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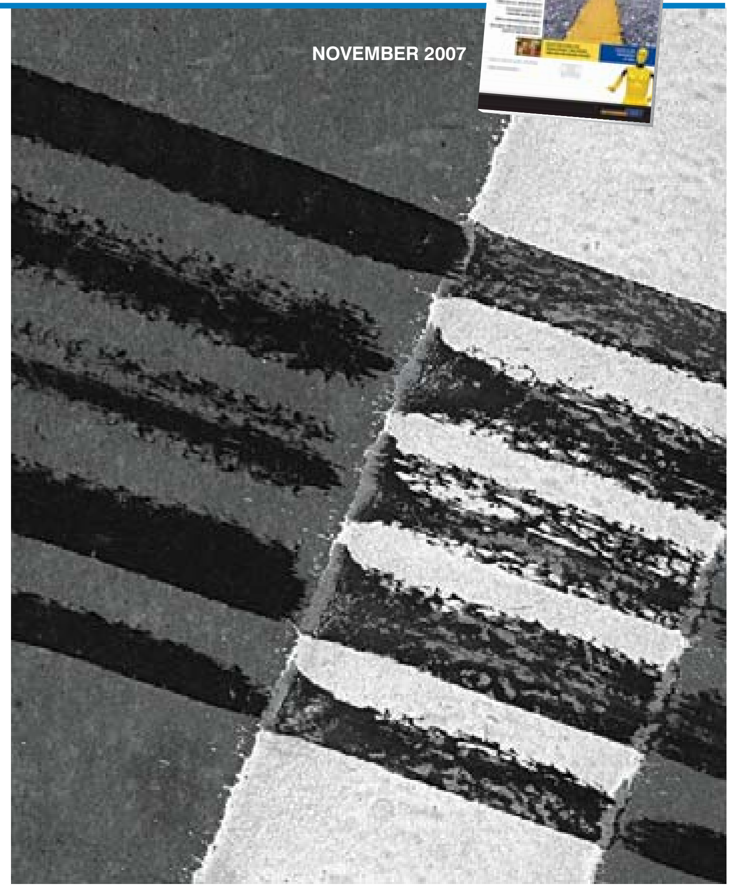

Auto accident reconstruction: The basics you must know

Understanding what the engineer is talking about and how conclusions are reached

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Introduction

What is Accident Reconstruction? Accident reconstruction is the process using scientific methodology to determine the circumstances, mechanics, and contributing factors associated with a collision. It requires a working knowledge of many disciplines including physics, vehicle dynamics, mathematics, photogrammetry, and computer applications (i.e. spreadsheets, AutoCAD, simulation or modeling tools, graphics and photo-management software). Questions such as, "How fast was the vehicle going at impact?" or "How much did the vehicle slow during the locked-wheel braking?" or "At what angles did the two vehicles collide?" can be answered by the reconstructionist after thorough evaluation of available information.

This article presents several basic concepts typically found in the area of investigation and reconstruction of vehicle collisions. The following material is not intended to be comprehensive, but should be considered an overview of fundamental principals. These concepts are presented as they commonly apply to collisions involving passenger cars. Other areas of analysis not included are collisions involving heavy trucks and other articulating vehicles, or impacts involving pedestrians, motorcycles and bicycles.

Information sources

Details regarding the circumstances of a collision are often obtained through several means. Two basic sources of information are the Traffic Collision Report, and photographs of the vehicles and collision scene. Additional sources to be considered are witness statements and deposition transcripts. Oftentimes the eye witnesses may fill the gaps between what can be observed in photographs and what the traffic officers included in their reports. Emergency personnel run-sheets, medical records, and autopsy reports can provide useful and thorough descriptions of occupant injuries. Injury location may be used to help support opinions regarding vehicle dynamics. Repair estimates, crash test reports, and vehicle specifications provide data necessary for calculations when vehicle weight, dimensions, and property damage are used. Published research and literature can help assist the reconstructionist when a specific engineering principal or phenomenon is being analyzed.

Vehicle inspection

Inspection of the collision vehicle is most helpful when performing a reconstruction. While the study of photographs of vehicle damage is important, many details about the degree of vehicle deformation can be vague or not fully documented in such photographs. Therefore, a vehicle inspection is often preferable. If a two-vehicle collision is being analyzed, inspection of both vehicles should be requested. This often requires additional leg work, because the location and condition of the other vehicle are seldom known.

Vast amounts of information can be gleaned by inspecting the collision vehicle, such as the quantification of the vehicle crush profile. In addition, simply standing next to, or even sitting in the damaged vehicle and considering the extent and direction of the structural deformation lends crucial insight into collision type and severity.

What can be learned at an inspection that cannot be learned from reviewing vehicle photographs? One example is the confirmation of ground contact to the vehicle undercarriage. Colliding vehicles will often pitch downward during the collision phase to the extent that suspension members or other undercarriage components strike the road surface and create a gouge. Along with pre-impact skid marks or post-impact tire marks, gouge marks are often among the list of physical evidence documented by the investigating traffic officer. Determination of which vehicle component interacted with the roadway and their location relative to some vehicle-fixed reference point may support opinions regarding vehicle position and heading at the time of impact. Photographs of the accident vehicles rarely depict undercarriage damage.

Another example supporting the utility of vehicle inspections can be the existence of grass or debris trapped in door openings. The existence of this material may help to confirm the door came open during the collision or rollover event. Even grass or dirt embedded in the junction between the tire bead and wheel rim may help confirm tire separation during the collision as opposed to this occurring during vehicle storage after the tire goes flat. Oftentimes, photographs do not yield this level of detail, and inspection of the vehicle is the only way to confirm these potential phenomenon.

Because evidence inside or outside the vehicle can only degrade with time, a secure and indoor vehicle storage is strongly recommended. Proper vehicle storage should be considered sooner rather than later.

Fundamental terms and common units

The results of the collision reconstruction may include pre-impact speed, vehicle heading, post-impact speed, and change of velocity (or delta-v). The principal direction of force, collision duration, and peak or average vehicle acceleration may also be evaluated. However, before one can fully comprehend the significance of the terms commonly used by reconstruction specialists, a review of fundamental terms and units may be helpful.

Four fundamental physical parameters are length, time, force and mass. Typical units for length (or distance) are inches, feet, or meters. For time, seconds are commonly used. The units of force are pounds or Newtons; for mass, slugs or kilograms. It should be noted that mass and weight are often used interchangeably, but the true relationship between mass and weight is **w = mg**, where **w** is weight, **m** is mass, and **g** is the gravitational constant equaling about 32.2 ft/s^2.

Derived terms and common units

Derived terms are algebraic combinations of the four fundamental parameters. Derived terms commonly used by the reconstructionist are velocity, acceleration, energy (work), and momentum. Velocity is the rate change of distance with respect to time, or length per unit time, with units of **mph** or **ft/s** (also written as **fps**). Acceleration is the rate change of velocity with respect to time, or length per unit time squared. Units for acceleration are **ft/s^2**, or **g's**.

Energy (work) is length times force (or force times distance), with units of **ft·lb**, or **in·lb**, and momentum is mass times velocity, with units of **lb·sec**, or **slug·ft/s**.

Speed and velocity are different entities, although in colloquial speech these two words are often, although inaccurately, used interchangeably. By definition, speed is a scalar quantity having only magnitude. Recall that speed is the rate change of distance. However, velocity is also the rate change of distance, but velocity is a vector quantity with magnitude and direction.

Additional terms and definitions

Several other important terms include delta-v (or Δv), principal direction of force (PDOF), center of gravity, yaw, coefficient of restitution, and coefficient of friction. Delta-v is the vector difference between the pre-impact and post-impact velocities, or the velocity difference between when the vehicles first come in contact to when they separate. Of note, the time between first contact and separation is called the collision phase of the impact, the time during which the vehicles deform. Therefore, by definition, Δv does not include any pre-braking speed loss or speed lost by the vehicle after separation before coming to rest.

Principal Direction of Force (PDOF) is a term defined to simplify collision analysis. The PDOF is the direction of the summation of all collision forces required to deform the vehicle. When two vehicles come in contact, they begin to deform at some force

level. The surfaces of each vehicle in contact change over time, because of vehicle deformation, and they continue to change throughout the collision phase. As an analogy, picture two rectangular sponges being pressed together. Initially, the two sponges may touch at the corners, or at each end, but with increased force, the area of the contact surface of each sponge increases. Similar in concept to the sponge, the structure of a vehicle deforms in an impact. Forces are required to deform a vehicle structure, however over the collision phase, the forces change direction and magnitude. As the vehicles continue to engage, new structures are deformed. Instead of analyzing the work and moment contributions of all these collision forces over all the directions of the impact, reconstructionists study the one collision force applied to the vehicle along the principal direction of force.

The direction of the PDOF is often given in terms of degrees or hours of a clock dial. For example, a force directed toward the front of a vehicle along its centerline would have a 0 degree or 12 o'clock PDOF. A force from the right would have a 90 degree or 3 o'clock PDOF. Furthermore, a force directed toward the rear of a vehicle along its centerline would have a 180 degree or 6 o'clock PDOF. Interestingly, Δv and PDOF are related in that the PDOF acts on the vehicle in the direction of the Δv.

The center of gravity, or **cg**, is simply the balance point of a vehicle. To simplify the analysis of a colliding vehicle, the entire mass of the vehicle is defined to be located at the **cg**. In reality, this does not occur, but still the vehicle's **cg** is a useful reference for study. One can calculate the fore-aft location of the **cg** by applying a moment balance using the front and rear axle weights. However, vehicle occupants can shift the **cg** fore or aft to some degree, and the apportionment of passenger weights to the front and rear axles should be considered. Also, the **cg** may actually be slightly to the left or right of the vehicle centerline, but for most applications one can assume the **cg** is centered laterally.

Yaw is rotation of the vehicle about a vertical axis passing through the vehicle **cg**. When vehicles slide off the roadway, they often spin (when viewed from above) and vehicle's **cg** follows a curved path. This curved path is indicative of a vehicle in yaw. Yaw will be studied in a misapplication of the skid to stop equation presented later.

Restitution is why vehicles often bounce away from the other vehicle or rebound from a rigid barrier after an impact. Vehicle collisions are called inelastic, and property damage often results. However, while the vehicle structure does deform, there is some portion of this damage that is restored. The restoring forces are what cause restitution.

The coefficient of restitution of two colliding objects is defined as the ratio of the relative rebound velocities to the relative impact velocities. The coefficient of restitution, commonly given the variable name ε, is unitless and can have a value of between 0 and 1. For two colliding vehicles, the equation for coefficient of restitution can be written as:

$$\varepsilon = (v_1' - v_2') / (v_1 - v_2)$$

where v_1 and v_2 designate the pre-impact velocities, and v_1' and v_2' designate the post-impact velocities, for vehicles 1 and 2 respectively. When a vehicle impacts a rigid barrier, the equation simplifies to:

$$\varepsilon = v_1' / v_1$$

Since the barrier has no velocity before and after impact, the v_2' and v_2 terms drop from the equation. By way of example, vehicles impacting a rigid barrier at 30 to 35 mph exhibit restitution values of between about 0.15 and 0.2. However, as collision speeds decrease, restitution often increases. For this reason, it is crucial to have accurate values of ε when studying a low-speed collision.

The coefficient of friction is why vehicles slow down, upon applying the brakes. The friction coefficient is also a unitless value. It is often given the variable name **F**, and is a measure of the relative slipperiness of two surfaces in contact. In the case of a vehicle in a locked-wheel skid, the two surfaces are the roadway and the tires. By definition, $\mu = F/w$, where **F** is the friction force that must be overcome to move an object of weight **w**.

As an illustration, a commonly used value for a vehicle's coefficient of friction under full locked-wheel braking on asphalt is 0.7. However, more accurate friction coefficients for a specific road surface may be obtained by conducting a brake test with an appropriate exemplar vehicle. Special consideration must also be used with ABS equipped vehicles.

Skid analysis

The general velocity equation is:

$$v_f^2 = v_i^2 + 2ad$$

where v_f is the final velocity in **fps**,
v_i is the initial velocity in **fps**,
a is acceleration (friction coefficient times **g**) in **ft/s²**,
and **d** is the skid distance, or length of the tire mark in feet.

This equation can be used for any condition when a vehicle changes velocity. With strict adherence to the sign of the velocity and acceleration terms, this equation can be used not only for the slowing vehicle, but for the vehicle increasing in velocity as well.

The general velocity equation is often applied to vehicles braking to a stop. In this case, v_f is zero, so the general equation simplifies to the skid to stop equation:

$$0 = v_i^2 + 2ad$$

or $$v_i^2 = -2ad$$

The general velocity equation can be rearranged algebraically so the value of v_f, v_i, **a** or **d** can be solved. Two examples will be used to illustrate this point.

Example 1

If a vehicle traveling at 60 mph suddenly brakes on asphalt (assume μ = 0.7), what is the final velocity after 132 feet of lock-wheel skid?

Here v_i = 60 mph or 88 fps
d = 132 feet
μ = 0.7, a = -0.7g

$v_f^2 = v_i^2 + 2ad$
$v_f = \text{sqrt}(v_i^2 + 2ad)$
$v_f = \text{sqrt}(88^2 - 2(0.7)(32.2)(132))$
$v_f = \text{sqrt}(7744 - 5950.56)$

v_f = 42.3 fps = 28.9 mph

Example 2

If a vehicle traveling at 60 mph suddenly brakes to a stop on asphalt (assume μ = 0.7), what is the length of the locked-wheel skid?

Here v_i = 60 mph or 88 fps
v_f = 0 mph
μ = 0.7, a = -0.7g

$v_f^2 = v_i^2 + 2ad$
$0 = v_i^2 + 2ad$
$d = -v_i^2/2a$
$d = -88^2/2(-0.7)(32.2)$
$d = 7744/45.08$

d = 171.8 feet

These examples are theoretical or text book applications of the general velocity equation. Consideration must be given to real world braking system components. For instance, vehicles do not leave skid marks immediately upon stepping on the brake pedal. The rotating wheels need time to slow and lock prior to leaving tire marks. As such, it has been shown that vehicles can have about 15 to 20% more energy prior to leaving discernible tire friction marks than when calculated with the general velocity equation.

The skid to stop equation is commonly applied in instances of rear-end or other "unavoidable" collisions. Estimates can be made of the distance necessary for a vehicle to skid to a stop based on a pre-braking speed and a friction coefficient. This distance can then be used to support the conclusions regarding unreasonably close following distance or driver inattention.

Misapplication of concept

Without proper training and experience, the skid to stop equation can be misapplied in certain situations. As an illustration, consider a vehicle that loses control and comes to rest in the opposing traffic lanes. Assume a detailed scene diagram including physical evidence shows the vehicle was in yaw. The path of the vehicle **cg** and vehicle orientation can be determined by using a scale cutout or rendering of the vehicle and placing it over tire marks on the diagram. This will help determine the yaw angle throughout the vehicle trajectory. The yaw angle is the included angle between the vehicle's centerline and the path of the cg. Assume an accurate coefficient of friction of the roadway was obtained by brake testing conducted on site.

Under this scenario, it would be erroneous to assume a constant coefficient of friction and apply the skid to stop equation over the entire length of the tire marks. Wheels roll in a direction perpendicular to the wheel axis, but wheels will slide in a direction parallel to the wheel axis. As such, when a vehicle is in yaw, the wheels will either roll, slide, or a combination of both depending on its yaw angle. Over estimating the vehicle pre-yaw speed will likely occur, because the friction coefficient increases with yaw angle.

To correctly calculate the friction coefficient, the distance over which the vehicle slides should be broken into segments, and the average yaw angle for each segment be determined. The coefficient of friction of each segment is the sine of the yaw angle multiplied by the coefficient of the friction determined through on-site brake testing. Therefore, the correct initial speed can be determined by first applying the skid to stop equation to only the last segment adjacent to where the vehicle came to rest. Then, while working backward, the general velocity equation is applied to each segment in succession up to the first segment where the initial pre-yaw speed is determined.

Collision analysis methods

The choice of method or methods employed to analyze a collision depends on the amount and type of information available. A momentum analysis can be used if there is adequate documentation of the physical evidence at the collision scene, such as pre-impact skid marks, point of impact, and vehicle rest positions. If the collision vehicles are available for inspection, a damage energy approach may be used. If, in the absence of the collision vehicles, photogrammetry may be used. Sometimes hand calculation methods can be supported or refined with the use of commercially available, computer-based reconstruction or simulation programs. Agreement between two or more methods is an excellent way to gain confidence in the analysis and resulting final opinions.

Momentum

The Law of Conservation of Momentum can be applied to vehicle collisions. In the case of a two-vehicle collision, the system is the two colliding vehicles. The Law states that the momentum of the system before and after the collision must be conserved, that is, the pre-impact momentum equals the post-impact momentum. The general momentum equation from which many useful forms can be derived is:

$$m_1v_1 + m_2v_2 = m_1v_1' + m_2v_2'$$

where m_1, m_2 are the masses of vehicles 1 and 2 respectively,

v_1, v_2 are the pre-impact velocities of vehicle 1 and 2 respectively,
and
v_1', v_2' are the post-impact veloci ties of vehicle 1 and 2 respectively

Momentum is a vector quantity having direction and magnitude. From the general equation, it can be seen that the units of momentum are **slugs** or **kg** (mass) times **ft/s** or **m/s** (velocity), or **lb·sec** or **N·sec**.

The main reason to use momentum is to determine the pre-impact speed of the vehicles. To begin the analysis, the mass, the direction before and after impact, and the post-impact speeds for each vehicle are needed. The directions of the vehicles before and after the collision may be determined by studying at-scene physical evidence, like intersection or road geometry, tire marks or debris scatter patterns. The general velocity equation, along with an appropriate deceleration, may be used to determined post-impact velocities.

Computer reconstruction

There are many commercially available reconstruction and simulation programs written specifically for personal computers costing from several hundred to several thousand dollars. The reason these tools are often used by the reconstruction specialist is because of the large number of calculations that can be completed over very small increments of time throughout the collision event. Also, input parameters can be slightly modified, and the new output to be considered will be available in less time than when doing calculations by hand. However, output from these tools is only as accurate as the data that is input.

Photogrammetry

Photogrammetry is a technique whereby photographs are used to determined relative size and location of physical evidence present at a collision scene. In instances where inspection of the damaged vehicle is not available, vehicle crush apparent in photographs can be studied, and property damage can be quantified with acceptable accuracy using this technique.

Good quality photographs are essential. Several views of the object taken from different angles are necessary to allow the photogrammetry software to establish user-selected reference points. Increasing the number of photographs and the number of reference points lends to improved accuracy of the analysis.

Conclusion

Collision reconstruction is the study of impacting objects that include passenger cars, vans, trucks, bicycles and pedestrians. Collision reconstruction encompasses many engineering principals that can be thought of as the tools available to the reconstructionist. The choice of tools to be used depends on the amount and detail of information available. One or more tools can be applied to study the same collision. Close agreement in the results obtained by two or more methods provides increased confidence.

Weiss

Kurt D. Weiss is an engineer consultant with Automotive Safety Research, Inc. He has more than 17 years of experience in the field of collision reconstruction supported by a Master of Science degree in Mechanical Engineering. Weiss has significant experience in forensic testing, including numerous tests of seat belt assemblies and sub-components, as well as full-scale vehicle sled tests. He has attended many technical sessions and has authored peer-reviewed papers regarding topics and phenomena relevant to collision reconstruction.