# POTENTIAL REDUCTION IN PEDESTRIAN COLLISIONS WITH AN AUTONOMOUS VEHICLE

**Maya Detwiller**
**Hampton C. Gabler**
Virginia Tech
United States

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## ABSTRACT

Background: In 2015, over 5300 pedestrians were fatally injured in U.S. traffic crashes. One benefit of emerging autonomous vehicles is that this technology may not only eliminate many driver errors, but could also eliminate or mitigate many of these pedestrian collisions. However, to achieve this goal, the vehicle must have sufficient time to detect and respond to the many ways in which vehicle-pedestrian collisions can occur. Depending on how early a potential collision is detected, countermeasures could include automated emergency braking (AEB), and deployment of an external airbag. The objective of this study was to determine the potential reduction in pedestrian crashes which could be achieved by a fully autonomous vehicle (AV).

Methods: This study was based upon 523 in-depth vehicle-to-pedestrian crash investigations extracted from the NHTSA Pedestrian Crash Data Study (PCDS). The approach was to codify AV performance as one of two comprehensive rule-based algorithms describing ideal AV driving behavior. The first algorithm was comprised of 12 rules which would constrain the AV to never violate traffic rules, e.g. failure to yield to a pedestrian in a crosswalk. The second algorithm was comprised of 13 additional rules which constrained the AV to drive cautiously in situations which could contain potential pedestrian conflicts, e.g., children darting out from between parked cars. Both algorithms were applied to each of the 523 cases assuming that the striking vehicle was an AV rather than the original car. We then reconstructed the earliest opportunity for an AV to detect the pedestrian, and potentially avoid the crash in each case.

Results: A total of 40% of the crashes in our dataset were the result of a driver violation, i.e. cases which the AV under Algorithm 1 would avoid. In the balance of the Algorithm 1 cases in which there was no driver violation, nearly 80% of the pedestrian were visible for over 1 second – allowing activation of AEB. For an AV equipped with Algorithm 2, all but 27 of 523 pedestrian conflicts would have been avoided. In most of these cases, there was sufficient time to activate AEB. However, there was one case in which a pedestrian would still be struck despite application of the rigorous Algorithm rules.

Discussion: This study found that even with idealized performance, perfect sensors and ideal weather, not all pedestrian conflicts could be avoided. Limitations in this study included the inability to account for pedestrian occlusion, the assumption of ideal weather, and no sensor degradation. Accounting for these factors would likely decrease the number of pedestrian crashes which could be avoided.

Conclusions: Even under best case conditions it is unlikely that an ideal AV could avoid every pedestrian to vehicle crash. Therefore, an AV will require safety features, such as a pedestrian-friendly front structure or an external airbag, to protect pedestrians. This study is the first of its kind to estimate the potential safety benefits of an AV in pedestrian crashes and has important implications for both automakers and regulatory bodies.

## INTRODUCTION

In 2015, 5,376 pedestrians were killed in traffic crashes accounting for 15% of all traffic related fatalities in the U.S (NCSA, 2017). One benefit of emerging autonomous vehicles will be that this technology may not only eliminate many driver errors, but may also eliminate many pedestrian crashes and deaths. However, to achieve this goal, the vehicle must be capable of detecting and responding to the many ways in which vehicle-pedestrian collisions occur. One method of determining how a vehicle would perform in the traffic environment is to analyze a large set of real-world crashes, and determine if the vehicle could have prevented or at least mitigated the crash in each case. Our study will follow this approach using case data collected in the Pedestrian Crash Data Study (PCDS) by NHTSA (1996).

There are three methods by which the assumed autonomous vehicle could respond to an impending crash: automated emergency braking, pedestrian airbags, and a soft, pedestrian-compliant, front structure design. Automated emergency braking can slow and sometimes stop the vehicle if a pedestrian is detected with sufficient time before impact. This method has the potential to avoid a crash and reduce the risk of injury if the crash cannot be avoided as injury risk is a strong function of impact speed (Rosén et al, 2011). If the crash cannot be prevented, a pedestrian external airbag could be deployed to prevent the pedestrian from striking rigid points on the vehicle such as the A-pillars or the base of the windshield. The final line of defense would be a soft front structure. The structure would deform when the pedestrian impacted the vehicle to absorb impact energy and lessen injury severity. Individually, no method can prevent crashes or injuries in every vehicle-pedestrian interaction, but when combined, these countermeasures would ensure at the very least a lower impact speed, and fewer rigid structures for a pedestrian to strike.

## OBJECTIVE

The objective of this study was to determine the potential reduction in pedestrian crashes which could be achieved by a fully autonomous vehicle.

## APPROACH

### Data Source

The study was based upon cases extracted from the Pedestrian Crash Data Study (PCDS). PCDS consists of 549 in-depth vehicle-to-pedestrian crash investigations collected from 1994 to 1998 from six U.S. urban areas. The six data collection areas for PCDS were the cities of Buffalo, NY; Ft. Lauderdale and Hollywood, FL; Dallas, TX; Chicago, IL; Seattle, WA; and San Antonio, TX. The PCDS provides cases from a diverse set of urban regions with a wide range of weather conditions and roads, ensuring a broad scope of possible environments for the vehicle to encounter.

PCDS is the most recent publicly available pedestrian crash study in the U.S. The strategy in using this older dataset is that, although vehicles in the 2015-2017 time frame will be much different than in 1994-1998, the types of vehicle-pedestrian conflicts, e.g. children dodging out from between parked cars, are unlikely to have greatly changed. In this study, the PCDS will be used exclusively as a source of pedestrian-vehicle potential conflicts to explore crash avoidance opportunities and limitations. Our study will not use PCDS for analysis of injury outcomes.

Cases were included in PCDS if they met the following criteria. First, each case involved a collision between a pedestrian and car or light truck. In PCDS, a pedestrian was defined to be any person on the roadway, sidewalk, private property, or a path adjacent to the roadway including persons in contact with the ground or roadway who may be pushing carts or wagons or holding onto a vehicle. Secondly, the crash itself had to meet the following conditions: (a) must include a forward moving, late model year (at the time of the study) applicable vehicle, (b) the striking portion of vehicle structure must be original equipment manufacturer (OEM) without previous damage and/or parts removed in the impact area (ex: no deer guards, winches, or snow plows), (c) the pedestrian impact(s) were the vehicle's only impact(s) and (d) the first point of contact between the vehicle and the pedestrian must be forward of the top of the A-pillar. Finally, the case was excluded if the vehicle or pedestrian (or surrogate in case of fatality) could not be located / interviewed and the vehicle damage measurements were not obtained within 24 hours of the crash.

If a crash involved more than one pedestrian, each pedestrian was regarded as a separate case. The final dataset was comprised of 531 crashes involving 549 individual pedestrians. The PCDS case data were available in two formats: a SAS dataset - in which all cases are available, and PDFs of the actual scanned case reports for 527 crashes involving 545 individual pedestrians. The scanned case reports included scene diagrams, distance measurements, scene photos in some cases, a prose description, a pedestrian assessment detailing the pedestrian's actions leading up to the crash and the injuries sustained, assessment of the driver actions before and after the crash, vehicle damage, as well as roadway details, and pedestrian and driver interviews.

**Hypothetical Autonomous Vehicle Algorithm**

The algorithms by which an AV would detect and respond to a potential pedestrian crash are highly proprietary and still under development by AV designers.

In our study, our approach was to instead codify AV performance as one of two comprehensive rule-based algorithms describing ideal AV driving behavior. The first algorithm was comprised of 12 rules which would constrain the AV to never violate traffic rules, e.g. failure to yield to a pedestrian in a crosswalk. The second algorithm was comprised of 13 additional rules which constrained the AV to drive cautiously in situations which could contain potential pedestrian conflicts, e.g., children darting out from between parked cars. When an AV under Algorithm 2 rules encountered a potentially hazardous situation, the vehicle would drive cautiously, more slowly, and even increase the distance to other vehicles. Algorithm 1 rules are shown in Table 1. Algorithm 2 rules are shown in Table 2.

*Table 1. Algorithm 1 for a Hypothetical Autonomous Vehicle*

| Rule | The Ideal Autonomous Vehicle: |
|---|---|
| 1 | Will not exceed the speed limit. |
| 2 | Will not turn across the path of other oncoming vehicles (e.g. intersection judgement error) |
| 3 | Will not turn into a flow of traffic without a clear view of oncoming traffic (including pedestrians and other vulnerable road users) and there being sufficient space. |
| 4 | Will yield to traffic that has right of way at intersections, side streets, etc. |
| 5 | Will stop at red lights, stop signs, railroad signs, crosswalks, etc. |
| 6 | Will not run into another stationary vehicle or barrier, etc. |
| 7 | Will keep a safe following distance to the vehicle ahead in the same lane. |
| 8 | Will not change lanes into the safe zone in front of another vehicle (i.e. will not cut in front of vehicles travelling at speed) |
| 9 | Will not lose control due to travelling too fast for a corner (except perhaps ice) |
| 10 | Will not overcorrect when making an evasive maneuver |
| 11 | Will never cross center lane or leave the roadway due to impairment or distraction |
| 12 | Will not have vision compromised by glare, a wet/dirty windshield or any other visibility problems, e.g., fog, rain, or snow. (AV sensors are better than human sensors) |

*Table 2. Algorithm 2 for a Hypothetical Autonomous Vehicle*

| Rule | The autonomous vehicle will drive cautiously when: |
|---|---|
| 1 | Any vehicle is stopped in front of it in a normal driving area of a roadway. |
| 2 | Pedestrians are present at an uncontrolled intersection (no traffic light) |
| 3 | Pedestrians are present on the sidewalk/road edge. Any of the following factors may increase the risk:<br>a. Children<br>b. Ball sports<br>c. Anything involving wheels, e.g.bikes, scooters, trolley etc.<br>d. Dogs<br>e. Frequent directional changes<br>f. drunkenness/un-coordination<br>g. Any pedestrian moving with a constant velocity towards the road |
| 4 | Pedestrians are present on the central median strip |
| 5 | Cars are parked on the road side |
| 6 | Car door is opening on a parked car along the road edge |

**Case Review Procedure**

The scene diagrams, prose summaries, and the reported driver/pedestrian actions in each hardcopy case file was examined individually using to determine whether an autonomous vehicle could have avoided the collision or mitigated the severity of the collision. Scene diagrams from 4 of the 527 collisions crashes did not have sufficient detail for the examination and were dropped from the analysis.

Both algorithms were applied to each of the 523 cases assuming that the striking vehicle was an AV rather than the original car. Cases that did not violate any of the Algorithm 1 rules were then checked for compliance with the Algorithm 2 Rules. The "Algorithm 2 Rules" defined risk mitigation that could govern a fully autonomous vehicle. If the vehicle was in a scenario that coincided with one or more of the Algorithm 2 rules, it was assumed that the vehicle would drive cautiously, more slowly, and even increase the distance to other vehicles in the following situations. If a case broke an Algorithm 2 Rule, this case was evaluated for the countermeasure deployment.

**Time to React**

The distance traveled by the pedestrian from the point of earliest detection until the point of impact was estimated from the scene diagram drawn by the case investigator. The point of earliest detection was assumed to be the edge of the roadway, or the portion of the roadway where the pedestrian first became visible, e.g. after emerging onto the road from between parked cars. Because this distance was not always annotated on the scene diagram, our study used the number of lanes crossed by the pedestrian as a surrogate for the distance traveled, $d$. Each lane was assumed to be 3 m wide, giving $d = 3m \times n_{lanes\ crossed}$. The time to react was computed using an assumed pedestrian travel speed. The PCDS investigators recorded whether the pedestrian was walking or running when impacted, but would not have been able to reliably specify the pedestrian travel speed. Pedestrians reported in PCDS as a running adult between the ages of 12 and 64 years old were assumed to be running at 4 m/s (a typical running speed). However, if a pedestrian was reported as walking, under the age of 12, or 65 years or older, their assumed travel speed was 2 m/s (a fast walking speed). The time to react $\Delta t$ was then computed assuming a constant velocity $\Delta t = \frac{d}{v}$ where $v$ = the pedestrian travel speed. Note that the faster the pedestrian speed, the shorter the time that the pedestrian would have been visible to an oncoming vehicle.

A small number of cases involved a pedestrian struck while travelling parallel to the flow of traffic. To compute a time to react in these cases, the pedestrian was assumed to be visible at a distance of 40 m (half a city block) by a vehicle traveling at 20 m/s (approximately 45 mph). The time to react would then be approximately 2 seconds after accounting for pedestrian travel speed.

**Countermeasure Deployment**

Our study considered three countermeasures by which an AV could avoid or mitigate a pedestrian crash: automated emergency braking, external deployment, and a pedestrian-friendly front structure. We assumed that automated emergency braking could be activated if a pedestrian was visible for at least one second before impact. This time interval would provide sufficient time for (a) the vehicle to detect and confirm that a pedestrian was in or about to enter into the vehicle's path, (b) time to activate brakes, and (c) time for the vehicle to decelerate to avoid the impact. If a pedestrian suddenly appeared with less than 1 second warning, we assumed that a pedestrian airbag could be deployed given a time to collision of at least 0.5 seconds. This time interval would provide sufficient time for (a) the vehicle to detect and confirm that a pedestrian was in or about to enter into the vehicle's path, (b) time to activate brakes and slow the car, and (c) time to deploy an external airbag prior to impact. For cases in which the pedestrian appeared with less than 0.5 seconds before impact, we assumed that there would not be sufficient time to either activate automated emergency braking or deploy an external airbag.

The relationship between time to react and the associated countermeasure is shown in Table 3:

***Table 3. Countermeasure Response Time Requirements***

| Group | Countermeasure | Time to React |
|---|---|---|
| 3 | Protection with Pedestrian Airbag and / or Speed Reduction | $\Delta t$ > 1s |
| 2 | Protection with Pedestrian Airbag | 0.5s < $\Delta t \leq$ 1s |
| 1 | Protection with Soft-Structure | $\Delta t \leq$ 0.5s |

## RESULTS

The results of applying Algorithm 1 and Algorithm 2 to the PCDS cases are shown in Table 4 and Figure 1. Application of Algorithm 1 to our dataset showed that an AV which simply obeyed traffic rules, e.g. yielding the right of way to pedestrians in a crosswalk, could have avoided 40% of the crashes in our dataset (209 of the 523 crashes). The addition of Algorithm 2 rules to Algorithm 1 could prevent an additional 55% of crashes (287 of 523 cases) for a total of 95% of pedestrian crashes avoided. The 5% balance of crashes (27 of 523) cases would require the deployment of pedestrian countermeasures, i.e. AEB, external airbags, and a pedestrian-friendly front structure.

***Table 4. Results of Autonomous Vehicle Algorithms in PCDS Cases***

| Case Classifications | | |
|---|---|---|
| Classification | Case Count | Percentage |
| Crashes Avoided using Algorithm 1 | 209 | 40% |
| Additional Crashes Avoided using Algorithm 2 | 287 | 55% |
| Conflicts not avoided | 27 | 5% |
| TOTAL | 523 | 100% |

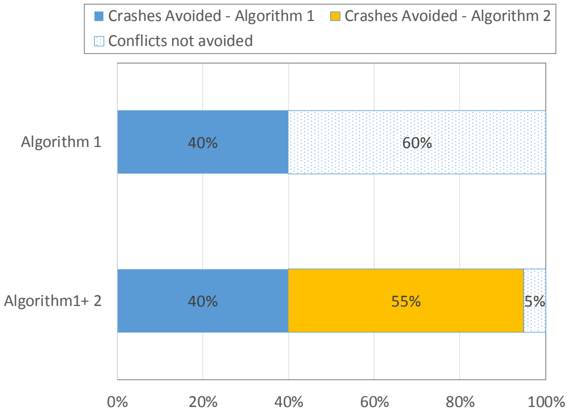

***Figure 1. Performance of Autonomous Vehicle Algorithms 1 and 2 in PCDS Cases***

Table 5 presents the number of violations of Algorithm 1 rules. The three leading violations were a) failure to yield, b) turning into a flow of traffic without a clear view of potential obstructions, e.g. pedestrians, and c) speeding. Note that some drivers may have violated multiple rules.

***Table 5. Algorithm 1 Rule Violations***

| Algorithm 1 Rule Violation | # of violations |
|---|---|
| 1. Speeding | 21 |
| 2. Turn across path of oncoming traffic | 0 |
| 3. Turn into flow of traffic without a clear view | 87 |
| 4. Failure to yield | 84 |
| 5. Failure to stop at a traffic signal | 1 |
| 6. Run into another stationary vehicle/barrier | 0 |
| 7. Unsafe following distance | 0 |
| 8. Cut in front of another vehicle | 6 |
| 9. Control lost after traveling too fast around a corner | 1 |
| 10. Overcorrecting from an evasive maneuver | 1 |
| 11. Center lane crossed due to impairment/distraction | 1 |
| 12. Vision compromised by glare or dirty windshield | 3 |
| 13. Other violations | |
| • Distracted driving | 3 |
| • Driving at night with headlights off | 1 |
| • Hit and run | 6 |

Table 6 presents the number of violations of Algorithm 2 rules. Note that some drivers may have violated multiple Algorithm 2 rules. An AV following Algorithm 2 would comply with all traffic regulations (Algorithm 1) and would also operate like the most cautious human driver. Algorithm 2, for example, would detect a pedestrian walking or running toward the edge of the roadway and to be cautious would assume that the pedestrian might continue along this path from off-road onto the roadway (132 of 373 violations). The Algorithm 2 equipped AV would drive cautiously near cars parked on the side of the road (65 of 373 violations), and in the presence of children (48 of 373 violations).

***Table 6. Algorithm 2 Rule Violations***

| **Algorithm 2 Rule Violation** | **# of violations** |
|---|---|
| 1. Vehicle stopped in front of driver | 38 |
| 2. Pedestrians at an uncontrolled intersection | 17 |
| 3. Pedestrians on the sidewalk/road edge | 9 |
| 3a. Children | 48 |
| 3b. Ball sports | 5 |
| 3c. Anything involving wheels | 0 |
| 3d. Dogs | 0 |
| 3e. Frequent directional changes | 9 |
| 3f. Drunkenness/Un-coordination | 14 |
| 3g. Pedestrian with a constant velocity towards the road | 132 |
| 4. Pedestrians in the median of the road | 29 |
| 5. Cars parked on the side of the road | 65 |
| 6. Car door opening on the side of the road | 7 |

An AV equipped with Algorithm 1 would have still encountered 60% of the pedestrian conflicts in PCDS, and would need to deploy vehicle-pedestrian countermeasures. The cumulative distribution of the available reaction time for all crashes in which the driver was not at fault is pictured in Figure 2. Note that the assumed pedestrian walking / running speed greatly affects the time available to a driver or AV to react to a pedestrian in the roadway. Using pedestrian speeds (walking – 2 m/s and running 4 m/s) based on investigator-recorded pedestrian behavior, 19% of AVs would have had 1 second or less to react to a pedestrian in the roadway. However if all pedestrians were running (pedestrian speed = 4m/s), approximately 40% of AVs would have had 1 second or less to react to a pedestrian in the road. Under the less restrictive bound of all pedestrians walking, (pedestrian speed = 2 m/s), 18% of AVs would have had 1 second or less to react.

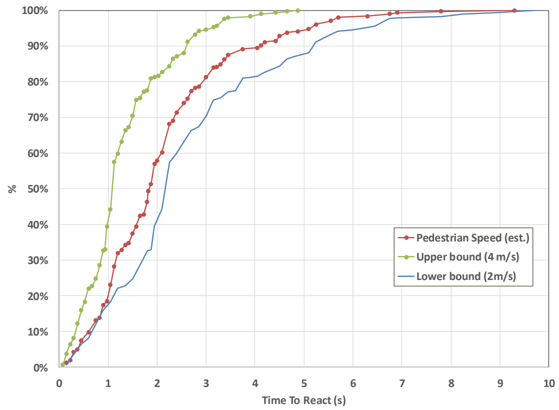

***Figure 2. Distribution of Reaction Times for Algorithm 1 equipped AVs***

***Table 7. Time to React to Pedestrian Conflict for Vehicles with Algorithm 1***

| Time to React | Counter-measure | Case Count | % |
|---|---|---|---|
| $\Delta t$ >= 1s | Automated Emergency Braking | 250 | 79.6% |
| 0.5s < $\Delta t < 1$s | External Airbag | 34 | 10.8% |
| $\Delta t \leq 0.5$s | Pedestrian Collision | 23 | 7.3% |
| Unknown/Not Evaluated | Not evaluated | 7 | 2.2% |
| TOTAL | | 314 | 100% |

As shown in Table 7, most Algorithm 1 AVs (79.6%) would have had sufficient time to deploy automated emergency braking to avoid the collision. In 10.8% of the conflicts, the AV would have had sufficient time to deploy an external airbag. However, in over 7% of the collisions, the Algorithm 1 vehicles would have still struck the pedestrian. In these cases, there would have been insufficient time to either brake to a stop or fully deploy an external airbag. This finding illustrates the need for AVs to continue to have pedestrian-friendly front structures.

An AV equipped with Algorithm 1 and 2 would have still encountered 27 pedestrian conflicts in our dataset. Table 8 presents the time that this AV would have had to react to these conflicts and the associated countermeasure that would be deployed. Most of the remaining conflicts (88.9%) encountered by an AV with Algorithm 2 could be avoided or mitigated by activation of automated emergency braking.

***Table 8. Time to React to Pedestrian Conflict for AVs equipped with Algorithm 2***

| Time to React | Counter-measure | Case Count | % |
|---|---|---|---|
| $\Delta t >= 1s$ | Automated Emergency Braking | 24 | 88.9% |
| $0.5s < \Delta t < 1s$ | External Airbag | 0 | - |
| $\Delta t \leq 0.5s$ | Pedestrian Collision | 1 | 3.7% |
| Unknown/Not Evaluated | Not evaluated | 2 | 7.4% |
| TOTAL | | 27 | 100% |

After evaluating all PCDS cases for an AV with Algorithm 2, only a single case would have still resulted in a collision without deployment of the external airbag or AEB activation. PCDS case 96-82611, pictured in Figure 3, involved a woman running through the vegetation of a median, obscuring the vehicle's view of her, and directly into the path of the vehicle. The available time for reaction was estimated to be 0.375s, less than the time needed to deploy a pedestrian airbag or activate automated emergency braking. The situation involved none of conditions enumerated in Algorithm 2 to alert the car to drive cautiously. The impact speed was estimated to be 31 kph (19 mph). The pedestrian's most severe injuries were tibia and fibular head fractures.

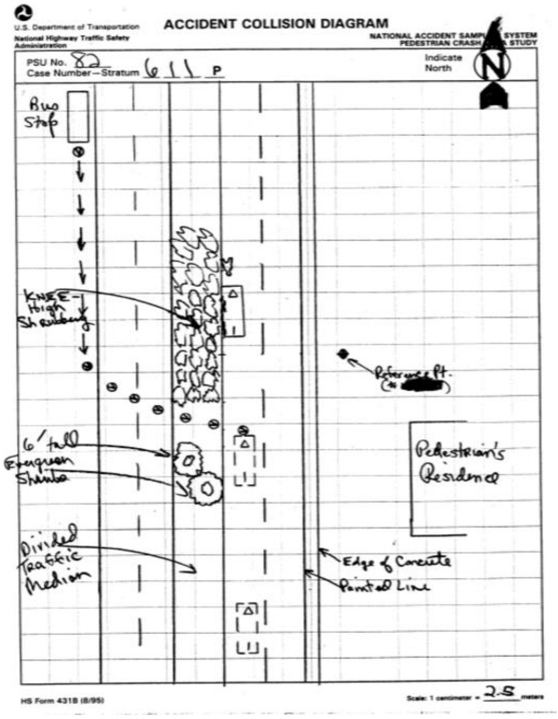

***Figure 3. Scene Diagram for the single case which would result in an AV-pedestrian collision after application of Algorithm 1 and 2 rules***

## DISCUSSIONS AND CONCLUSION

This study found that only one case out of 523 would have still resulted in a collision with our ideal autonomous vehicle before countermeasures could be deployed. The implications are, however, that it is unlikely that every pedestrian to vehicle crash can be avoided – even with an ideal autonomous vehicle. Therefore, an autonomous vehicle will require safety features, such as a soft, pedestrian-safe, front body structure or a pedestrian airbag, to mitigate the effects of one of these collisions. These features must take into account the wide variety of unique scenarios a fully autonomous vehicle will confront. Its safety features cannot be tailored to the majority of the crash events but must account for and perform perfectly in every situation if all pedestrian deaths are to be eliminated.

This analysis has provided a first of a kind study of whether an ideal autonomous car could avoid or mitigate all pedestrian crashes. However, several follow-up analyses could be explored to further study this issue. Follow-on research should address the sensing and response capabilities of an autonomous vehicle. Our study assumed perfect sensing regardless of weather conditions. Because 40% of the crashes in PCDS occurred under adverse visibility conditions which may degrade pedestrian detection, understanding how an autonomous vehicle's sensors and braking ability would be affected could provide guidance in choosing, placing, and programming sensors, developing new ways to see occluded traffic signals, and activating countermeasures in adverse weather.

### Limitations

This study had several limitations. Scene photos were only available for a few PCDS cases and pedestrian occlusion could not be assessed. Additional limitations included difficulty discerning the available time for response and avoidance for cases involving pedestrians travelling parallel to the flow of traffic, a lack of traffic light signal details, and occasionally contradictory or missing information on the reports. In addition, this study assumed two hypothetical AV algorithms. Future AV algorithms will likely respond in a unique manner to cases involving occluded pedestrians, poor visibility conditions, erratic pedestrian actions, pedestrians below a certain height, and pedestrians travelling parallel to the flow of traffic.

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