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Relative Frequency of U.S. Pedestrian Injuries Associated With Risk Measured in Component-Level Pedestrian Tests

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16. Abstract

U.S. pedestrian injury cases were analyzed to estimate the frequency of injuries associated with impacts to vehicle components that could be tested by available component-level pedestrian test equipment. The relative frequencies of injuries that could be affected by pedestrian headform tests, upper legform tests, and lower legform tests were compared. This comparison of injuries that could potentially be reduced or mitigated if vehicle performance were improved relative to each of the three test procedures was intended to evaluate the potential for each type of test to improve pedestrian protection. Pedestrian cases were drawn from the National Trauma Data Bank (NTDB) from 2007 to 2014 and the Pedestrian Crash Data Study (PCDS), collected from 1994 to 1998. Using both injury datasets, the percentages of pedestrians with injury to a body region evaluated by a given test procedure and attributed to a vehicle impact source expected to be in that procedure's test zone was estimated for all three component test procedures. Among serious and fatal injury cases (MAIS 3+), 37.8 percent of the total expected potential effects of the test procedures were associated with the headform test, 24.6 percent were associated with the upper legform test and 37.6 percent were associated with the lower legform test. When the analysis was limited to more severe injuries (MAIS 4+ or fatal cases), the influence of the headform test was substantially higher, while the relative influence of the upper legform and lower legform tests was reduced.

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EXECUTIVE SUMMARY

Injury data for U.S. pedestrians was analyzed to estimate the frequency of injuries associated with impacts to vehicle components that could be tested by available component-level pedestrian test equipment. The relative frequencies of injuries that could be affected by pedestrian headform tests, upper legform tests, and lower legform tests were compared. This comparison of injuries that could potentially be reduced or mitigated if vehicle performance were improved relative to each of the three test procedures was intended to evaluate the potential for each type of test to improve pedestrian protection.

The analysis of injuries potentially associated with each type of pedestrian component test involved defining for each of the types of tests (headform, upper legform, and lower legform):

(1) the body regions where injury risk could be evaluated using the given test tools, and
(2) the vehicle components expected to be within the test areas evaluated with those test tools.

U.S. pedestrian injury cases were then used to determine the relative real-world frequency of injuries relevant to each type of test, (i.e., injuries associated with body regions and vehicle components within the scope of each type of test).

For the purpose of determining the pedestrian body regions and impacting vehicle components that would be relevant to each of the three component-level types of pedestrian tests, it was assumed that the tests use the same test tools and procedures defined for European New Car Assessment Programme (Euro NCAP) pedestrian testing. As such, the injury measurements available in each test were assumed to correspond to the measurement capabilities of the Euro NCAP-prescribed headforms, upper legform, and Flex-PLI lower legform. The vehicle components associated with test procedures using each of the three test tools (the pedestrian headform, upper legform, and lower legform) were estimated in this study using the test zones defined for Euro NCAP pedestrian test procedures. For example, the instrumentation in the upper legform was assumed to be relevant to pedestrian injury to the hip, pelvis, and thigh, and based on Euro NCAP upper leg test procedures, it was assumed that the hood leading edge and grille would be in the test zone for this test tool. Therefore, the real-world injuries associated upper legform component tests in this study include all cases with hip, pelvis, or thigh injuries from impact to the hood leading edge or grille.

Data on the frequency of injuries by body region were drawn from pedestrian cases in the National Trauma Data Bank (NTDB) from 2007 to 2014. Among pedestrians with injury to each body region, the frequency with which pedestrians sustained those injuries in impacts to vehicle components associated with potential test zones for each test tool was estimated from the Pedestrian Crash Data Study (PCDS), collected from 1994 to 1998. Using both injury datasets, the percentages of pedestrians with injury to a body region evaluated by a given test procedure and attributed to a vehicle impact source expected to be in that procedure's test zone was estimated for all three test procedures, subject to the limitations described later in this report.

Injury severity was categorized using the Abbreviated Injury Score (AIS) for each injury and the Maximum Abbreviated Injury Score (MAIS) for each pedestrian. Among fatal and non-fatal cases involving serious injury or fatality (MAIS 3+), it was estimated that 22.2 percent of cases had AIS 3+ head/face injuries associated with impacts expected to be in the assumed headform test zone, 14.4 percent had AIS 3+ hip, pelvis, or thigh injuries associated with impacts expected to be in the potential upper legform test zone, and 22.0 percent of cases had AIS 3+ thigh, knee, or lower leg injuries associated with impacts expected to be in the potential test zone for the lower legform test procedure.

The analysis was repeated for several injury severity levels, and the results normalized to estimate the proportion of the total potential effects contributed by each of the three pedestrian test procedures at each severity level. Among serious and fatal injury cases (MAIS 3+), **37.8 percent** of the total expected potential effects of the test procedures were associated with the **headform test**, **24.6 percent** were associated with the **upper legform test** and **37.6 percent** were associated with the **lower legform test**. When the analysis was limited to more severe injuries (MAIS 4+ or fatal cases), the influence of the headform test was substantially higher, while the relative influence of the upper legform and lower legform tests was reduced.

1.0 INTRODUCTION

Objective: The objective of this analysis was to estimate the relative frequency of pedestrian injuries that could potentially be affected by available component-level pedestrian test equipment and procedures. Specifically, the intention was to determine what *proportion of injured pedestrians could be affected by each of the three Euro NCAP pedestrian test procedures*: headform tests, upper legform tests, and lower legform tests. The results may assist in prioritizing the importance of each of the three pedestrian test procedures according to each test procedure's potential effect on pedestrian safety.

Approach: The approach used to estimate the proportion of injured U.S. pedestrians who would potentially be *affected* by each of the three component-level pedestrian test procedures involved identifying the *body regions* and *vehicle components* associated with each test procedure. The concept was that pedestrians with injuries to a body region evaluated by a test procedure and attributed to a vehicle impact source expected to be in that procedure's testable zone would potentially be affected by the given test procedure.

There is no single case dataset that offers detailed injury and crash data on recent U.S. pedestrian crashes. The data needed for this analysis was combined from two different source datasets, selected for the following reasons.

The most comprehensive dataset of U.S. pedestrian cases that includes both injury frequency and details on vehicle components associated with each injury is NHTSA's Pedestrian Crash Data Study (PCDS), which includes 549 non-duplicate cases investigated from 1994 to 1998. While that data has been used previously to compare the frequency of injuries by body regions and injury source/vehicle components (Mallory, Fredriksson, Rosen, & Donnelly, 2012), its usefulness is limited in that it describes a crash population from more than 20 years ago. Therefore, analysis of cases from PCDS was supplemented with 2007-to-2014 trauma center pedestrian cases from the National Trauma Data Bank. While NTDB cases contain no vehicle source determination, they have injury documentation coded with the AIS for approximately 8,900 trauma-center-admitted pedestrians per year during the included period.

Therefore, data on injury frequency by *body region* was drawn from NTDB, which included more recent data and many more pedestrian cases than PCDS. Data on *vehicle components* associated with injury to each given body region were drawn from PCDS, which contains injury source information for each investigated case. Limitations associated with this approach are discussed in Section 4.0.

Definition of Potentially Affected Cases at Each Severity Level Analyzed: The analysis focused on cases with serious and worse injuries (MAIS 3+), including fatal and non-fatal cases. Among these serious-injury pedestrian cases, a case was defined as affected by one of the three component-level pedestrian test procedures if at least one of the AIS 3+ injuries in the case was in a body region associated with the test procedure, and was attributed to impact with a vehicle component expected to be in the testable zone for the test procedure.

The search was repeated for MAIS 2+ cases and MAIS 4+ cases to explore how the results differed if the analysis covered injuries of higher or lower severity. Among the MAIS 2+ cases, a case was defined as affected if at least one of the AIS 2+ injuries in the case involved an applicable body region and vehicle component, and similarly among the MAIS 4+ cases, a case was defined as affected if at least one of the AIS 4+ injuries involved an applicable body region and vehicle component.

Additionally, the analysis was repeated for fatal cases only. A fatal pedestrian case was defined as affected by a component-level pedestrian test procedure if it was coded with at least one AIS 3+ injury equal to the case MAIS and associated with a body region and vehicle component applicable to the given test procedure.

2.0 METHODS

2.1 Data Sources: PCDS and NTDB

Pedestrian case data was drawn from 1994-to-1998 PCDS cases and from 2007-to-2014 NTDB cases.

The PCDS dataset is based on pedestrian case investigations targeting vehicles of model year 1990 and newer (Calspan Corporation, KLD Associates, Inc., Transportation Safety Institute, & National Center for Statistics and Analysis, 1996, 1996), although the final dataset includes vehicles with model years between 1988 and 1999. PCDS cases were collected and reported by NHTSA and are publicly available at ftp://ftp.nhtsa.dot.gov/PED.

The NTDB dataset is an aggregation of U.S. trauma registry data, compiled annually by the American College of Surgeons (NTDB Research Data Set, 2014). Pedestrian cases were identified by an ICD-9-CM E-code specific to motor vehicle pedestrian crashes. NTDB cases are coded from medical records by each contributing trauma center. All trauma center admissions are included in the dataset, based on each hospital's admission criteria. The datasets used for the current study were the 2007-2014 Research Data Sets (RDS). Annual datasets can be obtained for research from www.facs.org/quality-programs/trauma/ntdb/datasets.

Inclusion criteria for crashes included in the two datasets differed. While NTDB has no vehicle information, and does not exclude cases based on vehicle type, model, or model year, PCDS includes only cases involving CDS-applicable vehicles (cars, light trucks, and vans with gross vehicle weight less than 10,000 pounds), limited by model year. Vehicles with impacts other than with the case pedestrian were excluded.

Inclusion criteria for pedestrians also differed between the two datasets. Among PCDS cases, pedestrians had to be struck by a forward-moving vehicle with a first contact forward of the A-pillar. Pedestrians were excluded from PCDS if the striking portion of the vehicle was not OEM equipment (e.g., after-market bull bars or grille guards) or if the pedestrians were laying or sitting at the time of impact.

All injuries in cases in PCDS are coded using the 1990 version of the AIS. In NTDB only a subset of cases is coded using AIS. Only NTDB cases with directly coded AIS scores were included in the current analysis: No codes translated from ICD-9 were used. For the NTDB years included in the analysis, all AIS codes were from the 1990/98 Update version of the AIS using the AISPCODE dataset. Any NTDB-coded injuries that were not consistent with this version of AIS were assumed to be erroneous and were dropped from the analysis.

2.2 Calculation of Cases Affected by Each Pedestrian Test Procedure

Euro NCAP includes three types of component-level tests that were considered in this analysis:

1. Headform impact tests,
2. Upper legform impact tests, and
3. Lower legform impact tests.

Each test is carried out by launching the impactor into *vehicle components* most likely to be contacted by the *body region* associated with the test tool. Assessments of the vehicle components are made based on the response of the impactor. In headform impact tests for example, the headform impactor (*body region*=HEAD) is launched onto vehicle components that can include the hood, windshield, A-pillars, cowl, top surface of fenders, hood leading edge, or grille and the resulting HIC value is computed as a means to assess the safety of these components. Each test procedure is performed at test locations on the vehicle that correspond to typical impact locations for the corresponding body region. For example, headform impact tests are typically performed at wraparound distances that correspond to typical head impact locations for children and adults in a 40 km/h pedestrian impact, while upper legform and lower legform tests are performed at impact heights corresponding to a standing adult pedestrian. The vehicle components evaluated by each test procedure are determined by the geometry of each vehicle.

The percentage of pedestrian cases expected to be affected by each component-level pedestrian test procedure was estimated as the product of the percentage of pedestrians with injury to a *body region* evaluated by that test procedure (from NTDB) and the percentage of injuries to that body region that are associated with *vehicle components* typically in the test zone for the given test procedure (from PCDS). The resulting product of these two percentages calculated from the two different pedestrian datasets, shown in Equation 1, is the percentage of pedestrians expected to be affected by each test procedure. Definitions of the body regions evaluated by each test procedure and the vehicle components associated with each test procedure are explained below, and the detailed methods for calculating the percentages needed for Equation 1 are included in Section 2.4.

Equation 1. Estimated percentage of pedestrians affected by each test procedure

Percentage of pedestrians with injury to a body region evaluated by test procedure	x	Percentage of injuries to that body region that are associated with impacts to components associated with given test procedure
(From NTDB)		(From PCDS)

The *body regions* evaluated by a given test procedure were identified based on their expected potential correlation with the injury risk measurements made by the test tools in each test procedure, as discussed in Section 2.3. For the headform and upper legform test analyses, all applicable body regions were combined for the analysis. For the lower legform test, individual affected body regions were analyzed separately, as described in the Lower Legform Test Procedure subsection of Section 2.3.

The *vehicle components* in the test zone for a given test procedure were estimated based on the test zones defined in Euro NCAP pedestrian test procedures. Since the vehicle components evaluated by a given test procedure can vary between vehicles, the applicability of each component-level test procedure was determined proportionally for components that were either:

1. Not expected to be in the test zone in every vehicle, or
2. Not expected to be entirely within the test zone.

For example, if the windshield is in the test zone for a particular test procedure x percent of the time, the proportional applicability (PA) of the windshield to that test procedure is x percent. It was assumed for the purposes of this evaluation that the component-level test procedures would be the same as those used in the pedestrian Euro NCAP procedures (Euro NCAP 2015b, Euro NCAP 2015a).

Where available, this estimate of PA was based on a study of the frequency of real-world impacts within the testable zone (Fredriksson, Rosen, & Kullgren, 2010). Otherwise, proportional applicability was estimated based on test zone determination on 12 vehicles tested at VRTC from 2014 to 2016 (Table 1). The 12 vehicles included 4 passenger cars, 3 standard SUVs, 2 small SUVs, 2 minivans, and 1 standard pickup truck. They represent a range of levels of pedestrian protection in recent model years. Proportional applicability was estimated for each vehicle component of interest by averaging the percentage of area of a given component that would be included in the test zone across all 12 measured vehicles. In contrast, the vehicle type distribution reported for 2016 vehicle sales was 44 percent passenger cars, 33 percent crossovers and minivans, and 23 percent light trucks and SUVs (National Highway Traffic Safety Administration, 2018), with a subsequent drop in passenger cars to 40 percent predicted by 2018 (U.S. Energy Information Administration, 2017). In comparison to these reported sales distributions, passenger cars were underrepresented in the set of 12 vehicles by about one vehicle and standard SUVs were overrepresented by about one vehicle. However, for the purpose of estimating the proportion of impacts to given vehicle components expected to be within the test zone, these 12 vehicles were determined to be reasonably representative of vehicle types in the fleet.

The applicability of injuries by body region and by impacted vehicle components is described in Section 2.3. The application of proportional applicability values to the calculation of cases affected by each pedestrian test procedure is discussed in Section 2.4.

Pedestrians with more than one injury associated with components expected to be in the testable zone for a given procedure were counted only once for that procedure. For pedestrians with applicable injuries for more than one test procedure (e.g., a lower extremity injury applicable to the lower legform test as well as a head injury applicable to the headform test), the pedestrian was counted once with each procedure.

Since both PCDS and NTDB include injuries from non-vehicle sources as well as from vehicle component impacts, the resulting estimate of the percentage of pedestrians with injuries associated with a given component-level pedestrian test procedure is a percentage of *all* pedestrians, and not limited to those injured in vehicle contacts.

Table 1. Vehicles Measured for Test Zone Estimation

Vehicle	Vehicle Type
2010 Kia Forte	Passenger Car
2010 Buick LaCrosse	Passenger Car
2010 Acura MDX	Standard SUV
2011 Hyundai Tucson	Small SUV
2011 Honda Odyssey	Minivan
2011 Jeep Grand Cherokee	Standard SUV
2015 Toyota Sienna	Minivan
2015 Ford F-150	Standard Pickup Truck
2016 Honda Fit	Passenger Car
2016 Chevrolet Malibu	Passenger Car
2016 Nissan Rogue	Small SUV
2016 Chevrolet Tahoe	Standard SUV

2.3 Body Regions and Vehicle Components Associated with Each Test Procedure

Headform Test Procedure

Applicable Body Region. The component-level pedestrian headform test procedure uses the Head Injury Criterion (HIC) to evaluate vehicle performance. It was assumed for the purposes of this analysis that injuries to the head and face body regions correlate with HIC. See Appendix A: Injury Classification, for a description of AIS injury codes included in each body region.

Applicable Vehicle Components. Based on Euro NCAP procedures, the headform test procedure generally applies to structures between a wraparound distance (WAD) of 1,000 to 2,100 mm. Depending on vehicle shape, vehicle components within this zone can include all or part of the windshield, A-pillars, cowl, wiper blades and mounts, hood, top surface of the fenders, hood leading edge, and grille. See Appendix B: Vehicle Components, for a description of PCDS injury source codes included in each vehicle component group. The proportional applicability for each of these vehicle components is estimated below.

Windshield and A-pillars: Head/face injuries associated with the windshield and/or A-pillar that occur forward of WAD 2,100 mm are in this vehicle component's testable zone. Real-world data was used to determine the proportion of injuries from impacts to the windshield and A-pillar that occur in the testable zone forward of WAD 2,100 mm. According to a study of pedestrian cases from the German In-Depth Accident Study (GIDAS) from 1998 to 2008, some 60 percent of pedestrian head impacts to windshields and A-pillars that resulted in AIS 3+ injuries occurred forward of the WAD 2,100 mm line (Fredriksson, Rosen, & Kullgren, 2010).

Therefore, among pedestrians who sustain injuries in impacts to the windshields or A-pillars, it was assumed that 60 percent would be expected to fall in the test zone for a pedestrian headform test, defined as in Euro NCAP. Therefore, PA of head/face injuries from windshield or A-pillar impacts was estimated to be 60 percent. This estimate is equivalent to stating that for 60 of every 100 pedestrians who sustain head/face injuries in impacts with windshields or A-pillars, the impact locations would fall within the zone to be tested in the Euro NCAP headform test zone and potentially be affected by this component-level test procedure.

Cowl: No epidemiological data was available regarding the applicability of component-level headform testing to head/face impacts to the cowl area, so an estimate of proportional applicability was drawn from data on the 12 vehicles measured at VRTC.

Windshield wipers and mounts were coded together in injury source codes in PCDS and could not be separated in this analysis. Wipers could be in the area of the windshield or the cowl area when impacted, while wiper mounts are most likely to be in the cowl area. Since injuries from impacts to the wiper mounts are expected to be more serious, all wiper component injuries were grouped with cowl injuries for the purposes of this analysis (Appendix B: Vehicle Components).

Euro NCAP headform test procedures define the test zone such that in any vehicle with an exposed cowl forward of 2,100 mm WAD, the cowl will be in the test zone. Therefore, among pedestrians who sustain injuries in impacts to the cowl area, the percentage of these impacts expected to be in the headform procedure test-zone can be estimated by determining the percentage of vehicles in which the rear reference line is located forward of a WAD of 2,100 mm. Since the rear reference line was located forward of 2,100 mm WAD in 9 of 12 (75%) of the VRTC measured vehicles, it was estimated that 75 percent of real-world head/face impacts to the cowl area would occur in a testable area of the vehicle for this component-level test. The proportional applicability of head/face impacts to the cowl area in the headform test procedure was, therefore, 75 percent.

Hood and Fender Top Surface: No epidemiological data were available regarding the Euro NCAP-applicability of head/face impacts to the hood and the top surface of the fender, so an estimate of proportional applicability was drawn from data on the 12 vehicles measured at VRTC.

The percentage of 2-dimensional hood surface area that is typically within the test zone was estimated by averaging the percentage of hood area in the test zone for the 12 VRTC-measured vehicles. In 8 vehicles, the hood extended forward of WAD 1,000 mm excluding an average of 25 percent of the surface area of the hood and top surface of the fender from the test zone (Figure 1).

In 3 vehicles, the rear hood and fender top surface extended beyond a WAD of 2,100 mm line, excluding an estimated average 7 percent of the hood and fender top surface from the test zone (Figure 2). Averaged across all 12 vehicles, it was estimated that 82 percent of the hood and fender top surface was between boundaries at WAD of 1,000 mm and WAD of 2,100 mm. It was assumed for the purpose of this analysis that the proportion of the hood and top surface of the fender that falls outside of the side reference lines is negligible so that it could be estimated that, on average across the fleet, 82 percent of the hood and fender top surface would be in the testable zone for the component-level headform test procedure.

In the absence of real-world epidemiological data on the frequency of head injuries associated with impact to the hood and fender top surface within the test zone for the Euro NCAP headform test procedure, it was correspondingly estimated that 82 percent of head injuries associated with impact to the hood and fender top surface would be in areas applicable to the headform test procedure, i.e., that proportional applicability of hood and fender top surface impacts to the headform test procedure is 82 percent.

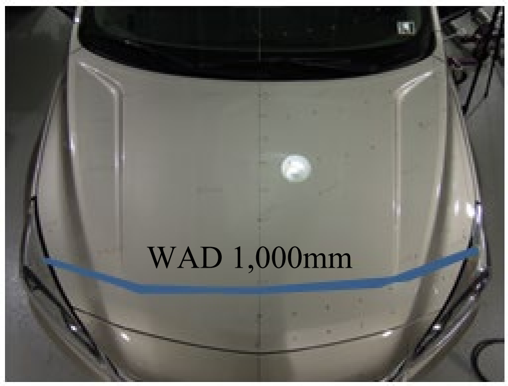

Figure 1. Chevy Malibu with forward portion of hood excluded forward of WAD 1,000 mm

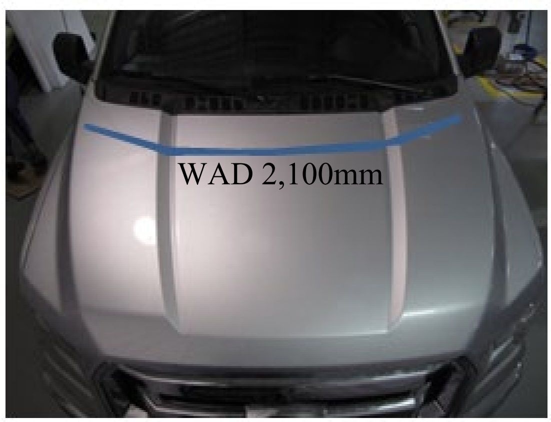

Figure 2. Ford F-150 with rearward portion of hood excluded beyond WAD 2,100 mm

Hood Leading Edge: No epidemiological data were available regarding the applicability of the typical test zone for the headform test procedure to head/face impacts to the hood leading edge, so an estimate of proportional applicability was drawn from data on the 12 vehicles measured at VRTC.

The Euro NCAP headform test zone generally includes the hood leading edge on any vehicle where the hood leading edge is above a WAD of 1,000 mm. It was assumed for the purpose of this analysis that the proportion of the hood leading edge located outside of the side reference lines was negligible, so that 100 percent of hood leading edge impacts would be considered within the testable zone on vehicles where the hood leading edge was higher than a WAD of 1,000 mm.

The hood leading edge was above the 1,000 mm WAD line in 4 of the 12 (33%) VRTC measured vehicles, so it was estimated that the proportional applicability of the hood leading edge to the headform test procedure was 33 percent, reflecting an estimate that one-third of head/face injuries from hood leading edge contact in the real-world would occur in the headform test zone. However, in a given pedestrian crash where a pedestrian sustains a head injury in an impact to the hood leading edge, the vehicle may be more likely to be a high front-end vehicle, since head impacts to this area would be more common in higher front-end vehicles than in lower front-end vehicles. Therefore, the 33 percent proportional applicability may underestimate the percentage of head injuries from hood leading edge impacts that would be in the headform test zone. However, no data were available to make a more detailed estimate of proportional applicability.

Grille: No epidemiological data were available regarding the applicability of headform tests in the Euro NCAP defined test zone to head/face impacts to the grille area, so an estimate of proportional applicability was drawn from data on the 12 vehicles measured at VRTC.

The percentage of grille area that is typically within the Euro NCAP test zone was estimated by averaging the percentage of grille area in the test zone for the 12 VRTC-measured vehicles. In 2 vehicles, an upper portion of the grille was within the test zone, beyond a WAD of 1,000 mm. Averaged across all 12 vehicles, it was estimated that 4 percent of the grille area was in the test zone, above 1,000 mm. It was therefore estimated that 4 percent of head injuries associated with impact to the grille would be in areas applicable to the headform test procedure.

Similar to the situation with head injuries caused by the hood leading edge, head injuries caused by the grille are expected to be more frequent in vehicles with high front ends. Therefore, 4 percent probably underestimates the percentage of head injuries from grille impact that would be in the headform test zone. However, no data were available to make a more detailed estimate of proportional applicability.

Upper Legform Test Procedure

Applicable Body Region. The current upper legform tests, as defined in the Euro NCAP pedestrian test procedure, use the bending moment and sum of forces measured by the upper legform test tool to evaluate vehicle performance. It was assumed for the purposes of this analysis that injury risk to the hip, pelvis, and thigh correlate with these injury measures.

Applicable Vehicle Components. Application of the upper legform test device was fundamentally changed by Euro NCAP in 2015. Previously, the legform was always directed to the hood leading edge, as that was considered the source of most hip and femur injuries. However, real-world data from GIDAS indicated that upper leg injuries are often sourced to other areas of the vehicle, and thus the impactor should be directed to whatever area interacts with the femur, which depends on the size and shape of a vehicle's front-end. The GIDAS data also indicated that AIS3+ pelvis injuries had actually become more prevalent in pedestrian collisions with late model vehicles (Zander, Gehring et al. 2015). As a result, the Euro NCAP procedure (beginning with version 8) now uses the ground reference to direct the legform to a target point coinciding with the femur level (WAD 775 mm). This analysis used the updated Euro NCAP procedure and thus, it was assumed that a component-level upper legform test would be applied at a WAD location of 775 mm.

Although the components evaluated by the upper legform tests depend on the geometry of the vehicle, no epidemiological data were available to determine what percentage of real-world vehicle front end injuries to the hip, pelvis, and thigh occur in areas that would be tested with an upper legform impact at a WAD of 775 mm. For example, the test may engage the hood, the hood leading edge, the grille, or a combination of these structures. In high front-end vehicles, such as the Ford F-150, the upper legform impact at a WAD of 775 mm primarily impacts the grille, below the hood leading edge. Correspondingly, however, it is likely that the hood leading edge on these high front-end vehicles is also higher than the hip, pelvis, and thigh of most pedestrians. This height scenario suggests that most real-world *injuries* to the hip, pelvis, or thigh from hood leading edge contact occur in smaller vehicles with a lower hood leading edge that is within the area tested with the upper legform test procedure. In other words, given that a pedestrian sustains a hood leading edge injury to the hip, pelvis, or thigh, it is likely that the height of the hood leading edge would be engaged by the legform impactor at a WAD of 775 mm. This assumption was necessary given that no epidemiological data are available on how frequently injuries to these body regions are sustained in impacts to the forward portion of hood or grille occur in areas that would be evaluated in the upper legform test at a WAD of 775 mm.

Therefore, in the absence of specific data to determine how often an injury to the hip, pelvis, or thigh from specific front-end structures within the vertical area tested by the upper legform test procedure, as well as within the lateral test boundaries of the upper leg test, it was assumed for the purposes of this analysis that 100 percent of injuries to these body regions from hood leading edge or grille impact would be affected by the upper legform test, which is equivalent to the assumption that the rate of upper leg and pelvis injuries due to WAD 775 mm impacts with modern vehicles is the same as the rate due to hood leading edge and grille contacts seen in PCDS cases from 1994 to 1998.

Lower Legform Test Procedure

Applicable Body Region. Component-level lower legform tests with the Flex-PLI legform, such as those defined in the Euro NCAP pedestrian lower legform test procedure, use the following measurements to evaluate vehicle performance: tibia bending moment, medial collateral ligament (MCL) elongation, and anterior/posterior collateral ligament (ACL/PCL) elongation. It was assumed for the purposes of this analysis that injuries correlating to these measures include the knee, lower leg (excluding the foot and ankle), and the thigh.

Thigh injuries were included despite the absence of explicit femur fracture measures in the test procedure. It was assumed that pedestrians who are positioned such that they are struck in the thigh by the structures tested in the Euro NCAP lower legform test will have a risk of femur fracture that will correlate with the risk of tibial fracture as measured in the Euro NCAP test. Based on geometry, and subsequently confirmed by case analysis in Table 6, the likelihood that a thigh injury will be associated with the bumper components is lower than the likelihood that a knee or lower-leg injury will be associated with the bumper components. Therefore, based on the presumption that aggregating thigh injuries with knee and lower leg injuries from NTDB and from

PCDS would be improperly averaging out the effects of these potentially very different injury scenarios, the percentage of pedestrians with thigh injuries associated with bumper impacts was calculated separately from the percentage of pedestrians with knee and lower leg injuries associated with bumper impacts. The ultimate aggregate estimate of the number of pedestrians with at least one injury to the thigh, knee, or lower leg attributed to the bumper is the sum of the percentage of pedestrians with *thigh* injury from bumper impact and the percentage of pedestrians with *knee or lower leg* injury from bumper impact minus the percentage of pedestrians that have bumper-associated injuries to both of these regions. This strategy avoids double-counting of cases potentially affected by the lower legform test procedure.

Applicable Vehicle Components. The lower legform test procedure is expected to apply to injuries associated with the bumper, including the valence. Although the Euro NCAP test zone is not as wide as the full width of the vehicle, this analysis assumed that applicable injuries from bumper impact outside the test zone were effectively negligible. Therefore, 100 percent of injuries from bumper/valence to the applicable body regions would be affected by a component-level pedestrian lower legform test procedure.

Summary of Applicability

The applicability of each of the three component-level pedestrian test procedures considered in this analysis is summarized in Table 2.

Table 2. Applicability of Each Component-Level Pedestrian Test Procedure

Test Procedure	Body Regions	Vehicle Components
Headform	Head Face	Proportional applicability of: Windshield & A-pillars (PA = 60%) Cowl, wiper blades, mountings (PA = 75%) Hood & top surface of fenders (PA = 82%) Hood leading edge (PA = 33%) Grille (PA = 4%)
Upper Legform	Hip Pelvis Thigh	Hood leading edge Grille } (PA = 100%)
Lower Legform	Thigh Knee Lower leg	Bumper (PA = 100%)

2.4 Calculation of Percentage of Cases Potentially Affected by Each Test Procedure

As explained in Section 2.2, the percentage of pedestrian cases affected by each component-level pedestrian test procedure was estimated as the product of the percentage of pedestrians with injury to a *body region* evaluated by that test procedure (from NTDB) and the percentage of injuries to that body region that are associated with a *vehicle component* expected to be in the test zone for the given test procedure (from PCDS).

Calculated for a given test procedure at a specific injury severity level (e.g., MAIS 3+ cases potentially affected by the headform test), the percentage of pedestrians with injury to a *body region* evaluated by that test procedure is simply the number of pedestrian cases in the NTDB dataset with injuries to the relevant body region at the severity level of interest, divided by the number of pedestrian cases with any injuries at that severity level. The percentage of injuries to that body region that are associated with a *vehicle component* in the test zone is calculated from PCDS: the number of PCDS cases with injury to that body region from impact to a component in the test zone, divided by the number of cases with injury to that body region from any source. For example, the percentage of AIS 3+ cases (fatal and non-fatal serious injury cases) potentially affected by the headform test is shown in Equation 2.

Equation 2. Percentage of MAIS 3+ cases potentially affected by the headform test

$$\frac{\text{Cases w/ AIS 3+ head injury}}{\text{Cases with MAIS 3+ injury}} \times \frac{\text{Cases w/ AIS 3+ head injury from impact in head test zone}}{\text{Cases with AIS 3+ head injury}}$$

Note, however, that not all cases with head injuries from components potentially in the test zone, actually resulted from impacts in the test zone, since many components are only partially in the test zone. In this calculation, PCDS cases with AIS 3+ head or face injuries from components with proportional applicability of less than 100 percent (i.e., the component is not expected to be in the test zone all vehicles or is not expected to be completely within the test zone) must therefore be individually adjusted. For example, pedestrians who sustained head injuries in hood impacts, will count as 0.82 pedestrians in this PCDS-estimated quotient, reflecting that 82 percent of pedestrians in this particular case scenario are expected to be affected by the headform test procedure according to Table 2.

If a pedestrian sustained AIS 3+ head or face injuries from impacts to multiple components in the test zone, this pedestrian's proportional applicability must be calculated to reflect the combined probability that at least one of those injuries occurred in a zone tested by the headform test. For example, the proportional applicability for a hypothetical pedestrian who sustained head or face injuries in separate impacts to the hood, cowl, and windshield would be calculated as shown in Equation 3.

Equation 3. Example PA for pedestrian with injuries from multiple sources

$$\begin{aligned} PA_{pedestrian} &= 1-(1-PA_{hood})(1-PA_{cowl})(1-PA_{windshield}) \\ &= 1-(1-0.82)(1-0.75)(1-0.60) \\ &= 98.2\% \end{aligned}$$

3.0 RESULTS

From 2007 to 2014 the NTDB datasets included 189,297 cases coded as motor vehicle pedestrian cases (Table 3). While all cases in the NTDB dataset were coded with ICD-9 injury codes, only 71,402 of these were directly coded with AIS injury codes. Only cases with directly coded AIS scores were included in the current analysis: no codes translated from ICD-9 were used. From PCDS, all 549 non-duplicate cases were included. Among AIS-coded NTDB cases and PCDS cases, there were 3,565 and 71 fatal cases, respectively. Note in Table 3 that the counts of pedestrians in each dataset at each MAIS level include fatal as well as non-fatal cases.

Table 3. NTDB and PCDS Cases Used in Analysis

	NTDB		PCDS	
Crash Years	2007 – 2014		1994 – 1998	
Pedestrian Cases (All Ages)	189,297		549	
Number of AIS-Coded Injury Cases	MAIS 1+	71,402	MAIS 1+	539
	MAIS 2+	64,856	MAIS 2+	301
	MAIS 3+	42,075	MAIS 3+	193
	MAIS 4+	17,093	MAIS 4+	109
	Fatal	3,565	Fatal	71

3.1 Headform Test Calculations

Table 4 shows results of calculations of the percentage of pedestrians potentially affected by a component-level headform test. The table shows, for example, that 43.9 percent of NTDB pedestrians with MAIS 3+ injuries have at least one AIS 3+ head or face injury. Among the 115 PCDS pedestrians with at least one AIS 3+ head or face injury, it was estimated that 58.0 (50.5%) of these sustained at least one of those head/face injuries in an impact to a vehicle component in the assumed headform test zone. Note that this PCDS-derived estimate of 58.0 pedestrians with head/face injuries in the headform test zone has been calculated according to the proportional applicability methods in Section 2.4, to account for the fact that some of the injuries from impacts to vehicle components that are at least partially in the test zone were assumed to have occurred outside of the test zone. For example, each individual pedestrian with a head injury from hood contact is counted as 0.82 pedestrians toward this sum of 58.0 pedestrians with head/face injuries in the test zone (because only 82% of pedestrians in this particular case scenario are expected to be affected by the headform test procedure). For individual head-injured pedestrians who impacted multiple components that were potentially in the test zone, the contribution to this sum was calculated for each pedestrian using the process shown in Equation 3.

The product of 43.9 percent and 50.5 percent is 22.2 percent, which is the estimated percentage of seriously injured pedestrians with at least one serious head/face injury associated with impact in an assumed headform test zone. This product represents an estimate that 22.2 percent of seriously injured pedestrians could potentially be affected by vehicle improvements made to improve performance in component-level headform tests.

Table 4. Headform Test Calculations

	NTDB Percentage of head/face injury among pedestrians injured at given severity level	**PCDS** Percentage of head/face injury associated with impact in test zone among pedestrians with head/face injury at given severity level	**Product** Percentage of injured pedestrians with at least one head/face injury attributed to impact in headform test zone
MAIS 2+	$\frac{33,121}{64,856} = 51.1\%$	$\frac{87.7}{170} = 51.6\%$	**26.3%**
MAIS 3+	$\frac{18,478}{42,075} = 43.9\%$	$\frac{58.0}{115} = 50.5\%$	**22.2%**
MAIS 4+	$\frac{11,579}{17,093} = 67.7\%$	$\frac{45.1}{90} = 50.1\%$	**34.0%**
Fatal	$\frac{2,412}{3,565} = 67.7\%$	$\frac{22.1}{42} = 52.6\%$	**35.6%**

Because of proportional applicability, the 58.0 PCDS pedestrians estimated to sustain AIS 3+ head injuries in impacts within the headform test zone includes fractional counts of pedestrians who impacted vehicle components that were not always expected to be within the test zone. For example, a pedestrian with head injuries from an impact to the windshield would only count as 0.6 pedestrians in this calculation since such an impact would only be expected to fall within the test zone in 60 percent of cases.

Compared to 22.2 percent of seriously injured pedestrians (MAIS 3+) who were estimated to have at least one injury that could potentially be affected by a component-level headform test, this estimate increased to 26.3 percent when moderately injured pedestrians (MAIS 2+) were included in the analysis (Table 4). Limiting the analysis to more severely injured pedestrians (MAIS 4+) increased the percentage of pedestrians with applicable injuries in the assumed headform test zone to 34.0 percent. Analyzing only fatal cases resulted in an estimate that 35.6 percent of cases would be expected to be affected by testing in the headform test zone.

3.2 Upper Legform Test Calculations

Table 5 shows results of calculations of the percentage of pedestrians potentially affected by a component-level upper legform test procedure. The table shows, for example, that 28.8 percent of NTDB pedestrians with MAIS 3+ injuries have at least one AIS 3 or greater hip, pelvis, or thigh injury. Among the 56 PCDS pedestrians with at least one AIS 3 or greater injury to this region, it was estimated that 28 (50.0%) of these sustained at least one of those injuries in an impact to a vehicle component applicable to the upper legform test (i.e., the hood leading edge or grille). The product of 28.8 percent and 50.0 percent is 14.4 percent, which is the estimated percentage of seriously injured pedestrians with at least one serious hip, pelvis, or thigh injury associated with impact in the assumed upper legform test zone. This product represents an estimate that 14.4 percent of seriously injured pedestrians could potentially be affected by vehicle improvements made to improve performance in component-level upper legform tests.

Table 5. Upper Legform Test Calculations

	NTDB Rate of hip, pelvis, or thigh injury among pedestrians injured at given severity level	**PCDS** Rate of hip, pelvis, or thigh injury associated with applicable vehicle component among pedestrians with head/face injury at given severity level	**Product** Percentage of injured pedestrians with at least one head/face injury attributed to impact in upper legform test zone
MAIS 2+	$\frac{17,130}{64,856} = 26.4\%$	$\frac{37}{78} = 47.4\%$	**12.5%**
MAIS 3+	$\frac{12,116}{42,075} = 28.8\%$	$\frac{28}{56} = 50.0\%$	**14.4%**
MAIS 4+	$\frac{897}{17,093} = 5.2\%$	$\frac{1}{3} = 33.3\%$	**1.7%**
Fatal	$\frac{369}{3,565} = 10.4\%$	$\frac{2}{4} = 50.0\%$	**5.2%**

Compared to 14.4 percent of seriously injured pedestrians (MAIS 3+) who were estimated to have at least one injury that could potentially be affected by a component-level upper legform test, this estimate dropped to 12.5 percent when moderately injured pedestrians were included in the analysis (MAIS 2+). Limiting the analysis to more severely injured pedestrians (MAIS 4+) dropped the percentage of affected pedestrians to 1.7 percent. Analyzing only fatal cases resulted in an estimate that 5.2 percent of cases would be expected to be affected by testing in the upper legform test zone.

3.3 Lower Legform Test Calculations

Table 6 shows results of calculations of the percentage of pedestrians potentially affected by a component-level lower legform test procedure. For MAIS 3+ cases, the table shows that 11.2 percent of NTDB pedestrians have at least one AIS 3+ thigh injury, 22.0 percent have at least one AIS 3+ knee or lower leg injury, and 1.8 percent have both a thigh injury and a knee or lower leg injury. Among the 27 PCDS cases with AIS 3+ thigh injuries, 13 included injuries attributed to bumper components, compared to 64 of 83 cases with knee and lower leg injuries that included injury to bumper components. In the 6 PCDS cases with injuries to both regions, there was only one case where one of those injuries in each region was attributed to the bumper. Correspondingly, it was estimated that 5.4 percent of seriously injured pedestrians (MAIS 3+) have at least one thigh injury that could potentially be affected by the lower legform test and 16.9 percent of pedestrians have at least one knee or lower leg injury that could potentially be affected by the lower legform test. Combining these two estimates, and subtracting the percentage of pedestrians in both groups (0.3%) to avoid double-counting them, it is estimated component-level Euro NCAP pedestrian lower legform test would affect at least one AIS 3+ injury among 22.0 percent of seriously injured pedestrians.

In comparison, it is estimated that 31.0 percent of moderately injured pedestrians (MAIS 2+) could potentially be affected by the lower legform test (Table 6). Limiting the analysis to more severely injured pedestrians (MAIS 4+) dropped the percentage of affected pedestrians to 0.4 percent. Analyzing only fatal cases resulted in an estimate that only 1.8 percent of cases would be expected to be affected by testing in the lower legform test zone. The percentage of injured occupants who could potentially be affected by the lower legform test dropped with increased injury severity, as a result of the fact that most lower extremity injuries are associated with relatively low severity codes on the AIS scale.

Table 6. Lower Legform Test Calculations

		NTDB Rate of injury to applicable body region among pedestrians injured at given severity level	**PCDS** Rate of injury to applicable body region associated with applicable component among pedestrians with given injury at given severity level	**Product** By body region	**Aggregate Product** Percentage of injured pedestrians with at least one thigh, knee, or lower leg injury attributed to impact in lower legform test zone
MAIS 2+	Thigh	$\frac{4,725}{64,856} = 7.3\%$	$\frac{22}{36} = 61.1\%$	4.5%	4.5% + 27.5% - 1.0% = **31.0%**
	Knee & Lower Leg	$\frac{22,520}{64,856} = 34.7\%$	$\frac{119}{150} = 79.3\%$	27.5%	
	Both	$\frac{1,694}{64,856} = 2.6\%$	$\frac{5}{13} = 38.5\%$	1.0%	
MAIS 3+	Thigh	$\frac{4,711}{42,075} = 11.2\%$	$\frac{13}{27} = 48.1\%$	5.4%	5.4% + 16.9% - 0.3% = **22.0%**
	Knee & Lower Leg	$\frac{9,242}{42,075} = 22.0\%$	$\frac{64}{83} = 77.1\%$	16.9%	
	Both	$\frac{773}{42,075} = 1.8\%$	$\frac{1}{6} = 16.7\%$	0.3%	
MAIS 4+	Thigh	$\frac{129}{17,093} = 0.8\%$	$\frac{1}{2} = 50\%$	0.4%	0.4% + 0.0% - 0.0% = **0.4%**
	Knee & Lower Leg	$\frac{0}{17,093} = 0\%$	$\frac{0}{0} = 0.0\%$	0.0%	
	Both	$\frac{0}{17,093} = 0\%$	$\frac{0}{0} = 0.0\%$	0.0%	
Fatal	Thigh	$\frac{95}{3,565} = 2.7\%$	$\frac{0}{1} = 0\%$	0%	0% + 1.8% - 0% = **1.8%**
	Knee & Lower Leg	$\frac{87}{3,565} = 2.4\%$	$\frac{3}{4} = 75.0\%$	1.8%	
	Both	$\frac{14}{3,565} = 0.4\%$	$\frac{0}{0} = 0\%$	0%	

3.4 Comparison of Results Among Test Procedures

The percentage of pedestrians affected by each component-level pedestrian test procedure at each injury case severity level, as shown in Table 4 through Table 6, is summarized in Figure 3. Pedestrians with injuries relevant to more than one test are counted with both tests so that a pedestrian among the 26.3 percent of MAIS 2+ injured pedestrians who could be affected by a headform test might also be among the 31.0 percent who could be affected by a lower legform test. This figure illustrates the estimate, for example, that changes made to improve performance in a component-level pedestrian headform test procedure could potentially affect 22.2 percent of MAIS 3+ cases and 34.0 percent of MAIS 4+ cases.

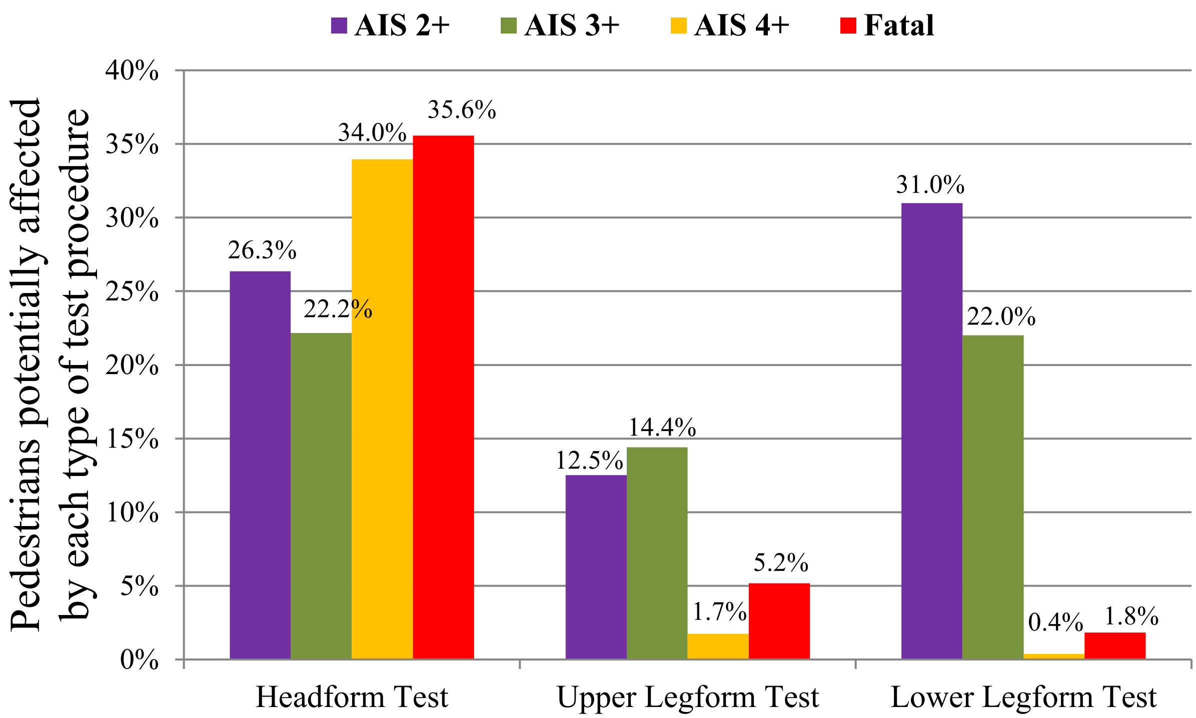

Figure 3. Comparison of pedestrians potentially affected by each type of test procedure

Next, the *relative* contribution of each of the three test procedures to potential improvements in pedestrian safety was estimated at each severity level. This estimate was made by dividing the estimated potential effect of each test procedure (from Figure 3) by the sum of the potential effects estimated for all three test procedures. This sum (in Table 7) shows the total potential effects for all three test procedures at each severity level. For example, among AIS 3+ injury cases, the summed total potential effect of the three test procedures (22.2%, 14.4%, and 22.0%) is 58.6 percent. This sum does not reflect the total percentage of pedestrians potentially affected by component-level pedestrian tests since pedestrians potentially affected by multiple tests are double-counted (e.g. a pedestrian with lower extremity and head injuries could be counted in both the percentage of pedestrians potentially affected by the headform test as well as the percentage of pedestrians potentially affected by one of the legform tests). Instead, this sum is an intermediate calculation only, used to estimate the proportion of the total potential improvement that can be apportioned to each of the three test procedures (by dividing the estimated potential effect of each test procedure by this sum). This resulting proportion can be used to compare the potential effect of each of the three test procedures.

Table 8 shows the resulting proportion of total potential effects accounted for by each of the three pedestrian test procedures. For example, the headform test contributes 37.8 percent of the total potential effect among AIS 3+ cases (22.2% divided by 58.6%), while the lower legform test contributes 37.6 percent of the total effect and the upper legform test contributes only 24.6 percent of the total effect.

If the analysis is expanded to include moderately injured pedestrians, the relative contribution of upper legform tests decreases to 17.9 percent while the relative contribution of a lower legform test increases to 44.4 percent. Limiting the analysis to only those involving severe injuries (MAIS 4+), or to fatal cases only, decreases the influence of lower legform and upper legform tests and increases the importance of a headform test procedure substantially. A headform test accounts for 94.1 percent of the potential effects of component-level testing among severe injury cases and 83.5 percent of the potential effects among fatal pedestrian cases.

Table 7. Sum of Total Potential Effects for Component-Level Pedestrian Test Procedures

	AIS 2+	AIS 3+	AIS 4+	Fatal Cases
Sum of Total Potential Effects From 3 Tests	69.9%	58.6%	36.1%	42.6%

Table 8. Proportion of Total Effects by Test Procedure

	AIS 2+	AIS 3+	AIS 4+	Fatal Cases
Headform Test	37.7%	37.8%	94.1%	83.5%
Upper Legform Test	17.9%	24.6%	4.8%	12.2%
Lower Legform Test	44.4%	37.6%	1.0%	4.3%

It should be noted that the calculations do not account for issues such as the possible variation in the percentage of accurately coded injuries for low-severity or high-severity injuries. For example, more minor injuries may be harder to source to a vehicle component because less severe injuries could be associated with less vehicle damage. In fatal cases, there may be less comprehensive injury coding, especially if death occurred before all injuries could be identified or fully diagnosed. Therefore, at each injury level, the potential effect of each pedestrian test procedure is evaluated only *relative* to the other two pedestrian test procedures by dividing it by the sum of the total potential effects of all three tests. The summed percentages should only be considered as the denominator for the normalized percentages in Table 8 and should not be compared among different severity levels or be interpreted as representing the percentage of the target population affected by component-level pedestrian tests overall.

4.0 DISCUSSION

For the purposes of the serious injury (MAIS 3+, including fatal cases) analysis in this study, a pedestrian case is defined as affected by a particular component-level pedestrian test procedure if it includes at least one AIS 3+ injury with a body region and vehicle component injury source associated with that test procedure. Similarly, in the moderate injury analysis (MAIS 2+), a case is defined as affected by a test procedure if it includes at least one AIS 2+ applicable injury and in the severe injury analysis (MAIS 4+) a case is defined as affected by a test procedure if it includes a least one AIS 4+ applicable injury. For the fatal case analysis, a case was defined as being affected by a given test procedure if there was an AIS 3+ injury equal to the case MAIS associated with a body region and vehicle component injury source applicable to the given procedure.

Among serious injury cases (MAIS 3+, including fatalities), component-level headform tests and lower legform tests are each associated with approximately 38 percent of the potential effects of component-level testing, and the upper legform test is associated with the remaining 25 percent of the potential effects. This distribution corresponds to approximately three-eighths of the effects attributed to the headform test, three-eighths to the lower legform test, and the remaining quarter attributed to the upper legform test.

If the analysis is expanded to include MAIS 2 pedestrian injury cases, the dataset includes many cases with less life-threatening injuries, especially cases with knee and lower leg injury. This elevated frequency of knee and lower leg injuries among lower severity injuries means that the relative contribution of the lower legform test among MAIS 2+ pedestrian cases is higher than in the MAIS 3+ analysis (44.4%). The relative contribution of the headform test among MAIS 2+ pedestrian cases remains approximately 38 percent, while the upper legform test is estimated to account for only 17.9 percent of the total potential effects of component-level test procedures in MAIS 2+ cases.

If the analysis is limited to include only pedestrians coded with severe injuries (AIS 4+, including fatalities), the relative contribution of the headform procedure increases to 94.1 percent of the total potential effects of component-level procedures. In contrast, the relative contribution of the lower legform procedure drops to only 1.0 percent of the total potential effects among severe injury cases. In these analyses of more serious injuries, the influence of lower extremity injuries drop because of the very small number of AIS 4+ lower extremity injuries in the dataset. While lower extremity injuries can carry a high risk of disability, they are associated with a relatively low risk of mortality. As a result, very few lower extremity injury codes exceed AIS 3, limiting the effect of legform testing on severe (MAIS 4+) or fatal pedestrian injury cases. In contrast, head injuries can be associated with a high risk of death or disability, so that the headform test has the potential to have a strong influence on pedestrian cases of all severity levels.

Thus, the selection of the MAIS reference level has a substantial effect on the prioritization of the pedestrian test procedures. Overall, the results for higher-severity injuries (MAIS 4+ and fatality analyses) are more consistent with a focus on reducing threat to life while the MAIS 2+ analysis places increased emphasis on injuries with the potential for short- or long-term disability. Prioritization of the tests based on MAIS 3+ cases may offer a balance between the frequency and disability associated with lower severity injuries and the mortality risk associated with higher AIS injuries.

Limitations and Cautions

It should be noted that the definition of cases that could potentially be affected by each type of pedestrian test procedure is not equivalent to the total potential benefit attributable to each, since the effectiveness of potential improvements in pedestrian protection associated with each test procedure was not estimated. The estimated number of cases affected also does not equate to a target population for component-level testing since the annual number of pedestrian cases in the NTDB dataset is not an estimate of the total number of pedestrians in U.S. crashes. Furthermore, the definition of affected pedestrians differed from a typical target population calculation. For example, for the serious injury analysis, any pedestrian with at least one AIS 3+ injury to an applicable body region in a testable zone of the vehicle counted as affected. This same pedestrian might not be included in a typical target population for this test procedure unless this applicable injury was also the pedestrian's highest AIS injury. The percentage of fatally injured pedestrians potentially affected by one of the test procedures was also calculated differently from a typical target population estimate. In the absence of information on each injury's contribution to the death in fatal cases, a fatal case was only identified as potentially affected by a test procedure if there was an applicable injury (i.e., associated with a body region and vehicle component injury source in the testable zone for a given test procedure) at a severity level of at least AIS 3 and equal to the case MAIS. While there are cases of fatality with MAIS 2 injuries, these were not included in the count of cases affected by each type of test procedure because of the increased likelihood that the injuries in these fatal cases may not have been fully diagnosed and coded.

Because it contains a very large number of relatively recent pedestrian cases, NTDB data was used for any part of the analysis for which it contained sufficient information. Use of the older PCDS data was limited to parts of the analysis for which more recent U.S. case data was not available. The age of the PCDS dataset means that case vehicles are not representative of the current U.S. fleet. For example, larger vehicles such as SUVs are under-represented in the older PCDS dataset. Since these vehicles have higher front ends than sedans, their higher frequency in the current fleet would be expected to lead to changes in frequency of injury to regions such as hips. The effects of these expected shifts in injury patterns with different vehicle types were partially addressed by using the more recent NTDB data to account for shifts in the distribution of injury frequency by body region. For example, although the percentages of hip injuries that were sourced to the hood-leading edge was estimated from PCDS data, the proportions of injuries that were hip injuries were drawn from the newer NTDB data.

If the more recent NTDB data had not been used to adjust the percentages of injuries occurring in each body region, and PCDS data alone had been used to estimate the percentages of pedestrians potentially affected by each test procedure, the results would have reflected injury priorities appropriate for the 1990s fleet. Using AIS 3+ injuries as an example, 58 PCDS case pedestrians would be assumed to be potentially affected by the headform test procedure (Table 4), 28 by the upper legform test procedure (Table 5), and 76 by the lower legform test procedure (Table 6). These numbers correspond to 30.0 percent of the 193 AIS 3+ injured pedestrians who could potentially be affected by the headform test procedure, 14.5 percent who could be affected by the upper legform test procedure and 39.4 percent who could be affected by the lower legform test procedure. In comparison, the current analysis that relies on injury distribution data from NTDB shows that 22.2 percent, 14.4 percent, and 22.0 percent of AIS 3+ injured pedestrians could potentially be affected by the headform, upper legform, and lower legform test procedures. These results suggest that using more recent injury distribution data from NTDB increases the relative importance of the upper legform test in the results and decreases the importance of the lower legform test, which is consistent with the increase in higher front-end vehicles in the fleet in the years subsequent to the PCDS data collection.

There are some changes in the fleet, however, that could not be addressed by using NTDB data to adjust the percentages of injuries occurring in each body region. Consider, for example, head injuries caused by the hood leading edge versus those caused by the hood. It is expected that in more recent pedestrian crashes, the increased numbers of higher front-end vehicles in the fleet since the years of the PCDS data collection would lead to increased proportions of head injuries from hood leading edge contact and decreased proportions of head injuries from hood impact. However, only a third of hood leading edge impacts are expected to be in the test zone (PA=33%), while the majority of hood impacts are expected to be in the headform test zone (PA=82%). In this case, relying on PCDS data to analyze the proportions of head injuries attributable to different vehicle components likely led to a higher estimate of the percentages of cases that could be affected by the headform test procedure than if more current data on head impact locations in late-model vehicle crashes were available.

While use of 2007-2014 NTDB data to update the distribution of injuries by body region from PCDS-era proportions helped the results to more accurately reflect recent pedestrian injury patterns, further updates may be useful to capture continued changes in the fleet after 2014. Updating or confirmation of this analysis with the most recent NTDB dataset available at the time of any future application of these results would be valuable for prioritizing the importance of the three pedestrian test procedures.

Combining data from NTDB and PCDS introduced several potential sources of error. As discussed in Section 2.1, the crash populations of pedestrians in the two datasets differ in:

- Included vehicle types,
- Included vehicle model years,
- Pedestrian age distribution,
- Serious injury distribution, and
- AIS version.

Additionally, PCDS cases included only pedestrians struck by forward-moving vehicles with first contacts forward of the A-pillars. While these differences are expected to affect the absolute accuracy of the estimates made since estimates are based on combined data from the two datasets, they are less likely to have a proportional effect on the results for each of the three types of test procedures.

Approximations necessarily had to be made to estimate the percentages of injuries to a given body region that would be expected to be in the test zone for a given test procedure. First, test zone boundaries were assumed to be equivalent to those defined in Euro NCAP. Second, some components may be in the assumed test zone in some vehicles but not in others. Similarly, portions of some vehicle components covered by the test procedure are expected to vary by vehicle geometry. Case data from PCDS was insufficient to determine for each injury and each impact whether a particular injury was associated with an impact that would be within the assumed test zone for a particular test procedure. Therefore, estimates were made based on the best information available from epidemiological studies and from vehicle measurements on a sample of 12 vehicles. While passenger cars were somewhat underrepresented and full-size SUVs somewhat overrepresented among these 12 vehicles, in comparison to recent vehicle sales, the analyzed vehicles represented a range of recent vehicle designs and were believed to be reasonably representative of the U.S. fleet.

The current evaluation does not analyze the injuries that are *not* covered by any of the three component-level test procedures discussed in this analysis. For example, thoracic injuries account for approximately 18 percent of serious pedestrian injuries in PCDS, while neck and abdomen injuries account for 4 percent and 5 percent respectively (Mallory, Fredriksson, Rosen, & Donnelly, 2012). However, none of these injuries were estimated to be affected by any of the test procedures in this analysis since risk of injury to those body regions is not directly estimated by the three types of component-level test tools considered in this study. It is possible that improvements made to reduce injury risk in the body regions targeted by these test procedures may also reduce risk of injury to body regions such as the thorax, spine, and abdomen. It has been suggested, for example, that there is a correlation between acceleration in pedestrian headform impact tests and chest injury risk (Han, Yang, Mizuno, & Matsui, 2012). If that correlation were confirmed, then thorax injuries could be counted with head and face injuries as potentially affected by headform test procedures. However, without more definitive information on the relationship between test tool output and injury risk to these body regions not specifically targeted, such as the neck, thorax, and abdomen, these were not included in the estimates of potential effects for each test procedure. In other words, it was assumed that a hood designed to do well in a Euro NCAP-style headform test would only mitigate head injuries, and that those hood countermeasures would not also improve thorax protection.

The analysis in this study was limited to descriptive statistics techniques and calculation of point estimates for two reasons: (1) PCDS and NTDB are both convenience samples from populations of injured pedestrians, making it problematic to use inferential statistics to estimate confidence intervals for the corresponding rates or proportions in the overall population. (2) Even if confidence intervals (or differences between proportions) could have been reliably calculated for the proportions estimated from each individual dataset, the end result is a function of estimates from both datasets, making it even more problematic to estimate confidence intervals for these calculated results. It is also recognized that results for AIS 2+, 3+ and 4+ injury severities rely on overlapping datasets of cases. Given that confidence intervals were not developed for these analyses, no correction was made for repeated use of the same data in the three separate analyses.

5.0 CONCLUSIONS

Although no single, current pedestrian crash dataset contained sufficient detail to estimate the frequency of real-world pedestrian injuries that could be potentially associated with specific component-level pedestrian test procedures, combining case data from the NTDB RDS and the PCDS datasets provided an opportunity to estimate the relative frequency of these injuries, subject to the limitations and cautions discussed above.

Among pedestrian crash cases involving serious injury or fatality (MAIS 3+) in the combined datasets, it was estimated that 22.2 percent of cases had AIS 3+ head/face injuries associated with impacts that could be affected by component pedestrian headform test, 14.4 percent had AIS 3+ hip, pelvis, or thigh injuries associated with impacts that could be affected by component pedestrian upper legform tests, and 22.0 percent of cases had AIS 3+ thigh, knee, or lower leg injuries associated with impacts that could be affected by component pedestrian lower legform tests.

When normalized to estimate the proportion of the total potential effects contributed by each of the three pedestrian test procedures at each severity level, **37.8 percent** of the total expected potential effects of the test procedures for seriously injured pedestrians (MAIS 3+) was associated with the **headform test**, **24.6 percent** was associated with the **upper legform test** and **37.6 percent** was associated with the **lower legform test**. When the analysis was limited to more severe injuries, the potential influence of the headform test was substantially higher, while the relative potential contribution of the upper legform and lower legform tests was reduced.

6.0 REFERENCES

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Appendix A: Injury Classification

Injury Group	AIS Codes				Injury Description
	REGION90	STRUTYPE	STRUSPEC	INJLEVEL	
Head/Face	1				Entire head region
	2				Entire face region
Pelvis/Hip	8	5	6		Hip – joint injury
		5	18	08, 10, 12	Femur fracture - head, inter-trochanteric, neck
		5	26, 28, 30		Pelvis fracture
Thigh	8	1	10, 30	4	Amputation (above knee), crush(knee or above)
		2	2		Femoral artery injury
		2	4		Femoral vein injury
		5	18	00, 01, 14, 18, 22	Femur fracture, shaft, subtro-chanteric, supracondylar
Knee	8	2	6, 8		Popliteal artery and vein
		4	4	4, 6	Collateral and cruciate liga-ment laceration
		4	10		Patellar tendon laceration
		5	8		Knee – joint injury
		5	18	4	Femur fracture – condylar
		5	24		Patella fracture
		5	34	06, 08, 10	Tibia fracture - condyles, in-tercondyloid spine

Injury Group	AIS Codes				Injury Description
	REGION90	STRUTYPE	STRUSPEC	INJLEVEL	
Lower Leg	8	1	10, 30	2	Amputation, crush below knee
		5	16	99, 02, 04, 05, 06	Fibula fracture (excludes malleoli)
		5	20	2	Leg or ankle fracture, NFS (Does not include any fractures specifically coded as distal or ankle)
		5	34	02, 04, 05, 20, 22, 99	Tibia fracture (excludes malleoli)
Ankle, Foot (Excluded)	8	1	40	2	Degloving injury, toes only
		3	2		Digital nerve
		4	2		Achilles tendon
		4	4	2	Laceration ligament - ankle
		5	14		Calcaneus fracture
		5	16	08,10,12, 14	Distal fibula (malleolar)
		5	20	0	Foot fracture
		5	22	0	Metatarsal, or tarsal fracture
		5	34	12,14,16, 18	Distal tibia (malleolar)
		5	02, 04, 10, 12		Ankle(tarsus) joint, foot joint, metatarsal, phalangeal, or interphalangeal joint, subtarsal, transtarsal, or transmetatarsal joint
		5	32,36		Talus, toe

Injury Group	AIS Codes				Injury Description
	REGION90	STRUTYPE	STRUSPEC	INJLEVEL	
Location Unknown (Excluded)	8	1	00, 02, 04, 06, 08		Skin\subcutaneous tissue\muscle NFS
		1	40	04,06	Degloving - thigh, calf, knee, ankle, sole of foot, entire extremity
		1	50, 59		Traumatic lower extremity injury & compartment syndrome
		1	60		
		1	10,30	0	Amputation, crush
		2	10, 12		Other named arteries and veins
		3	4		Sciatic nerve
		3	6		Femoral, tibial, peroneal nerve
		4	6		Muscle laceration/strain, location not specified
		4	8		Tendon laceration, location not specified
		9			
Unspecified External (Excluded)	9				All external injuries

Appendix B: Vehicle Components

Vehicle Component Group	Vehicle Component	PCDS Injury Source Code
Bumper	Bumper	700
	Valence	701
Grille	Grille	702
	Front lights	706, 707, 708
Hood Leading Edge	Hood leading edge	703
	Hood ornament	704, 705
Hood & Fender Top Surface	Hood	770
	Hood reinforced with under hood component	771
	Front fender top surface	772
Cowl	Cowl area	773
	Wiper blade and mountings	774
Windshield & A-Pillar	Windshield (glazing)	775
	Left and right A1-pillar	722, 742

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