Collision speed: detailed analysis of structural and mechanical deformation energy in a car and a motorcycle

Velocidade de colisão: análise detalhada da energia de deformação estrutural e mecânica em um carro e uma motocicleta

ABSTRACT
In this work, a detailed assessment of the structural and mechanical deformation energies caused by a traffic accident, involving a motorcycle and the passenger vehicle is carried out, with the objective of estimating the collision speed. Were, also verified vector orientations, braking marks and occupant launch projection for further comparative analysis with the photogrammetric method of estimating displacement speed. Finally, with the velocity values thus obtained, we compare with the result photogrammetric was performed. Thus, for the type of accident on the screen, we concluded that the best method of estimating the collision speed involving a car and a motorcycle was the combination between the method of reduction between axles and the method of mechanical deformations, resulting in the best approximation in relation to the photogrammetric result reaching 93% approximation to the photogrammetric result obtained.

Keywords: displacement speed, collision, deformation energy, photogrammetry, motorcycle crash, traffic accident.

RESUMO
Neste trabalho é realizada uma avaliação detalhada das energias de deformação estrutural e mecânica causadas por um acidente de trânsito, envolvendo motocicleta e veículo de passeio, com o objetivo de estimar a velocidade de colisão. Foram, também, verificadas orientações vetoriais, marcas de frenagem e projeção de lançamento de ocupantes para posterior análise comparativa com o método fotogramétrico de estimativa de velocidade de deslocamento. Por fim, com os valores de velocidade assim obtidos, comparamos com o resultado fotogramétrico realizado. Assim, para o tipo de acidente em tela, concluímos...
que o melhor método para estimar a velocidade de colisão envolvendo um carro e uma motocicleta foi a combinação entre o método de redução entre eixos e o método de deformações mecânicas, resultando na melhor aproximação em relação ao resultado fotogramétrico chegando a 93% de aproximação do resultado fotogramétrico obtido.

**Palavras-chave:** velocidade de deslocamento, colisão, energia de deformação, fotogrametria, colisão de motocicleta, acidente de trânsito.

### 1 INTRODUCTION

The energies of mechanical and structural deformations analyze have long been used in the reconstruction of accidental events of accidents and traffic accidents [3]. The completeness of the analysis of collisions involving motorcycles is more difficult when compared to those of accidents involving only automobiles. This fact is due, in part, to the reduced number of studies dealing with collisions between motorcycles and passenger vehicles [4]. Usually, in traffic accidents, the most questioned variable is the displacement speed [2]. With reasonable certainty is possible to estimate the displacement speed involving motorcycles [1]. Is the case when are considered the reduction of the axles of motorcycles [10]. In this work, are used the following pillars to achieve speed determination: Reduction of Distance in Between Motorcycle Axes; Braking Marks; Projection of Occupants and the collision estimation methodology based on Deformations in Vehicles [2; 3].

The case presented here was worthy of mention, as different expert techniques were used to analyze the event on screen. The scarcity of information about the elements presents at the accident site and the deficient photographic records of the motorcycle made it difficult and, at the same time, made this case interesting. Therefore, photogrammetry techniques were used [8], to corroborate the clarification of the accident analyzed here with greater robustness and accuracy.

Comparisons were made with the analyzes recorded by Kelley et all (2002), reference [10], testing our estimates. The speeds of the motorcycles in that work were monitored by mobile gun-type radar and we got by our method 95% of approximation.

### 2 MATERIALS AND METHODS

This is a traffic accident involving a motorcycle and passenger vehicle presented below. The collision occurred in the city of Cachoeira do Sul-RS: the motorcycle was
traveling through urban roads, where the speed limit is 40 km/h. In this meantime, the stopped passenger vehicle, suddenly, when performing a maneuver, positioned itself in the trajectory of the motorcycle, resulting in the collision.

Table 1. Characteristics of the vehicles involved. Source: Volkswagen Gol owner's manual and Suzuki V-Strom 650 owner's manual.

<table>
<thead>
<tr>
<th>Passenger vehicle Volkswagen Gol</th>
<th>Motorcycle Suzuki V-Strom 650</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width: 1,656 mm;</td>
<td>Width: 835 mm;</td>
</tr>
<tr>
<td>Length: 3,899 mm;</td>
<td>Length: 2,290 mm</td>
</tr>
<tr>
<td>Height: 1,451 mm;</td>
<td>Seat height: 835 mm;</td>
</tr>
<tr>
<td>Mass: 934 kg;</td>
<td>Massa: 215 kg;</td>
</tr>
<tr>
<td>Wheelbase: 2,465 mm.</td>
<td>Wheelbase: 1,560 mm.</td>
</tr>
</tbody>
</table>


The place where the accident happened is an asphalt pavement in good condition, with a slight slope, in an urban region, with a speed limit of 40 km/h. The accident occurred during the day, when the running surface was dry.

The images of the motorcycle's displacement in the moments before the collision, recorded by a surveillance camera in a property present at the accident site, promoted the accident on screen to the category of "case of studied".
2.1 DETERMINATION OF MOTORCYCLE DISPLACEMENT SPEED BY PHOTOGRAMMETRY TECHNIQUE.

Using photogrammetric techniques [8] it was possible to identify the speed at which the Suzuki motorcycle was traveling in the moments immediately before the collision with the Gol vehicle. Of interest, 65 meters of displacement recorded, computed by a surveillance camera present at the site of the event, which made it possible to estimate the speed of the motorcycle.

The video, recorded by a surveillance camera present in a property located at the accident site, had the following properties and characteristics.

- Format: AVI;
- Frame playback rate: 30 per second;
- Start of filming: instant 14:28:54, missing 01 frame for 14:28:55;
- Frame in which the motorcycle driver initiates a maneuver to avoid the collision: instant 14:28:57 with 15 frames reproduced;
- Number of frames = 76 ± 4
- Time elapsed from the beginning of filming to the maneuver to avoid collision = 2.5 seconds;
- Distance between the start of filming and the location of the motorcycle maneuver to avoid collision = 65 ± 1 (meter).
Therefore, considering the distance traveled to the elapsed time [3], it is concluded that the speed of displacement of the motorcycle was 93.6 km/h.

After the distance of 65 meters, used to estimate the speed of displacement of the motorcycle, tire marks left by the motorcycle observed.

2.2 VEHICLE DAMAGE LEVEL CHECKS

Verification and analysis of damage to vehicles occurred directly, in the case of the car and indirectly, by images, in the case of the motorcycle.
Mentioned already, the damages present on the motorcycle was analyzed indirectly, from the photographic record provided by the driver of the Gol vehicle involved in the accident and can be seen in figures 05, 06 and 07. We arrived at the accident site to carry out an examination of the location and vehicles, the motorcycle had already been removed, the Imagej software was used to examine the damage present on the Suzuki motorcycle involved in the collision. Imagej is an open access forensic tool, intended for image processing that allows, among others, verification of deformation measurements and image repositioning adjustments.
2.3 METHODS OF ESTIMATING COLLISION SPEED INVOLVING MOTORCYCLES

2.3.1 Motorcycle braking marks method

The estimate of speed reduction by braking marks [2], can be obtained from the following equation (Equation 1).

\[ v = \left( \frac{2g \mu d}{g} \right)^{1/2} \]

Where:

- \( v \) is the speed per brake marks in m/s;
- \( g \) is acceleration due to gravity in m/s²;
- \( \mu \) is the coefficient of friction;
- \( d \) is the braking distance in m.

2.3.2 Methods that consider only the reduction between the motorcycle axles

The wheelbase reduction method [4; 3; 1] used to estimate the collision speed of motorcycles against rigid barriers or motor vehicles. Two equations were used that relate the reduction of the distance between the motorcycle’s axles with the impact speed:
a. Wilson Toresan Junior [4], uses an equation that only considers the reduction between the motorcycle axles after the collision to estimate the speed in the moment of impact (Equation 2).

\[ v = A \times \frac{5}{3} + 5 \]  

(2)

Where:

\( v \) is the collision speed in km/h of the motorcycle;
\( A \) is the value, in centimeters, of the reduction in the wheelbase of the motorcycle.

The equation presented above does not consider the energy dissipated in the deformation of the vehicle, a situation that reduces the accuracy of this method. Also, bibliographic sources mention that the collided vehicle must be immobilized or at reduced speed and the collision angle of the motorcycle must be 900 in relation to the vehicle [2]. This method is restricted to deformations with magnitudes between 12 and 33 cm.

b. According to Ranvier [2], the equation obtained from practical tests carried out by Severy (1970), the following relation is valid (Equation 3).

\[ V_{mc} = (2.18 \times \Delta L_{wb}) + 10.3 \]  

(3)

Where:

\( V_{mc} \) is the motorcycle impact speed in miles per hour
\( \Delta L_{wb} \) is the decrease in wheelbase in inches.

2.3.3 Method that considers the reduction between axes of the motorcycle and the deformation of the vehicle

In an article published by Oren, Wade and Bill Wright [1], the authors concluded that the estimate of motorcycle collision speed based on the deformations of the motorcycle axle and the collided vehicle, called “total crush”, was the one that presented the best results result. However, according to those authors, even considering the deformations in the motorcycle and in the collided vehicle, the “total crush” method is only a good approximation.
The equation above (Equation 4) is used for collisions in regions considered less rigid, more deformable in the vehicle, such as doors and sides without support beams.

In expressions (4) and (5):

\[ V = 1.43(L + C) + 10.4 \] (4)

\[ V = 1.59(L + C) + 14.72 \] (5)

2.3.4 Methods of projecting motorcycle occupants

It is not uncommon for motorcycle occupants to be projected by inertia at the moment of collision landing on the ground, sliding or not on the pavement [2]. This approach refers to the projection of the passenger and is not about running over. The speed at which the occupant of the motorcycle travels is the same as the speed of the motorcycle, so the speed at which the rider is projected by inertia will be the impact speed of the motorcycle. In the case under analysis, the motorcycle rider did not slide after landing on the ground, therefore, the jump speed is the method to be used to estimate the speed of the motorcycle at the moment of the collision of the accidental event in question.

Daily, Shigemura and Daily [3], present an equation that relates the projection of vehicles/objects with the displacement speed, known as “jump speed” (Equation 6).

\[ v = 2.21 \frac{d}{(\cos \theta \cdot (h + d \cdot \tan \theta)^{1/2})} \] (6)

Where:

- \( v \) is the frame/hop speed (km/h);
- \( d \) is the occupant landing distance (m);
- \( h \) is the height of the object's center of gravity (m);
- \( \theta \) is the projection/jump angle (degrees).
In turn, Ranvier [2], presents the following equation for estimating motorcycle collision speed through occupant projection velocity (Equation 7).

\[ v = \frac{11.25 \times d}{d \pm h}^{1/2} \quad (7) \]

Where:

\( v \) is the occupant projection velocity in km/h;
\( d \) is the occupant projection distance in meters;
\( h \) is the height of the rider's center of gravity in meters.

Ranvier [2], presents the equation called “Searle’s general formula”; which uses the projection and the displacement of the conductors on the ground, after the collision, to estimate the collision speed of the motorcycle (Equation 8).

\[ v = \frac{\left( \frac{2 \times g \times \mu \times d}{\cos \theta} \right)^{1/2}}{\cos \theta} + (\mu \sin \theta) \quad (8) \]

Where:

\( \theta \) is the launch/projection angle in degrees;
\( d \) is the occupant displacement distance when landing, in meters;
\( \mu \) is the nominal coefficient of friction assumed 0.8.

2.4 METHOD OF ESTIMATING SPEED BY DEFORMATION IN THE VEHICLE

Methodology that was developed by Campbell, which is extensively discussed and detailed by Ranvier [2] and by Daily, Shigemura and Daily [3]. Let’s not forget that Campbell’s methodology has an uncertainty of 100%! In general, this Campbell method is not used in collisions involving motorcycles. However, we have images of the motorcycle's displacement immediately before the collision, a fact that allowed us to estimate, with great precision, the speed at which the motorcycle was moving. On the other hand, as other methods for estimating collision speeds, presented above, were used, it is believed to be possible and of great importance to estimate the collision speed of the motorcycle through the deformation method proposed by Campbell.

Basically, Campbell relates the energy needed to produce the resulting damage to the vehicle's structure: through the collision speed, the structure's stiffness
characteristics, and the area of the damaged region. For the case in question, we will use the deformation method with six measurements (Equations 9 to 13).

\[ E_{\text{deform}} = \frac{L}{5} \left[ 5G + \frac{A}{2}(X_1) + \frac{B}{6}(X_2 + X_3) \right] (1 + \tan^2(\theta)) \] (9)

\[ V_{\text{deform}} = \sqrt{\frac{2E_{\text{deform}}}{\mu}} \] (10)

Where:

- \( L \) is the width of the deformation in the vehicle;
- \( A \) is the stiffness coefficient without producing permanent deformation, in lb/in (tabulated experimental value);
- \( B \) is the stiffness per unit width in lb/in\(^2\) (tabulated experimental value);
- \( G \) is energy dissipated without producing permanent damage = \( A^2/2B \), in lb (or Newton);
- \( C_1 \) to \( C_6 \) are the strain depths in inches

\[ X_1 = C_1 + 2C_2 + 2C_3 + 2C_4 + 2C_5 + C_6; \] (11)

\[ X_2 = C_1^2 + 2C_2^2 + 2C_3^2 + 2C_4^2 + 2C_5^2 + C_6^2; \] (12)

\[ X_3 = C_1C_2 + C_2C_3 + C_3C_4 + C_4C_5 + C_5C_6. \] (13)

2.5 REFUND COEFFICIENT

During collisions, a complement of 15% to 25% of the energy is dissipated by mechanical deformation, in the form of sound and heat [3; 2]. Dissipation of energy that should not be ignored by those who seek to rebuild traffic accidents and who strive for the excellence of their work. In this analysis we will consider, for reasons of technical caution, the energy dissipated during the collision event at 18%.

3 RESULTS AND DISCUSSIONS

3.1 MOTORCYCLE COLLISION SPEED ESTIMATES

Before starting the studies and presenting the calculations about the velocity estimates by the methods proposed in this work, it is important to emphasize the duty to consider - under penalty of obtaining unreliable results -, all the energy dissipated in the accidental event, whether before, or after the impact. In the case in question, there were dissipations of kinetic energy through reduction of speed by braking, by the deformations observed in the vehicles involved (distance between axles in the motorcycle and
deformations in the bodywork of the Gol vehicle), and in the form of sound and/or heat (restitution coefficient).

3.1.1 Speed by braking marks

The motorcycle on canvas has an anti-lock braking system (ABS), a fact that makes it difficult to identify tire marks, when they occur, as they quickly tend to disappear due to the weather. Situation that occurred during the site examination of the case under analysis. However, from the examination of the images provided by the driver of the Gol involved in the collision, it was possible to identify braking marks at an interval of at least 11 meters.

The equation for speed reduction by braking marks for vehicles equipped with ABS is as follows [2]. Equations 14 and 15.

\[ v = (2g\mu_{ABS}d)^{1/2} \]  
\[ \mu_{ABS} = 1.09(1-%R)\mu_c \]  

Were:

\( \mu_c \) is the standard coefficient of friction for motorcycles;
\( %R \) is the percentage reduction of friction coefficients as a function of speed. Tabled in source [2].

\[ \mu_{ABS} = 0.694 \]

\[ v = 12.24 \text{ m/s} = 44.06 \text{ km/h} \]

* We emphasize that the average displacement speed of the motorcycle obtained by the photogrammetry method was 93.6 km/h.

3.1.2 Motorcycle travel speed by wheelbase reduction methods

Due to the angle at which the photographic record of the motorcycle was performed, it was not possible to measure the reduction of the wheelbase of the Suzuki motorcycle directly in the image. However, as the wheel-front fork set was registered in a favorable position, almost parallel, after adjustments with Imagej’s Projective Mapping
image repositioning function, it was possible to identify the deformation angle of the motorcycle's fork.

Figure 06- Measurements of deformations in the front shock absorbers.

Source: driver of the vehicle Gol involved in the accident, measures by the authors.

As mentioned above, deformation checks on the motorcycle fork were performed using Imagej software. After adjusting the image with the Projective Mapping function - photogrammetric function that allows the repositioning of the images - and considering that the wheel-fork-damper assembly was positioned in parallel, it was possible to measure the deformation angle of the motorcycle fork. As can be seen in Figure 07, above, the measurements of deformation in the front shock absorbers are different, a situation that occurred due to the motorcycle collision having occurred at an angle not perpendicular to the side of the vehicle (Figure 05). Due to the difference in deformations between the front shock absorbers, it was decided, as a good alternative, to determine the average between the deformations and then calculate the amount of shortening between the axles.

The angle of deformation of the front shock absorber, on the left side, was set at 34° and that of the front shock absorber on the right side at 11°. Therefore, the simple arithmetic mean between the deformation angles of the dampers is 22.5°.
Therefore, the deformation of the motorcycle's front axle shortened by **190 mm** = 7.48 in (1,560 mm – 1,370 mm).

3.1.2.1 Displacement speed from equation 2, item 2.3.2

\[ v = A \times \frac{5}{3} + 5 = 36.7 \text{ km/h} \]

As previously mentioned, tire marks were printed on the pavement of the accident site by the motorcycle prior to the collision (item A.). Therefore, using the quadratic velocity method, we have the following estimate of the motorcycle's impact velocity:

\[ v_{\text{displacement}} = (44.06^2 + 36.7^2)^{1/2} = 57.34 \text{ km/h} = 15.93 \text{ m/s} \]

In addition, part of the collision energy was dissipated in the form of sound and heat. Therefore, to add this portion of energy at the moment of the collision, we will use a coefficient of restitution of **18%**.

\[ E = (m \times v_{\text{imp}}^2)/2 \text{ Joule} \]

Where:

\[ m \text{ is the motorcycle's mass plus the rider's mass in kg.} \]
\[ E = (295 \times 15.93^2)/2 = 37,430.32 \text{ J} \]
\[ E_{\text{rest}} = E + 18\% = 44,167.78 \text{ J} \]
\[ v_{\text{desloc}} = [(2 \times E_{\text{rest}})/m]^{1/2} = 17.30 \text{ m/s} = 62.30 \text{ km/h} \]

Figure 07- Deformation of the motorcycle front axle.

Source: the authors.
3.1.2.2 Displacement speed from equation 3, item 2.3.2

\[ V_{mc} = (2.18 \Delta L_{wb}) + 10.3 = 26.6 \text{ mph} = 42.8 \text{ km/h} \]

Adding the speed by braking marks we have:

\[ V = (44.06^2 + 42.8^2)^{1/2} = 61.42 \text{ km/h} = 17.06 \text{ m/s} \]

Adding the portion related to the refund:

\[ E = (295 \times 17.06^2) / 2 = 42,928.93 \text{ J} \]

\[ E_{rest} = E + 18\% = 50,656.14 \text{ J} \]

\[ v_{desloc} = [(2 \times E_{rest})/m]^{1/2} = 18.53 \text{ m/s} = 66.71 \text{ km/h} \]

3.1.2.3 Displacement speed from equation 5, item 2.3.3

\[ V = 1.59(L + C) + 14.72 = 44.7 \text{ mph} = 72 \text{ km/h} \]

Adding the speed by braking marks and the coefficient of restitution, we have:

\[ V = (44.06^2 + 72^2)^{1/2} = 84.41 \text{ km/h} = 23.45 \text{ m/s} \]

\[ E = (295 \times 23.45^2) / 2 = 80,835.66 \text{ J} \]

\[ E_{rest} = E + 18\% = 95,386.08 \text{ J} \]

\[ v_{desloc} = [(2 \times E_{rest})/m]^{1/2} = 25.43 \text{ m/s} = 91.54 \text{ km/h} \]

3.1.3 Displacement speed by occupant projection method

According to the dimensional characteristics of the vehicles involved and the verifications at the accident site, we have to:
a = height from the motorcycle seat to the top of the roof of the Gol = 621 mm
b = distance from the motorcycle seat to the point of collision with the Goal = 1,385 mm;
θ = necessary angle, given the dimensional characteristics of the vehicles, for the motorcycle rider to fly over the Gol = 24° (tg\(^{-1}\) 621/1385);
h = height of the motorcycle rider's center of gravity = 850 mm;
d = the motorcycle rider's landing distance = 8.5 m.

3.1.3.1 Projection speed from equation 6, item 2.3.4

\[ v = \frac{2.21 \times d}{((\cos \theta \times (h + d \times \tan \theta))^{1/2})} = 9.5 \text{ m/s} = 34 \text{ km/h} \]

Adding the speed by braking marks and the coefficient of restitution, we have:

\[ V = \left(44.06^2 + 34^2\right)^{1/2} = 55.65 \text{ km/h} = 15.46 \text{ m/s} \]

\[ E = \frac{295 \times 15.46^2}{2} = 35,254.21 \text{ J} \]

\[ E_{\text{rest}} = E + 18\% = 41,599.97 \text{ J} \]

\[ v_{\text{desloc}} = \left(2 \times E_{\text{rest}} / m\right)^{1/2} = 16.79 \text{ m/s} = 60.46 \text{ km/h} \]

3.1.3.2 Projection speed from equation 7, item 2.3.4

\[ v = \frac{11.25 \times d}{((d \pm h)^{1/2})} = 31.2 \text{ km/h} \]

Adding the speed by braking marks and the coefficient of restitution, we have:

\[ V = \left(44.06^2 + 31.2^2\right)^{1/2} = 54 \text{ km/h} = 15 \text{ m/s} \]

\[ E = \frac{295 \times 15^2}{2} = 33,187.50 \text{ J} \]

\[ E_{\text{rest}} = E + 18\% = 39,161.25 \text{ J} \]
\[
v_{\text{desloc}} = \left(\frac{2^8E_{\text{rest}}}{m}\right)^{1/2} = 16.29 \text{ m/s} = 58.66 \text{ km/h}
\]

3.2 DISPLACEMENT SPEED BY THE DEFORMATION METHOD IN THE VEHICLE

In this item we will present the results of motorcycle collision speed estimates based on the equations presented in item 2.4.

Next, in figure 08, it is possible to observe the collision angle of the motorcycle on the side of the Gol.

Figure 08- Motorcycle collision angle on the side of the Gol vehicle.

The measurements carried out in the present deformations in the vehicle. Through the computational tool Imagej, it was possible to identify, the collision angle of the motorcycle on the side of the Goal. The collision angle, or main force direction angle (PDOF), was 24° (84° - 60°).

The values of the penetration and extent of damage are as follows:
We consider the characteristics, dimensions and distance between axles according to table 01. The vehicle under analysis falls into the stiffness category class 2. Passenger Car Classifications, with wheelbase range $94.8 < 101.6$ (in).

$$E_{\text{deform}} = \frac{L}{5}[5G + ((A/2)X_1) + ((B/6)(X_2 + X_3))](1 + \tan^2(\theta))$$

$$V_{\text{deform}} = (2E_{\text{deform}})^{1/2}/m$$

$$X_1 = C_1 + 2C_2 + 2C_3 + 2C_4 + 2C_5 + C_6 = 174 = 68.50 \text{ in}$$

$$X_2 = C_1^2 + 2C_2^2 + 2C_3^2 + 2C_4^2 + 2C_5^2 + C_6^2 = 623.32 \text{ in}^2$$

$$X_3 = C_1*C_2 + C_2*C_3 + C_3*C_4 + C_4*C_5 + C_5*C_6 = 249.49 \text{ in}^2$$

$$\tan^2(24) = 0.19$$
E_{\text{deform}} = 16.3\times[377.65 + ((50\times68.5)) + (11.03\times872.81)]\times1.19 = 260,494.9 \text{ lb.in}

E_{\text{deform}} = 16.3\times[377.65 + 3,425.0 + 9,627.1] \times1.19 = 260,494.9 \text{ lb.in}

V_{\text{deform}} = ((2\times260,494.9)/651)^{1/2} = 28.3 \text{ mph} = 45.3 \text{ km/h}

3.3 ENERGY TO MOVE THE GOL VEHICLE LATERALLY

To estimate the collision speed of the motorcycle due to collision, the total mass of this vehicle was considered since the impact was in the central region of the right side (fig 04).

\[
\frac{m \times v^2}{2} = \mu \times n \times g \times d
\]

Were:

\(m\) = motorcycle mass kg;
\(v\) = motorcycle velocity collision;
\(\mu\) = coefficient of friction = 0.7;
\(n\) = vehicle + pilot mass (934 + 95) kg;
\(g\) = 9.8 \text{ m/s}^2;
\(d\) = vehicle side drag (0.9 m).
\(v\) = \((6,359.5/147.5)^{1/2} = 6.6 \text{ m/s} = 23.76 \text{ km/h}

3.4 SPEED COMBINATION

Adding the speeds by brake marks, by reduction between axles and the coefficient of restitution, we have the following estimates of motorcycle collision speed:

3.4.1 Using the result obtained by equation 2 with that of the deformation of the Gol

\[
V = (44.06^2 + 36.7^2 + 45.3^2 + 23.76^2)^{1/2} = 76.8 \text{ km/h} = 21.34 \text{ m/s}
\]

\[
E = (295\times21.34^2)/2 = 67,203.6 \text{ J}
\]

\[
E_{\text{rest}} = E + 18\% = 79,300.2 \text{ J}
\]

\[
v_{\text{desloc}} = ((2\timesE_{\text{rest}})/m)^{1/2} = 23.18 \text{ m/s} = 83.47 \text{ km/h}
\]
3.4.2 Using the result obtained by the equation of the reduction between axles 3 with that of the deformation of the Gol

\[ V = (44.06^2 + 42.8^2 + 45.3^2 + 23.76^2)^{1/2} = 80 \text{ km/h} = 22.22 \text{ m/s} \]

\[ E = \frac{295 \times 22.22^2}{2} = 72,840 \text{ J} \]

\[ E_{\text{rest}} = E + 18\% = 85,951.2 \text{ J} \]

\[ v_{\text{desloc}} = \left(\frac{2 \times E_{\text{rest}}}{m}\right)^{1/2} = 24.14 \text{ m/s} = 87 \text{ km/h} \]

3.5 COMPARISON WITH SEVENTEEN MOTORCYCLE CRASH TESTS WORK RESULTS, REFERENCE [10]

In order to verify the accuracy of our methodology it was applied in tests #08, #12 e #13 in the work Seventeen Motorcycle Crash Tests into Vehicles and a Barrier [10].

3.5.1 Quantities involved and tests results.

| Table 03. Information about the tests #08, #12 e #13. Reference [10]. |
|-----------------------------------|-----------------|-----------------|-----------------|
|                                  | Test #08        | Test #12        | Test #13        |
| Motorcycle speed (mph)           | 46              | 30              | 42              |
| Motorcycle speed (lb)            | 615             | 631             | 625             |
| Vehicle located weight (lb)      | 1,538           | 2,052           | 3,576           |
| Collision location               | Lateral traseira| Roda dianteira  | Centro lateral  |
| Vehicle wheelbase (in)           | 113             | 113             | 113             |
| Vehicle side shift (in)          | 95              | 40              | 25              |
| Vehicle tire friction coefficient| 0.7             | 0.7             | 0.7             |
| Reduction between motorcycle axles (in) | 10.75 | 3.25 | 6.81 |
| C_1; C_2; C_3; C_4; C_5; C_6 (in) | 11; 13.5; 11.75; 4.5; 3.75; 3 | 0; 1.75; 3.25; 5.5; 0.75; 0 | 0; 3.5; 5; 10; 8; 3 |
| Vehicle deformation (in)         | 43              | 48              | 84              |

Source: reference [10].

3.5.1.1 Collision velocity of motorcycle to lateral drag the vehicle.

Accordingly \[\frac{m \times v^2}{2} = \mu \times n \times g \times d.\]
Table 04. Collision velocity of motorcycle to lateral drag the vehicle.

<table>
<thead>
<tr>
<th>Motorcycle speed (mph; km/h; m/s)</th>
<th>Test #08</th>
<th>Test #12</th>
<th>Test #13</th>
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<tbody>
<tr>
<td>20.48; 32.76; 9.1</td>
<td>15; 24; 6.72</td>
<td>25.12; 40.2; 7.03</td>
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</tr>
</tbody>
</table>

Source: the authors.

3.5.1.2 Motorcycle speed by the method of equation 3.

Table 05. Motorcycle speed by the method of equation 3.

<table>
<thead>
<tr>
<th>Motorcycle speed (mph; km/h; m/s)</th>
<th>Test #08</th>
<th>Test #12</th>
<th>Test #13</th>
</tr>
</thead>
<tbody>
<tr>
<td>33.75; 54; 15</td>
<td>17.38; 27.8; 7.72</td>
<td>25.12; 40.2; 11.17</td>
<td></td>
</tr>
</tbody>
</table>

Source: the authors.

3.5.1.3 Motorcycle speed according to the deformations in the vehicle.

According to the Campbell’s method (item 2.4).

Vehicle class 4;

A = 137 lb/in;
B = 95 lb/in²;
G = 98.8 lb;

Table 06. Motorcycle speed according Campbell method.

<table>
<thead>
<tr>
<th>E deformation (lb.in)</th>
<th>V deformation (mph; km/h; m/s)</th>
<th>Test #08</th>
<th>Test #12</th>
<th>Test #13</th>
</tr>
</thead>
<tbody>
<tr>
<td>218,703.8</td>
<td>26.7; 42.72; 11.87</td>
<td>218,703.8</td>
<td>27,921.6</td>
<td>227,495.5</td>
</tr>
</tbody>
</table>

Source: the authors.

3.5.1.4 Motorcycle speed after impact.

According to the equation \( v = \sqrt{\frac{2 \cdot g \cdot \mu \cdot d}{}} \).

Table 07. Motorcycle speed after impact.

<table>
<thead>
<tr>
<th>Motorcycle speed (mph; km/h; m/s)</th>
<th>Test #08</th>
<th>Test #12</th>
<th>Test #13</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>9.2; 14.76; 4.2</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Source: the authors.

3.5.1.5 Motorcycle displacement speed.

According quadratic method.

Table 08- Motorcycle displacement speed.

<table>
<thead>
<tr>
<th>Motorcycle speed (mph; km/h; m/s)</th>
<th>Test #08</th>
<th>Test #12</th>
<th>Test #13</th>
</tr>
</thead>
<tbody>
<tr>
<td>47.75; 76.25; 21.18</td>
<td>26.4; 42.3; 11.8</td>
<td>40; 64; 17.8</td>
<td></td>
</tr>
</tbody>
</table>

Source: the authors.
As mentioned in the 2.1. item, the speed of displacement of the motorcycle was 93.6 km/h by the photogrammetry technique. The following table presents the results for the estimates of motorcycle displacement speeds, obtained by the methods presented in this work:

<table>
<thead>
<tr>
<th>Method</th>
<th>Displacement velocity by the square sum method (km/h)</th>
<th>Approximation in percent (%) of the velocity obtained by the photogrammetry method (and radar methods by [10])</th>
<th>Seventeen Test [10], radar method (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eq. 7</td>
<td>58.66</td>
<td>62.67</td>
<td>X</td>
</tr>
<tr>
<td>Eq. 6</td>
<td>60.46</td>
<td>64.6</td>
<td>X</td>
</tr>
<tr>
<td>Eq. 2</td>
<td>63.30</td>
<td>67.63</td>
<td>X</td>
</tr>
<tr>
<td>Eq. 3</td>
<td>66.71</td>
<td>71.27</td>
<td>X</td>
</tr>
<tr>
<td>Eq. 5</td>
<td>91.54</td>
<td>97.8 (115; 84.7; 106)</td>
<td>53.28</td>
</tr>
<tr>
<td>Eq. 9, combined with Eq. 2</td>
<td>83.47</td>
<td>89.2</td>
<td>X</td>
</tr>
<tr>
<td>Eq. 9 combined with Eq. 3</td>
<td>87</td>
<td>93 (103; 88; 95.2)</td>
<td>47.65</td>
</tr>
</tbody>
</table>

Source: the authors.

Looking at the table above, it is possible to observe that the method of estimating velocity proposed by Oren Masory; Wade Bartlett e Bill Wright (2012), equation 5, was the one that most approached the result of the displacement velocity by the photogrammetry technique.

The method proposed and presented by us, that considers the deformation established between the axles of the motorcycle and the energies dissipated in impact (eq.9 with eq.3) present excellent approximation corresponding the speed determined photogrammetrically. In the same way, it was the method closest to the results of the tests #08, #12 e #13 obtained by mobile gun-type.

4 CONCLUSION

Considering the detailed analyzes on the levels of mechanical deformations in the vehicles involved in the event on screen, the examinations carried out on site, as well as the careful analyzes of the different calculation methods used, considering that, currently, the photogrammetric and radar methods are the closest to accuracy for determining speeds, within the scope of analysis carried out it was possible to conclude that:

The arrangement between the methods of mechanical deformations in the vehicle and the reduction between axles of the motorcycle (eq. 9 combined with eq. 3) which determined 87 km/h, resulted in a more up-to-date tool, in a renewing procedure. It was
93% in relation to the value obtained by the photogrammetric method and 95.2% corresponding to the speed obtained by mobile gun-type radar.
REFERENCES


