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Pedestrian Impact Analysis of Side-Swipe and Minor Overlap Conditions

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Abstract

This paper presents analyses of 21real-world pedestrian versus vehicle collisions that were video recorded from vehicle dash mounted cameras or surveillance cameras. These pedestrian collisions have in common an impact configuration where the pedestrian was at the side of the vehicle, or with a minimal overlap at the front corner of the vehicle (less than one foot overlap). These impacts would not be considered frontal impacts [1], and as a result determining the speed of the vehicle by existing methods that incorporate the pedestrian travel distance post impact, or by assessing vehicle damage, would not be applicable. This research examined the specific interaction of non-frontal, side-impact, and minimal overlap pedestrian impact configurations to assess the relationship between the speed of the vehicle at impact, the motion of the pedestrian before and after impact, and the associated post impact travel distances. The21analyzed events are categorized according to the type of impact configuration (side-impact or minimal corner overlap). The vehicle speed was also determined from the video, and the relationship between the vehicle speed and pedestrian distance traveled post impact are summarized.

Introduction and Background

The majority of vehicle versus pedestrian impacts can be classified as frontal impacts. "Car frontal impacts to pedestrians occur in 80 to 90 percent of car-pedestrian collisions" [2]. Further, research by Ravani et al [3] demonstrates that full frontal motor vehicle accidents account for 67% of all the vehicle versus pedestrian impacts they investigated, while 18% of the impacts investigated were into the side of the vehicle, and 13% into the corners. In full frontal impacts, "Severe head/face injuries are more often caused by vehicle contact than by ground or roadway surface contact" [4]. Side-swipe impacts, however, can also result in severe injury, due to the impacts with the side mirror or A-pillar, or subsequent impacts to the ground. While side-swipe impacts account for a lower percentage of all vehicle versus pedestrian impacts, the total number of injuries could be significant considering the 137,000 pedestrian injuries, and 6,000 deaths reported each year in the United States [5,6].

As noted in the Northwestern University Traffic Crash Reconstruction Book, regarding pedestrian impacts, "an issue is nearly always raised regarding the speed of the vehicle involved in the collision" [7]. However, the models that been developed for determining speed in reconstruction of pedestrian impacts primarily focuses on frontal collisions. These models are appropriate for estimating vehicle speed in frontal collisions because of several common observations that can be made about the nature of these collisions. For instance, Toor and Araszewski, observed that "during the motor vehicle accident, the pedestrian is often struck by the leading edge of the vehicle on the lower limbs. The initial contact is often followed by a more pronounced pedestrian/vehicle interaction" [8]. Toor further observed that "Upon impact the pedestrian is rapidly accelerated to a speed that is nearly equal to or less than the vehicle impact speed" [9]. However, for some of the impacts that were analyzed in the paper presented here, the pedestrian was accelerated to a very small portion of the vehicles speed, and without any subsequent, pronounced, vehicle pedestrian interaction. Differences between typical frontal impacts versus side-swipe impacts and minimal overlap impacts include the observation that in frontal impacts, "the large mass difference and the friction developed between the vehicle and pedestrian at impact will result in the pedestrian moving predominantly in the direction of the vehicle," [10] however side-swipe impacts and minimal overlap impacts do not follow this general rule.

The types of frontal impacts which make up the majority of vehicle versus pedestrian impacts are summarized into five main categories. As described by Ravani et al, the five main categories are: "wrap, forward projection, fender vault, roof vault, and somersault" [11].Side-swipe impacts and minimal overlap collisions, however, do not fit in these categories and hence, reconstruction of the vehicle's speeds using the models developed for these five categories do not work well with such impacts. The mathematical models presented in Toor's research utilized a projection efficiency of approximately 80% for wrap trajectories, and 100% for forward projection trajectories[12].In frontal impacts, this range was consistent, however for corner or side-swipe impacts the efficiency can be much lower. Toor also stated that “the empirical models yield accurate results when the considered collision has similar conditions as the test data referenced to derive the empirical relation” [13].In the case of corner and side-swipe impacts, these fall outside the similar conditions of testing used for the empirical model, and therefore the models are not applicable to side-swipe pedestrian impacts.

The case studies presented in this paper examine the relationship between vehicle speed, impact configuration, and throw distance for non-frontal impacts. From analysis of the live impacts, patterns were deduced to help develop analysis methods for estimated speeds of vehicles from the impact configuration and throw distances. Comparisons between models for estimating speed in side-swipe impacts are compared against models for frontal impacts as described by Toor, which was used with the wrap model as representative of frontal impacts most similar to the analyzed impacts. The typical pedestrian impact mathematical models do not work well with side-swipe impacts and minimal overlap conditions, though patterns for these types of impacts emerged through analysis of the video that allowed for estimation of vehicle speeds in non-frontal impacts.

Procedure and Methodology

This analysis began by obtaining video recordings of actual live impacts from the internet and social media platforms. The videos were analyzed to determine frame rate and other video specifications, then photogrammetrically analyzed to determine where the impact took place, the distance from impact to rest, and the location of rest of the pedestrian post impact. Speed of the vehicle at impact was either determined by photogrammetrically measuring the distance and time between two positions in the video (if land marks in the video were sufficient), or determining a range of speeds by measuring the time from impact to rest, and the estimated deceleration rate of the vehicle. The speed of the pedestrian prior to impact was also determined through similar methods. Trends were assessed regarding the orientation of the pedestrian at impact, and the resulting throw distance based on the vehicle speed. In general, the following steps were used in this methodology:

a. Obtained and downloaded source videos.
b. Categorized events.
c. Identified location and obtained or created scaled diagram of accident scene and involved vehicle.
d. Photogrammetrically analyzed the videos, determined impact location and configuration, pre-impact speeds, and points of rest of the vehicle and pedestrian.
e. Analyzed speeds of vehicles and travel distance of pedestrian.
f. Compared video analysis speed of vehicle to calculated vehicle impact speeds through known pedestrian impact analysis methods.
g. Based on analysis of the relationship between actual vehicle speeds and throw distance, developed a useful approach for estimating speed in side-swipe and minimal overlap configurations.

The comparison of analyzed video speeds for the striking vehicles to calculated speeds from pedestrian impact analysis models was performed to determine any trends relating to side-swipe and minimal overlap impacts and the resulting throw distances and vehicle speeds from these types of collisions. A summary of these trends and a description of their potential use is included.

Obtaining Source Videos

Video recordings of pedestrian impacts were found through internet searches, primarily on YouTube™. A total of 20 videos files were obtained, resulting in a total of 22 impacts analyzed. One video contained two pedestrian impacts, and another video included a traditional frontal wrap impact and was only used as comparison. The source videos were converted to mpeg file formats and verified against the source video to make sure frame count and resolution were maintained. Table 1 lists all the videos obtained from the internet including specifications of the video and file format. Video #1 and #17 are the same video but capture two pedestrian impacts and hence listed twice. Additionally, this table identified whether the location where the impact took place was known or unknown. If the location was known the latitude and longitude coordinates were listed.

TABLE 1 Downloaded videos and specifications

Impact #	Resolution	Frame Rate	Length of Video	Accident Location
1	480 × 360	24.00 fps	0:57	unknown
2	1280 × 720	29.97 fps	0:10	56.8770728, 53.2871092
3	604 × 348	20.00 fps	0:30	53.384114, 83.6144875
4	640 × 360	29.97 fps	0:08	48.4689419, 35.0125176
5	1280 × 720	23.98 fps	1:42	47.6137815,-122.1965232
6	1280 × 720	15.00 fps	0:14	unknown
7	1280 × 720	29.97 fps	0:08	35.852066,-78.696589
8	1280 × 720	30.00 fps	1:28	unknown
9	1280 × 720	15.00 fps	0:17	unknown
10	1280 × 720	29.97 fps	0:12	56.501785, 84.9488495
11	1280 × 720	29.97 fps	0:07	unknown
12	1280 × 720	29.97 fps	0:28	42.2842217,-71.0913604

Continued

Impact #	Resolution	Frame Rate	Length of Video	Accident Location
13	490 × 360	30.00 fps	0:55	47.6168344,-122.1430616
14	1280 × 720	29.97 fps	0:50	44.0968618,-70.2111314
15	1280 × 720	25.00 fps	0:09	unknown
16	1280 × 720	29.97 fps	0:06	unknown
17	480 × 360	24.00 fps	0:57	unknown
18	640 × 360	29.97 fps	0:11	unknown
19	1280 × 720	29.97 fps	0:06	55.005796, 82.967801
20	1280 × 720	29.97 fps	0:15	unknown
21	1280 × 720	29.97 fps	0:12	unknown

Categorization of the Events

The 21pedestrian impacts were separated into two categories: side-swipe impacts and minimal overlap impacts. This resulted in a total of 13samples in the category of side-swipe impacts, and 8samples of minimal overlap. Based on review of the video, the pedestrians that were struck by the front corner of the vehicle were labeled minimal overlap, which included impacts from the corner to approximately 12" maximum overlap with the front of the vehicle. Pedestrians that were struck along the side of the vehicle, rearward from the front corner, were labeled as side-swipe impacts. Table 2 identifies the impact categories utilized in the analysis.

TABLE 2 Categorization of the videos into impact types

Impact #	Resolution	Frame Rate	Length of Video	Accident Location	Impact Type
1	480 × 360	24.00 fps	0:57	unknown	side-swipe
2	1280 × 720	29.97 fps	0:10	56.8770728, 53.2871092	side-swipe
3	604 × 348	20.00 fps	0:30	53.384114, 83.6144875	side-swipe
4	640 × 360	29.97 fps	0:08	48.4689419, 35.0125176	side-swipe
5	1280 × 720	23.98 fps	1:42	47.6137815,-122.1965232	side-swipe
6	1280 × 720	15.00 fps	0:14	unknown	side-swipe
7	1280 × 720	29.97 fps	0:08	35.852066, -78.696589	side-swipe
8	1280 × 720	30.00 fps	1:28	unknown	side-swipe
9	1280 × 720	15.00 fps	0:17	unknown	side-swipe
10	1280 × 720	29.97 fps	0:12	56.501785, 84.9488495	side-swipe
11	1280 × 720	29.97 fps	0:07	unknown	side-swipe
12	1280 × 720	29.97 fps	0:28	42.2842217, -71.0913604	side-swipe
13	490 × 360	30.00 fps	0:55	47.6168344, -122.1430616	side-swipe
14	1280 × 720	29.97 fps	0:50	44.0968618, -70.2111314	min overlap
15	1280 × 720	25.00 fps	0:09	unknown	min overlap
16	1280 × 720	29.97 fps	0:06	unknown	min overlap
17	480 × 360	24.00 fps	0:57	unknown	min overlap
18	640 × 360	29.97 fps	0:11	unknown	min overlap
19	1280 × 720	29.97 fps	0:06	55.005796, 82.967801	min overlap
20	1280 × 720	29.97 fps	0:15	unknown	min overlap
21	1280 × 720	29.97 fps	0:12	unknown	min overlap

Continued

Identifying the Location of the Video and Production of Scaled Accident Diagrams

For each of the pedestrian impacts, scaled diagrams were created. These diagrams included the impact configuration between the pedestrian and the vehicle, the pre-impact speeds of the pedestrian and the vehicles, and post impact travel distance of both pedestrian and the vehicle. The creation of the scaled diagram and resulting speeds and positions were performed by locating and scaling an aerial where the incident occurred and creating a scaled model of the vehicle type. Photogrammetric analysis of the video was also performed to determine the position of the pedestrian and vehicle over time. Of the 21 impacts, ten had information in the video that identified where the impact occurred. In some instances, GPS coordinates were displayed on the video from the recording device or located in the metadata of the downloaded video file. For others, street signs, state license plates, or commercial properties identified the location, and a corresponding aerial was then obtained from Google Earth, Bing Maps, or Near Map. These aerials were imported and scaled in AutoCAD 2020, and linework drawn for lane lines, curbs, crosswalk marking, or other features that would be used to locate the pedestrian and vehicle at each frame in the video. Figure 1-3 demonstrate the process of analyzing the video, identifying the location from the name of the supermarket at the corner of the intersection, and generating a scaled diagram of the accident area.

The precise location for 9 out of the 21 impacts could not be identified, typically in a European country with no

FIGURE 1 Still frame from the source video file impact (12).mp4

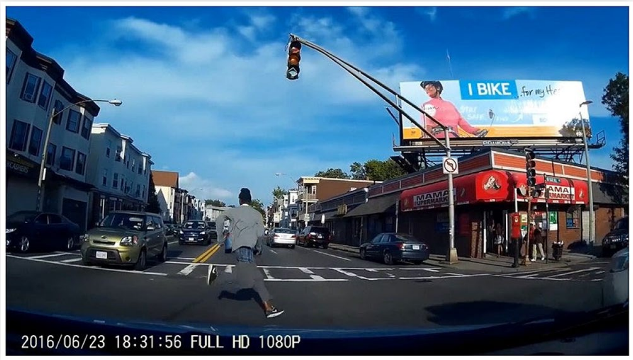
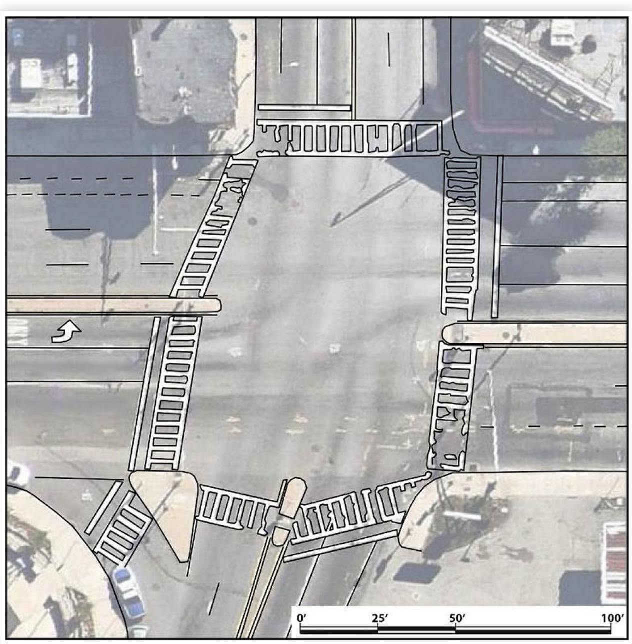


FIGURE 2 Identification of the accident location (Google Street View)

FIGURE 3 Scaled diagram including linework overlay of the intersection



searchable context. For these impacts, a scaled diagram was created based on a typical lane width of 3.5 meters for European sites [14], 12 feet for US Highway sites, and based on the scale of the vehicles, the average stride distances of the pedestrians, or other indicators that helped confirm dimensions in the video.

Photogrammetric Analysis of Pedestrian and Vehicle Positions and Speeds

Through photogrammetric and video analysis, an impact configuration between the pedestrian and the vehicle were determined and added to the scaled diagram. The majority of videos were 24.00 to 30 frames per second (fps), with two of the videos at the lower frame rate of 15fps, providing an acceptable time step for the analysis performed in this research. Sixteen of the videos were high definition, and 5 were standard definition, the lowest resolution measuring 480x360 pixels. Fortunately, for the lower resolution videos, the image quality was high, and the size of the objects being measured made up a large portion of the image, essentially bringing it on par with the higher definition videos. For 9 of the 21 impacts, the type of vehicle could be identified and additionally used as a scale references. Markings on the roadway in the aerial further located the impact in the scaled diagrams. For impacts where the aerials were not obtained, this impact was estimated based on the size of the vehicle and the assumed lane width. Placement of the pedestrian before and after impact used similar methods of photogrammetry and video analysis. For most of the videos, the high resolution of the aerials and clarity of the impact in the video made the placement in the diagram accurate. Figure 4 and Figure 5 demonstrate the scaled drawings created through this process, locating the pedestrian and vehicle at impact and at the points of rest.

FIGURE 4 Diagram of impact and rest positions for impact # 21

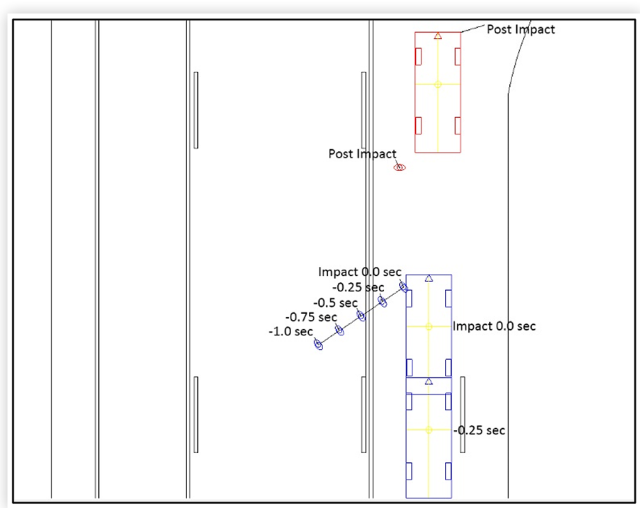


FIGURE 5 Diagram of impact and rest positions for impact # 6

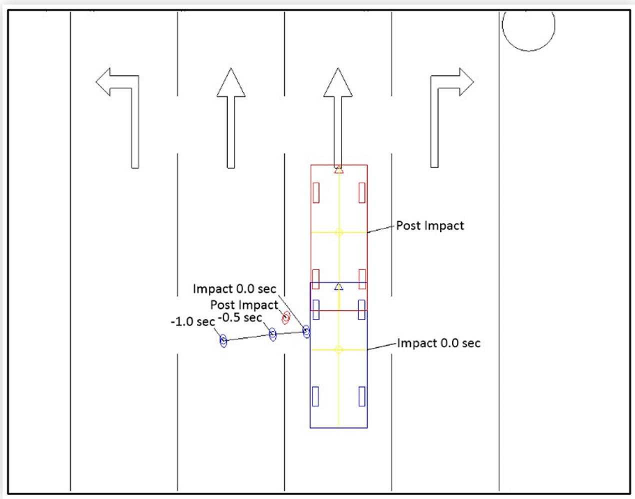


TABLE 3 Summary of vehicle speeds

Impact	Impact Category	Veh Speed (video analysis) [mph]
1	Side-swipe	9.5
2	Side-swipe	14.3
3	Side-swipe	22.5
4	Side-swipe	14.8
5	Side-swipe	15.7
6	Side-swipe	17.0
7	Side-swipe	32.9
8	Side-swipe	11.0
9	Side-swipe	11.0
10	Side-swipe	31.4
11	Side-swipe	20.0
12	Side-swipe	18.0
13	Side-swipe	38.9
14	Min Overlap	26.7
15	Min Overlap	7.6
16	Min Overlap	25.0
17	Min Overlap	9.6
18	Min Overlap	24.5
19	Min Overlap	14.0
20	Min Overlap	32.7
21	Min Overlap	36.8
22	Frontal	17.0

For 16of the 21 impacts, the speed of the vehicle was measured by determining two locations and averaging the speed based on the time stamp. For the remaining five impacts, the vehicle was decelerating at the time of impact, as evidence by brake lamps and through review of the motion in the video. For these impacts, a start and stop position was located on the scaled diagram and the initial velocity calculated, or a deceleration rate from braking was estimated, and the time from impact to rest determined from the video. With the ending velocity in both methods being zero miles per hour, the initial speed was calculated. Scaled diagrams of all 21 impacts are included in the appendix, categorized the same as in Table 2. A summary of calculated vehicle speeds for each impact is listed in Table 3. As summarized in this table, the vehicle speeds in the 21 analyzed impacts ranged between 9mph and 39mph.

Limitations in Existing Methods for Pedestrian Impact Analysis

In the case of forward projection and wrap pedestrian impacts, throw distance was more directly correlated to vehicle speed, as the pedestrian and vehicle approach achieving a common velocity, and the vehicle imparts the majority of its speed into the pedestrian. Therefore, throw distance was relatable through methods of calculation such as empirical models developed through research and testing by Appel, Sturtz, Wood, and Toor [15, 16, 17, 18]. Another method was to use an average deceleration for the pedestrian to calculate speed from throw distance, which was utilized in several pedestrian impact analysis methods summarized in Eubanks and Hill's book, "Pedestrian Accident Reconstruction and Litigation"[19]. However, in the case of side-swipe and minimal overlap pedestrian impacts researched for this paper, the actual vehicle speed can triple the calculated speed from these typical methods.

Current published literature, however, provides limited direction on analysis of pedestrian impacts in which the pedestrian was struck by the corner or side of the vehicle. Mentions of this type of impact in pedestrian impact publications may characterize the impact location and pedestrian trajectory after impact, but not a clear method for calculating vehicle speed. Eubanks and Hill compared the calculation of speed from the side-swipe and minimal overlap conditions versus an impact where the pedestrian was more centered on the vehicle and achieves a common velocity with the car. In these conditions, sometimes referred to as "partial" or "restricted corner" impacts "the pedestrian acquires an unknown percentage of the vehicle's speed which was generally quite a bit lower than the expected 60-100%" [20].

Fricke describes partial impacts as "an impact where none of the colliding surfaces attains a common velocity" [21].This observation was confirmed in the impacts analyzed in this research. In all of the impacts analyzed, the pedestrian never achieved a common velocity with the vehicle, but rather only a portion of the vehicles speed was imparted on the pedestrian in a manner that would project the pedestrian along the same path as the impacting vehicle.

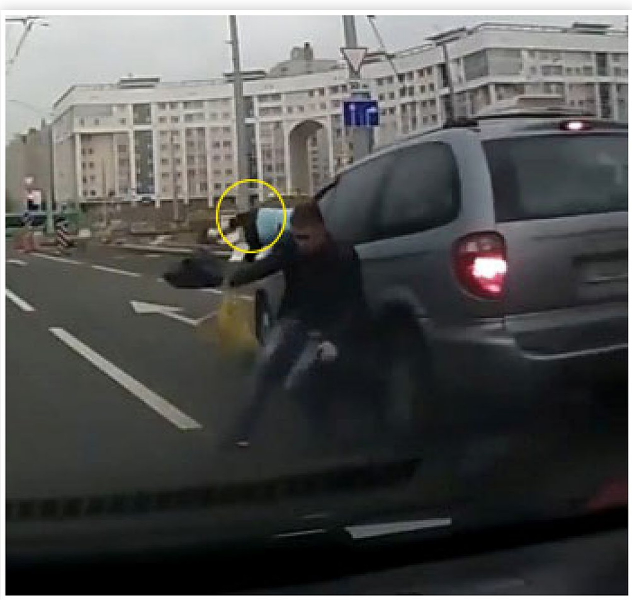
Other research recognized the difficulty in a clear model for calculating vehicle speed in corner and side-swipe impacts. As noted in the book "Pedestrian Accident Reconstruction and Litigation," a corner impact "can place additional forces on the body, either by a glancing blow, by transmitting a percentage of the vehicle's speed in the direction of the automobile, or by completely stopping the pedestrians forward movement" [22].

Further, articulated in the Northwestern Traffic Crash Reconstruction Book, “[the pedestrian] speed is nearly always less and never more than the vehicle speed. The reason for this is fairly obvious. In most cases, the collision between the vehicle and pedestrian is not centered. For these cases, the body is rotated as a result of the collision and does not reach the same velocity as the car” [23].

Real-World Example to Illustrate the Use of Empirical Models in Pedestrian Impacts

To illustrate the primary issue in this research (i.e., the limitation in using existing methodologies to determine vehicle speed in a side-swipe or minimal overlap impact), one of the downloaded videos was analyzed and used as an example. This video contained both a full-frontal impact and a side-swipe impact from the same vehicle at the same time. This video was classified as two separate impacts, #6 and #22. This impact occurred when two pedestrians were crossing the street together, one slightly ahead of the other. With this offset distance between the pedestrians, the further forward pedestrian was struck at the middle of the vehicle, but the trailing pedestrian impacted the side of the vehicle. Figure 6 is a zoomed still image from the video, showing the two different impact configurations. The male pedestrian is rotating in the foreground on the driver’s side of the vehicle, and visible over his right shoulder is a female pedestrian in black pants and a teal jacket wrapping on to the hood of the vehicle. A circle has been added to identify the female pedestrian.

FIGURE 6 Still frame from video of impacts #6 and #22



The throw distance was calculated for both pedestrians. The impact to the front of the vehicle resulted in the female pedestrian traveling forward 20.5 feet, and the side-swipe impact resulted in the male pedestrian travelinga total of 2.8 feet. Since calculating vehicle speed in a pedestrian collision can depend on the pedestrian throw distance, having two significantly different measurements can yield different vehicle speeds. An empirical formula developed by Toor and Araszewski was utilized to determine the vehicle speed based on a wrap impact. The wrap model was chosen because this model most closely matches the impact configuration of the female pedestrian. The formula presented in Toor’s paper [24] for empirically modeled wrap impacts is as follows:

$$10b)\ V_v = 9.84S^{0.57}$$

In the above formula, V_v is the vehicle speed in kilometers per hour (kph), and S is pedestrian throw distance in meters. In the model comparison from this publication, Toor notes that an average projection efficiency of 80% was considered for wrap trajectories [25], which is defined as “the ratio of the pedestrian launch speed and the vehicle impact speed” [26]. Projection efficiency, therefore, is a metric for the transfer of vehicle speed to pedestrian during impact, and wrap trajectories are assumed to be less than 100% efficient. Toor states in the discussion section that “the user must exercise caution that the case in hand meets the criteria of the model. In addition, the empirical models yield accurate results when the considered collision has similar conditions as the test data referenced to derive the empirical relation” [27].

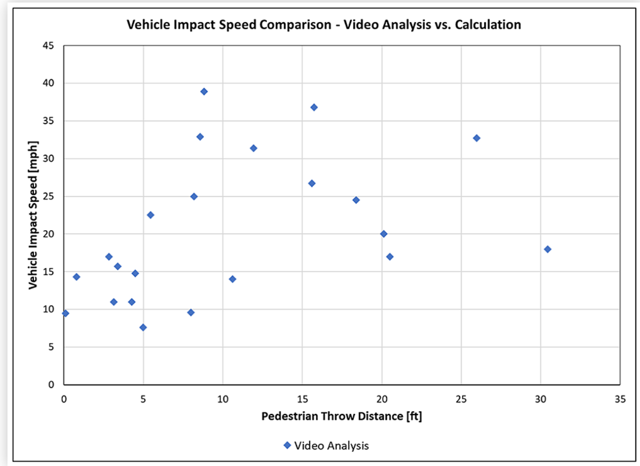
Based on this formula, the vehicle speed is calculated at either 17.4 mph or 5.6 mph, respectively. From analysis of the video, the actual speed of the vehicle is 17.0 mph, which demonstrates the reliability of determining speed for the frontal collision when using Toor’s empirical wrap formula method, but not for the male pedestrian’s impact to the side of the vehicle. For this second impact, the calculated vehicle speed with the wrap method was only 33% of the vehicle’s actual speed. This example illustrates how using an empirical model works for certain types of pedestrian impacts, but not for the side-swipe or minimal overlap conditions.

Developing a Model for Side-Swipe and Minimal Overlap Conditions

Utilization of the same Toor mathematical model, which determines speed of the vehicle based on the pedestrian throw distance, for all 21 side-swipe and corner impacts analyzed in this research, results in a similar pattern; the vehicle speeds calculated from the model are much lower than the actual speeds measured in the video. In an effort to develop a useful approach to analyzing vehicle speeds in these alternative impact conditions (side-swipe and minimal overlap conditions), the following steps were performed:

1. Plot the pedestrian throw distance and vehicle speed as calculated from video analysis for all 21 side-swipe and minimal overlap conditions.
2. Using an empirical model, calculate speed based on the throw distance (this assumes a wrap impact condition).
3. Compare and evaluate the calculated speeds (which were too low) to the actual speeds from video analysis.
4. Analyze the video to determine the amount of pedestrian engagement with the vehicle.
5. Determine a multiplier that accounts for the amount of engagement in side-swipe and minimal overlap conditions.
6. Evaluate the practical applications and classification in real world reconstruction if no video footage is available.

FIGURE 7 Vehicle impact speeds and pedestrian throw distance from video analysis



Plotting the Throw Distance and Speeds from Video Analysis

All 21 impacts were analyzed, including determining the speed of the vehicle at impact and the distance the pedestrian travels post impact. The throw distance was determined by measuring the location of the feet at impact to the location of the feet after impact. The pedestrians' feet were selected as the reference point for throw distance because in some cases the struck pedestrian was not thrown, but rather fell down or spun away from the striking vehicle. Had the center of gravity been used, the difference from the estimated center of gravity to the feet of the pedestrian when prone could result in an error of up to two feet or more in throw distance when including the distance from feet to center of gravity. In those cases where the pedestrian is thrown, not spun, the difference between the distance to the feet versus the center of gravity was less significant. However, to maintain consistency, all measurements were measured based on the location of the feet at impact, and after impact when the pedestrian was at rest. In the few scenarios where the pedestrian was not knocked to the ground, the distance where the pedestrian ended upright and no longer affected by the impact was measured. The data from the video analysis was plotted and shown in Figure 7.

Comparison of Empirical Model Speed Calculations

The authors utilized the Toor empirical wrap model to calculate vehicle impact speeds based on the throw distances determined from video analysis. Using Toor's formula, data was plotted for each of the 21 impacts. Figure 8 depicts the comparison of the Toor calculated speeds (orange) to the data plotted from video analysis.

FIGURE 8 Vehicle impact speed comparison chart: video analysis vs. calculation

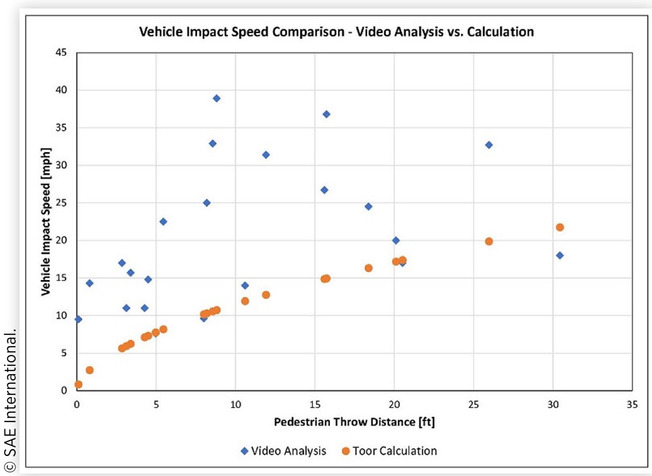


Table 4 shows the same calculated speeds using Toor's wrap method, and also includes the vehicle impact speeds determined through video analysis.

The comparison between calculated vehicle impact speeds and speeds from video analysis showed that the actual impact speed can be anywhere from approximately equal to calculated speed, to over five times more than the calculated speed. This discrepancy in calculated and actual vehicle speeds showed the importance of pedestrian impact configuration and trajectory analysis in accident reconstruction, as there are potentially large differences in calculated speed values that would negatively affect a reconstruction of a similar pedestrian collision.

TABLE 4 Vehicle speed comparison, Toor vs. video analysis

Impact	Impact Category	Ped distance [ft]	Calc Veh Speed (Toor Wrap Model, 2003) [mph]	Veh Speed (Video Analysis) [mph]
1	Side-swipe	0.10	0.8	9.5
2	Side-swipe	0.80	2.7	14.3
3	Side-swipe	5.45	8.2	22.5
4	Side-swipe	4.49	7.3	14.8
5	Side-swipe	3.39	6.2	15.7
6	Side-swipe	2.84	5.6	17.0
7	Side-swipe	8.56	10.6	32.9
8	Side-swipe	4.27	7.1	11.0
9	Side-swipe	3.12	5.9	11.0
10	Side-swipe	11.92	12.8	31.4
11	Side-swipe	20.11	17.2	20.0
12	Side-swipe	30.44	21.8	18.0
13	Side-swipe	8.81	10.7	38.9
14	Min Overlap	15.84	15.0	26.7
15	Min Overlap	4.97	7.7	7.6
16	Min Overlap	8.19	10.3	25.0
17	Min Overlap	8.00	10.2	9.6
18	Min Overlap	18.38	16.3	24.5
19	Min Overlap	10.60	11.9	14.0
20	Min Overlap	25.97	19.9	32.7
21	Min Overlap	15.73	14.9	36.8
22	Frontal	20.52	17.4	17.0

Analysis of Video to Evaluate Patterns of Engagement

In review of Figure 8 and Table 4, it was clear that in the side-swipe and minimal overlap impact configurations, the pedestrian only received a portion of the actual speed. But this pattern does not explain why some of the impacts have actual speeds that were close to the Toor calculated speeds, and some of the impacts are four to five times the calculated speed. There is still a large variation in and wide spread of speeds in the 21 impacts relative to the calculated Toor speeds. To understand if there are other patterns that explain this spread, each impact was analyzed with a focus on the configuration between the pedestrian and the vehicle, and how much engagement or contact the pedestrian had with the striking vehicle. In other words, since the actual vehicle speed had a range up to five times as high as the speeds calculated through an empirical model, an analysis was performed on each video to see if there were differences in how the pedestrian engaged with the vehicle that would explain the wide spread of data.

In analyzing each impact more closely, it was determined that some of the impacts had very little engagement between the pedestrian and the surface of the vehicle, while other impacts had more engagement. This difference of "less" and "more" engagement was evaluated to see if it explains why some vehicle speeds were closer to the Toor empirical model and other speeds were farther. As might be expected, analysis of the video showed that in general, the more engagement a pedestrian had with the vehicle (even if a side-swipe of minimal overlap condition) the more of the vehicle's speed was imparted on the pedestrian post impact. Figure 9 depicts an example of less engagement, where the pedestrian engaged the side of the van with minimal contact, and thus resulted in a minimal throw distance.

As seen in the video image sequence, the pedestrian was traversing an approximately perpendicular path across the roadway prior to impact; video analysis of the pedestrian's speed found he was traveling at approximately 5 mph, or a fast walk. However, he attempts to stop his forward motion immediately prior to impact but was carried into the area of the van's driver door as it passed across his walking path, pushing the pedestrian forward along the path of travel of the van. Clearly some of the van's speed was imparted onto the pedestrian in this impact, as his post-impact trajectory was close to the direction of travel of the van; however, he does

FIGURE 9 Extracted video frame sequence from Impact 7

not travel far after being struck, a much shorter throw distance than anticipated for a vehicle traveling 33 mph from video analysis. The calculated impact speed from the throw distance was approximately 11 mph, or one-third of the actual speed of the van.

A second example of less engagement, where the speed of the vehicle was much higher in actuality than what would be calculated using Toor was impact #13. In this sample, using the wrap formula would provide an impact speed of approximately 10 mph, when in fact the vehicle was traveling nearly 40 mph. In this impact, a pedestrian runs across the intersection through a crosswalk and then strikes the oncoming vehicle in the area of the driver's door. The contact caused the pedestrian to be knocked off his feet in the vehicle's direction of travel. However, he was not thrown a distance that would be assumed from a 40 mph wrap impact. A still frame sequence of impact 13, with frames at one-second intervals, is shown in Figure 10.

In contrast to impacts with less engagement are those were there is more engagement. More engagement was characterized by greater overlap of the pedestrian's body with the frontal area of the striking vehicle, such as along the front bumper, headlight, hood, windshield, and A-pillar. Impacts with more engagement would be those impacts where the actual speed as determined in video was closer to the speed determined through Toor's empirical model. Figure 11 depicts Impact 18 in which two pedestrians were crossing the street, but only one was struck by the front corner of the vehicle, then contacted the windshield and A-pillar region prior to separating from the striking vehicle.

FIGURE 10 Extracted video frame sequence from impact 13 at one-second intervals

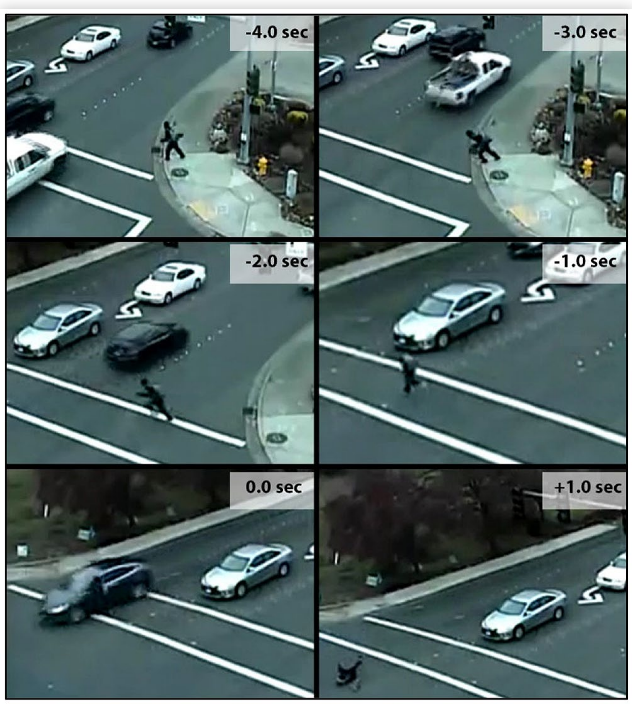


FIGURE 11 Extracted video frame sequence from impact 18

In a case such as the above impact, a higher percentage of the vehicle's impact speed was imparted on the pedestrian due to increased engagement with the pedestrian's body and structures of the vehicle. Toor's method of calculating vehicle impact speed from throw distance incorporates a higher projection efficiency, therefore resulting in a throw distance more consistent with a traditional wrap impact configuration. In impacts with less engagement, the projection efficiency was much lower, and the throw distance was not representative of the vehicle's impact speed when calculations are performed. This trend was discussed in some of the mentioned pedestrian impact publications, including Eubanks and Hill's 1998 book on the subject in which they state projection efficiency can be lower than 60%; however, in this research the authors found instances where efficiency was even below 20% in less engagement impacts. This trend agrees with the expected physics involved in a less engagement impact, where the forces were transferred from vehicle to pedestrian mainly through sliding friction, and no common velocity was reached between the pedestrian and striking vehicle.

Developing a Multiplier

A trendline was selected in the chart for the calculated data, which plots a best-fit line based on a selected formula for the line, in this case a power function as that is the format of Toor's wrap formula. As shown in Figure 12, the trendline fits the data, and the formula was identical to Toor's empirical wrap formula previously shown, except with speed in miles per hour and distance in feet. Given that the data was calculated using the specified formula, it was not surprising that the trendline should match the calculated data.

As the above charts illustrates, most of the actual impact speeds from video analysis fall above the line of Toor's calculation, showing that these side-swipe and minimal overlap impacts resulted in an underestimation of vehicle impact speed when using typical analysis methods relying on pedestrian throw distances.

The division of impacts based on more engagement or less engagement contact between pedestrian and striking vehicle showed that more engagement impacts have vehicle speeds closer to the calculated speed and less engagement impacts have a much larger gap between actual and calculated vehicle speeds. Figure 13 depicts a color-coded grouping of those impacts with less engagement, and those with more engagement. Blue represented the side-swipe and minimal overlap with less engagement (the group farthest from Toor's trendline) and red represents the side-swipe and minimal overlap with more engagement (the group closest to Toor's trendline).

Figure 14 is a chart of vehicle impact speeds versus pedestrian throw distance for impacts classified as more engagement, and Figure 15 is a chart for impacts classified as less engagement. As in Figure 13, blue icons indicate less engagement impacts, and red indicates more engagement impacts.

One potential method of application of the data and analysis presented in this paper is classifying an impact as either more or less engagement, then utilizing a multiplier

FIGURE 12 Vehicle impact speed comparison chart: video analysis vs. calculation, with power function trendline

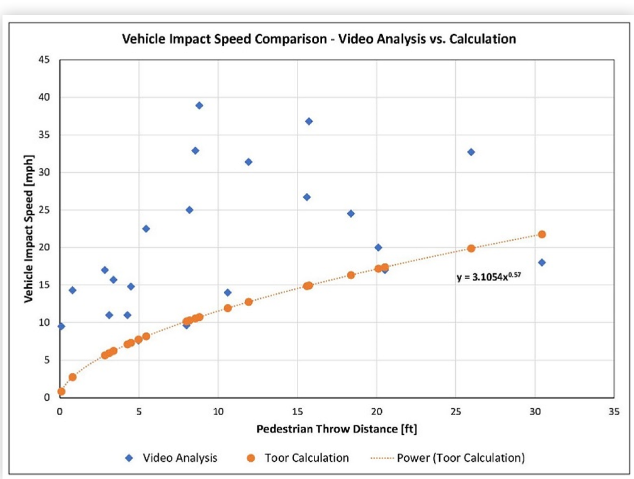


FIGURE 13 Vehicle impact speed comparison, more and less engagement

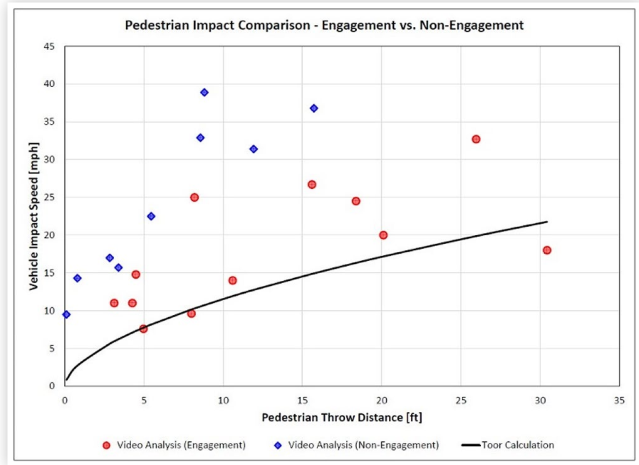


FIGURE 14 Vehicle impact speed comparison, more engagement impacts

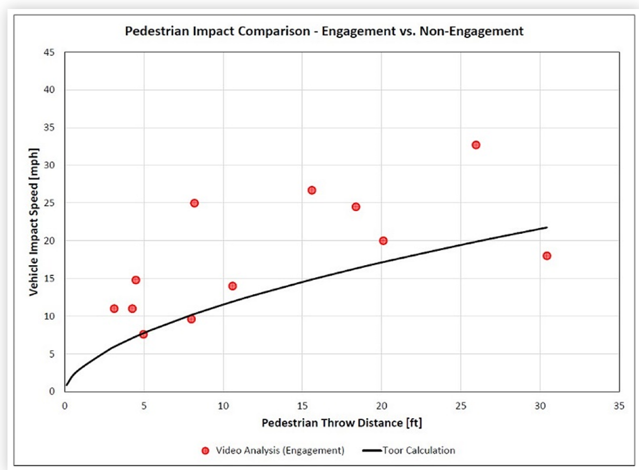


FIGURE 15 Vehicle impact speed comparison, less engagement impacts

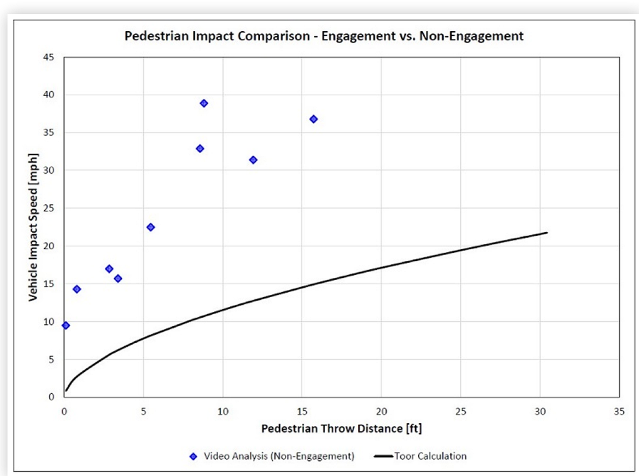


TABLE 5 More engagement multiplier, calculated to actual vehicle speed

Impact	Impact Category	Calc Veh Speed (Toor Wrap Model, 2003) [mph]	Veh Speed (Video Analysis) [mph]	Multiplier, Calculated Speed to Actual Speed	Average Multiplier
4	Side-swipe	7.3	14.8	2.0	1.5
8	Side-swipe	7.1	11.0	1.5	
9	Side-swipe	5.9	11.0	1.9	
11	Side-swipe	17.2	20.0	1.2	
12	Side-swipe	21.8	18.0	0.8	
14	Min Overlap	14.9	26.7	1.8	
15	Min Overlap	7.7	7.6	1.0	
16	Min Overlap	10.3	25.0	2.4	
17	Min Overlap	10.2	9.6	0.9	
18	Min Overlap	16.3	24.5	1.5	
19	Min Overlap	11.9	14.0	1.2	
20	Min Overlap	19.9	32.7	1.6	

TABLE 6 Less engagement multiplier, calculated to actual vehicle speed

Impact	Impact Category	Calc Veh Speed (Toor Wrap Model, 2003) [mph]	Veh Speed (Video Analysis) [mph]	Multiplier, Calculated Speed to Actual Speed	Average Multiplier
2	Side-swipe	2.7	14.3	5.2	3.1
3	Side-swipe	8.2	22.5	2.8	
5	Side-swipe	6.2	15.7	2.5	
6	Side-swipe	5.6	17.0	3.0	
7	Side-swipe	10.6	32.9	3.1	
10	Side-swipe	12.8	31.4	2.5	
13	Side-swipe	10.7	38.9	3.6	
21	Min Overlap	14.9	36.8	2.5	

extracted from the data, which is applied to a calculated vehicle impact speed from Toor's formula. In the case of more engagement impacts analyzed in this paper, the average multiplier value to approximate actual impact speed from calculated speed is 1.5, with a range from 0.8 to 2.4. For less engagement impacts, the average multiplier is 3.1, with a range from 2.5 to 5.2. Note that Impact 1 was eliminated from the less engagement average and range due to being an outlier in the data (multiplier of 11.4). Table 5 shows the more engagement classification multiplier with average, and Table 6 shows the less engagement classification multiplier with average.

As shown in Tables 5 and 6, the energy imparted to the pedestrian was a function of how much engagement occurred between the pedestrian and the vehicle. The data, unsurprisingly, showed that the less engagement between the pedestrian and the vehicle, the lower the calculated speed was for the vehicle based on the throw distances. What was helpful in this study to determine the engagement of the pedestrians was the videos of the accidents. Impacts may not have video, however, and an investigator may need to rely on physical evidence at the scene, testimony, or evidence on the vehicle. The following section classifies and summarizes evidence that may likely be examined and documented in real world investigations that can help in understanding the impact configuration and how much engagement might have occurred between the pedestrian and the vehicle.

Classification and Identification from Evidence

In contrast, here is an example of how Toor's empirical calculation does work, despite it being a side-swipe impact: Figure 16 is an example where it is a side-swipe configuration, but because of the speed of the pedestrian pre impact, there is more engagement with the vehicle, and a result more of the speed of the vehicle imparted on to the pedestrian post impact.

In this example, review of the video showed more engagement between the pedestrian and vehicle, such as contact with the front corner of the vehicle (headlight, front bumper, front edge of fender), and/or with the A-pillar and windshield, and in some cases the pedestrian was lifted off the ground and was airborne during the initial part of the throw trajectory. This impact was closer to a typical wrap, since the pedestrian almost achieved a common velocity, and for this reason the speed calculations from the Toor model was the same as measured in the video. In this respect it was an outlier for the pedestrian impacts analyzed in this research, but a good example of the amount of engagement needed to be consistent with speed calculations from wrap models.

Further analysis of the differences between less and more engagement extracted another variable with an effect on the

FIGURE 16 Extracted video frame sequence from impact 12

classification of impact configuration: distance from the front corner of the vehicle at which the pedestrian contacted the striking vehicle. During the video analysis process, the location of the pedestrian was measured longitudinally from the front bumper, along the side of the vehicle. The measurement was taken from the furthest forward point of the vehicle, which was along the centerline of the vehicle, i.e., the longitudinal distance back from the front bumper where the pedestrian was struck. While there were several different vehicle types, makes, and models present in the analyzed videos, each with varying physical dimensions, a trend of impact locations on the vehicles was observed: less engagement impacts were located an average distance of 4.5 feet back from the most forward point on the front of the vehicle, while more engagement impacts were on average approximately 1.8 feet back. Figure 17 shows the pedestrian impact configurations for all analyzed videos placed around a representative vehicle model, including outlines showing the maximum dimensions for the outside of the vehicle as used for dimensions of impact location.

FIGURE 17 Pedestrian impact locations on striking vehicle (all videos)

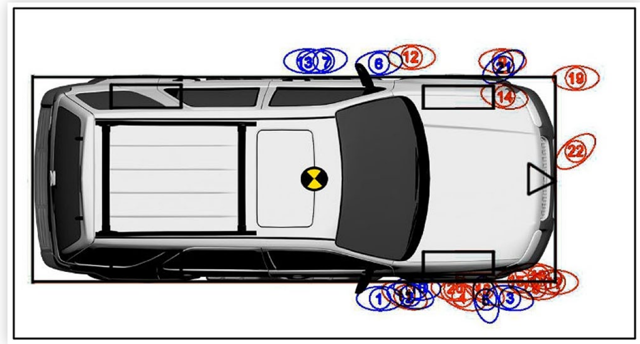


FIGURE 18 Pedestrian impact locations on striking vehicle (more engagement)

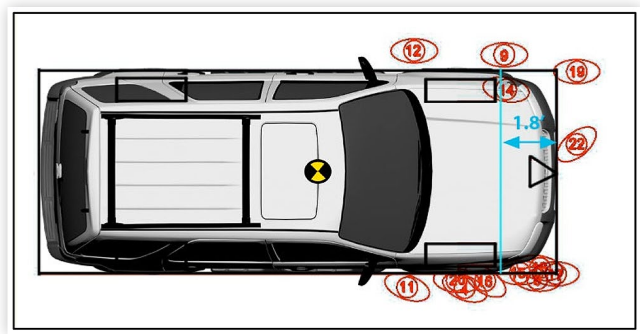
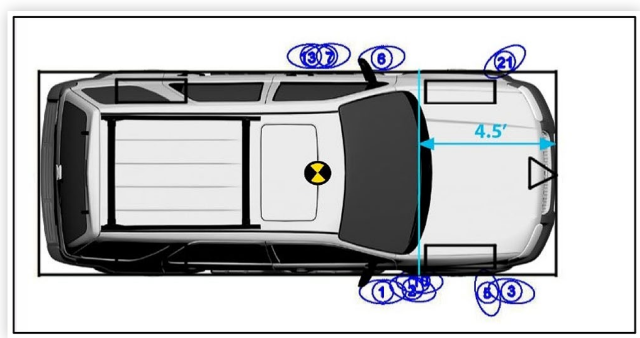


FIGURE 19 Pedestrian impact locations on striking vehicle (less engagement)



Figures 18 and 19 represent the same impact locations, but broken down into either more engagement (Figure 18) or less engagement (Figure 19) impact classifications. In Figure 18, there is a blue line with a 1.8 foot dimension representing the average impact distance back from the front of the vehicle and Figure 19 has a corresponding blue line showing the average impact distance of 4.5 feet.

In the case of more engagement impacts, with an average distance back of 1.8 feet, the pedestrian was more likely to be struck by the front bumper, headlight, and front fender of the vehicle, all of which provide a greater mechanical engagement and transmit more of the vehicle's impact speed into the pedestrian. The engagement impacts shown further back from the average dimension, such as impacts 11 and 12,were typically when the pedestrian engaged the A-pillar and windshield of the striking vehicle, which also increased the mechanical engagement and therefore the transmitted speed to the pedestrian. An additional factor of engagement on side-swipe impacts was the speed at which the pedestrian was traveling prior to impact; for example, as in the previously shown image sequence in Figure 16, the pedestrian had a high velocity perpendicular to the travel direction of the striking vehicle. In these cases, the pedestrian's forward speed and momentum carried their body into the striking vehicle, creating a larger overlap and allowing higher engagement with the vehicle, typically in the A-pillar and windshield area. This in turn created higher friction and increased throw distance of the pedestrian, more closely mimicking a traditional wrap impact throw distance.

The average distance of 4.5 feet back for less engagement impacts placed the pedestrian contact more likely in the area of the front fender, driver or front passenger door, or B-pillar, which on most vehicles are relatively flat surfaces that do not impart significant frictional forces to the pedestrian during contact. In these cases more sliding contact occurs between the pedestrian and vehicle, and the vehicle imparts a lower percentage of its impact speed into the pedestrian, resulting in the previously displayed shorter throw distances for a given vehicle impact speed.

Typical less engagement impacts may leave little evidence of contact between the vehicle and the pedestrian. Less engagement contacts may leave light abrasions on the sides of the vehicle with little permanent deformation, or if there is permanent deformation, the damage is limited to minor deflection to a larger body panel on the side of the vehicle, such as a door or fender. Similar to slower speed pedestrian impacts, the evidence on the side of a vehicle can be minor abrasions or surface cleaning marks from the clothing worn by the pedestrian [28]. Due to the small size and effects of the scuffing evidence, it may be hard to see or inconclusive as to its origin. It is therefore important for the investigator to look closely at the scuffing and compare that to the geometry of the pedestrian as well as the type of clothing and accessories worn, such as a backpack. Evidence of less engagement contact can also be found by surface cleaning of road grime and dirt collected on the vehicle, or deposited fibers collected on the vehicle, which should also be considered and matched to the clothing/accessories of the pedestrian.

More engagement impacts typically occur closer to front of the vehicle and have more defined and permanent damage. Evidence of engagement can be seen in damage to the headlights, front bumper, fog lights, hood, and the front corner of the fender. The damage in these areas is more pronounced with more deformation and fractured parts, such as the lenses and trim pieces around the lights. Although the more engagement impacts typically occur near the front of the vehicle, they can also occur further towards the back near the vehicle's A-pillar. Deformation to the A-pillar is a clear indication that there was engagement with the pedestrian, as is damage to the windshield.

The investigator must also look at the evidence at left at the scene by the vehicle. Skid marks left by the vehicle pre or post impact can be used to evaluate the speed of the vehicle and compared to the pedestrian throw analysis. Also, evidence left by the pedestrian can be used for evaluation; items that are thrown from the pedestrian such as drinks in their hand can leave fluid trails placed at the scene and sometimes on the vehicle, for example. All the evidence must be considered in the investigator's analysis to determine the best method suited for the impact.

Conclusions

Results of the analyses presented in this paper demonstrate that established methods used in a pedestrian accident reconstruction can sometimes underestimate the vehicle's speed when it involves a side-swipe or minor overlap impact with a pedestrian. Although empirical methods such as Toor do well in predicting the vehicle speeds in forward projection and wrap models, it can also underpredict the speed by as much as four times that of the actual value, as shown by research presented here.

In a side-swipe or minimal overlap impact, the pedestrian and vehicle do not reach a common velocity. In fact, the pedestrian only reached a percentage of the vehicle's speed, which can be as little as 20%. Video analysis of the of pedestrian impacts showed that a multiplier of 1.5 to 3 can be used with Toor's empirical wrap method to estimate the vehicle speed. To further refine which multiplier to use, the investigator may need to determine how much engagement has occurred between the pedestrian and the striking vehicle.

If the vehicle exhibits damage consistent with more engagement(previously outlined in this paper), then a multiplier of 1.5 may be applicable. If evidence supports a minimal engagement with the pedestrian, a 3.1 multiplier may be more applicable.

Not all side-swipe or minor overlap impacts require a multiplier when using the Toor empirical method. All the physical evidence on the vehicle and at the scene should be evaluated to determine what method best fits the available data.

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