Road Safety: Accident Analysis And Reconstruction

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SYNOPSIS

This work focuses, in this first phase, on accident analysis and reconstruction, with the purpose of devoting a second phase on the analysis of risk levels. The present paper defines synthetically the analysis of procedures and methodologies related to poor safety conditions, turning in the last part in a applicative example. Since the year 2000, a certain number of accidents have been recorded in Pavia, and are recollected and reconstructed according to the procedures developed and formalized in the Road Accident Reconstruction Laboratory of Pavia University. All accident cases have been recollected in a database, in which the most significant information and variables have been evidenced, forming the basis of reading and interpreting of the results.
Particular attention has been dedicated to the influence of velocity on accident dynamics and its consequences. In particular attention must be given to the different velocity values that occur following the instant of impact, at the moment in which the braking system starts and the event is perceived by drivers.
The driver's behaviour is examined through the analysis of possible passing manouvers, that are consequently reconstructed according to choices and behaviours differing from the ones used during the accident.
We must consider the consequences that would have been produced if the vehicles had different velocity values.

INTRODUCTION

A well-established trend, emerged in the last years, shows that people movements and trade have increased notably. The consequent challenge to transport has been mainly on the roads capacity, and in Italy this phenomenon is more evident than elsewhere. It is clear that the general growth in the number of circulating vehicles has significantly increased the traffic flow on all road categories.
Such an increase in circulation brings with it many numerous negative impacts: the main one is the development of unsafe traffic situations, which are the origin of many road accidents.
Traffic accidents bring with them elevated costs in macro-economic terms, with heavier ramifications if we consider the damage to the involved people and the loss of human life, in the most serious events.
The road accidents weigh, with a large rate, on the national sanitary system, they cause permanent or temporary working inability, they impose remarkable costs to the road casualties families and they damage five million vehicles per year. From such evidences the necessity of interventions emerges to limit the negative effects of the road transport.
In such perspective the Italian government has promoted the elaboration of the National Plan for the road safety, that aims to reduce by 40% the number of the road casualties within the year 2010, according to the European Union directives.
This study wants to offer a small contribution in this direction and intends to deal in details with the accidents analysis. The objective is to deepen the study and the accident reconstruction, aiming to investigate every involved variable.

METHODOLOGY

An accident reconstruction is inevitably linked to the quantity and quality of the available data. The choice of the reconstruction method and the reliability of the results are accordingly subordinates to the data that can be used.
In general the mechanics of the road accident is divided in different phases; the principal phases are: pre - impact, impact and post - impact.
Every phase can be divided in more segments, individualized by every change of one of the variable linked to the accident.
Each of the phases is characterized by some variable, that can be considered constant within the phase. Every phase can be studied independently from the others, aiming to define the physical laws influencing it.

An accident reconstruction can be conducted in chronological order or in inverse sense, or, contemporaneously, from both senses, up to reach the same instant, verifying the coincidence of the calculated values; this choice depends on the available data. Following the most frequent procedure, the reconstruction begins from the point of arrest, because this is usually known. In fact, when the police officers reach the accident scene, they almost always notice the vehicles catch position.
Inside every phase of pre-impact and post-impact the vehicles motion can be held uniform or uniformly accelerated, with enough approximation. Then the vehicles move following the laws of the kinematics, in these phases.
The crash is studied resorting to the application of fundamental physics laws instead, such as the energy conservation principle and the momentum conservation principle, and to the joined use of them.
The procedures of schematisation and coding of an accident, as real phenomenon, is nevertheless afflicted with uncertainty, linked to the difficulty of determining some parameters and to their variability.
Uncertainty is treated through the introduction of variation intervals, whose width depends on the hazard level of the unknown parameters and on the variability of the consequential results from empiric simulations, such as sliding test and crash test.
This criterion seems rather simplifying, but it allows to consider every variable linked to the accident and to analyse the road accidents majority.
In the following paragraphs some procedures will be recalled, used in the different phases of the road accident analysis and then a particular reconstruction will be treated.

The Energy Maintenance Principle Application

The energy of the system constituted by the vehicles in collision (in the instant following to the crash) must equal the energy of the same system in the first contact instant among the involved vehicles.
After the impact, a part of the kinetic energy of the system constituted by the vehicles before the collision, become energy of the vehicles deformation. Determining this quota of energy is very important in the crash study. In fact the amount of energy dissipated by the vehicles during the crash is almost entirely assignable to the vehicles deformation; other small quantities of energy, of negligible entity, are due to the interaction between the vehicles and the external environment during the phase of crash. The impact duration is appraisable in few tenth of a second.
The global energy of the system dissipated during the crash can be determined, in terms of speed, through the EES (Equivalent Energy Speed); it is estimated using data from crash-test.
The crash-tests simulate different typologies of crash (vehicle - vehicle, vehicle - deformable barrier, vehicle – rigid barrier). With these tests it is possible to measure the values assumed by some variables during the crash, such as speed, acceleration and stiffness of the vehicles.
Comparing the type and the shape of the deformation of a vehicle involved in an accident with those of the vehicles during the crash-tests, it is possible to quantify the amount of dissipated energy during the crash. The EES is the index expressing this energy in terms of speed.

Campbell Algorithm

The dissipated energy in inelastic deformation can also be calculated through the application of Campbell algorithm.
The generic form of the algorithm is:

$$E_d = \sum_{i=1}^{n-1} w_i \left(\frac{B}{6} \cdot \frac{c_{i+1}^3 - c_i^3}{c_{i+1} - c_i} + \frac{A}{2} \cdot (c_{i+1} + c_i) + G \right) \cdot (1 + \tan^2 \vartheta) \qquad (1)$$

$$w_i = L_{i+1} - L_i$$

where:
E_d = Energy dissipated (in-lbs)
w = width of crush region (in)
A = maximum force per inch of damage width which will cause permanent damage (lb/in)
B = stiffness per inch on damage width (lb/in^2)
c_i = deformation measurements (in)
G = A^2/2B (lbs)
θ = angle of force direction (°).

Dissipated energy results from the width and the depth of the deformed zone, the vehicle stiffness parameters and the inclination angle of the principal impact force with the normal to the surface deformed, in the point individualized by the straight line of application of the impact force.

The stiffness parameters have been drawn in crash-test, for different typologies of vehicles, different locations of the damage and for the various materials, constituent the components of the vehicle interested by the deformation.
The measures of the deformation are taken on the damaged vehicles with a standardized methodology.
The most difficulty in the application of such algorithm is linked to the determination of the impact force angle. On the subject an evaluation can be effected, beginning from the examination of the impact zones, through the correspondence of the damages on the vehicles at the moment of maximum interpenetration and the analysis of the shape of deformation: this procedure allows to assume the value of the angle in a certain variation interval, and therefore with a certain degree of reliability.
The stiffness coefficients vary with relation to the zone of deformed vehicle.
We can value with other techniques energy's quota moved to the external environment, which is mainly due to the resistance of the air and the friction of the tires on the road paving, but its value can be considered negligible in relationship to the dissipated energy in deformation, especially in very serious collisions.
Campbell algorithm can be used only in rather uniform deformations, and in accidents where the impact force is almost perpendicular to the impacted surface. This last condition is justified by the fact that the values of the stiffness coefficients are obtained through crash tests in collisions satisfying such ties.
Campbell algorithm is not applicable in accidents introducing particular characteristics: a rollover of the vehicle (in fact such type of motion is characterized by the presence of deformations distributed in a not uniform way); in collisions with damages developed vertically; in collisions involving zones of the vehicles not studied in crash-tests.

The Momentum Conservation Principle Application

The momentum conservation principle is synthesized in 2.

$$\sum Q = \sum Q' \qquad (2)$$

Q is the momentum before the impact;
Q' is the momentum after the impact;
The momentum is defined in 3:

$$Q = m \cdot v \qquad (3)$$

where: m is the vehicle mass;
v is the vehicle speed.

Select a system of Cartesian axes (passing for example through the mass centre of one of the vehicles at the moment of first contact on impact), the pre-crash and post-crash momentum components on such axes are calculated getting a system in which the unknown factors are the velocities of the vehicles entering the collision and the escape velocity after the collision. This system is solved preventively calculating the velocities after the collision, using kinematical formulas appropriate to the case.
The obtained results from the application of the momentum conservation principle are particularly sensitive to the choice of the directions in entrance and in exit on impact of the vehicles mass centre. These directions can be individualized with good precision if there are tire marks from braking, acceleration, sliding or observable scrape marks on the road paving.
The application of the momentum conservation principle doesn't produce satisfactory results in the following cases: when there is a great mass difference among the vehicles involved in the accident, because the results variation intervals are amplified; when measurable displacements of both the vehicles are not recorded, as a result of the crash; when the vehicles on impact have a not orthogonal configuration. In these last two situations a variation of few degrees in the choice of the mass centre direction produces notable variations in the results.

Searle Formula

In the accidents between a vehicle and a motorcycle, when the rider's body on impact separates from the motorcycle and lands down far from the position of his motorbike, or when a pedestrian is impacted by a vehicle, it is possible to study the trajectory of the body tossed into the air after the impact with the theory of a bullet motion.
However in most the situations we know only the body distance from the impact point to the rest position and not the distance from the impact to the point of first contact with the ground; for this reason the theory of a bullet motion is not enough.

The distance covered by the body, after the first contact with the ground, can be divided in two phases: in the first one the body rebounds and in the second one it slides. The body is launched with a projection angle and it is characterized by a coefficient of rebound and a friction coefficient.
The Searle formula defines the speed getting out of the collision (which can be also equal to the one getting in, if there is no the vehicles); considering the described parameters, we have:

$$v = \frac{\sqrt{2 \cdot \mu \cdot g \cdot s}}{(\cos\theta + \mu \cdot \sin\theta)} \qquad (6)$$

where:
s is the distance among the throwing point and the rest position (m)
μ is the drag factor of the surface and depends on the typical movement of the body in the following phases after the impact
g is the acceleration of gravity (m/s^2)
θ is the takeoff angle.

The drag factor depending on the typical movement of the body in the phases following the crash is equal to μ.
Speed mostly results influenced by the friction coefficient for small takeoff angles; such dependence decreases for greater angles.
In the most cases the takeoff angle is not known; consequently it is possible to assume an angle value varying in a certain interval, on account of this uncertainty. The variation intervals of the takeoff angle are determined by opportune crash-tests.
You can also proceed considering the values of the takeoff angle minimizing or maximizing the Searle formula. The least value is given by:

$$\tan\theta = \mu \qquad (7)$$

and therefore it is drawn:

$$v_{\min} = \sqrt{\frac{2 \cdot \mu \cdot g \cdot s}{1 + \mu^2}} \qquad (8)$$

The maximum value is given by the relationship:

$$v_{\max} = \sqrt{2 \cdot \mu \cdot g \cdot s} \qquad (9)$$

The 9 is applicable only in cases where the takeoff angle is lower than a critical angle, that is equal to:

$$\vartheta_{crit} = 180° - 2 \cdot arctg\frac{1}{\mu} \qquad (10)$$

For values of the takeoff angle exceeding the critical angle, the interval superior extreme cannot be defined.
Speed is inclusive in a variation interval whose width varies with the friction coefficient and the distance between the impact point and the rest point of the body.
The body speed after the impact is usually smaller than the vehicle speed on impact. Therefore it is possible to express the body speed as a percentage of the vehicle speed.
When collisions happen on gradient roads, the formula must be modified. The trajectory can be studied in the two extreme cases in which the body is moving into the air or is sliding all through the distance. The speed of the body moving into the air must be increased by a factor equal to:

$$(1 + \sin\alpha) \qquad (11)$$

where α is the slope of the road.
When the body slides, speed must be increased by a factor equal to:

$$(\cos\alpha + \frac{1}{\mu}\sin\alpha) \qquad (12)$$

Tumbling

The road accidents in which the tumbling of one or more vehicles happens may show various configurations, and reconstruction is possible only using experience and crash-tests.
The tumbling of a vehicle happens when the projection of its barycentre on the road paving falls out of the area delimited by its tires.
The distance of tumbling is the space between the point in which the vehicle begins its tumbling and the one in which it stops. Crash-tests allow the measurement of the middle value of acceleration on this stretch. The

diagram in Figure 1 reassumes the results of 41 crash-tests (Orlowski, Hight, Segal and Young). The average acceleration of tumbling, esteemed by these crash-tests, is 0.42 g within the 0.36 g - 0.61 g range.
The crash-tests performed by Warner show acceleration values between 0.3 g and 0.5 g, for tumbling producing the scraping of vehicles on their roof and/or on their side, against made-up or unmade road.
Some accidents introduce cases of multiple tumbling, in which the distance of tumbling is function of the vehicle number of tumbling.
The crash-tests in Figure 1 are related to multiple tumbling. These crash-tests have been performed on different vehicles typologies, with two tumbling average.

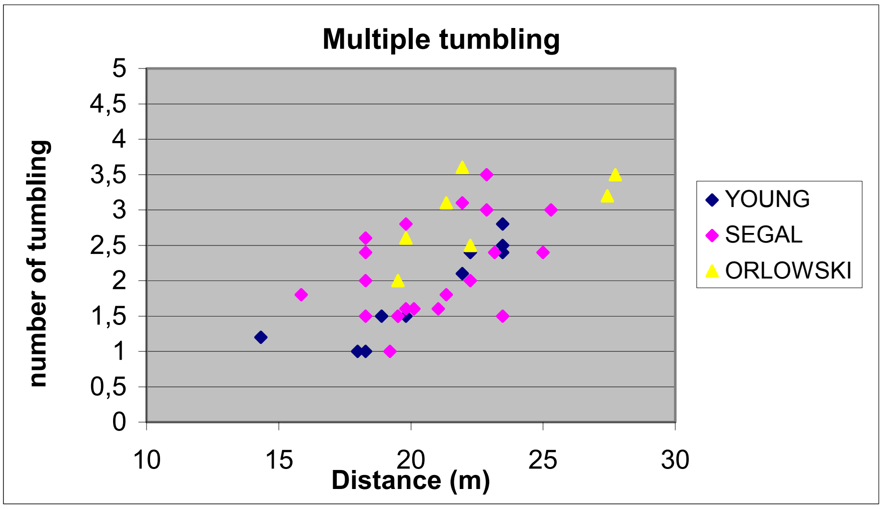

Figure 1 Number of tumbling related to the tumbling distance.

The studies conducted by Orlowski et al. (1989) show that most cases examined present a single, complete or partial tumbling [6].
Other crash-tests, performed by the same group [6], show that on average a vehicle completes a rotation of 90° every 0.25 sec during a tumbling. The external side of the tumbling vehicle takes about twice the time to touch the ground, and it is usually this side that leaves signs on the road paving. This generally happens for vehicles which have their width greater than their height. The inner side has not enough time before meeting the ground to acquire such a speed to leave visible signs on the road paving.
Vehicles that have height comparable to width (Off-roads, etc.) generally mark the road paving with their inner side.
The analysis of marks left on the road paving and of vehicles deformations allow to start the tumbling reconstruction. During the tumbling, the vehicle alternates periods in which it rotates about one of its axes and lines in which it slides. It is useful to divide the length of the tumbling into many segments and try to assign to each segment the type of motion characterizing the vehicle in that segment.
In the crash-tests conducted by Orlowski the speeds of translation and rotation during the tumbling of the vehicle were monitored. The results indicated that the speed of translation decreases to an average value of 3 m/s in correspondence with every impact with the ground. The speed of rotation undergoes an increase in the initial phase, arriving at a maximum value from which decreasing until the vehicle comes to a rest.
The analysis of the vehicle and the road surface is fundamental to the reconstruction of the tumbling.
The first contact point of the vehicle is usually indicated by the glass presence. The outer side, impacting on the ground, leaves fragments of glass distributed over a wide surface. Other useful elements individualizing the tumbling dynamics can be the presence on the road surface of possible scars and sliding left by the tires.

Crash-test and Sliding-test Databases

Databases are used in the reconstruction phase. They are a collection of results of crash-tests and sliding-tests. For instance, the databases are able to give the value of the energy dissipated during the crash in terms of speed, according to the deformation caused by the accident and visible on the vehicle.
Crash-tests are simulation tests conducted on various categories of vehicles. Such tests give the stiffness of vehicle materials, as well as vehicle speed, acceleration and crash force.
The tests simulate crashes among vehicles of the same category, vehicles of different categories and among vehicles and deformable or rigid barriers [7].
The data is acquired by accelerometers, photographic supports and deformation measurement devices.
Fig 2 shows a crash-test in which a vehicle collides at high speed against a rigid barrier. The impact is frontal.

Figure 3 shows the crash-test of a vehicle launched at notable speed against a deformable barrier; the impact is between the left anterior part and the barrier.

Figure 2. Crash-test vehicle - rigid barrier.

Figure 3 Crash-test vehicle - deformable barrier.

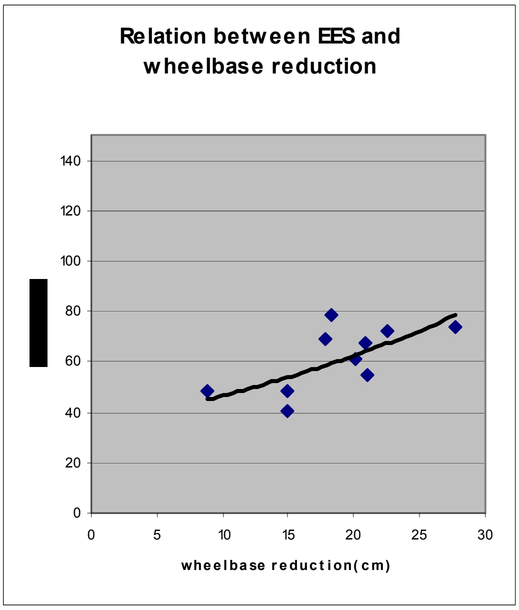

Figure 4 Crash-test motorcycle – vehicle (Ref. Adamson et al., 2002)

Crash tests on motorcycles include simulation tests of crashes between motorcycles (frontal part) and vehicles or deformable and rigid barriers. The speed of the crash impact is determined according to the shortening of the motorcycle length, caused by the crash; the length is measured by the distance between the wheels axles. In the figures 4 and 5 are proposed some diagrams derived by crash-testing, return the values of the deformation energy, in terms of speed, according to the wheelbase shortening.

Sliding-tests are performed to obtain friction coefficients or drag factors, in different typologies of movement, and according to the vehicles decelerations, proceeding with uniformly decelerated motion. Such tests simulate the motion of heavy vehicles, cars, motorcycles and pedestrians, and they provide decelerations values, in relationship to road surface, type of brakes and skid-marks left by vehicles, or according to scrape marks consistence and depth of on the road surface.

There are other sliding-tests related to motorcycles and people sliding or rolling on the road paving. Such tests give decelerations values assumed during motion, in relationship to type of motorcycle, movement typology and other closely related variables.

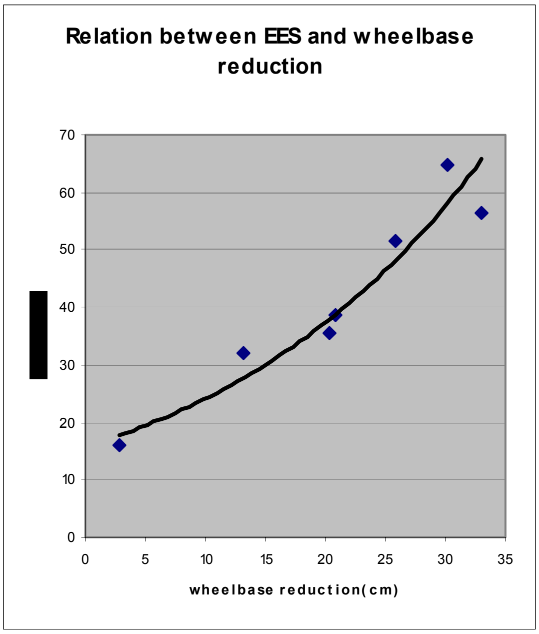

Figure 5 Crash-test motorcycle – rigid barrier (Ref. Adamson et al., 2002)

The deceleration values given by these tests are susceptible to variations within a certain interval. The impossibility to obtain precise values is due to the fact that, in every vehicles category, different variables characterizing every single movement can take part, in phase of simulation.
Tables 1 and 2 are examples of crash tests results.

Roadway condition	Acceleration value (m/s^2)					
	For Automobile Skid-marks		For Truck Skid-marks		For Motorcycle Skid-marks	
	Nominal	Range	Nominal	Range	Nominal	Range
Dry asphalt	-7,5	± 0,6	-6,5	± 0,5	Both tyres: -8,5 Front only: -6,4 Rear only: -3,5	±0,6 ±0,5 ±0,5
Wet asphalt	-6,5	±0,6	-5,5	± 0,5	-7,5	±0,6
Dry packed	-6,9	±1,5	-6,9	± 1,5	-6,9	±1,5
Dry loose gravel	-5,5	±1,5	-5,5	±1,5	-5,5	±1,5

Table 1 Typical acceleration values for automobiles, trucks and motorcycles on different roadway surfaces (Ref. Warner et al., 1983, Frick and Riley, 1994, Ouellet, 1997, Otte, 2000)

Table 1 shows some deceleration values, applicable through the braking distance, assumed by sliding-tests; such values are a function of vehicle categories, types of road surface and skid-marks.
Table 2 presents some acceleration values of motorcycles and pedestrians sliding on different surfaces.
Scooters differ from motorcycles in weight, body shape, outer surface material, and performance. Some specific experimental studies have attested that acceleration, constant in the sliding phase, settles at around 4 - 4,5 m/s^2.
In this study the Pc-crash Version 7.0 software is used to limit the variation range of the most uncertain parameters. Such software is available for the dynamics simulation and reconstruction of road accidents.

Condition	Acceleration value (m/s^2)	
	Nominal	Range
Motorcycle sliding on asphalt or concrete	-5,5	± 1,5
Motorcycle sliding on gravel	-8,5	± 2,0
Motorcycle tumbling	-8,5	± 1,0
Human body sliding on asphalt or concrete	-9,8	± 1,0
Human body tumbling	-8,8	± 0,8

Table 2 Typical acceleration values for motorcycles and riders under different sliding and tumbling conditions (Ref. Collins, 1979, Ouellet, 1997)

RECONSTRUCTION OF AN ACCIDENT

The reconstruction methodology is here applied to a really happened accident, involving two vehicles [8]. The collision occurred in town, at a four branches junction, three of which two-way and the fourth one one-way, in west direction. There weren't any road signs, except for a one-way sign.
Weather and visibility were good. The road surface (asphalt) was recently made up, and it was dry.
The involved vehicles were a Mercedes 190 2.0 and a Peugeot 205 1.6. The first car had the following characteristics: weight of the vehicle 1110 kg, weight of driver 70 kg and total weight 1180 kg. The second car had the following values: weight of vehicle 850 kg, weight of driver 70 kg and total weight 920 kg.
The first vehicle, indicated as "Mercedes", was damaged on the whole frontal part, that was pushed to the right during the impact (Figure 6).
According to a crash tests database (with similar body structure vehicles), the dissipated energy in deformation is equal to an EES value of 26-28 km/h.

Figure 6 First vehicle damage (Mercedes 190 2.0).

Figure 7 Second vehicle damage (Peugeot 205 1.6).

The damaged zone of the second vehicle, identified as "Peugeot", is the central part of the right side. This has been also moved toward the back part of the car, as it can be seen by the position of the right front

fender (Figure 7). The EES value estimation, conducted with same criteria of the first vehicle, is equal to 31-33 km/h.
The driver of the Mercedes said he entered in the intersection with east – west direction; during this movement the view on the right side was free, and the left side has not preventively checked, because he had the right of way. Near the intersection he saw a vehicle to his left, he braked, but he didn't avoid the impact.
The driver of the Peugeot said he was travelling at a moderate speed, from south to north. The visibility toward right was obstructed by a hedge. Just after the end of the hedge he has seen a vehicle on the right, he braked locking the wheels, but he didn't avoid the impact. After the impact the vehicle slid sideways just out of the intersection.

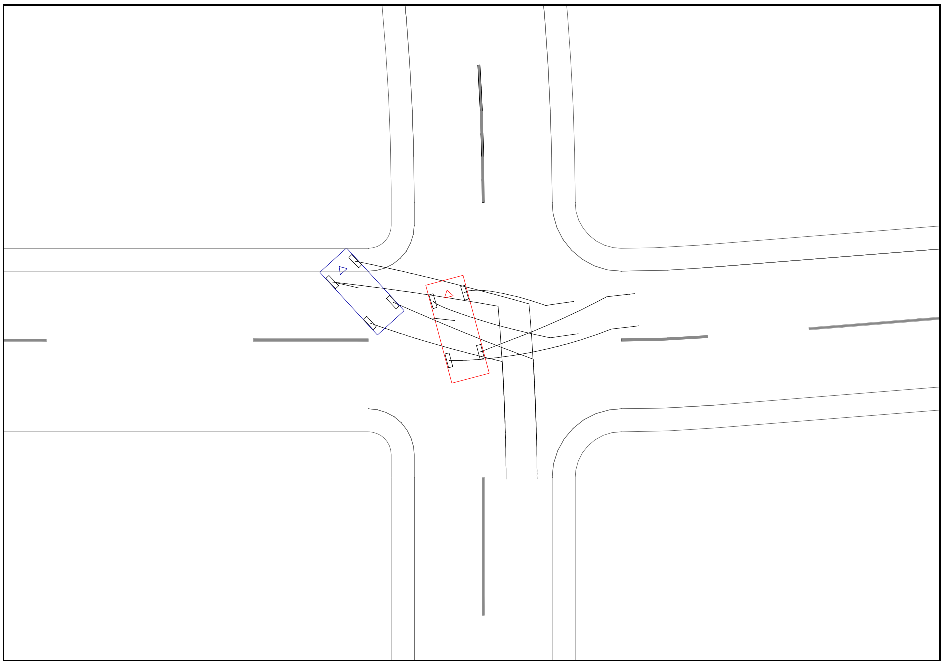

Figure 8 Intersection plan and vehicles rest position

The Figure 8 shows the plan of the intersection and vehicles rest position as measured on scene. The determination of the positions of the cars at impact is easily determined, because on accident scene there were skid-marks of both vehicles, that suddenly changed direction becoming sliding marks. The vehicles impact positions are just in the point in which the traces of braking changed direction.
The reconstruction of the accident started from the analysis of the vehicles and their deformations [9]: considering the final position and proceeding to the point of impact the manoeuvres and movements of the vehicles are described.
From the rest point to the impact point we assume for both vehicles a deceleration in condition of rotation-translation motion on a new dry asphalt surface. Considering a "drag factor" of around 0,71 – 0,81 (as in Table 1), according to the conditions of the road surface found, the value of deceleration used for both the vehicles is:

$a = 7{,}5 \pm 0{,}5 \text{ m/s}^2$

The distances from the impact point to the rest point have been measured on the plan, considering the line travelled by the centre of mass. The position of the centre of mass has been determined considering a distribution of the static weight equal to 60% on the anterior axle and 40% on the back one, for both the vehicles.
The distance travelled by the Peugeot in the post-impact phase is:

d_P (rest-impact) = 7 m

the same travelled by the Mercedes is:

d_M (rest-impact) = 5,1 m
Applying the laws that regulate the kinematics of the motion, because the variable related to the post-impact phase are known, it is possible to calculate the speeds of the vehicles just after the impact.

$$v = \sqrt{2 \cdot a \cdot d}$$

v'_M = 8,75 ± 0,3 m/s = 31,5 ± 1 km/h
v'_P = 10,25 ± 0,3 m/s = 36,9 ± 1 km/h

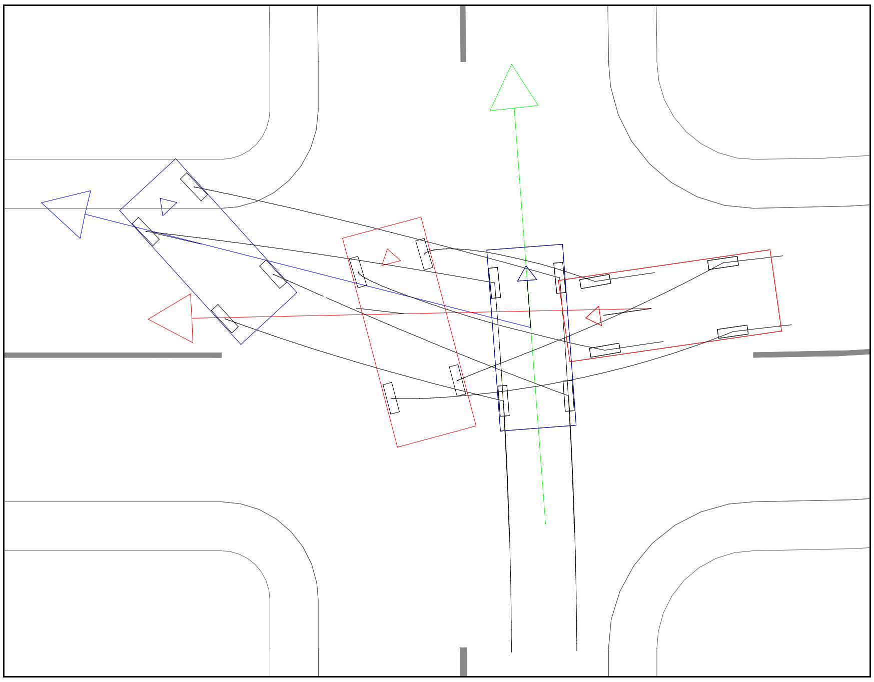

Figure 9 Vehicle centre of mass directions after separation.

To the impact phase a momentum conservation is applied. To determine the direction assumed by the centres of mass of the vehicles at the separation phase, it is used the direction of the centres of mass from the impact position to the rest position. The interaction between the vehicles and road pavement in the post-impact phase didn't vary in consistent way the direction of the centre of mass.
In Figure 9 are visualized the considered direction, taking as axle of reference for the trigonometric calculations the longitudinal axle of the Peugeot in the impact position. The direction of this axle coincides with the direction of the Peugeot just before the impact. The impact direction of the Mercedes was measured in the plan as the impact found configuration. The speeds of the vehicles just after the collision are known (in values and direction) and also the speeds at impact in direction. It is so possible to calculate the impact speed values.

v_P (impact) = 18,1 ± 2 km/h
v_M (impact) = 58,9 ± 2 km/h

The impact is simulated with the software PC-Crash 7.0 [10]. The input variables inserted in the software are the characteristics of the two vehicles, the impact configuration and the speeds as calculated.
Figure 10 shows the graphic application of the momentum conservation, used in reconstruction for the calculation of the speeds to the impact: the direction of the impulse is underlined in blue. The axle k is the direction of the motion of the Mercedes at impact.
In Figure 11 is visualized the application of the software PC-Crash; the vector of underlined blue colour points out the impulse vector.
It is possible to notice as the impulse vector calculated in the reconstruction and through the application of the software PC-Crash is the same in direction and value. This is an index of correctness of the hands calculations, as the rest positions of the vehicles found on scene, that coincide with rest position in PC-Crash project (Figure 12).
This shows that the reconstruction of the dynamics of the accident determined is correct: in fact the software, introducing the inputs calculated in reconstruction, gives as output the rest positions of the vehicles.
The direction of the impulse coincides with the direction of the residual deformations found on the vehicles, further confirmation of the reliability of the reconstruction.

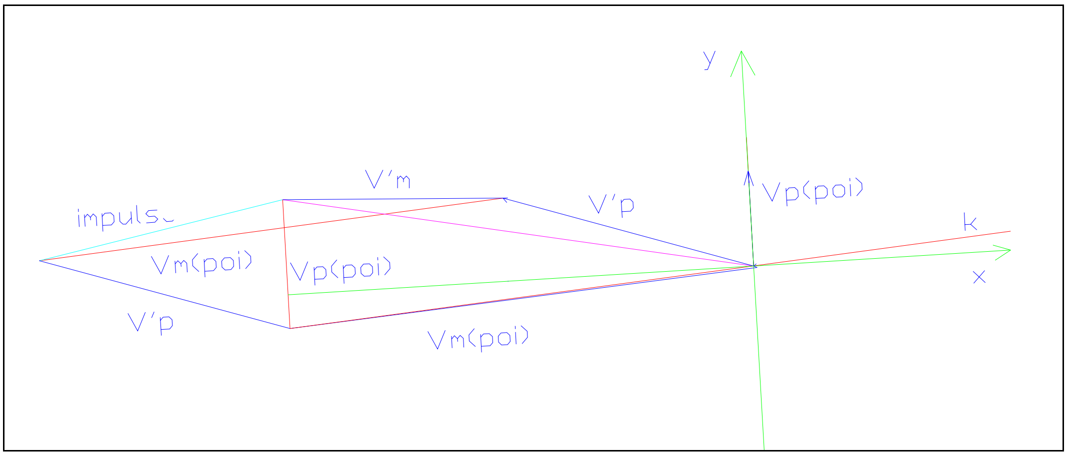

Figure 10 Graphic application of conservation of momentum.

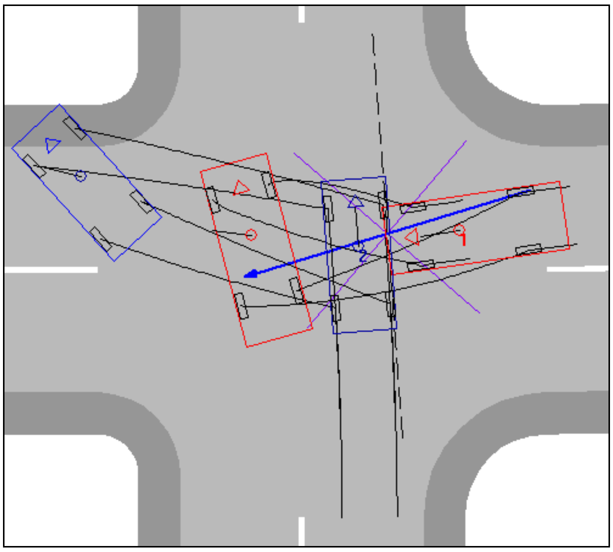

Figure 11 PC-Crash application.

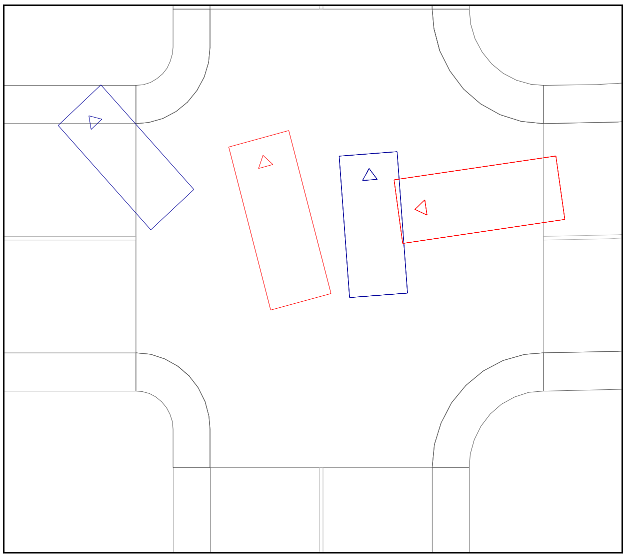

Figure 12 Rest position from PC-Crash

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The presence on the road surface of skid-marks left by the tires of both vehicles allows to calculate the vehicles speeds to the beginning of lockup of wheels, through a kinematical calculations.

The decelerations of the vehicles during braking phase have been esteemed according to the conditions of the road surface, using the results of sliding-test for vehicles under conditions of full braking on new dry asphalt surface. It is assumed for both vehicles an average acceleration value of:

$$a_{lockup} \approx 7{,}5 \pm 0{,}5 m/s^2 .$$

Skid-marks produced by vehicles have been measured in the plan:

d_M (lockup) = 1,5 m
d_P (lockup) = 7,5 m

$$v_{lockup} = \sqrt{v_{impact}{}^2 + 2 \cdot a \cdot d}$$

$$V_{Mlockup} = \sqrt{16{,}4^2 + 2 \cdot 7{,}5 \cdot 1{,}5} = 17 m/s = 61{,}3 km/h$$

$$V_{Plockup} = \sqrt{5{,}1^2 + 2 \cdot 7{,}5 \cdot 7{,}5} = 11{,}8 m/s = 42{,}3 km/h$$

The time during this phase is:

$$t_{lockup} = \frac{v_{lockup} - v_{impact}}{a_{lockup}}$$

$$t_{Mlockup} = \frac{17 - 16{,}4}{7{,}5} = 0{,}08 \sec$$

$$t_{Plockup} = \frac{11{,}8 - 5{,}1}{7{,}5} = 0{,}89 \sec$$

Some experimental studies reveal that from the start of braking (foot on the pedal) to the wheels locking the deceleration of the vehicle grows from zero to a maximum value (static friction); it decreases afterwards and it is nearly constant during the lockup of the wheels (dynamic friction). During this type of motion it is assumed a constant deceleration, equal to the average value of the deceleration that grows from zero to the maximum value. During this time, around 0,2 sec for cars, the deceleration has been assumed equal to 4 m/s^2 (average deceleration from 0 to maximum typical values).
The speed in the instant in which the braking system begins working (foot on the pedal) is:

$$v_{braking} = v_{lockup} + at$$

$$v_{Mbraking} = 17 + 0{,}2 \cdot 4 = 17{,}8 m/s = 64{,}1 km/h$$

$$v_{Pbraking} = 11{,}8 + 0{,}2 \cdot 4 = 12{,}6 m/s = 45{,}4 km/h$$

During this time, the Peugeot distance travelled was:

$$d_P = \frac{\left(v_{braking}{}^2 - v_{lockup}{}^2\right)}{2a} = \left(12{,}6^2 - 11{,}8^2\right)\frac{1}{2 \cdot 4} = 2{,}4m$$

During the reaction phase of the driver, before braking, it is supposed that the vehicles were proceeding at constant speed. If the time from perception to the beginning of the locking wheels is one second, the time until the starting of the braking is 0,8 seconds.
The distance travelled in this phase by the Peugeot is:

d_{Pr} =12,6*0,8 = 10,1 m

The total distance travelled by the Peugeot from the point of impact to the point of perception is the sum of the distance of braking, the distance travelled during the lag time and the distance travelled during the reaction phase:

$$d_{PTot} = 7{,}5 + 2{,}4 + 10{,}1 = 20m$$

The Peugeot, in the instant in which the driver perceived the approaching Mercedes (1,9 seconds before the impact), is 20 m from the impact point, and the speed was about 45 km/h.
The vehicles positions at the perception time of the Peugeot driver are shown in Figure 13.

Supposing that also the time from the perception to the beginning of the Mercedes locking wheels is 1 second, the driver perceived the Peugeot about 1,1 seconds before the impact.
The distance travelled during the lag time is:

$$d_M = \frac{\left(v_{braking}{}^2 - v_{lockup}{}^2\right)}{2a} = \left(17{,}8^2 - 17^2\right)\frac{1}{2 \cdot 4} = 3{,}5m$$

The distance travelled from the instant of perception to the beginning of the braking is:

d_{Pr} = 17,8*0,8 = 14,2m

We calculate now the position of the Mercedes at the instant in which it was perceived by the Peugeot, therefore about 1,9 sec before the impact. From the instant of perception of the Mercedes is considered a constant speed motion for 0,8 sec. The travelled distance is therefore:

$$d_M = 17{,}8 \cdot 0{,}8 = 14{,}2m$$

The total distance travelled by the Mercedes in 1,9 sec, from the impact point until the instant in which the Peugeot driver perceived the presence of the other vehicle, is the sum of the partial distances previously calculated.

$$d_{M(tot)} = 1{,}5 + 3{,}5 + 14{,}2 + 14{,}2 = 33{,}4m$$

In plan it is shown that, in the position of perception, the Peugeot has just passed the visual obstruction constituted by the hedge. As it is calculated, the Mercedes driver perceived the Peugeot 0,8 second later, because, as he said, he was not thinking that a vehicle coming from its left would not have gave him the right of way.

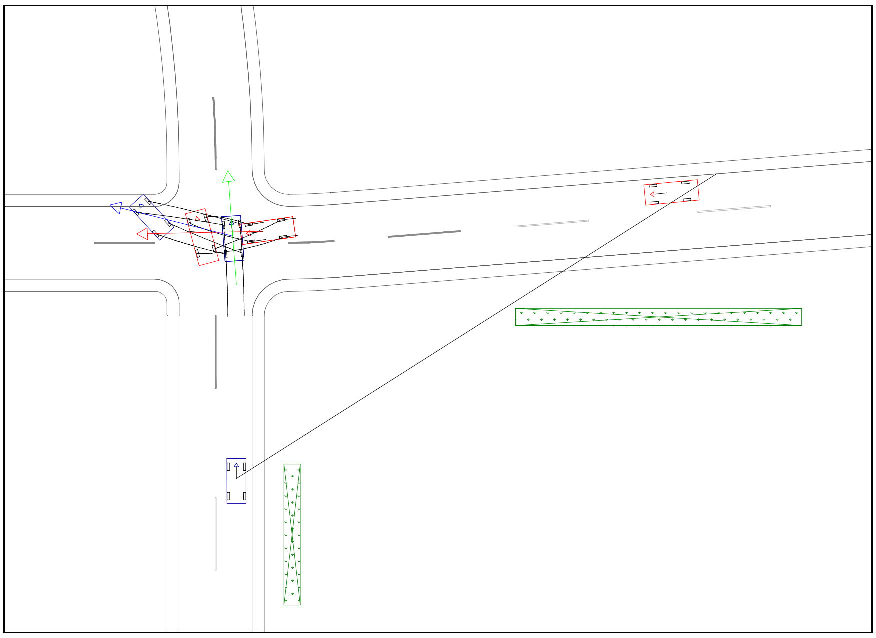

Figure 13 Vehicles positions at Peugeot perception time

ANALYSIS OF POSSIBLE EVASIVE MANOEUVRES

Case 1 - The Driver Of the Mercedes Decides to Accelerate to Avoid The Collision

At the start of braking (foot on the pedal) the Mercedes was about 0,3 seconds from the impact. In this hypothesis we suppose that in this time the Mercedes accelerates with a constant acceleration, about 1,5 m/s^2, reasonable for this vehicle and for its speed in that instant.
The braking distance of the Mercedes, was about 5 m long. Covering these 5 m in acceleration, the Mercedes would have had at the impact a speed value of:

$$v_{impact} = \sqrt{v_a^2 + 2 \cdot a \cdot d} = 17{,}8^2 + 2 * 1{,}5 * 5 = 18{,}2 m/s = 65{,}6 km/h$$

and the time is:

$$t_{Macc} = \frac{18{,}2 - 17{,}8}{1{,}5} = 0{,}27 \sec$$

The Mercedes therefore would have saved 0,03 seconds to cover the 5 meters and the two vehicles would have reached the impact with the same configuration, but with a slightly higher speed of the Mercedes 8due to the acceleration). In this case the collision would not have been avoided and in that situation the decision to brake was correct.

Case 2 - The Driver Of the Mercedes Perceives the Peugeot 0,5 sec before

In this case we hypothesize that the Mercedes driver perceived the Peugeot 0,5 sec before than it happened, as soon as the Peugeot was visible out of the hedge: this situation would be occurred if the Mercedes driver had checked approaching vehicles from his left. In this case the instant of perception for the Mercedes driver is therefore 1,6 seconds before the impact, and since its speed is 17,8 m/s, it is 28 m from the impact.
From the instant in which the driver begins to brake, he spends 0,2 sec up to the locking wheels; during this time the vehicle brakes with a constant average deceleration of 4 m/s^2 (average deceleration from zero to maximum available). The speed at the beginning of locking wheels will be therefore 17 m/s. The distance covered by the instant of beginning braking to the instant of locking wheels is 3,5 m.
Since the Mercedes covered 14,2 m (0,8 seconds) in reaction and 3,5 m (0,2 seconds) during the phase of braking, at the instant of locking wheels was 10,4 m from the impact.

The speed of the Mercedes at impact will be therefore:

$$v_M(impact) = \sqrt{v_{lockup}^2 - 2 \cdot a \cdot d}$$

considering the same deceleration as before (7,5 m/s^2), we have:

$$v_M(impact) = \sqrt{17^2 - 2 \cdot 7{,}5 \cdot 10{,}4} = 11{,}5 m/s = 41{,}5 km/h$$

that is about 17 km/h less than it happened.
The time during the phase of locking wheels is:

$$t_{Mlockup} = \frac{17 - 11{,}5}{7{,}5} = 0{,}73 \sec$$

The Mercedes would have reached the impact 0,6 second later, allowing the Peugeot to go on.
The Peugeot speed at impact was 18 km/h and it was braking with deceleration of 7,5 m/s^2. If the Peugeot had kept on braking for 0,6 seconds more, it would have had the speed:

$$v_{+0,6} = v_{impact} - at = 5 - 7{,}5 * 0{,}6 = 0{,}5 m/s = 1{,}8 km/h$$

and it would have covered a further space, equal to:

$$d_P = \frac{\left(v_{impact}^{\ 2} - v_{+0,6}^{\ 2}\right)}{2a} = \left(5^2 - 0,5^2\right)\frac{1}{2 \cdot 7,5} = 1,7m \cdot$$

So also in this case the collision would not have been avoided, but it would have had a different configuration (Figure 14) with smaller damages due to the lower speed of Mercedes.

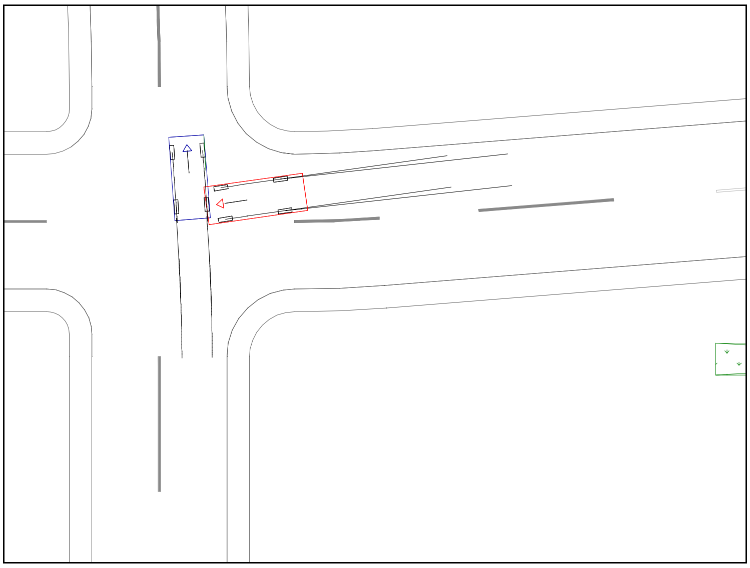

Figure 14 Impact configuration (case 2)

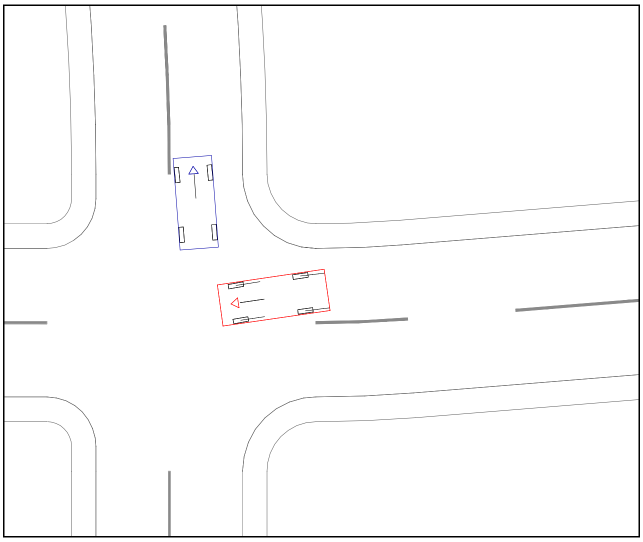

Figure 15 Vehicles positions. Mercedes at impact (case 3)

Case 3 - The Driver Of the Peugeot Decide to Accelerate Rather than to Brake

We hypothesize that the Peugeot driver decides to accelerate. Considering that at the instant of the perception of the Mercedes the Peugeot speed was about 45 km/h, we use an average acceleration value a = 1 m/s2 (typical for that vehicle).
The time from the instant of beginning braking to the impact was 1,1 seconds, comprehensive of the braking phase before to lock the wheels. If in this distance the Peugeot had accelerated, it would have had a speed of:

$$v_P = v_{acc} + at$$

$$v_P = 12,6 + 1 \cdot 1,1 = 13,7 m/s = 49,4 km/h \,.$$

In this phase the Peugeot would have covered a space of:

$$d_P = \frac{\left(v_P^{\ 2} - v_{acc}^{\ 2}\right)}{2a} = \left(13,7^2 - 12,6^2\right)\frac{1}{2 \cdot 1} = 14,5m$$

The distance covered by braking Peugeot was 10 m long; so if the driver of the vehicle had accelerated rather than braking, he would have covered about 4,5 m more, and he would have avoided the impact passing in front of the Mercedes (Figure 15).

CONCLUSIONS

This reconstruction methodology could appear simple, but it allows to consider every variable linked to the accident and to estimate it according to the tests results. The target of the methodology is to determine the causing factor of the accident and to study the avoidance possibilities.

The width of results values is directly linked with parameters interval of assumption. Best it is the knowledge of these assumption and more reliable is the reconstruction of the accident dynamics and kinematics.

The reconstruction of a real phenomenon as an accident sometimes implies the impossibility to get precise answers, because evidences on scene are not enough to reconstruct the accident.

The correct point of impact location, rest positions and vehicles directions before and after impact are very important for a good parameters assumption. The correct interpretation of the evidences left by the vehicles on the road surface during the accident is an important factor to calculate speeds, time and distance covered by vehicles. It is also important, for safety analysis, the study of the different consequences if the drivers behaviours had been different. The first results define how much the human behaviour is linked to the definition of the risk level and as different decisions can bring to different results.

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