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Reconstruction of Vehicle-Pedestrian Collisions Including an Unknown Point of Impact

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Abstract

Numerous algebraic formulas and mathematical models exist for the reconstruction of vehicle speed of a vehicle-pedestrian collision using pedestrian throw distance. Unfortunately a common occurrence is that the throw distance is not known because no evidence exists to locate the point of impact. When this is the case almost all formulas and models lose their utility. The model developed by Han and Brach published by SAE in 2001 is an exception because it can reconstruct vehicle speed based on the distance between the rest positions of the vehicle and pedestrian. The Han-Brach model is comprehensive and contains crash parameters such as pedestrian launch angle, height of the center of gravity of the pedestrian at launch, pedestrian-road surface friction, vehicle-road surface friction, road grade angle, etc. Such an approach provides versatility and allows variations of these variables to be taken into account for investigation of uncertainty. Example reconstructions are presented in this paper for wrap and forward projection collisions using the relative rest positions of the vehicle and the pedestrian. Comparisons of the example wrap collision reconstruction are made with other formulas found in the literature.

The main features of the Han-Brach model are summarized and discussed. Reconstruction sensitivity is investigated by using the method of Design of Experiments (DOE) to rank the importance of the model's significant variables such as pedestrian launch angle and road friction.

Introduction

Algebraic formulas and mathematical models for relating pedestrian throw distance to vehicle speed and/or vehicle speed to pedestrian throw distance are found in numerous publications [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18]. For purposes of reconstruction these are typically in the functional form of $v_c = f(s_p)$; that is, for a known throw distance, s_p, the corresponding vehicle speed, v_c, can be calculated. Various categories or types of collision configurations are described in the literature such as wrap collision, forward projection, carry, fender vault, roof vault, somersault, etc. [2, 17, 22]. Some formulas are associated with one type of collision. Some are based on, or developed from, a statistical analysis of test data, some mathematical models are derived or based on physics/mechanics and some on both test data and mechanics (hybrid models). Some formulas have been experimentally validated; others not.

Formulas developed using statistical data can be said to be self-validated and typically are presented with upper and lower test variance-based limits. **It is critical to be aware that variances due to differences in test conditions should not be used to establish uncertainty of the reconstruction of a specific accident.** Statistical model variances result from changes in test-to-test conditions such as differences in the vehicle geometry, pedestrian characteristics and dummy types, the pavement characteristics, etc., not from variations in the conditions corresponding to the reconstruction of a specific vehicle-pedestrian-road. Another property of statistical models to note is that they are unable to explicitly model the effect of variables such as the pedestrian-ground frictional drag.

Another technique of modeling vehicle-pedestrian collisions is to use a multi-body modeling software program described in [19, 28] such as MADYMO and PC-Crash. These are often computationally intensive, require trial-and-error, iterative approaches and require the point of impact to be known for reconstruction. In addition, required crash information such as pedestrian body position at impact, pedestrian physical characteristics, vehicle geometry, vehicle compliance, etc. often are unknown. This technique is not covered here.

One of the frustrations of the reconstruction of a vehicle-pedestrian accident often arises when the rest position of the pedestrian is known and the rest position of the vehicle is known but there is no physical evidence to indicate where the impact occurred (location of the point of initial contact between the vehicle and pedestrian). Consequently, the throw distance is unknown. If the rest positions of the pedestrian and vehicle are known then the relative distance, d, between rest positions can be calculated (see Figure 1). If d is a parameter of a model, then a reconstruction can be based on that parameter; this is the case for the Han-Brach model [7]. The concept of using d to reconstruct speed is not new [20], but in order to do so the vehicle-pedestrian model must contain d as a parameter. Examples of such reconstructions are presented in this paper.

Another issue that frequently arises when reconstructing a vehicle-pedestrian collision is which of the model variables is most critical in obtaining an accurate solution. Another way of stating this is: what is the sensitivity of the solution/reconstruction to each of the input variables. This sensitivity is investigated in this paper using the method of the Design of Experiments (DOE). The use of DOE allows input variables to be ranked according to their relative sensitivity.

Note that experimental data are not used in this paper because the Han-Brach model has already been validated using experimental data [7]; the Baysian technique has also been applied [27]. The purpose of this paper is to illustrate the utility of the model.

List of Variables

Figure 1 illustrates the scenario used by the Han-Brach model. The definitions/descriptions of the parameters (variables) are as follows:

$\boldsymbol{a_2}$ - deceleration of the vehicle over the distance s_2, g's; $(0 \le \alpha)$

$\boldsymbol{d}$ - distance between the rest position of the vehicle and the pedestrian (positive if the throw distance is beyond the rest position of the vehicle; otherwise negative),

$\boldsymbol{f_p}$ - average drag resistance coefficient of the pedestrian over distance s,

$\boldsymbol{h}$ - height of the cg of the pedestrian at launch,

$\boldsymbol{R}$ - distance of travel of pedestrian from launch to initial contact with the ground (Range),

$\boldsymbol{m_c}$ - mass of vehicle,

$\boldsymbol{m_p}$ - mass of pedestrian,

$\boldsymbol{s_0}$ - distance of travel (at constant speed) of the vehicle between the time of initial contact to the time of launch of the pedestrian $(0 \le s_0)$,

$\boldsymbol{s_1}$ - distance of travel of the vehicle at constant speed following launch (no deceleration; $s_1 \le 0$),

$\boldsymbol{s_2}$ - distance of travel to rest of the vehicle at constant deceleration, a_2, (braking), $0 \le a_2$,

$\boldsymbol{s}$ - distance of travel of the pedestrian between point of initial contact with the ground and rest,

$\boldsymbol{s_p}$ - throw distance of the pedestrian,

$\boldsymbol{v_{c0}}$ - speed of the vehicle at initial contact with the pedestrian,

$\boldsymbol{v_{p0}}$ - speed of the pedestrian's cg at launch,

$\boldsymbol{v_{pRx}}$ - the speed in the x direction of the pedestrian at the end of the trajectory,

$\boldsymbol{v_{pRy}}$ - the speed in the y direction of the pedestrian at the end of the trajectory,

$\boldsymbol{v'_{pRx}}$ - the speed in the x direction of the pedestrian immediately following impact with the ground,

$\boldsymbol{x}$ - coordinate along the road in the direction of the heading of the vehicle,

$\boldsymbol{y}$ - coordinate perpendicular to x,

$\boldsymbol{x_L}$ - x distance traveled by the pedestrian's cg between first contact and launch - secondary contact $(0 \le x_L)$,

$\boldsymbol{\phi}$ - grade angle of road, degrees

$\boldsymbol{\tau}$ - time, the time of initial contact is $\tau = 0$

$\boldsymbol{\theta}$ - angle of launch of the pedestrian from the vehicle,

$\boldsymbol{\mu}$ - impulse ratio at ground impact of pedestrian (typically equal to f_p)

Equations of Han-Brach Model

A summary of the equations of the Han-Brach model is presented here. A full exposition is given in [7, 21]. The throw distance is:

$$s_p = x_L + R + s \tag{1}$$

The vehicle's speed after impact with the pedestrian is:

$$v'_{c0} = \frac{m_c}{m_c + m_p} v_{c0} \tag{2}$$

the launch speed of the pedestrian is given by v_{p0},

$$v_{p0} = \alpha v'_{c0} \tag{3}$$

where α is a rebound factor, usually unity [6, 7

]. The range, R, (distance of travel from launch to ground impact in the x direction) of the pedestrian travel is:

$$R = v_{p0} \cos\theta\, \tau_R - g \sin\theta\, \tau_R^2 / 2 \tag{4}$$

where the time of flight, τ_R, is

$$\tau_R = \frac{v_{p0} \sin\theta}{g \cos\varphi} + \frac{\sqrt{v_{p0}^2 \sin^2\theta + 2gh\cos\varphi}}{g\cos\varphi} \tag{5}$$

The pedestrian's speed in the x direction at the time of initial contact with the ground is v_{pRx}. The speed of the pedestrian in the x direction following impact with the ground (this effect is ignored by most formulas and models) is

$$v'_{pRx} = v_{pRx} + \mu v_{pRy} \tag{6}$$

Note that the downward component of the pedestrian's speed, v_{pRy}, is negative; thus $v'_{pRx} < v_{pRx}$, effectively taking into account a speed reduction of the pedestrian due to the impact. The distance of travel of the pedestrian along the ground from impact to rest is s, where:

$$s = \frac{(v'_{pRx})^2}{2g(f_p \cos\varphi + \sin\varphi)} \tag{7}$$

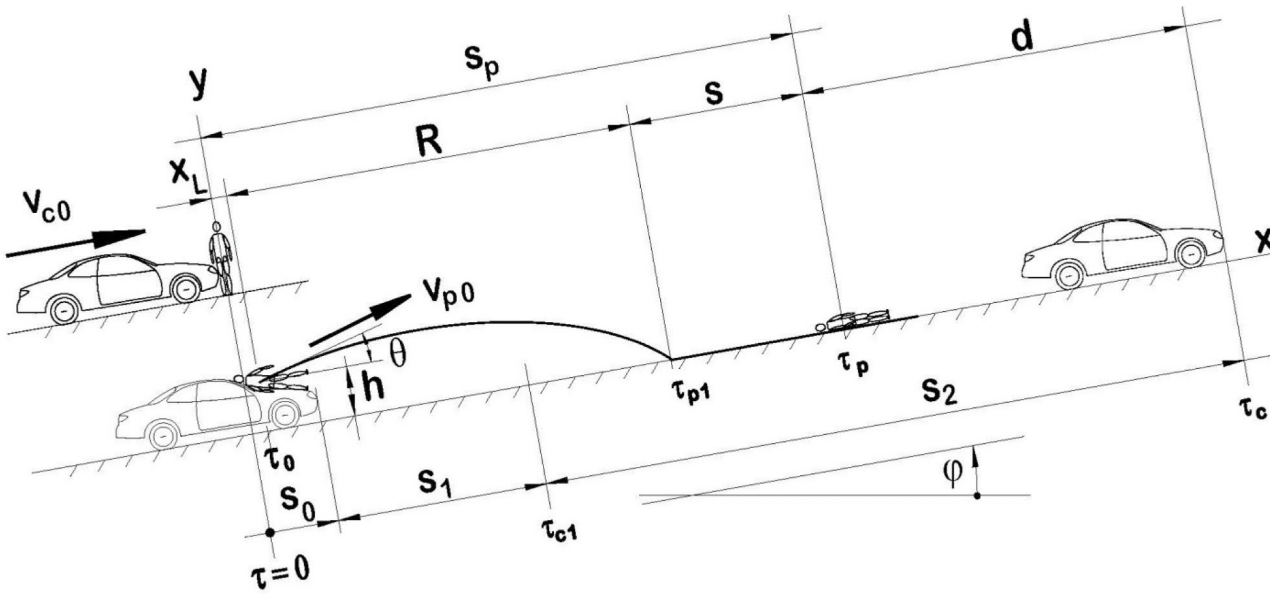

Figure 1. Coordinates, variables and events corresponding to a vehicle-pedestrian collision

The distance of travel of the vehicle, s_v, is:

$$s_v = s_0 + s_1 + \frac{(v'_{c0})^2}{2a_2 g}$$

(8)

Finally, the relative distance between rest positions of the pedestrian and vehicle is:

$$d = s_v - s_p$$

(9)

Note that the model equation form is $s_p = f(v_{c0})$, that is, throw distance can be computed given the initial speed of the vehicle. The goal of a reconstruction is to compute v_{c0} from given model parameters such as throw distance. A set of such equations similar to above of the form, $v_{c0} = f(s_p)$ is available [8]. However, it is convenient to place the above equations into a spreadsheet and use the Solver (or Goal Seek) optimization features of the spreadsheet to reach an inverse solution, that is, a reconstruction.

Some comments are made here relative to the validity of the model equations given above. With a proper choice of parameter values, the Han-Brach model is capable of simulation of all types of vehicle pedestrian collisions (wrap, forward projection, fender vault, roof vault, somersault, etc.) [2, 17, 22]. However, the Han-Brach model has been *validated* [7, 28] for only wrap and forward projection collisions. This limitation is due primarily to the lack of experimental data for collision types other than wrap and forward projections.

	A	B	C	D
1	Example 1.xls			**Analysis of Pedestrian Throw Distance from Initial Conditions**
2	9/18/2014			
3	NOTATION, COORDINATES, UNITS & VARIABLES:			
4	x	-		coordinate parallel to ground
5	y	-		coordinate perpendicular to ground
6				
7	**INPUT INFORMATION (KNOWNS):**			
8	a_2	0.90		deceleration of vehicle over distance s_2, g's
9	f_p	0.70		drag resistance coefficient of pedestrian over distance s
10	g	32.17	ft/s²	acceleration of gravity
11	h	2.25	ft	height of pedestrian center of gravity at launch, t_0
12	s_1	0.00	ft	distance of travel of vehicle at uniform speed
13	v_{c0}	50.00	ft/s	initial speed of vehicle
14		34.1	mph	initial speed of vehicle
15	x_L	2.50	ft	x-distance of pedestrian from initial contact to launch
16	α	1.00		ratio of pedestrian speed to vehicle speed at time of launch
17	θ	10.00	deg	angle of launch of pedestrian relative to x axis
18	φ	0.00	deg	road grade angle
19	μ	0.70		impulse ratio for pedestrian-ground impact
20	m_c	100.00	lb-s²/ft	mass of vehicle, weight / g
21	m_p	6.00	lb-s²/ft	mass of pedestrian, weight / g
22				
23	**OUTPUT INFORMATION (UNKNOWNS):**			
24	v'_{c0}	**47.17**	ft/s	velocity of vehicle after impact with pedestrian
25	v_{p0}	**47.17**	ft/s	initial speed of pedestrian
26	R	**32.84**	ft	range of pedestrian throw, launch to ground impact
27	t_{p1}	**0.81**	s	time from impact to pedestrian initial contact with ground
28	s	**29.20**	ft	pedestrian ground contact distance, impact to rest
29	s_p	**64.54**	ft	throw distance; total distance from initial contact to pedestrian rest
30	t_p	**2.42**	s	total time of travel of pedestrian, initial contact to rest
31	t_{c1}	**0.11**	s	time of travel of vehicle to travel from initial contact to $s_0 + s_1$
32	s_0	**5.30**	ft	distance of travel of vehicle with pedestrian contact
33	s_2	**38.42**	ft	distance of travel of vehicle with uniform deceleration, a_2
34	$s_0+s_1+s_2$	**43.72**	ft	total distance of travel of vehicle
35	t_c	**1.74**	s	vehicle travel time, initial contact to rest
36	d	**-20.82**	ft	distance between rest positions of vehicle and pedestrian

Figure 2. Spreadsheet solution of the wrap example for an arbitrary initial vehicle speed.

Example Reconstruction Using Relative Rest Positions (Wrap Collision)

For this hypothetical example, suppose a pedestrian is struck by a low front-profile vehicle and with windshield damage caused by an impact by the pedestrian's head; these characterize a wrap collision. Based on the best estimation of the collision conditions, $a_2 = 0.9$, $f_p = \mu = 0.7$, $h = 2.25$ ft = 0.69 m, $s_1 = 0$, $x_L = 2.5$ ft = 0.76 m, $\alpha = 1$, φ = 0, $m_c = 100$ lb-s^2/ft = 1459 kg, $m_p = 6$ lb-s^2/ft = 88 kg. For this example, scene measurements indicate that the rest position of the center of gravity of the pedestrian was 15 ft (4.6 m) farther from the point of impact than the rest position of the front of the vehicle, that is, $d = -15$ ft (-4.6 m); see Fig. 1. No evidence exists to establish the launch angle, θ and so a nominal value of $\theta = 10°$ is chosen here. (Normally, a suitable range of θ would be used for an actual reconstruction, but this is not done for this example.) Also, the sensitivity of a reconstruction to values of θ and other variables is presented later.) Figure 2 shows a spreadsheet using the above data and arbitrarily setting the speed of the vehicle as $v_{c0} = 50$ ft/s = 15.2 m/s = 34.1 mph. These conditions give a distance $d = -20.82$ ft = -6.35 m.

	A	B	C	D
1	Example 2.xls			Analysis of Pedestrian Throw Distance from Initial Conditions
2	9/18/2014			
3	NOTATION, COORDINATES, UNITS & VARIABLES:			
4	x	-		coordinate parallel to ground
5	y	-		coordinate perpendicular to ground
6				
7	**INPUT INFORMATION (KNOWNS):**			
8	a_2	0.90		deceleration of vehicle over distance s_2, g's
9	f_p	0.70		drag resistance coefficient of pedestrian over distance s
10	g	32.17	ft/s²	acceleration of gravity
11	h	2.25	ft	height of pedestrian center of gravity at launch, t_0
12	s_1	0.00	ft	distance of travel of vehicle at uniform speed
13	v_{c0}	42.90	ft/s	initial speed of vehicle
14		29.2	mph	initial speed of vehicle
15	x_L	2.50	ft	x-distance of pedestrian from initial contact to launch
16	α	1.00		ratio of pedestrian speed to vehicle speed at time of launch
17	θ	10.00	deg	angle of launch of pedestrian relative to x axis
18	φ	0.00	deg	road grade angle
19	μ	0.70		impulse ratio for pedestrian-ground impact
20	m_c	100.00	lb-s²/ft	mass of vehicle, weight / g
21	m_p	6.00	lb-s²/ft	mass of pedestrian, weight / g
22				
23	**OUTPUT INFORMATION (UNKNOWNS):**			
24	v'_{c0}	**40.47**	ft/s	velocity of vehicle after impact with pedestrian
25	v_{p0}	**40.47**	ft/s	initial speed of pedestrian
26	R	**25.96**	ft	range of pedestrian throw, launch to ground impact
27	t_{p1}	**0.78**	s	time from impact to pedestrian initial contact with ground
28	s	**20.11**	ft	pedestrian ground contact distance, impact to rest
29	s_p	**48.58**	ft	throw distance; total distance from initial contact to pedestrian rest
30	t_p	**2.11**	s	total time of travel of pedestrian, initial contact to rest
31	t_{c1}	**0.13**	s	time of travel of vehicle to travel from initial contact to $s_0 + s_1$
32	s_0	**5.30**	ft	distance of travel of vehicle with pedestrian contact
33	s_2	**28.28**	ft	distance of travel of vehicle with uniform deceleration, a_2
34	$s_0+s_1+s_2$	**33.58**	ft	total distance of travel of vehicle
35	t_c	**1.53**	s	vehicle travel time, initial contact to rest
36	d	**-15.00**	ft	distance between rest positions of vehicle and pedestrian

Figure 3. Spreadsheet reconstruction of the wrap example for a relative distance of $d = -15$ ft

Scene measurements indicated that $d = -15$ ft = -4.6 m and the vehicle speed could be changed in the spreadsheet by trial and error until this value is reached. However, Excel allows the use of a *Goal Seek* feature. Use of *Goal Seek* results directly in the values shown in Fig 3, which indicates that for $d = -15$ ft = -4.6 m, the vehicle speed was 42.9 ft/s = 29.2 mph = 47.1 kph. Along with other information, the reconstruction also indicates that the throw distance $s_p = 48.58$ ft = 14.8 m.

This ends the wrap reconstruction example, however the value of the throw distance is used below to make comparisons with other throw distance formulas and pedestrian impact models.

Comparison with other formulas and models: Although other vehicle-pedestrian throw models are unable to carry out reconstructions based on the relative rest position distance, d, it is informative to compare with other pedestrian throw models the results of the above using the Han-Brach throw distance.

Evans & Smith [20] use curve fitting techniques to establish the formula

$$v_{c0} = \sqrt{3.58^2 s_p} = 13.7 m/s \tag{10}$$

which gives the values listed in Table 1.

Happer, et al. [18] likewise establish a formula using curve fitting techniques which can be written as:

$$v_{c0} = -0.72 + \sqrt{3.53^2 s_p} = 12.9 m/s \tag{11}$$

which gives the values listed in Table 1.

Wood's hybrid model [5] provides a vehicle speed range based on a combination of mechanics and experimental data (in SI units):

$$v_{c0} = c_w \sqrt{s_p} \tag{12}$$

$c_w = 2.5$: $v_{c0} = 31.4$ ft/s = 21.4 mph = 34.4 kph

$c_w = 3.6$: $v_{c0} = 45.2$ ft/s = 30.8 mph = 49.6 kph

$c_w = 4.5$: $v_{c0} = 56.4$ ft/s = 38.5 mph = 61.9 kph

The Searle model [9] is a mechanics model derived using concepts of force, mass and acceleration. The model uses an average frictional drag coefficient, μ_S, for the overall pedestrian travel from impact to rest. This coefficient is intended to include the effect of the speed reduction due to the pedestrian's initial impact with the ground and gives reasonably accurate results with the use of values of $\mu_S = f_p$, the physical frictional drag coefficient of the pedestrian travel over the ground distance, s. The use of the average drag coefficient has lead to confusion in the literature [23]. Using the notation of this paper, the Searle formula is:

$$v_{c0} = \frac{\sqrt{2\mu_S g(s_p - h)}}{\cos\theta + \mu_S \sin\theta} \tag{13}$$

Measurement of the frictional drag using the entire throw distance, S, gives a value of $\mu_S = 0.51$.

Measurement of the frictional drag coefficient over the actual ground contact distance gives a value of $\mu_S = f_p = 0.70$; Table 1 shows the results of the Searle formula using these two values.

The various methods listed in Table 1 encompass mechanics models, data-based models and hybrid models and yield similar results. Comparisons of results from different models or formulas can be useful to establish reliability of a reconstruction. It would be prudent for an analyst to compare the results of a reconstruction with those of different models as a check.

Table 1. Vehicle Speed, V_{co}, from Throw Distance s_p = 48.58 ft = 14.81 m

	ft/s	mph	kph
Han-Brach	42.9	29.2	47.1
Evans & Smith [20]	44.9	30.6	49.3
Happer, et al. [18]	42.2	28.3	46.3
Wood Hybrid Model [5]	45.4	31.0	49.9
Searle Formula [9]; μ_s=0.51	39.6	27.0	43.5
Searle Formula [9]; μ_s=0.70	41.7	28.4	45.7

Table 2. DOE 4 Full Factorial Layout for s_p

run	x_1 (a_2)	x_2 (f_p)	x_3 (x_L)	x_4 (θ)	s_p, ft
1	-1	-1	-1	-1	24.65
2	1	-1	-1	-1	24.65
3	-1	1	-1	-1	22.08
4	1	1	-1	-1	22.08
5	-1	-1	1	-1	25.65
6	1	-1	1	-1	25.65
7	-1	1	1	-1	23.08
8	1	1	1	-1	23.08
9	-1	-1	-1	1	27.78
10	1	-1	-1	1	27.78
11	-1	1	-1	1	25.45
12	1	1	-1	1	25.45
13	-1	-1	1	1	28.78
14	1	-1	1	1	28.78
15	-1	1	1	1	26.45
16	1	1	1	1	26.45
ME:	0.00	-2.46	1.00	3.25	

Table 3. DOE 4 Full Factorial Layout for d

run	x_1 (a_2)	x_2 (f_p)	x_3 (x_L)	x_4 (θ)	d, ft
1	-1	-1	-1	-1	-6.75
2	1	-1	-1	-1	-8.42
3	-1	1	-1	-1	-4.17
4	1	1	-1	-1	-5.84
5	-1	-1	1	-1	-5.90
6	1	-1	1	-1	-7.60
7	-1	1	1	-1	-3.32
8	1	1	1	-1	-5.03
9	-1	-1	-1	1	-9.88
10	1	-1	-1	1	-11.55
11	-1	1	-1	1	-7.54
12	1	1	-1	1	-9.21
13	-1	-1	1	1	-9.03
14	1	-1	1	1	-10.73
15	-1	1	1	1	-6.69
16	1	1	1	1	-8.40
ME:	-1.69	2.46	0.83	-3.25	

Example Reconstruction using Relative Rest Positions (Forward Projection Collision)

The conditions in the above wrap collision example are now used to examine the results of a reconstruction of a forward projection collision. That is, the following analysis presents the results of a reconstruction of a pedestrian hit by a vehicle with a high, vertical front surface such as a large pickup truck, bus or heavy truck. The relative rest positions still correspond to $d = -15$ ft = −4.6 m. With two exceptions, all collision variables remain identical. For a forward projection collision the exceptions are that the variables x_L and θ must both be zero [21]; see Fig. 1.

Using the spreadsheet approach, the results for this example are that the preimpact vehicle speed is $vc0$ = 37.7 mph = 60.7 kph and the throw distance is sp = 62.0 ft = 18.9 m. These are considerably different from the wrap collision and illustrates that the choice of input variable values must correspond to the type of collision.

Singularity of Solutions: A special case can occur when a solution based on d cannot be found using spreadsheet optimization techniques. This can occur when $d \sim 0$. In such cases, it is best to use a trial-and-error approach and observe the behavior of the solution as parameters are changed.

Sensitivity of Reconstruction Variables: Throw Distance

The following sensitivity analysis of four input variables is based upon a wrap collision with a vehicle speed of 20 mph (32.2 kph). Table 2 shows a full, 4-variable Design-of-Experiment layout [24, 25] where the variables are $x_1 = a_2$, $x_2 = f_p$, $x_3 = x_L$ and $x_4 = \theta$ and the response is the throw distance, s_p. In a DOE analysis, each of the variables is given two values, one low and one high. The −1 and +1 values in the table in the column under each variable schematically represent the positions of the low and high values in the layout, respectively, for the 16 possible variable combinations (runs). The respective low and high values chosen here are a_2 = (0.8, 0.9), f_p = (0.6, 0.7), x_L = (1.5, 2.5, ft) and θ = (5°, 15°). These values are arbitrarily chosen to be nominal, representative changes for a typical reconstruction that will yield observable changes in the response variable, the throw distance.

The response (here s_p) is calculated using the Han-Brach model for each of the 16 combinations of high and low values. The DOE algorithm (not shown) determines a measure of the relative effect of the changes in response indicated by ME (Main Effect) of response values as shown in the bottom row of Table 1. These are ME($\pm a_2$) = 0.0, ME($\pm f_p$) = −2.46, ME($\pm x_L$) = 1.00 and ME($\pm\theta$) = 3.25. A positive ME indicates that an increase of a variable increases the response and a negative ME indicates that an increase in a variable decreases the response.

The largest ME is for θ and shows that the change from 5° to 15° has the greatest (positive) affect on the throw distance of all of the variable changes. The next significant ME magnitude is −2.46 for the pedestrian sliding coefficient. It is negative because an increase in the sliding coefficient decreases the throw distance. The next largest is ME($\pm x_L$) = 1.00. Finally, the ME for the vehicle tire sliding coefficient, a_2, is zero. This makes sense because this variable has no affect on the throw distance. These results indicate, for example, that the angle of launch, θ, has an effect on the throw distance |3.25/−2.46| = 1.3 times greater than the effect of changes in the pedestrian's frictional drag coefficient.

It should be mentioned that in addition to the effect of changes in the variable values on the response, DOE also determines the effect of any interactions of variable changes. That is, for example, a combined change of x_L and θ could have a synergistic effect on the response. It turns out that only two variables, f_p and θ, caused an interaction effect, but it was negligible with ME($\pm f_p$, $\pm\theta$) = −0.12. Effects of all other variable interactions were identically 0.

Sensitivity of Reconstruction Variables: Relative Distance to Rest

The sensitivity of variable changes on *throw distance* was just examined. Here, the sensitivity of a reconstruction based on the *relative rest positions* for a wrap collision is now examined with respect to the same 4 variables as just done and for the same vehicle speed, v_{c0} = 20 mph (32.2 kph). That is, the DOE response now is d, the relative rest position distance and the sensitivity of, or effect of changes in, $x_1 = a_2$, $x_2 = f_p$, $x_3 = x_L$ and $x_4 = \theta$ is examined. The results of the full 4-variable DOE analysis are presented in Table 3. The main effects are ME(±a_2) = −1.69, ME(±f_p) = 2.46, ME(±x_L) = 0.83 and ME(±θ) = −3.25.

The variable with the greatest sensitivity is, again, the launch angle θ, but now with a negative sign (an increase in θ decreases the relative rest position). The effect of the pedestrian drag coefficient is, again, 2.46 but with a positive sign; an increase in f_p increases the separation. As can be expected, when reconstructing a vehicle-pedestrian collision based on d, the vehicle deceleration coefficient, a_2, now plays a role with a main effect of −1.69. The more quickly the vehicle slows, the smaller the relative rest position distance.

Another way of illustrating the main effects of a DOE [24] is to display the results using a normal probability plot. This is shown in Figure 4 where the Main Effects and interactions are graphically shown by their horizontal distance from zero. All unmarked points are second-order or higher interactions.

Conclusions

Using a hypothetical wrap collision, it was shown that the preimpact vehicle speed of a vehicle-pedestrian collision can be reconstructed using accident data including the relative rest positions of the vehicle and pedestrian - without knowing the point of impact. Not only can this be done using the Han-Brach model but when the equations are cast in a spreadsheet, a speed reconstruction can be carried out with a single keystroke (using the optimization capabilities of the spreadsheet). For the example chosen, it was also shown that use of the Han-Brach model gives results that are close to those obtained by other models, including those based directly on experimental measurements. By example (forward projection versus wrap), it is shown that the results of reconstructions of different types of vehicle-pedestrian collisions can vary significantly, implying that proper use of modeling equations is necessary for an accurate reconstruction. To reach accurate results the assumptions of the model should also be observed such as uniform deceleration of the vehicle. The vehicle-pedestrian impact model should be appropriate for the type of collision and not be used for excluded collision types such as a carry collision.

In addition, a nominal range for the launch angle of 5° to 15° (10° ± 5°) was used in this paper for wrap collisions, however, larger angles have been reported. Using MADYMO simulations, Hamacher, et al. [28] observed launch angles for adults as high as 30°. Fitting this paper's model equations to experimental data [7] found some angles as high as 35°, but the majority was in the range of 4.2° to 13.1°.

The levels of reconstruction sensitivity of four input variables of a vehicle-pedestrian wrap collision were calculated using Design of Experiments (DOE). Whether determining the throw distance or the relative rest position distance, the angle of launch of the pedestrian had the greatest effect. The pedestrian frictional drag coefficient and the vehicle frictional drag coefficient also had significant effects when basing a reconstruction on the relative rest positions. Because little or no evidence typically exists to determine the pedestrian launch angle (of collisions other than the forward projection type) it was necessary to choose a representative value for the reconstruction. In practice, it is possible to bracket the launch angle for an actual reconstruction. This will be a necessary process until more data is obtained from tests and/or actual collision records [26].

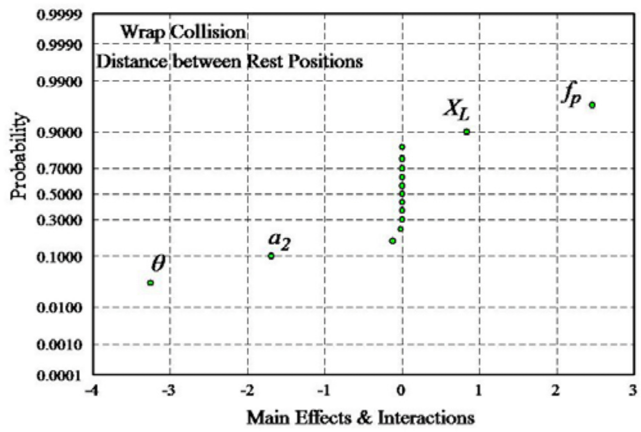

Figure 4. Graphical illustration of significant variables.

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