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A case study of nighttime pedestrian automatic emergency braking performance under different roadway lighting and pedestrian clothing conditions

January 2025

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INTRODUCTION

Fatal pedestrian crashes have increased 80% since 2009 and nearly three-quarters of these crashes occur in darkness (Kidd et al. 2023). Decreased illumination at night reduces the driver's contrast sensitivity and the ability to detect and recognize pedestrians. Automatic emergency braking (AEB) systems with pedestrian detection (PAEB) reduce the rate of police-reported pedestrian crashes by 27% (Cicchino 2022), but these benefits were not observed at night in unlit conditions where pedestrian fatality risk is highest (Sullivan and Flannagan 2002). Roadway lighting and retroreflective pedestrian clothing improve pedestrian conspicuity for human drivers, but whether these treatments improve PAEB performance at night is unclear.

Warnings signs, rapid flashing beacons, and other treatments that provide advanced warning of pedestrians make drivers more likely to yield during the day (Fitzpatrick and Park 2021) but do not improve nighttime detection of pedestrians; increasing lighting is more effective (Bhagavathula and Gibbons 2023). The Federal Highway Administration (FHWA) recommends that roadway luminaires at crosswalks provide a vertical luminance level of 20 lux when measured 1.5 m above the road surface and be placed at least 3 m before the crosswalk to render the pedestrian in positive contrast (Federal Highway Administration 2022).

Increasing the contrast and retroreflectivity of garments worn by pedestrians makes them more visible at night (e.g., Babić et al. 2021), but does not necessarily make them easier to identify by humans. Applying retroreflective materials to limbs and joints on the body like the wrists and ankles facilitates biological motion perception (e.g., Karn et al. 2022; Wood 2023), which enhances the nighttime conspicuity of vulnerable road users to drivers (e.g., Balk et al. 2008; Tyrrell et al. 2016; Wood 2023).

PAEB systems perform worse in the dark. On average, PAEB systems respond later and reduce speed less when approaching an adult mannequin standing in the road or crossing it at night with low beams compared with during the day and at night with high beams (Kidd et al. 2024). Presumably, increasing lighting at night would help PAEB systems detect and avoid pedestrians. Roadway treatments and pedestrian clothing that illuminate crosswalks and increase pedestrian nighttime conspicuity may improve camera-based PAEB performance when low beams are used. Conversely, camera-based PAEB systems may not benefit from these treatments if the treatments distort the human form expected by the system (e.g., Charlebois et al. 2023). This study evaluated how increasing pedestrian conspicuity using clothing or through increased roadway lighting affected PAEB performance.

METHODS

Three small SUVs were included in this study: a 2023 Mazda CX-5, a 2023 Honda CR-V, and a 2023 Subaru Forester. Each PAEB system was enabled by one or more forward-facing cameras, and two systems also had radar. Vehicle speed, longitudinal and lateral acceleration, longitudinal and lateral position, and angular velocity were measured with GPS and an inertial measurement unit. Video of the forward view and instrument cluster were recorded.

PAEB system performance was evaluated in two test scenarios with an adult mannequin (Figure 1): (1) a nearside scenario where the mannequin traversed a crosswalk beginning at the nearside of the road and (2) a far side scenario where the mannequin traversed a crosswalk beginning at the far side of the road. In both scenarios, the test vehicle approached the mannequin at 40 km/h and, without intervention, impacted the mannequin at 25% of the vehicle's width.

The amount of roadway lighting and the mannequin's clothing were manipulated. There were three roadway lighting conditions: 0 lux, 10 lux, and 20 lux, on average, when measured 1.5 m above the ground at each crosswalk ladder rung. The adult mannequin was dressed in (a) black clothing, (b) black clothing with a men's ProViz Reflect360 high-visibility running jacket, (c) black clothing with 3-cm wide retroreflective strips placed at major joints and limbs in a biological motion configuration, or (d) white clothing (Figure 1).

A total of 26 experimental conditions were evaluated; 24 tested PAEB performance in every combination of scenario, roadway lighting, and clothing condition when low beams were used, and two tested PAEB performance when the adult mannequin was in black clothing and high beams were used in the nearside and far side scenarios. PAEB performance was measured in up to three trials for each experimental condition. Testing in an experimental condition was stopped if the PAEB system evidenced a pattern of nonresponse, did not reduce speed more than 3 km/h in two consecutive trials, or reduced speed at least 37 km/h in two consecutive trials.

Percent speed reduction prior to impact was computed for each trial as the difference in vehicle speed when AEB began and at impact divided by the vehicle speed when AEB began. A percent speed reduction less than 100% indicates a collision. Data were aggregated across the nearside and far side scenarios. Descriptive statistics were used to examine PAEB performance across roadway and clothing conditions separately for each vehicle due to the small vehicle sample size and the performance variation between vehicles; inferential statistics were not performed.

RESULTS

A collision occurred in 59% of 167 trials. The Honda CR-V collided with the pedestrian in 84% of 55 trials, the Mazda CX-9 in 88% of 59 trials, and the Subaru Forester in 2% of 53 trials. On average, the PAEB systems reduced speed by 53% across trials. The average speed reduction for the Honda was 22%, for the Mazda was 41%, and for the Subaru was 98%.

Without roadway lighting, the PAEB system in the Honda reduced speed by 40% when the pedestrian was in black and high beams were used; it did not reduce speed when the pedestrian was in black and low beams were used (Figure 2). The Honda PAEB system reduced speed when 10 lux and 20 lux of roadway lighting was present and low beams were used, but only when the pedestrian was dressed in black or white clothing. The percent speed reduction when the pedestrian was in white clothing and 10 lux or 20 lux of roadway lighting was present was greater than when the pedestrian was in black and high beams were used without roadway lighting. The Honda PAEB system did not reduce speed in any trial where the pedestrian was wearing the ProViz Reflect360 jacket or retroreflective strips in a biological motion configuration.

The CX-5's PAEB system reduced speed by 68% when the pedestrian was wearing black and high beams were used without roadway lighting but only by 30% when low beams were used without roadway lighting. When the pedestrian wore black, the CX-5's PAEB system reduced speed by 31%, on average, with 10 lux of roadway lighting and by 84% with 20 lux of roadway lighting (Figure 2). The CX-5's PAEB system reduced speed by 53%, 58%, and 62%, with 0 lux, 10 lux, and 20 lux of roadway lighting, respectively, when the pedestrian was wearing the ProViz Reflect360 jacket. The system reduced speed by 34%, on average, when the pedestrian was wearing white with little change as roadway lighting increased. The Mazda CX-5's PAEB system did not reduce speed when the pedestrian was wearing black clothing with retroreflective strips in a biological motion configuration, regardless of the amount of roadway lighting.

The PAEB system in the Subaru reduced speed by 100% in every trial except one where the pedestrian was wearing retroreflective strips in a biological motion configuration with 10 lux of roadway lighting (Figure 2).

DISCUSSION

PAEB systems are not as effective for preventing pedestrian crashes at night compared with the day (Cicchino 2022), but increasing vehicle lighting makes PAEB performance similar to daytime (Kidd et al. 2024). This study examined if increasing pedestrian conspicuity with more roadway lighting and more conspicuous clothing also improves PAEB system performance. The findings indicated that these treatments inconsistently affected PAEB system performance among the three systems examined.

Consistent with past research (Kidd et al. 2024), PAEB systems in the Honda and Mazda reduced speed more when high beams were used and the pedestrian was wearing black than when low beams were used without roadway lighting. Presumably, increasing lighting from other sources would benefit PAEB system performance similarly, but the effects of increasing roadway lighting were inconsistent across the vehicle sample. The CR-V's PAEB system reduced speed more with increased roadway lighting but only when the pedestrian was wearing black or white. The CX-5's PAEB system reduced speed substantially more with 20 lux of roadway lighting when the pedestrian was wearing black and reduced speed slightly more as roadway lighting increased when the pedestrian was wearing the ProViz Reflect 360 jacket. Although increasing roadway lighting did not consistently benefit PAEB system performance, there was no evidence that PAEB performance was degraded by increased roadway lighting

Retroreflective strips at major joints facilitates biological motion perception by humans (e.g., Balk et al. 2008), but the findings indicated that it does not provide the same benefit for any of the PAEB systems, and possibly even confounded them. The CR-V and CX-5 PAEB systems did not respond to the pedestrian when it was wearing retroreflective strips, even though both reduced speed when the mannequin was only wearing black. It is unclear why the CR-V and CX-5 PAEB systems were unresponsive to the biological motion configuration, but the finding is concerning considering that roadway workers and emergency personnel wear clothing with similar features to mitigate risk during on-roadway exposure. The PAEB systems may have viewed the retroreflective strips on black clothing as a segmented form rather than a complete human form. Safety clothing worn by roadway workers and emergency personnel have retroreflective strips on highly fluorescent material. It is possible that retroreflective strips in a biological motion configuration on more reflective clothing like those worn by roadway workers and emergency personnel do not distort the human form and detection by PAEB systems; this is a question for future research. Nonetheless, the findings suggest that existing PAEB system hardware is insufficient, or detection algorithms are too brittle to cope with variations in the appearance of pedestrians.

Testing organizations around the world use mannequins meeting specific requirements to evaluate PAEB system performance (SAE International 2023). The requirements are designed to make the mannequin appear as a person to various sensors, but also may encourage narrow design of PAEB system algorithms that would limit real-world performance. Testing organizations should consider including additional clothing options that change the conspicuity and form of the mannequin to encourage robust PAEB system design.

In conclusion, the findings suggest that additional vehicle lighting enhances PAEB system performance but other methods for increasing pedestrian conspicuity may not. Providing 20 lux of average lighting at crosswalks per FHWA recommendations helps make pedestrians more conspicuous at night to people but may only benefit PAEB system performance in some circumstances. PAEB systems were sensitive to the clothing worn by the pedestrian mannequin, which underscores the need to improve PAEB hardware and detection algorithms to reduce the sensitivity to variations in clothing. Testing organizations also should consider varying clothing when evaluating PAEB performance.

ACKNOWLEDGMENTS

This work was supported by the Insurance Institute for Highway Safety (IIHS). The authors would like to thank David Aylor, Zack Horridge, Steve Griffin, Ken Melville, Philip Floyd, John Liebengood, Jason Shifflett, Dan Purdy, and Skye King of IIHS for supporting data collection. The authors also thank Brian Philips, Joeseph Cheung, and Keith Sinclair at FHWA for providing technical guidance.

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FIGURES

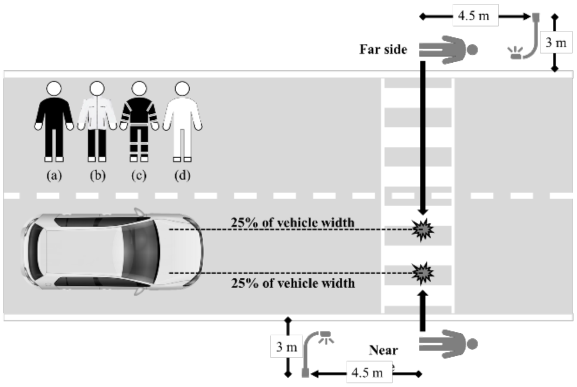

Figure 1. PAEB test scenarios, roadway lighting location, and pedestrian clothing conditions.

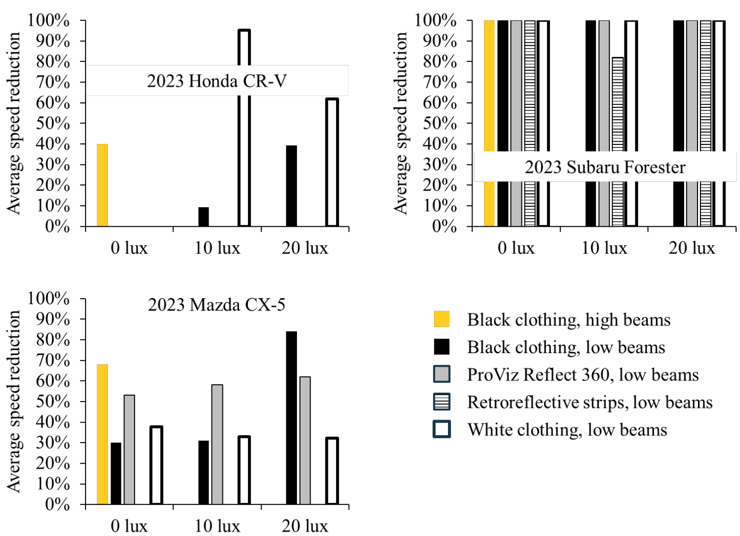

Figure 2. Average speed reduction for each vehicle by lighting and clothing condition.