle-pedestrian interaction. However, since data is somewhat limited in terms of the relative effects of these factors on head impact location, for this study the lateral difference was assumed to be zero for simplicity of locating headform impact points. An overview of the pedestrian headform impact setup and impact locations is shown in Figure 6.

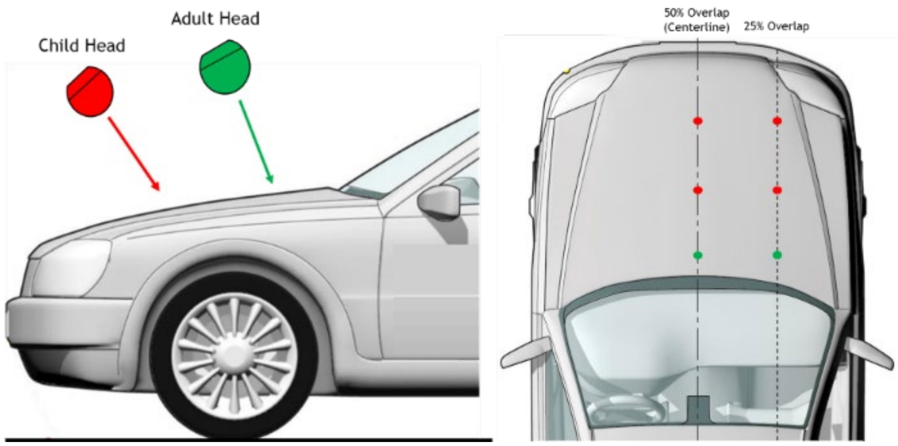

Figure 6. Crashworthiness pedestrian headform impact setup and impact locations

The effectiveness of active hood systems was also evaluated for those vehicles in which these systems were equipped. For an active hood system, the total response time (TRT) of a hood deployment is the total time from pedestrian contact until full deployment of the hood. Different stature pedestrians (i.e., 6-year-old, 5th female, 50th male, and 95th male) have different wrap around distances (WADs) when struck by the front end of a given vehicle (Figure 7). Thus, the pedestrians will also have a range of head impact times. To be most effective, any active hood system's TRT should be less than the head impact times for pedestrians of all sizes.

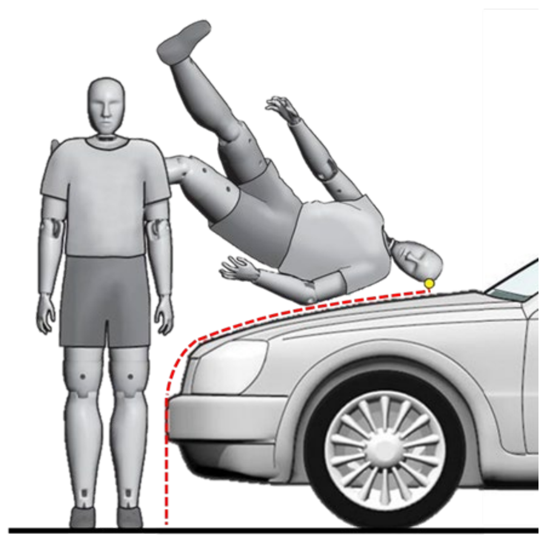

Figure 7. Wrap around distance (WAD) for a given stature shown by the red dotted line

Through simulations, a vehicle manufacturer can determine the head impact time (HIT) for a given stature (i.e., WAD) and how that relates to the total response time of the active hood system. Figure 8 below shows an example plot of head impact time versus stature (WAD) and how that relates to the total response time. If the system is fully deployed and remains in the intended position prior to the HIT of a given stature pedestrian (i.e., if TRT < HIT), then all headform tests shall be performed with the hood in the fully deployed position and there will be no need to trigger any active elements during the test. If the system is not fully deployed before the HIT of a given stature (i.e., TRT > HIT), then all grid points forward of the corresponding WAD are tested dynamically. In Figure 8, for example, the 6-year-old should be tested dynamically while the 5th female, 50th male, and 95th male should be tested in the fully deployed position. For systems that do not remain in a permanently deployed position and descend back down immediately after deployment, dynamic tests are required for all grid points.

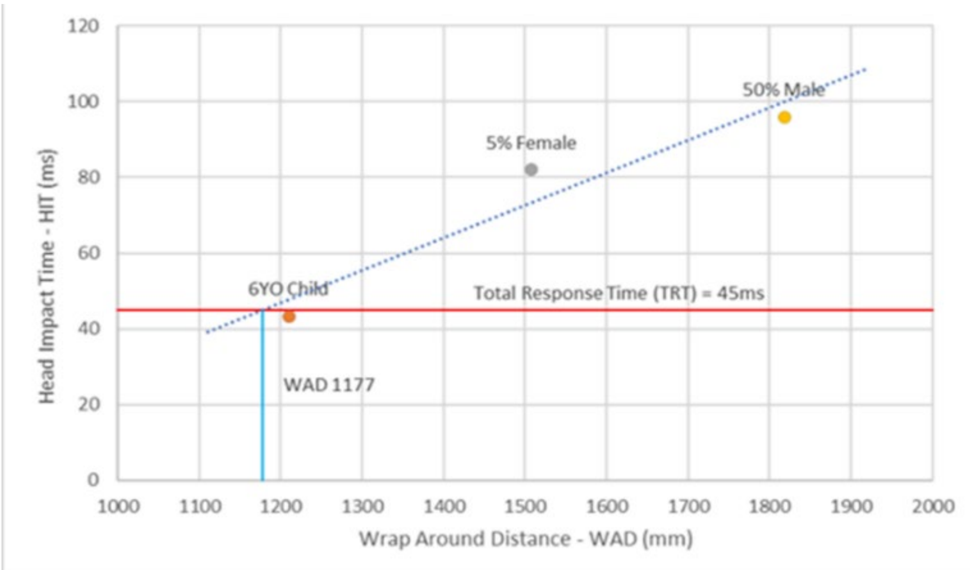

Figure 8. Head impact time (HIT) versus wrap around distance (WAD) and the relationship with the active hood total response time (TRT)

Two of the four vehicles tested have active hood technologies: the Buick Regal and Volkswagen Arteon. According to both GM and Volkswagen, the total response time of both hood deployments are less than the head impact time for all statures. Additionally, both hoods remain in a permanently deployed state. Therefore, head impacts to the active hood systems of both vehicles were performed in the fully deployed state (i.e., deployed-static).

To evaluate the risk of serious head injury due to impact, the head injury criterion over a duration of 15 ms (HIC15) was calculated for each headform impact, which is derived from the resultant head acceleration and defined in the equation below. A larger HIC15 value indicates a more serious head injury.

$$HIC = \left\{ \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)dt \right]^{2.5} (t_2 - t_1) \right\}_{max}$$

Results

The PAEB vehicle-to-pedestrian impact speeds were used to inform the crashworthiness head impact speeds, therefore, the following sections present only the data in which PAEB testing resulted in an impact between the vehicle and the pedestrian test mannequin.

2016 Chevrolet Malibu

All S1a and S1b scenario tests at 40 kph resulted in a reduced speed impact with the pedestrian test mannequin (Table 2), meaning the Chevrolet Malibu PAEB system activated and reduced the vehicle speed, but impact still occurred. The average speed reduction from the 40 kph test speed was approximately 10 kph, resulting in an average impact speed with the pedestrian test mannequin of 30 kph.

Table 2. 2016 Chevrolet Malibu PAEB results that ended in an impact with a pedestrian (no impacts were observed in S1c tests)

Scenario	Ped Test Speed	SV Test Speed	FCW Audible Alert	PAEB Activation	Impact	Speed Reduction	Impact Speed
	kph	kph				kph	kph
S1/a	5	40	yes	yes	yes	11.4	28.6
			yes	yes	yes	7.5	32.5
			yes	yes	yes	11.6	28.4
S1/b	5	40	yes	yes	yes	11.4	28.6
			yes	yes	yes	10.7	29.3
			yes	yes	yes	8.1	31.9

Chevrolet Malibu pedestrian headform impact locations along the 25-percent and 50-percent overlaps are shown in Figure 9. Reduced speed headform impacts were performed at 30 kph, the average impact speed from the PAEB testing. Pedestrian headform HIC15 results for the standard 40 kph and 30 kph PAEB reduced impact speeds are shown in Table 3.

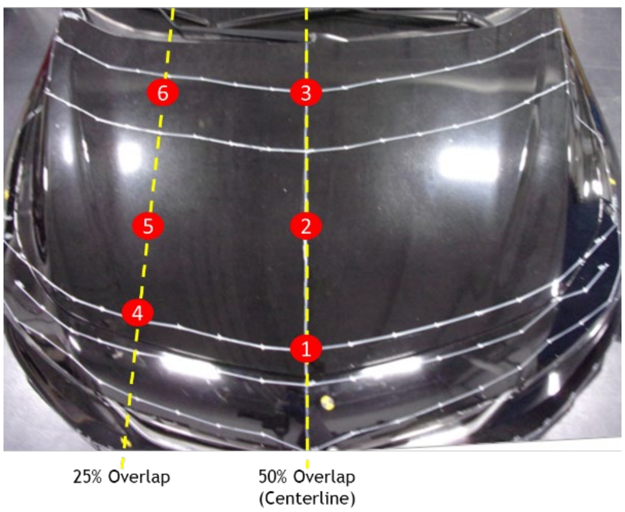

Figure 9. 2016 Chevrolet Malibu pedestrian headform impact locations

Table 3. 2016 Chevrolet Malibu pedestrian headform impact results

2016 Chevrolet Malibu				
Impact Location	Coordinates	HIC15 Results		
		40 kph	PAEB Reduced Speed 30 kph	% Reduction
1	C,0,0	1013	564	44%
2	C,3.5,0	374	198	47%
3	C,7,0	589	188	68%
4	C,1,4.5	1096	432	61%
5	C,3.5,4.5	762	303	60%
6	C,7,4.5	514	*516	0%

*The reduced speed test at impact location 6 was not at the same location as in the 40 kph test but closer to the cowl, which may explain the similar HIC results.

2020 Subaru Outback

During all test scenarios (S1a, S1b, and S1c) at 40 kph, the Subaru Outback PAEB system activated and avoided all collisions with the pedestrian test mannequin. During test scenarios S1b and S1c at 16 kph, all collisions were avoided. During the S1a test scenario at 16 kph, the Subaru Outback impacted the pedestrian test mannequin with minimal reduction in speed. The PAEB results for the S1a 16 kph tests that resulted in an impact between the Subaru Outback and the pedestrian test mannequin are shown in Table 4 below.

Table 4. 2020 Subaru Outback PAEB results that ended in an impact with a pedestrian (no impacts were observed in S1b or S1c tests)

Scenario	Ped Test Speed	SV Test Speed	FCW Audible Alert	PAEB Activation	Impact	Speed Reduction	Impact Speed
	kph	kph				kph	kph
S1/a	5	16	yes	yes	yes	1.6	14.9
			no	no	yes	0.0	16.2
			no	no	yes	0.0	16.4

Subaru Outback pedestrian headform impact locations along the 25-percent and 50-percent overlaps are shown in Figure 10. The Subaru Outback avoided all pedestrian collisions in the 40 kph scenario. Therefore, no reduced speed impacts were performed for the 40 kph scenarios. Pedestrian headform HIC15 results for the standard 40 kph impact speed are shown in Table 5.

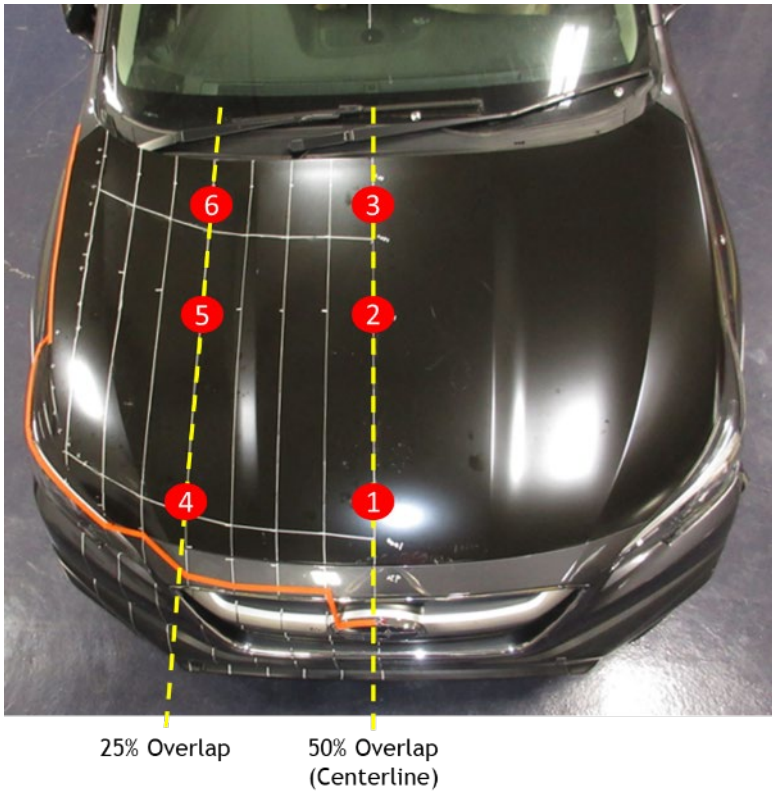

Figure 10. 2020 Subaru Outback pedestrian headform impact locations

Table 5. 2020 Subaru Outback pedestrian headform impact results

2020 Subaru Outback				
Impact Location	**Coordinates**	**HIC15 Results**		
		40 kph	***PAEB Reduced Speed 0 kph**	**% Reduction**
1	C,1,0	741	0	100%
2	C,5,0	441	0	100%
3	A,8,0	329	0	100%
4	C,1,+4	1023	0	100%
5	C,5,+4	545	0	100%
6	A,8,+4	418	0	100%

*The Subaru Outback avoided impacts with the pedestrian test mannequin during all 40 kph scenarios.

Although the Subaru Outback avoided impacts with the pedestrian test mannequin at all 40 kph scenarios, impacts did occur during the S1a scenario at 16 kph. Headform impacts were also performed at 16 kph and the resulting HIC values are provided in Appendix A.

2018 Buick Regal

During all test scenarios at 40 kph, the Buick Regal PAEB system activated, and vehicle speed was reduced. However, the Buick Regal still collided with the pedestrian test mannequin during all tests at 40 kph. The PAEB tests that resulted in an impact between the subject vehicle and the pedestrian test mannequin are shown in Table 6 below. The speed reduction from the 40 kph test speed varied from 14 kph to 29 kph, resulting in impact speeds with the pedestrian test mannequin between 11 kph and 26 kph. No collisions occurred during 16 kph test scenarios.

Table 6. 2018 Buick Regal PAEB results that ended in an impact with a pedestrian

Scenario	Ped Test Speed	SV Test Speed	FCW Audible Alert	PAEB Activation	Impact	Speed Reduction	Impact Speed
	kph	kph				kph	kph
S1/a	5	40	yes	yes	yes	15.9	24.6
			yes	yes	yes	16.9	22.8
S1/b	5	40	yes	yes	yes	21.9	17.5
			yes	yes	yes	28.5	11.3
			yes	yes	yes	18.5	21.8
			yes	yes	yes	17.6	22.3
S1/c	5	40	yes	yes	yes	18.1	22.3
			yes	yes	yes	13.7	26.5

Buick Regal pedestrian headform impact locations along the 25-percent and 50-percent overlaps are shown in Figure 11. Since the PAEB impact speeds varied greatly, it was decided that instead of taking the average of the PAEB impact speeds, to use the greatest PAEB impact speed as a worst-case scenario for the headform impacts. Therefore, reduced speed headform impacts were performed at 26 kph for the Buick Regal. Note that this highest impact speed was observed in the S1c 75-percent overlap condition. For the purposes of the impact test, it was decided that this speed could be applied at the 25-percent overlap location because the underhood structures and clearances for the Regal were observed to be symmetric between driver and passenger sides. Pedestrian headform HIC15 results for the standard 40 kph and 26 kph PAEB reduced impact speeds are shown in Table 7.

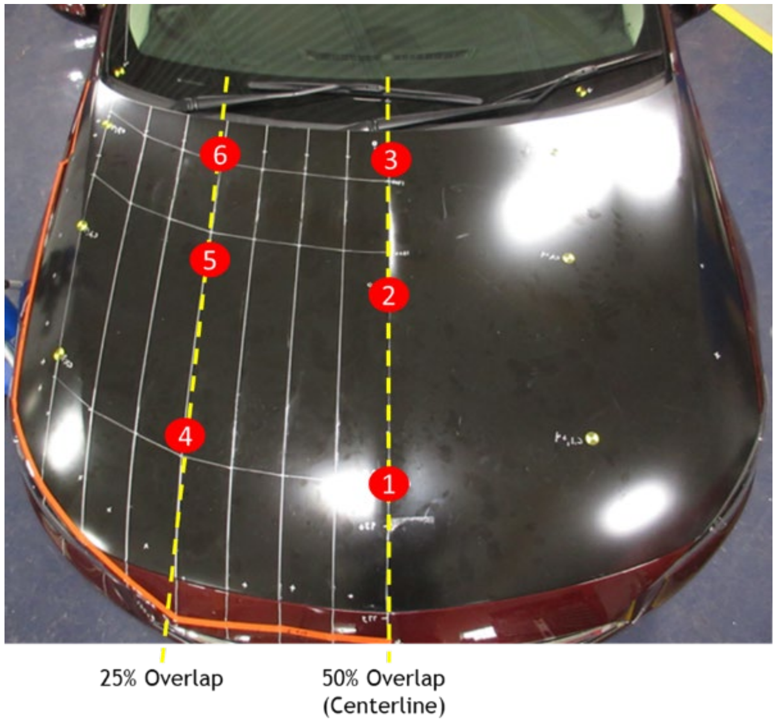

Figure 11. 2018 Buick Regal pedestrian headform impact locations

Table 7. 2018 Buick Regal pedestrian headform impact results on a standard, non-deployed hood

2018 Buick Regal (Standard, Non-Deployed Hood)				
Impact Location	**Coordinates**	**HIC15 Results**		
		40 kph	**PAEB Reduced Speed 26 kph**	**% Reduction**
1	C,0,0	641	253	61%
2	C,4,0	396	132	67%
3	A,8,0	817	495	39%
4	C,1,+4	834	281	66%
5	C,5,+4	905	161	82%
6	A,8,+4	1205	483	60%

The Buick Regal is equipped with an active hood system, which was also evaluated. According to GM, the total response time of the hood deployment is less than the head impact time for all statures or wrap around distances. Additionally, the hood remains in a permanently deployed state once it is activated or popped up. Therefore, head impacts to the active hood system were performed in the fully deployed state (i.e., deployed-static). Head impacts were performed on the fully deployed hood of the Buick Regal at the same six impact locations and at the same impact speeds of 40 kph and 26 kph. Pedestrian headform HIC15 results at 40 kph and 26 kph to the Buick Regal active hood are shown in Table 8.

Table 8. 2018 Buick Regal active hood headform impact results

2018 Buick Regal (Active Hood)			
Impact Location	Coordinates	HIC15 Results	
		Active Hood 40 kph	Active Hood 26 kph
1	C,0,0	464	188
2	C,4,0	367	121
3	A,8,0	251	148
4	C,1,+4	550	176
5	C,5,+4	365	124
6	A,8,+4	229	110

2021 Volkswagen Arteon

During the S1a test scenarios at 40 kph, the Volkswagen Arteon PAEB system activated, and vehicle speed was reduced. The Volkswagen Arteon collided with the pedestrian test mannequin during tests at 40 kph at 25-percent overlap (S1a). No collisions occurred at 50-percent overlap (S1b) and 75-percent overlap (S1c). The PAEB results that resulted in an impact between the subject vehicle and the pedestrian test mannequin are shown in Table 9 below. The speed reduction from the 40 kph test speed varied between 13 kph to 26 kph, resulting in impact speeds with the pedestrian test mannequin between 14 kph and 26 kph. No collisions occurred during 16 kph test scenarios.

Table 9. 2021 Volkswagen Arteon PAEB results that ended in an impact with the mannequin (S1b and S1c scenarios did not result in an impact)

Scenario	Ped Test Speed	SV Test Speed	FCW Audible Alert	PAEB Activation	Impact	Speed Reduction	Impact Speed
	kph	kph				kph	kph
S1/a	5	40	yes	yes	yes	21.6	18.6
			yes	yes	yes	13.4	26.1
			yes	yes	yes	25.8	14.5

Volkswagen Arteon pedestrian headform impact locations along the 25-percent and 50-percent overlaps are shown in Figure 12. Since the PAEB impact speeds varied greatly, as with the Buick Regal, the greatest PAEB impact speed was taken as a worst-case scenario. Therefore, reduced speed headform impacts were performed at 26 kph for the Volkswagen Arteon. In Table 10, pedestrian headform HIC15 results for the standard 40 kph impact speed are shown for all impact locations while results for the 26 kph PAEB reduced impact speeds are shown at 25-percent overlap (impact locations 4, 5, and 6).

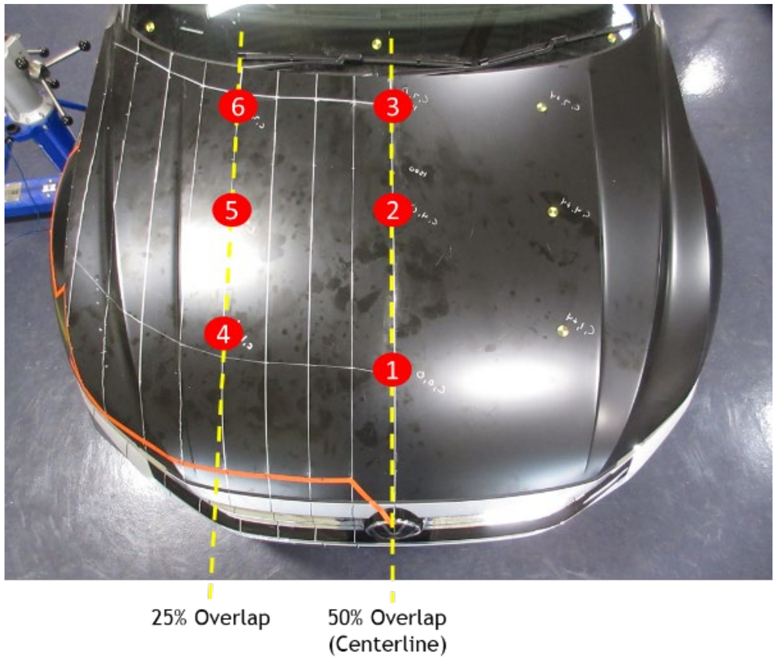

Figure 12. 2021 Volkswagen Arteon pedestrian headform impact locations

Table 10. 2021 Volkswagen Arteon pedestrian headform impact results

2021 VW Arteon (Standard, Non-Deployed Hood)				
Impact Location	**Coordinates**	**HIC15 Results**		
		40 kph	**PAEB Reduced Speed 26 kph**	**% Reduction**
1	C,0,0	1088	0	100%
2	C,4,0	394	0	100%
3	C,7,0	833	0	100%
4	C,1,+4	913	270	70%
5	C,4,+4	505	170	66%
6	C,7,+4	835	245	71%

Although the Volkswagen Arteon avoided impacts with the pedestrian test mannequin during the 40 kph S1b scenarios (50% overlap - impact locations 1, 2, and 3), headform impacts were performed at the 26 kph reduced speed, and the resulting HIC values are provided in Appendix A.

The Volkswagen Arteon is also equipped with an active hood system, which was evaluated. According to Volkswagen, the total response time of the hood deployment is less than the HIT for all statures or WADs. Additionally, the hood remains in a permanently deployed state once it is activated or popped up. Therefore, head impacts to the active hood system were also performed in the fully deployed state (i.e., deployed-static). Head impacts were performed on the fully deployed hood of the Volkswagen Arteon at the same three impact locations where PAEB tests resulted in an impact with the pedestrian test mannequin and at the same impact speeds of 40 kph and 26 kph. Pedestrian headform HIC15 results at 40 kph and 26 kph to the Volkswagen Arteon active hood are shown in Table 11.

Table 11. 2021 Volkswagen Arteon active hood headform impact results

2021 VW Arteon (Active Hood)			
Impact Location	**Coordinates**	**HIC15 Results**	
		Active Hood 40 kph	**Active Hood 26 kph**
4	C,1,+4	775	277
5	C,4,+4	414	154
6	C,7,+4	411	138

Additional fully deployed active hood impacts were performed on the Volkswagen Arteon at 50-percent overlap (impact locations 1, 2, and 3) at both 40 kph and 26 kph. HIC15 results for these tests are provided in Table 13.

Discussion

At the 40 kph subject vehicle test speed, the PAEB systems were activated in all four of the vehicles tested and all four vehicle speeds were reduced prior to impact with the pedestrian test mannequin. At the 40 kph test speed, the Subaru Outback avoided contact with the pedestrian while the Chevrolet Malibu, Buick Regal, and Volkswagen Arteon collided with the pedestrian, but at reduced speeds. For the Chevrolet Malibu, Buick Regal, and Volkswagen Arteon, pedestrian headform impacts were performed at these same reduced speeds and at 40 kph. Although the Subaru Outback avoided contact with a pedestrian at 40 kph, its PAEB system failed to activate at 16 kph, where it collided with the pedestrian with no reduction in speed. For the Subaru Outback, pedestrian headform impacts were performed at the standard 40 kph with no reduced speed impacts. However, headform impacts were also performed at 16 kph (results in Appendix A) but excluded from any comparisons.

To evaluate the risk of serious head injury due to impact, HIC15 was calculated for each headform impact where a larger HIC15 value indicates a more serious head injury. The Global Technical Regulation on Pedestrian Safety (GTR No. 9) also specifies areas within the testable hood where HIC15 must not exceed 1000 or 1700. Euro NCAP also uses HIC15 to evaluate and score the performance of a vehicle in protecting pedestrians. A HIC15 value of 650 (the full point threshold for Euro NCAP scoring) is associated with a 9% risk of AIS 3+ head injury while a HIC15 value of 1700 (the zero-point threshold for Euro NCAP scoring) is associated with a 49% risk of AIS 3+ injury. The probability of death for a given HIC value can also be calculated from the following equations:

For HIC15 < 880

$$Probability\ of\ Death = (0.00197 * HIC15) + 0.563$$

For HIC15 > 880

$$Probability\ of\ Death = (0.0386 * HIC15) - 31.7$$

The HIC15 values calculated from the 40 kph and PAEB reduced speed impacts are summarized for the Chevrolet Malibu in Table 3, Subaru Outback in Table 5, Buick Regal in Table 7, and Volkswagen Arteon in Table 10. In order to visualize how a reduction in speed affects the severity of pedestrian head impacts, the average HIC15 values at 40 kph and reduced speeds are presented in Figure 13, with the average probabilities of death shown, for vehicles in which PAEB tests resulted in an impact with the pedestrian test mannequin. At 40 kph headform impact speeds, a majority of the HIC15 values are below 1,000, indicating that the head protection performance for these vehicles are already fairly good. The Subaru Outback is not shown in Figure 13 since impacts at 40 kph were avoided during PAEB testing. However, 40 kph head impacts to the Subaru Outback resulted in an average HIC15 value of 583. At reduced impact speeds, which result from the implementation of a PAEB system installed on these vehicles, the HIC15 values decreased greatly.

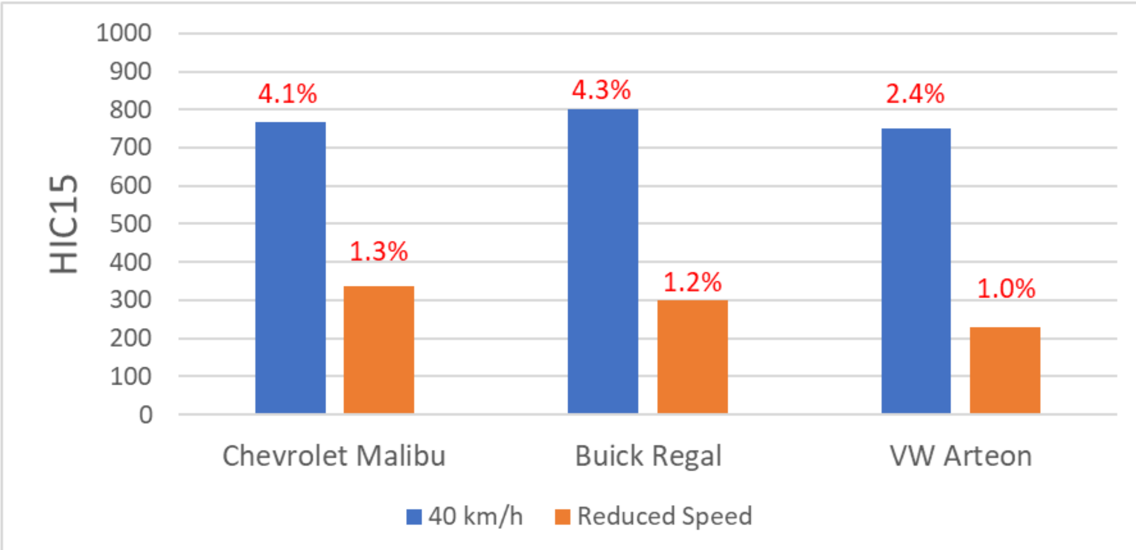

Figure 13. Average HIC15 values at 40 kph and reduced speeds for each of the vehicles tested (probabilities of death are shown in red)

Two of the vehicles tested, the Buick Regal and Volkswagen Arteon, are also equipped with active hood systems that lift the rear of the hood upon contact with a pedestrian to provide more clearance to engine components and provide a more "cushioned" impact. These active hood systems were also evaluated at 40 kph and at the PAEB reduced speeds and were tested in their fully deployed states. HIC15 results for the Buick Regal with its hood in the normal state and fully deployed state are shown in Table 12. Looking at Figure 14, for a given speed (blue vs grey, orange vs yellow), headform impacts to the Buick Regal with the hood in a fully deployed state resulted in lower HIC15 values than those in a normal hood state. Like the implementation of a PAEB system, it appears that the implementation of an active hood system would also reduce the severity of head impacts.

Table 12. HIC15 results for the Buick Regal with its hood in the normal state and fully deployed state at 40 kph and 26 kph headform impact speeds

2018 Buick Regal					
Coordinates	Impact Location	HIC15 Results			
		Normal Hood		Active Hood	
		40 kph	26 kph	40 kph	26 kph
C,0,0	1	641	253	464	188
C,4,0	2	396	132	367	121
A,8,0	3	817	495	251	148
C,1,+4	4	834	281	550	176
C,5,+4	5	905	161	365	124
A,8,+4	6	1205	483	229	110

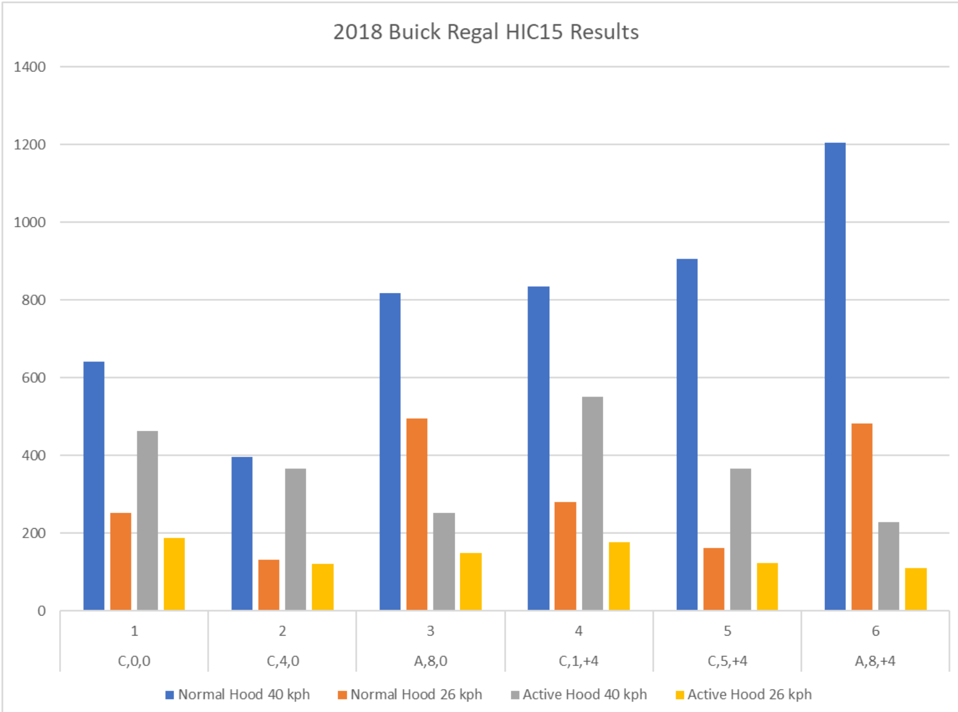

Figure 14. Comparison of HIC15 results for the Buick Regal with its hood in the normal state and fully deployed state at 40 kph and 26 kph headform impact speeds

HIC15 results for the Volkswagen Arteon with its hood in the normal state and fully deployed state are shown in Table 13. Looking at Figure 15, at 40 kph (blue vs grey), in five of the six headform impacts to the Volkswagen Arteon, HIC15 results were lower in tests with the hood in a fully deployed state than those in a normal hood state. At impact location 2 (C,4,0), a 40 kph impact to the fully deployed hood resulted in a higher HIC15 value than a 40 kph impact to the normal hood. However, both HIC15 values indicate a low probability of injury. Comparing the 26 kph reduced speed impacts (orange vs yellow), HIC15 results in tests with the hood in the fully deployed state were sometimes lower and sometimes higher than those in a normal state. However, all HIC15 values at the 26 kph reduced impact speeds were low, indicating a low probability of injury. Like the Buick Regal, it appears that the implementation of an active hood system would also reduce the severity of head impacts.

Table 13. HIC15 results for the Volkswagen Arteon with its hood in the normal state and fully deployed state at 40 kph and 26 kph headform impact speeds

2021 VW Arteon					
Coordinates	Impact Location	HIC15 Results			
		Normal Hood		Active Hood	
		40 kph	26 kph	40 kph	26 kph
C,0,0	1	1088	341	1050	367
C,4,0	2	394	146	467	183
C,7,0	3	833	256	484	154
C,1,+4	4	913	270	775	277
C,4,+4	5	505	170	414	154
C,7,+4	6	835	245	411	138

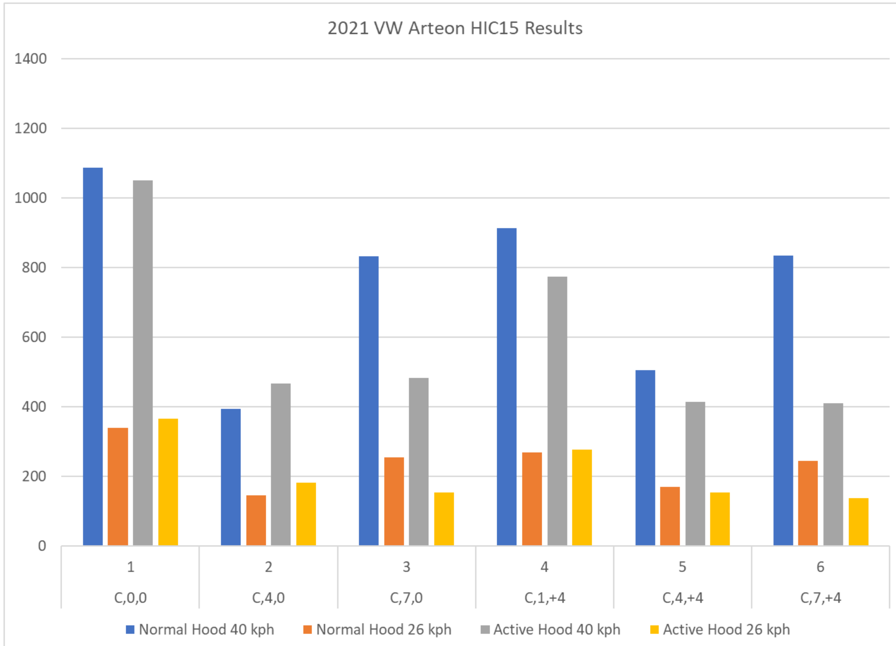

Figure 15. Comparison of HIC15 results for the Volkswagen Arteon with its hood in the normal state and fully deployed state at 40 kph and 26 kph headform impact speeds

For the two vehicles tested, the presence of either a PAEB system to reduce vehicle speed or an active hood system to provide more cushioning reduce the severity of pedestrian head impacts. Although both systems are effective in reducing the HIC15 values of head impacts, reducing vehicle impact speed might be more effective than having an active hood. Figure 16 and Figure 17 compares 40 kph (blue) and reduced speed (orange) headform impacts to a normal hood with 40 kph headform impacts to a deployed active hood (grey) for the Buick Regal and Volkswagen Arteon, respectively. Although the active hood system for the Buick Regal was effective in reducing HIC15 values at all 6 impact locations, reducing vehicle speed was more effective in 4 out of 6 test locations. On the other hand, with the Volkswagen Arteon, speed reduction was more effective in reducing the HIC15 values of head impacts at all test locations.

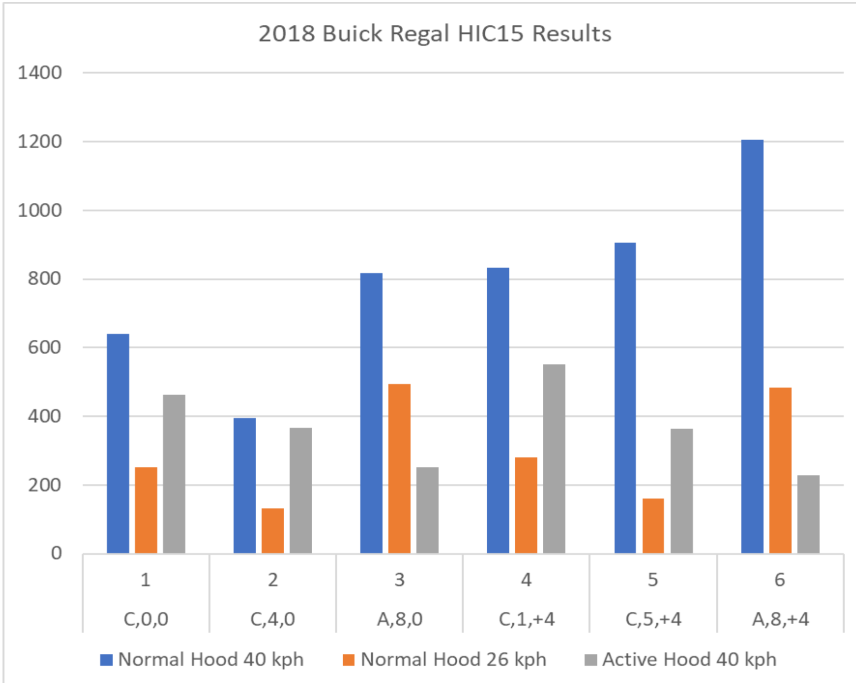

Figure 16. Reduction of HIC15 values for the Buick Regal due to a reduction of impact speed versus the presence of an active hood

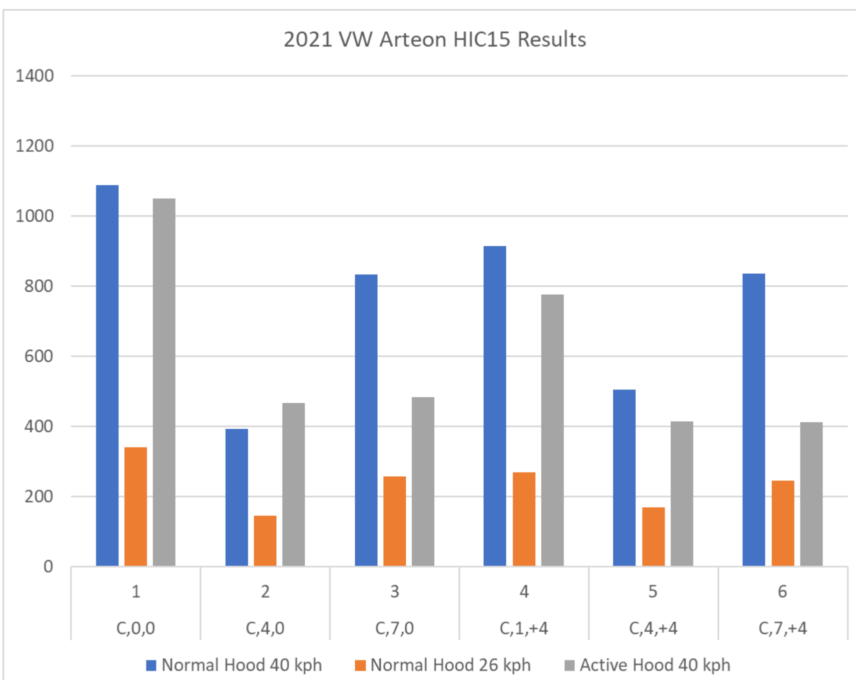

Figure 17. Reduction of HIC15 values for the Volkswagen Arteon due to a reduction of impact speed versus the presence of an active hood

Conclusions

- Crash avoidance PAEB test results were used to determine crashworthiness pedestrian headform impact speeds and locations.
- At a 40 kph test speed, the PAEB systems of all four vehicles in this study activated and vehicle speeds were reduced prior to impact with a pedestrian.
- Pedestrian headform impacts were performed at 40 kph and at PAEB reduced speeds on normal and fully deployed active hoods.
- The hoods of the four vehicles tested performed well in protecting against pedestrian head injuries as a majority of HIC15 values at 40 kph impact speeds were below 1000 with a low probability of fatality.
- Reducing the vehicle impact speed or providing a more cushioned impact via an active hood system were found to reduce the HIC15 values to an even lower risk of injury.
- By exploring a combined CA/CW testing approach to get a sense of real-world performance, the data collected in this study provided a glimpse of the relative impact of speed reduction versus crashworthiness countermeasures.

References

Chevrolet. (2016). *Chevrolet Malibu owner's manual*. https://cdn.dealereprocess.org/cdn/servicemanuals/chevrolet/2016-malibu.pdf

GM. (2018). *Buick Regal owner's manual.* www.buick.com/bypass/pcf/gma-content-api/resources/sites/GMA/content/staging/MANUALS/4000/MA4187/en_US/5.0/18i_BUI_Regal_OM_en_US_U_84234152B_2018MAR28_2P.pdf

Haus. S., Sherony, R., & Gabler, H. (2019). Estimated benefit of automated emergency braking systems for vehicle–pedestrian crashes in the United States. *Traffic Injury Prevention, 20*, sup1, S171-S176.

National Center for Statistics and Analysis. (2022, October). *Traffic safety facts 2020: A compilation of motor vehicle crash data* (Report No. DOT HS 813 375). National Highway Traffic Safety Administration. https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/813375

National Highway Traffic Safety Administration. (2019, September). *Pedestrian automatic emergency brake system confirmation test (working draft;* Docket No. NHTSA-2019-0102). www.regulations.gov/document/NHTSA-2019-0102-0005

NHTSA. (2022, March). *New Car Assessment Program; Request for comments* Federal Register, 87 (46): 13452 - 13521 (Docket No. NHTSA-2021-0002). www.govinfo.gov/app/details/FR-2022-03-09/2022-04894

NHTSA. (2023, June). *Automatic emergency braking systems for light vehicles.* Federal Register, 88 (113): 38632 - 38736 (Docket No. NHTSA-2023-0021-0007). www.regulations.gov/document/NHTSA-2023-0021-0007

Office of Information and Regulatory Affairs. (2022). *Pedestrian safety global technical regulation* (Unified Regulatory Agenda, Regulatory Identification Number 2127-AK98). www.reginfo.gov/public/do/eAgendaViewRule?pubId=202204&RIN=2127-AK98

Subaru. (2022). Subaru Outback owner's manual. www.subaru.com/owners/vehicle-resources.html

Volkswagen. (2021). Volkswagen Arteon owner's manual. https://api.ownersmanualvw.com/#/vin/WVWTR7AN6ME002804/content/en-us:3G8012723SH:0

Yanagisawa, M., Swanson, E., Azeredo, P., & Najm, W. G. (2017, April). *Estimation of potential safety benefits for pedestrian crash avoidance/mitigation systems* (Report No. DOT HS 812 400). National Highway Traffic Safety Administration.

Appendix A.

Table A1. HIC results from 16 kph headform impacts to 2020 Subaru Outback

2020 Subaru Outback		
Impact Location	**Coordinates**	**HIC15 Results**
		16 kph
1	C,1,0	79
2	C,5,0	68
3	A,8,0	42
4	C,1,+4	145
5	C,5,+4	57
6	A,8,+4	35

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