Forensic collision investigation

A PRIMER FOR COURTS

THE ROYAL SOCIETY

RSE
The Royal Society of Edinburgh
KNOWLEDGE MADE USEFUL

This primer is produced by the Royal Society and the Royal Society of Edinburgh in conjunction with the Judicial College, the Judicial Institute and the Judicial Studies Board for Northern Ireland.

Forensic collision investigation: a primer for courts
Issued: January 2022 DES7309
ISBN: 978-1-78252-571-4

To request additional copies of this document please contact:

The Royal Society
6 – 9 Carlton House Terrace
London SW1Y 5AG
T +44 20 7451 2571
E law@royalsociety.org
W royalsociety.org/science-and-law

This primer can be viewed online at
royalsociety.org/science-and-law

Contents

Science and the law primers
Foreword

The judicial primers project is a unique collaboration between members of the judiciary, the Royal Society and the Royal Society of Edinburgh. The primers have been created under the direction of a Steering Group initially chaired by Lord Hughes of Ombersley who was succeeded by Dame Anne Rafferty DBE, and are designed to assist the judiciary when handling scientific evidence in the courtroom. They have been written by leading scientists and members of the judiciary, peer reviewed by practitioners and approved by the Councils of the Royal Society and the Royal Society of Edinburgh.

Each primer presents an easily understood, accurate position on the scientific topic in question, and considers the limitations of the science and the challenges associated with its application. The way scientific evidence is used can vary between jurisdictions, but the underpinning science and methodologies remain consistent. For this reason we trust these primers will prove helpful in many jurisdictions throughout the world and assist the judiciary in their understanding of scientific topics. The primers are not intended to replace expert scientific evidence; they are intended to help understand it and assess it, by providing a basic, and so far as possible uncontroversial, statement of the underlying science.

The production of this primer on understanding forensic collision investigation has been led by Dame Amanda Yip. We are most grateful to her and to the Executive Director of the Royal Society, Dr Julie Maxton CBE, the Chief Executive of the Royal Society of Edinburgh, Dr Rebekah Widdowfield, and the members of the Primers Steering Group, the Editorial Board and the Writing Group. Please see the back page for a full list of acknowledgements.

Sir Adrian Smith
President of the Royal Society

Sir John Ball
President of the Royal Society of Edinburgh

1. Summary, introduction and scope

The aim of this primer is to assist the judiciary and legal professionals in understanding the principles and practice of the collection and analysis of evidence from a road collision, as presented in the courts.

Forensic collision investigation is the analysis of the available physical evidence from the scene of a road collision and from an examination of the vehicles, together with an interpretation of human factors, such as reaction time, to assist the court to reach a conclusion as to the way in which the incident occurred. The process is concerned with the vehicles, their occupants and any pedestrians involved in the moments leading to the collision, the collision itself and what happened afterwards. Usually the assessment of the speeds of the vehicles and the opportunities for the drivers to respond to any hazards that arise are of primary importance. Investigations look at eyewitness testimony both to consider the plausibility of what is said when compared with the physical evidence and to assist in resolving any ambiguities in the interpretation of the physical evidence. However, it is important to remember that it remains exclusively the province of the judge or jury to assess the reliability and credibility of the witnesses and to decide the facts and questions of legal responsibility, based on all the available evidence (Liddell v. Middleton [1996] PIQR P36).

An investigation typically follows a number of stages. First there is the collection and recording of the available evidence, followed by an analysis of that evidence together with calculations to assess what happened and how the collision came about. A report is then prepared for the court. It is for the court to decide whether the evidence is admissible.

Collision investigation is a wide-ranging subject encompassing Newtonian mechanics, highway characteristics, mathematical methods, human behaviour and materials science. This primer cannot equip the judiciary and legal professionals with this knowledge but it should be useful for signposting where problems may arise and where external expertise may be needed.

The primer has five further sections and two appendices. Section 2 considers the collection and sources of physical evidence at the scene of a collision. Section 3 describes the scientific methods used to analyse and reconstruct the events leading to the collision and the collision itself, based on the available evidence. Emphasis is placed on sources of uncertainty and approximation in the reconstruction of an accident as presented to the court. Section 4 addresses the questions the court may wish to consider in collisions involving pedestrians. The use of computers in reconstructing collisions is discussed in Section 5. Section 6 considers human factors, such as when an object or person could be perceived in the lighting available at the time of the accident and the response times of drivers.

2. Collection and sources of evidence

2.1 Who collects the evidence?

In most of the UK, the collection of evidence and the subsequent preparation of expert witness reports in criminal cases is performed by trained police staff (see Section 3.1). In Northern Ireland, Forensic Science Northern Ireland (FSNI) will usually attend the scene of a fatal collision and will jointly conduct the investigation with the police. They will also be responsible for interpreting and presenting the technical evidence to the courts. However, FSNI will only rarely be involved in the investigation of collisions that do not involve a fatality. In most other European countries the police collect and record the physical evidence, after which a qualified engineer performs the analysis and writes the report.

Almost all the evidence from the scene of a collision will be recorded by the police, but sometimes there are photographs etc from passers-by or occasionally from the press. The best quality evidence will be gathered by trained collision investigators, although they may be asked to attend only when injuries are fatal or appear likely to be. If everyone involved in the collision survives and there are no criminal proceedings, the investigator may be asked to complete a brief report only for internal use by the police, and their evidence, such as photographs, measurements and survey data, may be filed away and remain unprocessed. This can impede eventual civil proceedings.

2.2 Sources of evidence

2.2.1 Tyre marks

Tyre marks deposited on a road or other surface may provide information about the behaviour of the vehicle which made them. A rolling wheel can produce a tyre print on soft surfaces such as mud. Sliding and locked wheels produce smears on soft surfaces and skid or scuff marks on hard dry surfaces. However, locked-wheel tyre marks have become more scarce because anti-lock brake systems (ABS), which in most circumstances prevent the wheels locking, have been gradually introduced from about 1984 and have been mandatory on all new cars in the European Union (EU) since 2015. Tyre marks can sometimes, but not always, be produced by ABS-equipped vehicles, although they are much less distinct. The benefit of ABS is not only improved braking on most surfaces, but also the retention of the ability to steer (it not being possible to steer with locked wheels). Figure 1 shows marks made during ABS braking. The lengths of ABS braking marks or, on the relatively rare occasions when they occur, locked wheel skid marks can in most circumstances be used to estimate the speed of the vehicle which made them. A locked wheel which has left a tyre mark also receives a characteristic ‘burn’ on the tyre from where it has been in contact with the ground. This is helpful in identifying which tyre on a vehicle made a mark. Where a vehicle has not remained at the scene of a collision, tyre marks can be helpful in identifying it.

FIGURE 1

ABS tyre marks. Note that they curve, showing that the driver was able to steer.

Vehicles which are being steered hard on a curved path can also produce marks owing to their tyres scuffing on the road surface. When the steering is so hard as to take the tyres very close to the limit of the available friction with the road, characteristic striated tyre marks are produced by the buckling of the tyres. The curvature of these marks can generally be used to assess the speed of the vehicle; see Section 3.3. They are commonly known as critical speed or critical yaw marks, and an example is shown in Figure 2.

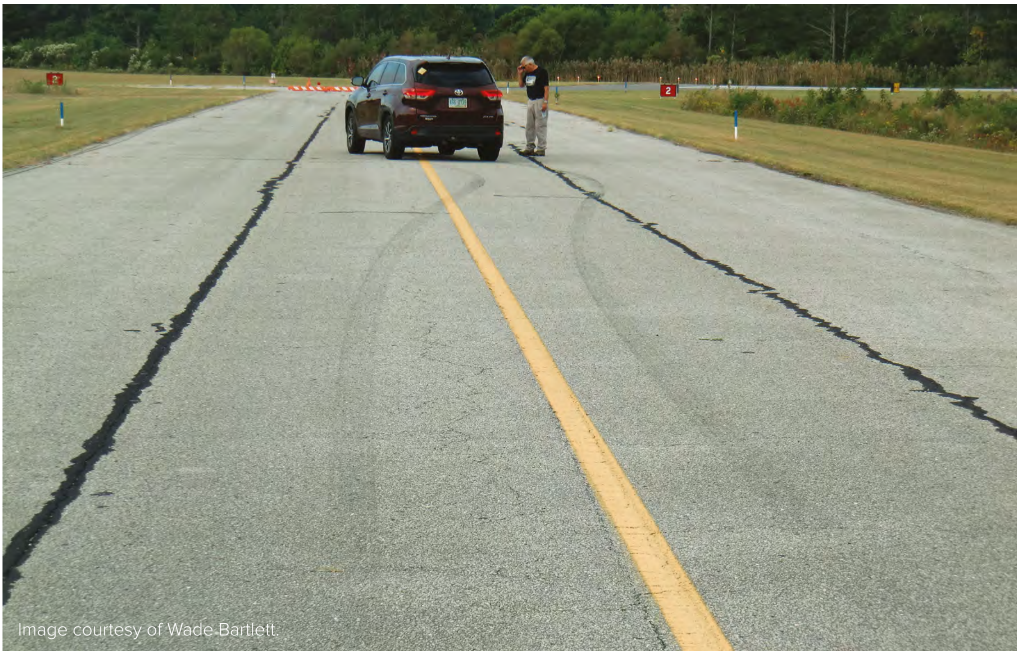


Image courtesy of Wade Bartlett.

FIGURE 2

Critical speed marks.

The vehicle was travelling away from the camera and the marks were left by the wheels on the outside of the curve: the more clearly defined, striated, mark was made by the front left tyre; the less distinct mark to the left was made by the rear left tyre, tracking outside the path of the front tyre. Occasionally there will be a similar pair of marks made by the tyres on the inside of the curve: had they been present in the event shown here, they would have been to the right of these marks. The striations are the diagonal stripes that are visible within the length of the clearer mark.

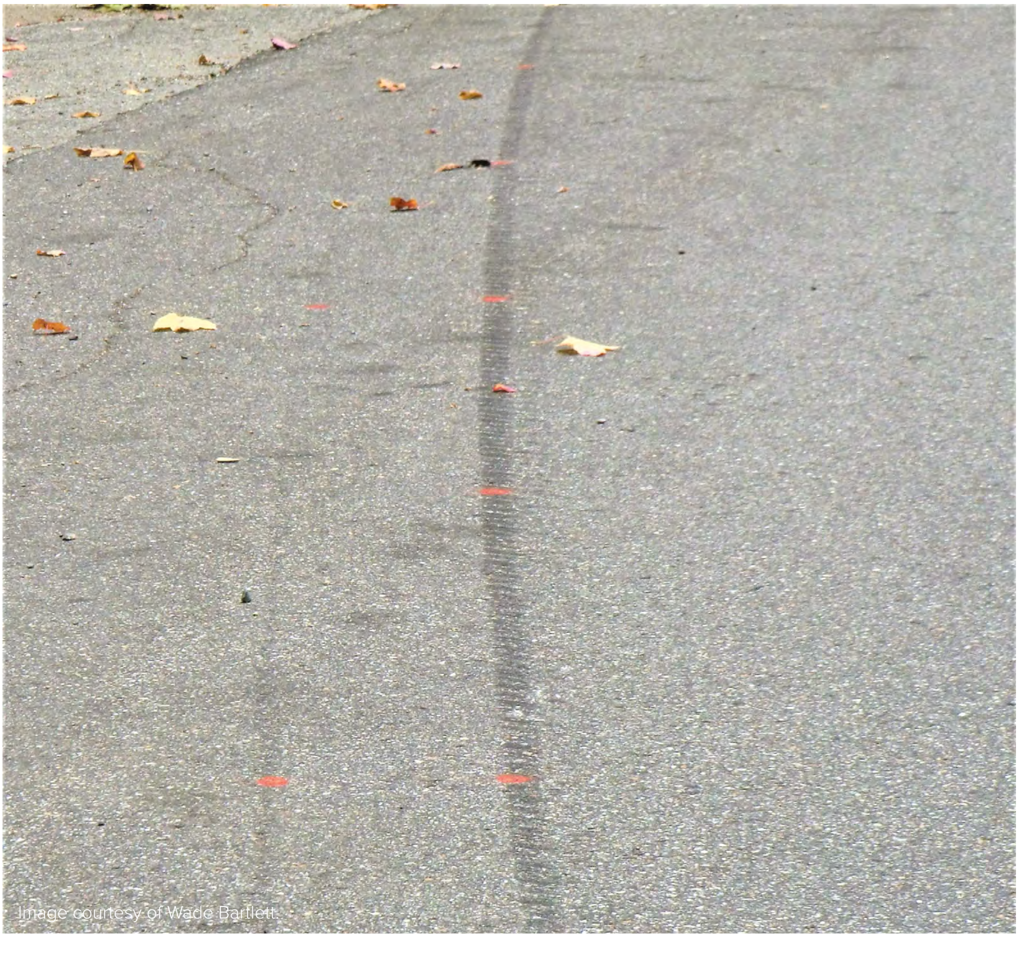


Image courtesy of Wade Bartlett

2.2.2 Other evidence from the scene of a collision

In a collision, items are frequently detached from vehicles, eg windscreen glass or plastic from light lenses. The position of the debris on the road surface can be used to estimate the position of a vehicle when the collision occurred, provided account is taken of the velocity of the vehicle at the moment of collision. However, items under internal stress, such as fragments from toughened glass windows, can be projected away from the vehicle in a different direction, and this too needs consideration.

In pedestrian collisions, the point of impact with a vehicle can sometimes leave a small scuff on the road from the footwear of the pedestrian. Bicycles and motorcycles also sometimes leave scuff marks from their tyres when they are struck. The point where a person lands and then comes to rest may also be evident. Techniques exist to estimate the speed of a striking vehicle from the distance between the impact and rest points: these are discussed in Section 3.2 and Appendix B. Bicycles and motorcycles also often leave scratches in or paint smears on the road surface if they slide a distance, the length of which can also be used to estimate speed; see Section 3.5.3.

The primary tools for recording evidence at the scene of a collision are photographs of the features of interest and a scale plan to show the location of those features. Measurements will often be made using an electronic device, and the plan will be drawn with a computer-aided design (CAD) system. Electronic measuring devices include a point-by-point surveying device called a 'total station', laser scanning, Global Positioning System (GPS) point-by-point measurements and photogrammetry. All of these collect data in three dimensions, and therefore three-dimensional models of scenes can be made which may demonstrate what can and cannot be seen by participants and witnesses. With point-by-point survey methods the position of any single point is likely to be accurate to about ±20 mm, depending on the degree of care taken by the surveyor. With a laser scanner the accuracy should be even greater, although it will be reduced significantly if the angle of incidence to the surfaces being measured is shallow. This is common with scans of more distant road surfaces; to reduce these errors and to capture areas hidden behind other objects, a number of separate scans is generally required. The separate scans are then combined to produce a composite scan of the entire scene. However, centimetre-level precision is frequently not necessary for scene measurements; in many circumstances, measurements with a simple measuring wheel will be sufficient.

Certain features in the prepared scale plan, such as dashed white lines along the centre of the road, may be generated by the CAD software without reference to their actual locations. This comes about because to survey the overall path of the line along the road is quicker than surveying each individual line segment. This can lead to the position of debris next to a line in a photograph appearing to be in a different position on a plan. If the position of the start and finish of a particular dash within the overall line is important, for example because of a tyre mark overlaid on it, then the surveyor should record those points explicitly.

Drones or a crane are used in some cases to take an overhead photograph of the scene, and it is becoming common to use such photographs, suitably annotated, to replace the scale plan. Although not to scale and suffering from optical distortions, these do serve to demonstrate the relative positions of various features of interest.

Satellite or aerial images are also commonly used to provide a template from which a plan of the road layout can be drawn, provided the images are up to date. Using suitable software, the image can also be scaled. Such images do not, of course, contain the vehicles involved or any marks or debris, but these can be added to the image if sufficient photographs exist to estimate their positions.

2.2.3 Evidence from vehicles and occupants

The overall pattern of damage to vehicles can yield information as to the way in which a collision occurred. For example, it can reveal which parts of two vehicles came into contact, the direction of the impact force onto a vehicle and, in favourable circumstances, how much speed was lost by, or imparted to, a vehicle. Careful recording of damage is therefore essential.

Defects in vehicles can contribute to a collision, eg faulty brakes or steering systems and inadequate tyre treads (see also Appendix B.2). An examination of the vehicles involved will generally be performed in more serious incidents. Where a component has failed, the question arises as to whether it failed before the collision, and therefore contributed to the event, or it was damaged in the collision itself. An assessment of the reason for a failure may require the services of a materials scientist or an expert in tyre technology and behaviour.

Some types of speedometer freeze if the power supply is interrupted, as may happen in a crash. The frozen reading can then be helpful in assessing the speed at that moment (Goddard and Price, 2017). However, the reliability of such readings does depend on the particular model of speedometer; at best, the reading can only indicate the speed when power was lost, which may not have occurred at the very start of a collision sequence.

An analysis of any filament bulbs fitted to a vehicle can also yield information as to whether the bulb was illuminated. For example, it may be possible to identify whether brake lights were illuminated and therefore that the brakes were activated at impact. However, no method is yet known for performing the same analysis with light-emitting diode (LED) lamps. It should also be noted that many modern vehicles have autonomous braking systems; see Appendix B.3. If such a system is fitted the illumination of the brake lights does not necessarily mean the driver was operating the brake pedal. This may have implications, for example, when using closed-circuit television (CCTV) evidence of a collision and considering if and when a driver reacted.

Examination of seat belts can provide information as to whether they were in use. If they are neatly stowed and clamped after a substantial collision it is likely they were not used. A belt which is in use will yield slightly in a frontal impact, resulting in stretching and marking of the belt. However, specialist training is necessary to distinguish between faint marks caused in moderately severe collisions and wear or polish marks from everyday use. It is also necessary to consider both the position of the marks on the seat belt and the fitment of any devices such as pre-tensioners to ensure that the marks are due to restraining an occupant rather than the pre-tensioning device, or the occupant connecting the belt but not actually wearing it.

Occupants of vehicles can also provide physical evidence. Injury to occupants can often be correlated with damage to the interior of the vehicle, providing information on how they moved relative to the vehicle during the collision and therefore the direction of forces on the vehicle. Their injuries can also provide information as to whether seat belts were in use. These are generally known from medical examination, but appropriately qualified and experienced engineers can often provide useful insight. It should be noted that the occupant protection systems in modern vehicles were developed primarily by engineers by studying injury patterns and mechanisms, and not by medical professionals.

2.2.4 Electronic data from vehicles

In modern vehicles there are numerous electronic devices which record data, although the accessibility, resolution and accuracy of the data vary widely. The data may come from sources within the vehicle (speedometer, tachograph (for larger goods and passenger vehicles), throttle and brake application, the state of various control systems etc) or externally – principally location and speed derived from GPS signals. Such data may be readable by anyone with the appropriate downloading software, but the validation and interpretation of the data should be undertaken by someone who understands the data sources and any shortcomings they have. Appendix A describes the current principal sources of these electronic data and their limitations. This is a rapidly changing scene, with new electronic recording devices being developed and introduced into vehicles.

3. Collision reconstruction

3.1 Who investigates collisions?

The majority of collision investigators deployed by the police in the UK are either serving police officers or civilian police staff, except in Northern Ireland, as mentioned in Section 2.1. These investigators are likely to hold either a City and Guilds qualification (discontinued in 2013) or a University Certificate of Professional Development (UCPD) awarded by De Montfort University, or else a Scottish Police College certificate validated by the Scottish Qualifications Authority (SQA). These qualifications are broadly similar and are based on a mixture of practical and academic skills. They do not involve the same level of analytical and mathematical skills as those developed in a university degree in engineering or physics.

Police in the UK, being focused on possible criminal prosecutions, have traditionally been taught to write their reports in such a way as to take any uncertainty in a direction which is favourable to the potentially culpable party. For example, this usually involves stating the minimum speed which their calculations indicate for the vehicle, rather than giving the most likely speed or saying how much more the speed could possibly be. Different considerations may apply in civil cases, where the most likely speed is often required, and may even mislead potential litigants. A shift towards reporting 'best estimate' speeds rather than minimum speeds is, however, taking place in response to a requirement by the Forensic Science Regulator.

3.2 Speed from tyre marks

Whenever a car is braked, the tyres slip against the road surface. This is known as tyre slip and is usually expressed as a percentage, with 0% representing a fully rolling wheel and 100% representing a non-rotating, locked wheel. Initially the slip increases with increasing braking force, typically reaching a maximum at around 15 – 20% slip. Beyond 20% slip the braking force reduces and wheel lock quickly follows. The term 'skidding' is often used wherever there is slip, but collision investigators tend to use the word 'skidding' when one or more tyres have locked, corresponding to 100% slip.

In the past, skid marks were used extensively to estimate the speeds of vehicles involved in collisions, but these have become rarer following the progressive introduction of ABS. In ABS braking the slip of the tyres is regulated, generally keeping the amount at around 15 – 20% in smaller vehicles. Systems for larger vehicles work slightly differently, cycling between free rolling and locking up. Tyre marks from ABS-equipped vehicles are therefore much rarer but can still be found on occasion, particularly for large goods vehicles. There can be a difference in the deceleration achieved by different vehicles equipped with ABS. Caution should therefore be exercised by an investigator attempting to calculate the speed of a vehicle from ABS tyre marks, the more so if the nearside and offside tyres are on different surfaces or the vehicle moves from one surface onto another. In such situations, the sophistication of the ABS will influence the deceleration. It should also be noted that goods trailers do not always have ABS fitted to every axle. There can be occasions when locked wheel marks are left by the tyres on some axles of such a vehicle, and this does not necessarily indicate a defect in the brakes. ABS will not work at very low speeds, so short skid marks can often be found just before a vehicle stops.

From the length of a tyre mark at the scene of a collision, and knowing the speed of the vehicle at the end of the tyre mark, it is possible to assess the speed of the vehicle at the beginning of the tyre mark. This calculation relies on an estimate of the vehicle's deceleration, which is generally assumed to be constant throughout the braking as long as the road is dry, which is when most tyre marks are left.

When there are tyre marks at the scene of a collision, Appendix B describes how they are used to estimate the speeds of the vehicles involved and the uncertainties that arise. The technique is not limited to vehicles that brake to a stop. If the final speed is not zero, then it is possible to use that value together with the deceleration and length of the tyre mark to calculate the initial speed. It is not correct, as is sometimes naively done, to simply add the final speed to the speed indicated by the tyre mark in isolation. The correct mathematical procedure is shown in Appendix B.4. Different methods, such as the assessment of speed from momentum or damage described in Sections 3.5.1 and 5.2, may sometimes be used to calculate the speed of a vehicle at the end of a sequence of tyre marks left by that vehicle.

Since January 2016 all new motorcycles with an engine capacity over 125 cc have been fitted with ABS. At the time of writing this primer, there is insufficient test data available to clarify the interpretation that should be placed upon the presence, or absence, of tyre marks from motorcycles fitted with ABS.

3.3 Speed from critical speed marks

The curved and striated tyre marks generally known as 'critical speed marks' are an indication that the car which made them was travelling at or near the maximum speed that could be sustained along the curved path it was following. Figure 2 shows a typical set of marks. The radius of the curved path is found by measuring a section of the marks at the accident scene; using a simple equation, the speed of the car is then calculated from the radius and an estimate of the sliding frictional force (see Appendix B.1). The equation effectively assumes that the speed of the car changes little over the measured section, and this is justified provided the marks do not diverge by more than about half the track width of the vehicle (which is typically about 1.5 metres). The method is valid whether or not the car is fitted with ABS. The simple equation can be modified for scenarios where there is a lateral slope owing to the road having a crossfall. It should be noted, however, that striated tyre marks can be generated in ways other than by steering, eg by a vehicle spinning after a collision. The technique is not applicable in those cases.

The radius of curvature of the offside front tyre mark of a car at critical speed has been found to reflect the radius of the path of the vehicle as a whole with sufficient accuracy, provided certain guidelines are met for the appearance of the marks over the section to be measured (Lambourn, 1989). It is possible to measure the radius with a simple tape measure, but it requires great care to achieve good accuracy. Police collision investigators nowadays tend to measure the marks either from an electronic total station survey or from a laser scan of the scene, although the latter method often requires the marks to be highlighted on the ground so that they can be identified in the scanned image.

The accuracy of this technique depends on the exact manner in which the vehicle was being driven, eg whether under constant power, coasting or being braked or else with incorrect tyre inflation pressures. A standard published by the Society of Automotive Engineers (SAE Ground Vehicle Standard, 2017) draws on a comprehensive review of the published research and states that conservatively, without regard to the manner of driving, the range of uncertainty could be from -13.5% (erring with a calculated speed too low) to +10% (erring with a calculated speed too high). If the manner of driving is known, or can be stated as a probability, the range can be reduced with reference to the research literature, eg as listed in the SAE document.

Normally it is the sliding frictional force which is used in the calculations (Wach, 2013), which is usually assessed via a skid test with locked wheel braking. Occasionally, if testing has been done with active ABS, a value closer to the peak force will have been employed. The use of this higher value will tend to overestimate the speed, and some researchers advocate using an average of the sliding and ABS values (Cliff *et al.*, 2004).

Since November 2014 the fitting of Electronic Stability Control (ESC) has been mandatory on all new cars sold in the EU, although it has been present in some models since 1995. In a sharp steering manoeuvre ESC cuts the engine power and selectively applies the brakes to retain control if an imminent loss of control is detected; this reduces significantly the probability of clear critical speed marks being left. It does not invalidate the calculation method as long as the tyre marks under consideration are true critical speed marks. However, with ABS or ESC, it is possible to leave curved tyre marks as a result of heavy braking while cornering, which may look similar, but the application of the critical speed equation to such marks would be erroneous and would lead to an overestimate of the speed. It is therefore essential that the nature of the marks is examined by an experienced collision investigator to identify that striations are present, or that the progression of the marks indicates their nature, before applying this technique to a set of tyre marks.

3.4 Aquaplaning

Aquaplaning, or hydroplaning as it is sometimes called, occurs when a layer of water builds between one or more tyres of a vehicle and the road, leading to loss of contact and therefore of braking and steering ability. It is a term which is often misunderstood and misused. There are occasions when a vehicle goes out of control on a wet road and it is asserted that the vehicle must have aquaplaned. Usually no marks are found on the road to identify the path of the vehicle beforehand; however, marks found on a soft verge can be used to infer a general course of the vehicle in the latter stages of its trajectory, but not the origin of the loss of control.

Before invoking suggestions of aquaplaning, it should be noted that inadequate tyre tread depth, the vehicle speed and the texture of the road surface can in themselves combine to create a situation in which a driver is unable to brake or steer sufficiently to avoid an obstacle or negotiate a curve in the roadway. This does not necessarily mean that the tyres ever reached a true state of aquaplaning.

A typical scenario in which a loss of control could occur in very wet conditions, without aquaplaning, would arise if a vehicle were fitted with almost new tyres on the front wheels and tyres with little or no tread on the rear wheels. Particularly when travelling at high speed, such a car could be directionally unstable and may oversteer when cornering (Williams and Evans, 1983).

The Horne equation (Horne and Dreher, 1963) is sometimes used to assess the threshold speed at which aquaplaning occurs in terms of the tyre pressure. When applied to road vehicles it is too simplistic. The shape and size of the tyre contact print need to be taken into account, bearing in mind that the print can change significantly when the vehicle is carrying more mass (weight), as with a goods vehicle (Horne, 1984). The texture depth of the road surface and the efficiency of the tread pattern of the tyre at dispelling water are also significant factors. Some vehicles can aquaplane at less than the threshold speed of the Horne equation and others may not aquaplane until they reach speeds significantly higher than the Horne threshold speed (Navin, 1995).

Loss of control without true aquaplaning can also occur as a result of asymmetric tyre drag, which is when the tyres on one side of the vehicle encounter deeper water than those on the other side (Hight *et al.*, 1990). When travelling at speed this can cause a 'pull' on the steering, leading to a partial loss of directional stability. A driver may instinctively apply corrective steering, which may lead to further swerving and possibly total loss of control as the vehicle leaves the area of deep water.

3.5 Other speed calculations

3.5.1 Momentum

In addition to tyre mark analysis, there are physical principles including the conservation of linear momentum and the conservation of angular momentum which can be used to analyse the motion of vehicles just before and just after an impact. When two vehicles collide, their total linear momentum is the same immediately before and after the collision, as is their total angular momentum. Strictly speaking these conservation laws are valid when the only forces acting on the vehicles are those acting between them during the impact. However, there will be other forces acting on them during the impact that arise from friction of the tyres on the road. In a severe collision these forces are negligible in comparison with the impact forces acting between the vehicles during the short period of the impact, but the cumulative effect of the tyre forces over a longer period of time, ie while the vehicles are moving to rest, can be as great as, or greater than, the effect of the impact.

There is another relevant conservation law in physics, namely the conservation of energy. To apply it to a collision requires an estimate of the energy absorbed in damaging the vehicles at impact. This is discussed in Section 5.2.

The court is likely to be interested in the speeds of the vehicles just before their impact. The conservation of linear momentum can be used to assess the speeds of vehicles only at the moment of impact. Provided the investigator can assess the post-impact velocities (speeds and directions) of the two vehicles, then together with the masses of each, and knowing the directions from which they approached the collision, it is usually possible to calculate the impact speeds. However, if the pre-impact directions are collinear (either nose-to-tail or head-on), knowing the masses of the vehicles and their velocities after the impact is insufficient to assess their velocities before impact. In that situation one needs either an estimate of the energy loss in the collision or the pre-impact speed of one of the vehicles to be able to assess the pre-impact speed of the other vehicle, otherwise the calculation is not possible.

There are some circumstances in which the equations used can become sensitive to small changes in the input data. One arises when the mass of one vehicle is several times the mass of the other. In this situation the calculated pre-impact speed of the lighter vehicle becomes more sensitive to the post-impact velocities, and the greater the difference in vehicle masses, the greater the sensitivity. For example, in a car-to-motorcycle impact any pre-impact velocity calculated for the motorcycle will be of limited accuracy whereas the velocity calculated for the heavier vehicle in such a collision will be much less sensitive to the accuracy of the data.

Impacts close to head-on or nose-to-tail also become particularly sensitive to the exact angle used for the calculations, as the impact angle tends towards a straight line. When the impact angle is within about 10° of a straight line a more realistic result may be calculated by treating the impact as head-on or nose-to-tail instead, although, as before, this will require additional input data.

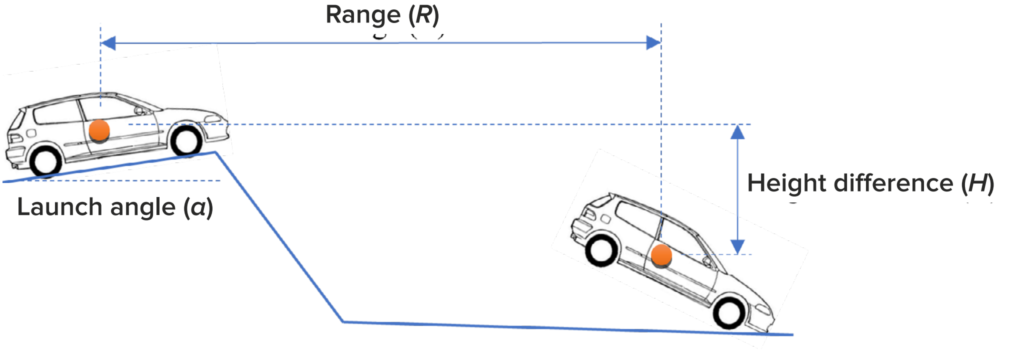
3.5.2 Projectiles

When an object – a whole vehicle, a part of a vehicle or something struck by a vehicle – is projected from one known point to another, the initial speed of the object can be calculated from the distance it travelled using a simple formula, provided the launch angle is known and also provided air resistance can be ignored. The neglect of air resistance is reasonable if the object is compact and heavy. If there is a significant difference in height between the take-off and landing sites that also has to be taken into account in the calculation.

If debris is projected from a vehicle on impact the launch angle is usually not known. If its initial landing point and its launch point are known, then the distance it has travelled can be measured. This distance is called the range, R. The minimum speed at which the debris was launched may be calculated by assuming an optimum value for the launch angle α, ie the angle which gives the maximum range for a given speed. In some circumstances this provides a useful estimate of the minimum speed for the vehicle itself. On the level the optimum launch angle is 45°. If the true launch angle lies between 30° and 60° the error in the calculated minimum speed will be no more than 8%. This is why in criminal investigations it is common to assume 45° for the launch angle. But if there is a significant difference in height, H, between the launch and landing heights a different optimum launch angle is calculated using a simple formula involving the range and height difference. If the launch height is greater (or less) than the landing height then the optimum launch angle is less (or greater) than 45°. The minimum launch speed of the projectile is then easily calculated.

FIGURE 3

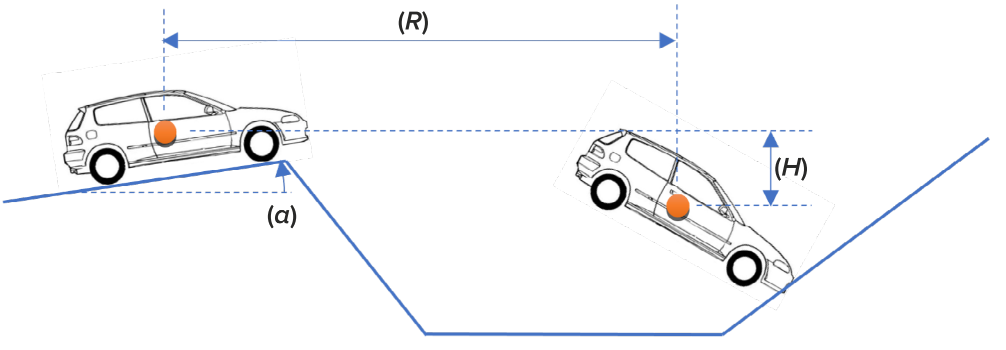
Vehicle launch from a ledge. The orange dot is the centre of gravity of the car.



If the object is large, the range *R* of its trajectory is defined by how far its centre of gravity travels horizontally. An example would be a whole car driving off a ledge, as in Figure 3. It would be incorrect to say that the range is defined by where the car lands. Similarly the distance *H* the car falls is defined by the difference in height of its centre of gravity when its front wheels leave the ledge and when the car first strikes the ground. In some circumstances a vehicle may strike a more vertical surface first, such as when a car drives into a hole at roadworks and strikes the opposite wall of the hole, as shown in Figure 4. It is evident in Figures 3 and 4 that the rotation of the vehicle during its flight has to be taken into account to obtain the correct values of *R* and *H*. This usually requires computer modelling.

FIGURE 4

Vehicle launch from a ledge into a hole and striking the opposite wall.



Further complexities arise if the vehicle has travelled only a short distance on a 'launch ramp' between leaving the roadway and becoming airborne. The effects of the vehicle's suspension compressing and then rebounding can result in the actual launch angle being significantly different from the angle of the ramp.

3.5.3 Tumbling and sliding

The motion of an object which has tumbled along the ground cannot be modelled in detail because it depends significantly on the structure of the object, how it deforms, how it started to tumble and the surfaces on which the tumbling occurred. As with rolling a die, the general direction of its motion can be predicted, but its exact path cannot.

When a rider falls from a motorcycle or bicycle and the machine falls to the ground, it may slide on its side, or tumble or a combination of both. Marks left on the ground and the vehicle will assist in identifying whether the vehicle has slid, tumbled or both, since tumbling marks will usually be intermittent whereas sliding marks will be more continuous. To assess the speed of a motorcycle or other vehicle that has travelled in such a manner, it is necessary to measure the overall length of the motion from the first mark to where it ended. This distance is normally used in calculations, not the lengths of individual scratches or scuffs.

Although less accurate than assessing speed from tyre marks, the speed lost when sliding or tumbling is assessed by identifying the average deceleration of the vehicle, similarly characterised by an effective coefficient of friction. Many research papers have attempted to assess the coefficient by dropping motorcycles from moving vehicles at known speeds and measuring the distance they travel to rest (Lambourn, 1991; Medwell *et al.*, 1997; Meuwissen and Spatjens, 2013). However, when the test vehicle (motorcycle) lands on the ground there is a momentary pulse of high deceleration, which slows the motorcycle at a higher rate than occurs during the subsequent sliding. The magnitude of this pulse depends on the height from which the motorcycle is dropped (Wood *et al.*, 2008). If drop tests have been undertaken an expert should make it clear whether the initial high deceleration has been allowed for in the subsequent assessment of the coefficient of friction.

If evidence is presented to the Court relating to speed lost by a sliding motorcycle or other object, it should be clarified how the deceleration was assessed. If it has been assessed by reference to published research, it should be clarified whether the tests were drop tests, in which the motocycle was dropped at speed and allowed to slide to rest, or slide tests, in which the motorcycle was pulled relatively slowly along the road surface.

A better approach, when possible, is to measure the coefficient of friction by means of a drag test at the scene. Sometimes a drag test is carried out for part of a vehicle, such as a panel of the bodywork, by dragging it along the ground. In these tests it is important that the part is loaded to prevent it from bouncing and to ensure it engages realistically with the surface rather than skating over it. Published tests will be helpful, but care must be taken that they are a reasonable match to the surface in question. For example, it has been shown that the effective friction of a verge can vary with the type of grass, whether it is long or short, dry or wet. It should also be noted that fibreglass fairings on motorcycles usually reduce the coefficient of friction. Published tests are usually carried out on level surfaces. Gradients present in the surface under consideration will modify the deceleration.

Calculations of this type are not always suitable for incidents involving bicycles struck by motor vehicles since they are sometimes propelled forcefully to the ground or become momentarily trapped under the impacting vehicle, impeding the start of the trajectory.

While motorcycles tend to slide, cars and larger vehicles will more often develop a tumbling motion. On occasion the rollover can be initiated purely by the vehicle cornering too quickly without hitting anything, although this is usually only with taller vehicles such as vans and lorries. It can also be initiated by an impact with another vehicle, or by starting to slide out of control and then encountering a 'trip' hazard, such as a kerb or uneven ground.

Published empirical research tends to show higher overall decelerations for vehicles that are tumbling than for those that are sliding. It also shows that taller vehicles that tumble end-over-end are unlikely to be accurately represented by tests which involve vehicles tumbling side-over-side. It is vital that any results of tests presented to the court are closely related to the circumstances of the event under consideration. A rule of thumb used for many years is that a tumbling vehicle will decelerate at an average rate of between 0.4g and 0.65g, where g is the acceleration due to gravity (g = 9.8 m/s^2). More recent research (Rose *et al.*, 2018) suggests that the lower end of the range is more commonly applicable, and some tests have shown deceleration rates of a little over 0.3g.

3.5.4 Contaminated road surfaces

Sometimes a vehicle skids on a surface that is heavily contaminated with, for example, mud, spilt diesel fuel or gravel. Water itself could be classed as a contaminant, and while the effects of liquid water and ice have been thoroughly researched (eg Sabey *et al*. 1970; Martin & Schaefer, 1996), other materials can be discussed only in general terms. In all cases the amount of friction between a tyre and the road surface is a complex function of tread depth, road surface texture, the particular properties of the contaminant and perhaps the temperature.

The friction of wet surfaces is discussed in Appendix B. For other contaminants, the literature may provide some guidance, eg Lambourn and Viner (2006), Meyers and Austin (2012) and Granlund (2017), although the clear message from research testing is how variable the results are for a given contaminant, depending on the surface texture, tread depth and speed of the vehicle. The only certain procedure is to carry out testing at the scene in question with an appropriate vehicle under the same conditions.

The table of typical coefficients of friction of various surfaces which appeared in several editions of a classic collision investigation book (Stannard-Baker, 1953, 1957, 1963, 1975) should be mentioned. This table is frequently encountered in other publications and also in the manuals of various teaching institutions. Although the values given in that table are reasonable, the current edition of the same book (now authored by Fricke) acknowledges their limitations and no longer includes the table on which so many continue to rely (Fricke, 2010).

4. Collisions with pedestrians

4.1 Introduction

There are several aspects of collisions between vehicles and pedestrians that are of interest to the courts. These may include:

- the impact speed of the car;
- whether the pedestrian was running or walking;
- the direction in which the pedestrian was moving or facing; and
- the potential for the injuries sustained by the pedestrian to be reduced if the impact speed had been lower.

Some of these topics are explored well in the literature. Car design has changed considerably in the last few decades and therefore certain aspects of the older literature must be treated with caution.

4.2 Typical collision

The textbook description of a typical car-pedestrian collision is that an adult pedestrian will first have their legs struck by the bumper of the vehicle. At impact speeds of a few miles per hour (mph) the pedestrian may fall onto the bonnet, or the friction between their feet and the ground may be sufficient to hold them so that they fall away from the car. At higher speeds the impact will sweep the pedestrian's legs from under them so that they fall against the bonnet and tend to slide up it, leading to a secondary impact with the pedestrian's torso. If the collision speed is less than around 15 mph it is unlikely that there will be a substantial contact between the pedestrian's head and the vehicle. But at speeds of more than around 15 mph the pedestrian's head will also strike the vehicle. As the impact speed increases there is a higher probability of the head contact being severe.

The combined effect of these impacts to the legs, torso and head is to propel the pedestrian along the road in the same direction as the vehicle. The pedestrian will be accelerated to a speed similar to that of the vehicle but may then move ahead of the vehicle if it is braking, or else over the roof and land behind it if it is not braking. The vehicle will slow down slightly owing to some of its momentum being transferred to the pedestrian; however, since the vehicle is many times heavier than the pedestrian, this is a small effect (eg Ashton, 1982).

A paper by Ravani *et al.* (1981) categorised the 'typical' movement of pedestrians struck by vehicles into five classes:

- Wrap, in which the pedestrian 'wraps' onto the bonnet of the vehicle before being projected ahead of it. In these cases the initial contact is below the centre of gravity of the victim.
- Forward projection, in which the pedestrian's upper torso is rapidly accelerated in the direction of the vehicle and projected ahead of it. This is common for cases of children hit by cars and adults hit by vehicles with a relatively vertical front face.
- Fender (bumper) vault, which is usually associated with impacts close to the front corner of a vehicle. In these cases the pedestrian falls to the side of the vehicle rather than onto the bonnet.
- Roof vault, in which the pedestrian is projected into the air.
- Somersault, which is an extension of the 'wrap' classification to encompass cases in which the pedestrian somersaults before landing.

This classification is still in common use, although most reconstructions will refer only to 'wrap' or 'forward projection'. Marking and damage to the vehicle will usually indicate whether the pedestrian sustained a wrap, a roof vault or a somersault. With changes in vehicle shapes there is a difficulty in defining the difference between forward projection and wrap in some cases. Some published research gives slightly different calculations for wrap and forward projection trajectories; others do not make a distinction.

The five classes have been found to be adequate descriptors for only about 80% of accidents studied. For example, glancing collisions are outside the classification.

4.3 Assessing the speed of a vehicle from pedestrian projection distance

This discussion relates to pedestrians who are projected by the collision. If a pedestrian is carried, pushed or pulled along the road there is no simple relationship between the speed of the vehicle and the distance the pedestrian travels after impact.

The pedestrian projection distance is normally defined as the distance along the roadway from the point of impact to the final resting position of their centre of gravity, and not to where they first land. If at least part of the pedestrian's trajectory is across the roadway, it may be partly or wholly due to their own pre-impact speed.

There are numerous scientific papers in the literature both describing the physics of combining the airborne and sliding components of the pedestrian's motion (eg Han and Brach, 2001; Wood *et al.*, 2005; Searle, 2009) and giving test data (Sturtz *et al.*, 1976; Brun-Cassan *et al.*, 1984; Randles *et al.*, 2001; Fugger *et al.*, 2002; Otte, 2004; Becke and Marten, 2009), which are used to 'calibrate' the mathematical models. Hague (2001) describes a mathematical model based on assessing speed from the distance a pedestrian actually slides, rather than the overall projection distance. The ranges of speeds predicted by the various models have a high degree of overlap largely because they all use overlapping sets of experimental data to fit the parameters of the models.

The issues that may arise in the models include:

- Does the vehicle's shape have a significant effect on the calculations?
- Does the pedestrian's stature have a significant effect on the calculations?
- Does the vehicle's and/or the pedestrian's mass matter?
- What if the pedestrian was struck by the corner of the vehicle?
- What if the pedestrian was carried on the vehicle, or bounced on it more than once?
- Does the walking/running speed of the pedestrian matter?

The vehicle's shape matters: if the vehicle has a flat front, such as a bus, then the pedestrian will be accelerated up to a common speed with the vehicle. This is known as a 100% projection efficiency. However, if the vehicle has a low front, such as a sports car, then the contact may be insufficient to accelerate the pedestrian up to a common speed with the car, and the impact is said to have less than 100% projection efficiency. For example, if a car strikes a pedestrian at 40 mph but the pedestrian is accelerated to a speed of only 36 mph along the road, this is a 90% projection efficiency. A calculation based on pedestrian projection may underestimate the speed of the car unless the projection efficiency is considered.

The stature of the pedestrian can matter in certain situations. For example, a small child struck by a car is likely to have a 100% projection efficiency, whereas an adult struck by the same car may have more slippage during the bonnet and windscreen contacts, giving a lower efficiency. A child may, therefore, be likely to travel slightly further than an adult if struck at the same speed by certain vehicles, while the difference will be negligible if the adult pedestrian is struck by a high, relatively flat-fronted vehicle.

The vehicle's mass matters insofar as the ratio of the masses of the pedestrian and the vehicle affects the amount by which the car is slowed by the impact. For example, if a 1,000 kg car is travelling at 40 mph and strikes a stationary 100 kg pedestrian, the mass ratio is 10:1. Assuming the two parties reach a common speed (100% projection efficiency), conservation of momentum dictates that the impact will slow the car to 36 mph and the pedestrian will be projected along the road at that speed. If the car has a mass of 2,000 kg, the common final speed will be 38 mph. This speed loss is often ignored in the literature, where comparisons are sometimes made between impact speeds and pedestrian projection distances which effectively ignore conservation of momentum. The modification for the mass ratio is small, however, and is usually within the range of speeds of the vehicle estimated by an expert. If a pedestrian is in collision with a lighter vehicle such as a motorcycle the correction due to the mass ratio will be more significant.

Inevitably there is a range of collision types, from a pedestrian suffering a full frontal impact with a vehicle to a glancing impact along the side of a vehicle. The published data show that pedestrian projection calculations are generally robust as long as there is a full frontal impact, although the spread of the data should never be overlooked.

One set of tests (Kasanický and Kohut, 2009) involved pedestrian dummies struck by the corners of vehicles, such that only one leg was struck but the upper body still contacted the bonnet or windscreen. These tests gave projection distances of around 10% less than for a full frontal impact. However, in some of the tests the struck leg received only a glancing blow and projection calculations based on those tests would be wholly unreliable indicators of vehicle impact speeds. It has been suggested that as long as a pedestrian's head engages within the width of the vehicle, projection distance calculations remain valid. However, insufficient research data exist to support that suggestion. Collisions in which a pedestrian leans forward, such that their head is struck by the vehicle but their legs and torso are not, clearly cannot be reliably reconstructed on the basis of projection distance.

Neale *et al.* (2021) analysed 21 real pedestrian collisions recorded on dashboard cameras (dashcams) or by CCTV where the pedestrian was at the side of the vehicle or had minimal overlap with its front corner. They examined the specific interaction of these non-frontal, side-impact and minimal overlap configurations to assess the relationship between the speed of the vehicle at impact, the motion of the pedestrian before and after impact and the associated post-impact travel distances. The 21 events were then categorised as either side impact or minimal corner overlap and the vehicle speeds were determined from the recordings. This led Neale *et al*. (2021) to suggest that speeds found from the throw distance formula of Toor *et al.* (2002) are too low by a factor of about 3 in the case of a side impact and about 1.5 when there was a minimal corner overlap.

All mathematical models that relate projection distance to impact speed make assumptions. They are sensitive to the vehicle profile and the deceleration that the pedestrian experiences when they land and slide or tumble to rest. For these reasons, a range should be given for the estimated speed. Papers vary, but one well-known source (Evans and Smith, 1999) suggests a range of ± 5 mph. Another (Simms and Wood, 2009) suggests that a larger range is appropriate, with separate figures for the 'probable', 'normal' and 'overall' ranges.

The analyses described above are for relatively level, dry road surfaces. Wet road conditions or where there is a steep road gradient will cause the range of possible speeds to widen further, unless specific measurements are made to refine the model for the specific circumstances of the accident.

It should also be noted that the centre of a calculated range is often referred to as the 'probable' speed in the literature. Although that may be true in a statistical sense when a large number of accidents involving a variety of shapes, sizes and orientations for both the vehicle and the pedestrian are sampled, it should not be misconstrued as being necessarily the most probable value of impact speed for the specific impact orientation, vehicle profile, etc pertaining to the collision in question.

4.4 Assessing the speed of a vehicle from the extent and location of the damage

Some investigators may present evidence suggesting a reliable relationship between the impact speed of a car and the extent and location of vehicle damage caused. However, any such correlation must be tempered with numerous caveats and there is no commonly accepted formula relating the extent or location of the damage to the impact speed.

Rules of thumb in the literature (eg Ashton, 1982; Toor *et al.*, 2002) suggest that, in general, for collisions with adult pedestrians:

- At speeds below 12 mph, vehicle damage is generally limited to cleaning of the dust and dirt on its surface.
- At 15 mph, head contacts will generally be found on the vehicle bonnet.
- At 25 – 30 mph, head contacts will tend to be near the bottom of the windscreen and clearly defined dents will occur to body panels.
- At impact speeds above 30 mph, body contact with the roof might occur; at speeds of 40 mph or more, they are more likely to occur.

These rules of thumb are accepted as valid generalisations for the vehicle population that existed when they were formulated. However, that was at a time when the typical car shape was of the 'three-box' pattern (ie flat-topped engine compartment, passenger compartment and boot), which is somewhat different from the present vehicle style with its more sloping front. Furthermore the stature of the pedestrian must always be taken into account. The gait cycle of a pedestrian, and their angle of travel relative to the vehicle, influences the way they rotate onto the car at impact. For example, a pedestrian who is running and is struck at a moment when their feet are not in forceful contact with the ground will have a different head trajectory on impact from a pedestrian who was standing still when struck.

The mass of the pedestrian will also have some influence on the damage. The extent of the damage will be influenced by the relative closing speed between the pedestrian and the vehicle, not the vehicle's speed in isolation. A pedestrian running towards a vehicle may result in a relative closing speed of perhaps 10 – 15 mph higher than if the pedestrian had been walking or running across the path of the vehicle.

The degree of the damage will also be influenced by car design. Car design is changing and some parts are designed to deform more easily when struck, in order to absorb more of the impact energy. Comparison of damage to modern cars with tests that were published 10 or 20 years ago may be misleading, or at least require qualification.

As closing speed increases, the location of a head contact tends to 'slip' rearwards on the vehicle, such that a pedestrian's head contact at high speed will tend to be higher on a windscreen than a contact with an identical pedestrian at low speed. There are papers in the literature which suggest a threshold speed for a pedestrian's head to contact the lower part of the windscreen and a higher threshold speed for the contact to be on the upper part of the windscreen. However, these papers tend to take no account of pedestrian's stature or the size of the vehicle, eg an adult pedestrian struck by a modern small car with a short bonnet is likely to contact the upper windscreen irrespective of the impact speed. Any assertion of an impact speed based upon the location of the head contact must be supported by appropriate test data specific to the size of vehicle involved in the collision (Dettinger, 1997).

The extent of the damage caused to a vehicle's windscreen if impacted by a pedestrian or cyclist will increase with the impact speed. However, there are many factors that influence the extent of the damage in an individual accident, such as the location of the damage (how close it is to the edge of the windscreen), the mass of the pedestrian and the angle of incidence. There is no robust method for quantifying the impact speed of the vehicle from the damage sustained to its windscreen in a pedestrian or cyclist impact.

4.5 The direction in which the pedestrian was facing

In cases where witness evidence is absent, or inconsistent, there may be a need to establish the direction in which a pedestrian was facing, and therefore travelling, when the collision occurred, usually as part of an assessment of how long they may have been in the road.

Medical evidence may assist in those cases where a direction or source of an injury can be identified. However, there can be exceptions, particularly for head injuries. Injuries can arise from either the vehicular contact or the ground contact. If the right leg of a pedestrian walking into the path of the car from the left is leading at the moment of impact they will tend to start rotating anticlockwise such that their head turns away from the vehicle. But if their right leg is trailing at impact, the upper torso and head rotate clockwise (Coley *et al.*, 2001; Liangliang *et al.*, 2018). Sometimes, particularly with a tall pedestrian, this rotation can be sufficient for the head to face away from or towards the vehicle before it contacts the bonnet or windscreen.

It is possible that a pedestrian will turn towards the approaching vehicle at the last moment and sustain facial injuries. If this injury is considered in isolation it may give a misleading impression of the pedestrian's impact orientation. It is therefore important to consider the full complement of injuries, even though the focus of litigation may be on one or two particular injuries.

It is also important to ascertain whether the injuries are caused by vehicle contact, the subsequent ground contact or both (Simms & Wood, 2010). This will require correlation of injuries with contact marks on the vehicle. Any injuries caused by contact with the ground will be difficult if not impossible to relate to the pedestrian's orientation prior to being struck by a vehicle.

4.6 Assessing the travelling speed of the pedestrian from marks to the vehicle

The motion of a pedestrian across a roadway will sometimes create a sequence of marks on the car. For example, if the pedestrian is walking from the nearside kerb, the first contact might be expected to be slightly closer to the nearside of the car than the subsequent torso contact, and the head contact further towards the offside of the car. If the pedestrian is running there will be an increase in the offset between the marks. However, there may be difficulties in using these offsets to assess a pedestrian's speed in some cases; for example, owing to the pedestrian leaning forwards or backwards while accelerating or slowing, the offset varying during the gait cycle and difficulties in identifying where in the gait cycle the pedestrian was at impact (Elliott *et al.*, 2010; Glynn and Wood, 2015).

If the collision involves a pedestrian of small stature and a vehicle with a high front, such as a child struck by a flat-fronted van, the offset in the damage pattern will be reduced.

Mathematical modelling is providing some useful insights into the calculation of pedestrian speed from damage offset, but the experimental data required to verify such models are very limited (eg Rohm and Schimmelpfennig, 1995).

In summary it is often possible to identify that a pedestrian was moving slowly such as walking, or quickly such as jogging or running, but an assertion that greater accuracy in the speed estimate can be achieved should be subjected to close scrutiny.

4.7 Estimating a pedestrian's travel speed from published data

An investigator will often attempt to estimate the time available for the driver to perceive and react to the emerging hazard of a collision with a pedestrian. A critical factor is how quickly the pedestrian was moving before the impact. The driver's perception/reaction time is discussed in Section 6. Unless there is evidence (such as CCTV recording) of the pedestrian's movement, the investigator will have to rely on published data for their estimate, together with the evidence of whether the pedestrian was running, jogging or walking across the road. As discussed in Section 4.6, physical evidence can assist to some extent, but there is a tendency to oversimplify.

An abundance of published data exist for the walking speeds of pedestrians, including data taking age and sex into account (eg Eubanks *et al.*, 1999; Vaughan and Bain, 2000; Dunbar *et al.*, 2004; Bartels and Erbsmehl, 2014; Crabtree *et al.*, 2014; Windisch and Senatli, 2015). Most of these papers give broadly consistent values for the mean walking speed of adult pedestrians, but only some give an indication of the spread of walking speed (usually the 15th and 85th percentile values). A reconstruction based on such published evidence must take account of the spread of walking speed within any population, as well as the reduction in walking speed of the elderly (eg Imms and Edholm, 1981; Asher *et al.*, 2012).

Starting from a stationary position, pedestrians take between one and two steps before they reach a steady speed. Some of the published data include this initial acceleration phase in the time taken to reach a given distance, and others do not. The investigator needs to check that the data they have used is appropriate for the case in hand, because including the acceleration phase can add several tenths of a second to the calculated pedestrian crossing time. Several papers, eg Fugger *et al.* (2000), Vaughan and Bain (2000) and Zębala *et al.* (2013), include assessment of the initial acceleration period in their investigation.

Data for jogging or running speeds are less frequently reported. The same question applies as for walking; namely, whether the pedestrian started to cross the road from a stationary position so that an initial acceleration phase needs to be taken into account. Terminology can also become ill-defined. For example, the paper by Zębala *et al.* (2013) contains graphs of distance covered versus time for slow walking, normal walking, fast walking, running and sprinting, but not jogging. Should a person who is described as breaking into a 'bit of a jog' be described as fast walking or running?

One often reported study (Eubanks *et al.*, 1999) quotes jogging speeds based on a sample of joggers in a beach resort area. Such joggers are more likely to be wearing appropriate footwear and clothing, and may be more likely to be practised at jogging than a person wearing winter clothing who is described as 'jogging'.

As a guide, the following table illustrates the typical ranges of pedestrian speeds quoted in the literature referred to above, although occasional and often special studies give results outside these ranges. In the table (as an example) the 85th percentile speed for a 6 year old child walking is 2.3 m/s. This means that 85% of 6 year old children walk at speeds of 2.3m/s or less. (m/s is short for metres per second: 1 m/s is about 3.3 feet per second or 2.2 miles per hour.)

TABLE 1

Typical ranges of pedestrian speeds.

Subject	Mode	15th percentile	50th percentile	85th percentile
3 year old child	Walking range		0.4 m/s – 1.0 m/s	
6 year old child	Walking	1.3 m/s	1.5 m/s	2.3 m/s
Teenager/adult	Walking	1.2 m/s	1.6 m/s	2.0 m/s
70+ year old adult	Walking	0.7 m/s	1.0 m/s	1.3 m/s
80+ or infirm adult	Walking	0.5 m/s	0.8 m/s	1.0 m/s
3 year old child	Jogging range		1.4 m/s – 1.9 m/s	
6 year old child	Jogging	2 m/s	2.8 m/s	3.3 m/s
Teenager/adult	Jogging	3 m/s	3.8 m/s	4.5 m/s
3 year old child	Running range		1.6 m/s – 3.1 m/s	
Teenager/adult	Running	4.5 m/s	6.0 m/s	7.0 m/s

4.8 Injury causation and vehicle speed

There is a good correlation between the closing speed in a vehicle-pedestrian collision and the probability of a certain severity of injury being caused (Ashton and Mackay, 1979; Cuerden *et al.*, 2007; Richards, 2010). A reduction in impact speed would, in general, be expected to reduce the likelihood of a severe injury arising. Although the significance of that statistical reduction is a matter for the court, not the experts, it should be noted that there are some occasions when a lower speed may not reduce the probability of severe injury and may even increase it. For example, in an incident where a car travelling at an urban speed collides with a pedestrian moving across the path of the car, the pedestrian's head may hit the windscreen. This is unlikely to cause a very serious injury because the windscreen glass will yield to some extent. But if at a lower approach speed the pedestrian's head would have hit a more rigid part of the car, such as the frame of the windscreen, because the pedestrian had moved further across its path, the impact could be more injurious. It is then for the court to determine the causative potency of the vehicle's speed at impact.

5. The use of computers in collision reconstruction

5.1 Introduction

There are three distinct areas where computers are used to investigate road collisions:

1. Numerical calculations made separately from any illustration of the events, for which the commonest example is the calculation of vehicle speed based on measurements of impact damage. The output includes a representation of the damage profile of the vehicle, which can be compared with the actual damage profile.
2. Animations, which are used to illustrate and explore the parameters of a collision, such as the time available to the car driver to perceive and react to an emerging pedestrian before a collision occurred. Animations are used to answer 'what if …' questions. The person generating an animation has complete control of the velocity and direction of all objects, with the risk that they might put forward scenarios that actually violate the laws of physics.
3. Simulations of collisions, in which vehicles and people are constrained to obey the laws of physics. These are generally used to calculate the velocities of vehicles etc in a collision. Again, the events are illustrated.

5.2 Vehicle speed from impact damage

Specialised computer programs are used by vehicle manufacturers to predict the extent and nature of damage that one of their vehicles may sustain when it is involved in a collision (eg LS-Dyna, Pam-Crash). These programs are normally used for proprietary research and development purposes. They require values for many vehicle parameters that are available only to the manufacturers and not to investigators presenting evidence to a court. They are therefore rarely, if ever, used by collision investigators.

The following discussion relates to cars and vans. Lorries, pedal cycles and motorcycles are not included.

In 1975 R McHenry wrote a computer program called CRASH. It required the user to input the extent of damage to each vehicle in a two-vehicle collision, or the damage to a single vehicle if it hit a rigid object such as a tree or concrete block. With knowledge of 'crush stiffness coefficients' for each vehicle (described below) the program would calculate the energy dissipated in causing the damage. When the energy dissipated was combined with the vehicle masses, the program would use conservation of momentum to calculate the velocity change (the 'delta-V') on impact for each vehicle.

Using this information, the vehicle velocities just before impact could be calculated. Various commercial versions of the CRASH program are now in use, but they all rely on essentially the same mathematical formulae, physical assumptions and input data.

To assess the extent of vehicle damage it is imagined that each vehicle body can be represented by an array of 'springs'. At very low impact speeds, for example during vehicle parking, there is usually no permanent damage, and the flexing of the car body is reversed when the cars are separated. This is called elastic deformation and no significant amount of energy is dissipated. But at higher impact speeds permanent, inelastic deformation takes place, which absorbs energy. To simulate both behaviours, the springs used to represent the car body should return to their original lengths at very low impact speeds but be crushed permanently at higher impact speeds. This is captured in the relationship between the compressive force applied to each representative spring and the extent to which it is compressed. The compression of the spring is called 'crush'. The relationship between force and crush is measured by tests in which cars are crashed head-on into rigid blocks at different speeds. The curves are fitted mathematically using parameters called crush stiffness coefficients. The damage sustained by a vehicle is sampled by measuring the crush at a set of points in the vehicle.

The accuracy of estimates of speed based upon impact damage depends upon three issues:

1. The accuracy of the stiffness coefficients used by the computer program, bearing in mind the internal structure of the car is ignored completely.

2. The suitability of the chosen stiffness coefficients for the impact configuration being assessed.

3. The variability of the crush measurements depending on where on the car they are taken.

When using speed-from-damage programs, vehicles are assigned to a particular size category and each category has generic crush stiffness values deemed to be representative of vehicles in that class. The original stiffness values used in CRASH3 were the best available to model cars of that era in the USA (Monk and Guenther, 1983), but car design and the regulations governing car crashworthiness have developed over the years. Various papers (Lennard *et al.*, 1998; Hague, 2005; Wang and Gabler, 2007; Wiacek *et al.*, 2015) have provided statistical analysis of crash tests to assess more modern stiffness coefficients, but there is no universally recognised set of stiffness data that is more recent than that developed to represent cars available in the USA in the first part of the 1990s. There is a large American database of crash tests where one may find data on cars that some may claim are similar to those involved in a specific accident, and there are programs (Vomhof, 2011) designed to calculate crush stiffness coefficients from crash test data. However, suggestions that stiffness coefficients derived in this way are as accurate as claimed should be questioned. The CRASH3 model is based on a premise that the coefficients used do not vary with the actual speed or the crush profile. As an example, it would be fallacious to suggest that stiffness estimates based on full width test crashes at 20 mph and 30 mph into vertical concrete test blocks will accurately represent the crush characteristics of a car which strikes a narrow object, such as a 0.5 metre wide tree, at 50 mph, or a car that partially underruns a lorry trailer, where the forces would be concentrated above the bumper or suspension mounts of the car. There are ways of correcting, at least partially, for some of these differences (Neades, 2011), but these rely on mathematical models of an idealised vehicle.

The investigator should clarify how any stiffness coefficients used have been obtained and clarify the nature of the crash tests relied upon, even if they relate to an identical car model. It is not suggested that the calculation is of no value, but the appropriate confidence level to be associated with the reconstruction needs to be established.

The third issue listed above relates to the measurement of vehicle damage. It may be far from obvious how the measurements should be made in a repeatable and consistent way. There are protocols taught on crush measurement courses (Tumbas and Smith, 1988; Neades and Shephard, 2009) which will minimise, but not eliminate, some measurement uncertainties. The investigator should be able to explain how the measurements were taken and give the range of calculated speeds expected for realistic variations of the measurements.

The final parameter that is required to complete the damage analysis is known as the principal direction of force that acted to cause the observed damage to each vehicle. For a given speed, at impact the nature and extent of the damage sustained by a vehicle will vary with the principal direction of force. It is usually estimated by the investigator and the dependence of the calculated speed at impact on this parameter should be included in an analysis of the collision.

5.3 Animations

All modern animation and simulation programs have the facility to import plans or diagrams, often including three-dimensional point cloud data from a laser scanner. They also have the capability for the user to draw plans, including three-dimensional objects such as trees and buildings. These act as a background against which an animation can be viewed.

A typical example of when an animation might be used would be to explore the time available to a car driver to perceive and react to an emerging pedestrian before a collision occurred. The 'onset of visibility' is a trivial parameter to calculate if a parked car is treated as a simple box, but when the curved and complex shape of a real car is treated explicitly, including such things as a sloping bonnet and windscreen, defining the onset of visibility is less straightforward. An animation may then assist in identifying a range of times over which the pedestrian becomes progressively more visible over or around the shape of the vehicle for any particular combination of speed and direction for each of the parties.

5.4 Simulations

Simulations are generally performed by specifying a set of input parameters, such as speed, course and mass for each party, and then repeatedly solving the equations of motion, momentum, etc over successive small time increments to assess how the involved parties will move and interact. This could involve a vehicle leaving complex tyre marks on a roadway, or one or more parties or vehicles colliding. The predicted outcome, such as the predicted path taken by a car as it spins to rest, is then compared with the known data, such as the tyre marks found at the scene, to assess the correctness or otherwise of the starting conditions which were assumed. The starting conditions are then 'fine-tuned' and the simulation repeated until a satisfactory match is found. With some programs the simulation can be automatically repeated many times with the input values varied randomly within specified ranges to assess the sensitivity of the answers to modest changes of input values. This is known as Monte Carlo simulation.

Every simulation program is based on a series of idealised mathematical models to calculate the development of an object's motion over time. For example, consider a car that collides with a pedestrian and spins to a stop. Underlying a video of a simulation that may be presented to the court there will be a mathematical model of the pedestrian, comprising several dozen segments (eg a foot, a lower leg, an upper leg) linked by joints, each with its own defined characteristics. The simulation program will usually have a library of default settings for the properties of each of these elements, but the user will generally be able to override default values with specific data, if available. It may need to be clarified not only which default values have been overwritten, but also whether it was appropriate to do so, and how sensitive the output is to variations in the input data. A user who is not familiar with the details of the program, or who does not have sufficient understanding of the underlying physics, might proceed without an awareness of whether the default values are appropriate for their case or could alter parameters within the program to unrealistic values in order to get a match, which could degrade the accuracy or reliability of the simulation in a manner that would be hard to detect without close scrutiny. There is no universally accepted method to test the accuracy and reliability of a simulation other than to check the sensitivity of its predictions to the input data, assuming it is based on correct physics.

Each of the common simulation programs is supported by published papers showing how far they are capable of faithfully reproducing various test scenarios or collisions. However, there is a wide range of possible scenarios that the programs are designed to reconstruct, and no validation test will encompass all of them. It will be for the expert presenting the evidence to clarify to the court the applicability of the software and to justify the particular values for the many variables that have been used in the simulation.

It is not possible to rank the various programs in order of merit, partly because such ranking can be subjective and partly because each of the programs is the subject of continuous development.

6. Human factors

6.1 Introduction

The human element is often the most difficult aspect of a collision to analyse and replicate in a reconstruction. Whereas earlier sections have benefited from being able to apply the laws of physics to develop an understanding of how a collision occurred, there are no such laws governing the performance of humans. Instead there are only general principles and observations. In this primer we cannot provide a complete guide to human factors in collision investigation. The aim is to highlight the limitations of data and comments on the human element presented to the court. General principles about reaction time, visibility and conspicuity are discussed. Many other human factors, such as fatigue, medication, distraction and glare, pertinent to road crashes are not included. Although the court is concerned with an objective standard, the variation in human performance is large and replication or reconstruction of an event is often fraught with difficulties. Not only do humans vary from each other, but each human's performance varies by time of day, level of arousal, fatigue and other factors. A crash will not usually have a single cause (McKnight, 1972). No single piece of research will have focused on the unique combination of factors that the court will be considering.

6.2 Viewpoint and evidence

It may seem obvious, but the court cannot look through the eyes of the driver and relive the exact set of circumstances that led to the crash. Significant evidence may come from science where similar events have been considered and data gathered from human participants in experiments and tests. The viewpoint for this section is based on the science of human factors and cognitive psychology. The science of human factors is the study of people in their built environment and considers how humans deploy their limited physical and cognitive abilities in a complex, dynamic environment. Human factors are studied in both engineering and psychology. Cognitive psychology is the study of perception, acquisition and use of knowledge, and limitations and functioning of memory. When human factors scientists study driving it is usually in laboratory settings, where it is not the crash that is of interest per se but how driving provides a means to test theories of human performance in a setting familiar to the driver. Human factors psychologists are interested in the processes of human cognition involved in a crash, rather than the mechanics of a crash.

Apart from occasions when a driver falls asleep or suffers a severe medical episode, it is often found that three or more independent factors conspire to cause an accident. These factors may include vehicle failure, driver impairment, environmental factors and/or a failure of the driver to cope with the task presented. In a review of driver vision and vehicle visibility, Hills (1980, p. 184) pointed out that a vehicle accident is 'not normally due to one single cause but, rather is the result of a combination of causes'. Wulf *et al.* (1989) also concluded that there can be several variables which may cause an accident, some of them occurring in interaction.

6.3 Perception reaction time

The UK Highway Code (HMSO) is often cited as a guide to reaction time. But there is no evidence that the timings inferred by the quoted 'thinking distances' therein are based on any research or scientific thought. Since the 1880s psychologists have used reaction time as a measure of the complexity of a task, or a comparison measure to ascertain whether the human under test finds one condition or set of circumstances more difficult than another. In comparison, crash investigators often attribute an exact amount of time a person should take to detect a hazard. There is no scientific basis for this practice.

Reaction time is a measure of how long it takes a person to respond physically to a stimulus. In the driving domain, this is normally how long it takes a driver to react to an unanticipated stimulus, such as a pedestrian walking out in front of them or a vehicle emerging from a blind side road. There are many variables that can affect a driver's reaction time, such as age, gender, health, expectation(s), time of day, state of arousal, drugs and alcohol, cognitive load/workload, divided attention and the angular position of the hazard (Krauss, 2015).

Reaction time consists of four sequential stages: (1) detection, (2) perception, (3) recognition and (4) physical response. There are many models of this process. The model presented here (Perchonok and Pollack, 1981; Krauss, 2015) is a summary of the key factors and is most commonly used by collision investigators.

Stage 1 is where the light from the hazard reaches the driver's retina. The human field of view is limited, and drivers need to move their eyes to scan a whole scene. Although an observer may gain a general awareness of a shape appearing in the periphery of the visual field, they need to look directly at it to interpret it. They can look directly at only one small part of the scene at a time. There must be enough light from the hazard to allow a signal to be sent from the eye, possibly even as a blurred image, to the brain, so the brain can start the next process of interpreting what is seen. Often the threshold for visibility is not met by a dark object on an unlit road, when the driver may be looking elsewhere in the road environment. Where a driver directs their eyes is based on expectation of the location of hazards and experience. It also requires their attention to be focused on the driving task, and not on a mobile phone, GPS, the vehicle controls or some other distraction.

Stage 2 is where the brain tries to understand what is in the road. It seeks to establish where the edges of the hazard are. Matters such as contrast are important. The brain seeks to establish whether there is a hazard, to separate it from its background; whether it is stationary or moving; and whether it needs to be identified in the next stage of perception reaction time (PRT).

Stage 3 is the most important process, as the brain needs to recognise that there is a hazard in the road. Without recognition no appropriate action can be taken. Expectation influences what the brain 'sees'. Unfamiliar or unexpected items will not allow the brain to 'see' what is present. A dark object in the road may be a pedestrian, or simply a shadow in the uneven road surface, litter or a reflection.

Stage 4 is deciding what to do and then taking the appropriate action. The driver not only has to recognise what is in the environment but decide what action to take and then take it. Braking or sounding the horn might be good in some circumstances, but not in others. Making a decision and actioning it takes time. In some cases the sequence of events immediately before a collision is so rapid that the driver's reaction is instinctive and precedes any cognitive weighing up of the situation and how to respond to it.

Anything that delays any of these factors may extend reaction time, eg poor visual conspicuity of pedestrians at night may delay detection. Tiredness or fatigue may delay perception and/or recognition stages. Divided attention or distraction has been shown to increase crash risk, with the use of mobile phones, carrying passengers and use of other electronic devices found to be most highly correlated with crash risk (Ghazizadeh and Boyle, 2009). This is most likely due to the increased reaction time.

The fastest possible human reaction time is 180 milliseconds for a single response to a single visual stimulus, but responses to auditory stimuli can be faster. However, this is recorded in a laboratory setting and the stimulus is expected. Such figures have little relevance to real-life reaction times when driving (Hole and Langham, 1997). Expectation has been defined as 'a predisposition of people to believe that things will happen or be arranged in a certain way' (Krauss, 2015, p. 13). If an event is unexpected, then reaction times may be greatly increased. Hole and Langham (1997) suggest that this may be up to ten times compared with laboratory conditions. Drivers develop expectations based on the behaviour of other road users. When a road user deviates from the expected norm, drivers can take longer to react. When confronted with a hazard on the road in good daylight the reaction time of an alert driver can be expected to vary between 0.5 and 3.5 seconds or more, depending on the particular circumstances of the hazard and the factors discussed above (Krauss, 2015).

How long should a driver take to react? When a signal reaches the brain, it must be interpreted and some form of identification must occur. Science tells us that perception is 90% conception. An object seen at an unusual angle, or which is unexpected, or out of context in the road environment, may not be correctly perceived for what it is and the final stage of taking appropriate action may not occur.

Ascribing a precise reaction time to any specific situation cannot be justified scientifically. For the court, a reaction time should take into account the unique, complex sequence of operations that the driver had to undertake, as well as any other factors that may affect their time to react, such as lighting and visibility. It must be recognised that whoever undertakes a reconstruction knows that there was something to detect, unlike the driver.

There is no robust 'look-up table' or formulae that can predict the range of human reaction times operating in the environment and in the conditions of the incident. For example, there are no reliable formulae that add a fraction of a second for reduced visibility, or add a fraction of a second for complex vehicle controls, and then adjust the calculation for driver fatigue.

Software that has become well known for estimating PRT is the I.DRR program by Muttart (2019). It allows the user to enter details of the incident, such as the nature of the hazard, the manoeuvre being made by the driver and any other driver, lighting conditions and so on, from which a figure for the likely PRT is generated. While going through this procedure could give the user some insight into the factors which would affect a driver's response, it must be understood that it cannot provide a definitive figure. In cases where the PRT is critical in the analysis of an event and perhaps how it might have been avoided, and where this program or any other way of simply estimating PRT is employed, it would be necessary to establish whether the expert producing the estimate has an understanding of the factors which might affect it, and the range of uncertainty which might be put on the estimate.

A key question for any reconstruction is whether to start the clock from the point at which the hazard was above the detection threshold or at the point a driver could be expected to direct their gaze, allowing them to see something in the road, bearing in mind that they are monitoring the road ahead, while possibly dealing with complex in-cab systems.

6.4 The senses and perception

The majority of psychological research on driver error has focused on the perceptual abilities of the driver. Driver vision is the only sense tested before a driver gets a licence. It is thought that 95% of the information a driver uses is visual, although there is little evidence to suggest an exact percentage. Drivers selectively attend to some part of the road environment where their experience has shown the most likely source of hazards will be found. These behaviours allow the driver to deal with the information that they need to understand from outside and inside the vehicle. As a consequence a driver is not capable of seeing everything in their environment. The most common type of accident subjected to forensic examination in court results from the 'looked but failed to see' error.

6.4.1 Looking and failing to see

The 'looked but failed to see' (LBFS) error, or 'looked but did not see' (Sabey and Staughton, 1975), refers to a set of circumstances where a driver accounts for an accident by failing to detect another road user in time to avoid a collision. Cairney and Catchpole (1996) estimate that 69 – 80% of all intersection accidents are failures by one driver to 'see' another until it is too late. Rumar (1990) describes late detection or LBFS error as a common problem accounting for the majority of multi-vehicle accidents throughout Europe. A detection error is the basic cause, claims Rumar, because without detection no further processing of information, or decision processes, can take place. Rumar identified two important causes of the late detection error:

1. A lapse of expectation, illustrated by the failure to look for a particular class of road user or a failure to look in the appropriate direction.

2. A difficulty with perceptual thresholds, illustrated by the failure to discern the relevant stimuli in lower levels of ambient illumination or in situations where vehicles approach in the peripheral visual field.

Hills (1980) describes the LBFS error as a problem of the misjudgement of speed and distance and incorrect interpretation of visual information by the driver.

6.4.2 Conspicuity versus visibility

Visibility and conspicuity are often conflated by investigators. The court is interested in conspicuity, not visibility. Visibility refers to the ability of the driver to see the hazard in their environment. There are two types of conspicuity relevant to the court.

Physical or sensory conspicuity

Conspicuity, in the context of laboratory research, refers to physical properties of the hazard: its size, luminance, contrast and colour and motion in relation to its background (Cole and Jenkins, 1984). Conspicuity can be defined partly as the ability of an object to 'pop out' (Treisman, 1986; Enns, 1990) from its background, either by its comparative novelty, by its comparative brightness or by the hazard's intrinsic properties to attract attention. Deficiency in colour vision may reduce the conspicuity of an object, especially in the absence of experience or other visual clues such as motion or change of position. Hills (1980) gives a useful definition of physical conspicuity: 'It can be defined partly as the extent to which the object is above the just visible limit. It is therefore subject to the same factors as visibility, the most significant of these being the visual size of the object, its contrast with its background against which it is seen, the ambient light levels and any source of glare'.

Cognitive conspicuity

Cognitive conspicuity depends on the observer and what they consider relevant rather than the physical properties of the hazard. Critical to the detection of hazards is the role of expectation. A driver will take longer to detect a pedestrian in an environment such as a motorway, where they are not expected, than in a city centre, where pedestrians are common.

Something that is physically conspicuous may have little meaning to the observer or is so unexpected that it is not cognitively conspicuous. Police vehicles are sometimes involved in accidents where drivers claim they did not see them. While such vehicles are physically conspicuous, if they are stationary in lane one, two or three on a motorway the driver may not react correctly because they are expected to be moving. The driver may also have a false impression of their own speed. Without checking the speedometer the perception of their speed is based to a large extent on the rate of flow of texture across their peripheral field of vision. This can be impaired in fog and after driving for some time on a motorway, and a variety of other circumstances including the roughness of the road surface, stroboscopic lighting conditions, the presence of parked vehicles and the height of street lighting.

Often a reconstruction tests visibility where someone is asked: “Can you see the pedestrian?”. But what should be tested and understood by the court is that conspicuity is viewer-dependent and based on expectation.

6.5 Summary

When considering evidence as to the driver’s performance, the following key issues may need to be considered.

1. Whether published data provided by an expert can be applied to a particular incident, with a particular driver. There are limited physical tests that can replicate reliably the reaction of a driver to the emergence of the hazard.
2. Whether a simulation of the collision, which has led to data and conclusions presented to the court, reflects the driver’s actual experience of the accident.
3. Whether a reconstruction of the accident used hindsight, and whether it tested the visibility of the hazard and not its conspicuity.
4. When photographs or videos are shown in evidence, whether there is a warning as to their limited ability to replicate the driver’s perception of the events leading to the collision.
5. When a numerical estimate has been made of the expected PRT, whether the expert producing the estimate has an understanding of the factors which might affect it and the range of uncertainty associated with the estimate.

Appendix A: Electronic data

As noted in Section 2.2.4 the range and sophistication of electronic devices that are fitted to vehicles are rapidly increasing and this section is intended to give only a broad overview of the range of devices currently in common use.

A.1 CCTV cameras and dashboard cameras

Video evidence will often be available from static CCTV cameras or cameras mounted within moving vehicles (dashcams). These can often show which lane a vehicle is travelling in and provide evidence of changes of speed or course of both the vehicle in which it is mounted and vehicles that are in view of the camera.

Most CCTV systems have a fundamental recording rate of either 25 or 30 frames per second. However, this would generate large amounts of data within a short period, causing storage issues, and many recorders store only a fraction of the frames and not always at a fixed frequency. The difficulties of interpreting the time interval between images can be compounded because sometimes the images do not have a 'time-stamp' or else have one which displays to the nearest second only. The analyst has to be aware of this and be able to explain how the interval between frames has been ascertained.

The original recorder may have been obtained by the analyst with its associated software, enabling the record to be viewed and copied. There are many manufacturers of such equipment and a correspondingly large number of players. Many players will produce an electronic file that can be played on a computer or standard domestic DVD player, although these files will sometimes omit the meta-data (hidden data about the frames, sometimes including the time-stamp) and this can limit any subsequent analysis.

To work out the velocity of another moving vehicle, the analyst needs to take account of the velocity of the vehicle in which the dashcam is mounted. The vehicle speed display on the captions of a dashcam will usually have been derived from a GPS signal and will lag behind the recorded events by a second or more, depending on the device. To circumvent this lag in the speed display, it is normal to assess the speed of the vehicle by measuring its progression past fixed points such as road markings or street furniture.

Sometimes a video file played on a computer monitor will be recorded by an investigator by pointing a camera (often in a mobile telephone) at the monitor. This will greatly degrade the resolution, omit all meta-data and can cause other problems if the original and re-recording devices run at different frame rates. For these reasons, CCTV evidence should not be accepted at face value, but should be presented by a person who has a good understanding of the system which produced it. The UK Forensic Science Regulator has produced a Code of Practice for the capture and processing of all video files (Forensic Science Regulator, 2020).

A.2 Tachographs

A tachograph is a device which records the driver's hours of work, distances travelled and speeds attained. Virtually all goods vehicles with a maximum mass over 3.5 tonnes and passenger vehicles with more than nine seats are required under EU regulations to be fitted with tachographs, although there are various exemptions. Analogue tachographs, which record the data on a circular paper chart, are obsolescent, and all modern vehicles that fall within the regulations are now fitted with electronic tachographs that produce an electronic data file. However, where there is a recording on a paper chart it is important that it is examined by an expert analyst using a special microscope.

In digital tachographs the hours of work are stored for a considerable period within the instrument, but the speed file will typically be overwritten within 14 days of driving. The data will often have been seized by the police before then, using a downloading device which is available only to them and other official agencies. The speed data themselves are recorded at a rate of only once per second, although some frequently encountered devices record with an interval of 0.25 seconds at the time of an incident.

The tachograph record of speed is usually generated from sensors measuring wheel speed, and the installation must be regularly calibrated for accuracy. If the calibration is inaccurate there will be a percentage error in the speed data, although it is generally possible to adjust the figures to allow for this error and to provide reliable evidence.

Unless a collision is sufficient to cause a sudden and almost instantaneous change of speed of the vehicle, the occurrence of an impact may not be identifiable in a digital recording. This means, for example, that in a case where a vehicle has braked to rest and a collision has occurred, it should be possible to calculate the distance that the vehicle would have travelled while braking, but the whereabouts of the collision within that braking period may not be identifiable from the tachograph record in isolation.

While tachographs do not continuously record position either along or across a roadway, the latest generation, introduced in June 2019, have a GPS link through which they record the starting place of the daily working period, the location after every 3 hours of accumulated driving time and the end place of the daily working period.

A.3 Data recorders

The low cost of modern electronics has led to a rapidly expanding market for various data recorders to be fitted to vehicles. They may broadly be divided into two types:

- journey data recorders;
- event data recorders.

The following is a short description of various journey and event data recorders that may be encountered, but in a developing market it is often the case that one recorder could be deemed to fit into more than one of the following categories. Thus, some journey data recorders (which in general are not intended to be used for collision investigations, even though they often contain useful information) also have a limited capacity to record certain details about a specific event.

A.3.1 Journey data recorders

A.3.1.1 Fleet data recorders and insurance 'black boxes'

Many vehicle fleets now use devices fitted to the vehicle that send a regular update signal identifying the position of the vehicle at certain intervals (eg Terrafix, Trackstar, Tracker, Tetra, Inca). These data are normally stored by the fleet manager or the company that provided the equipment, and the data can be retrieved from them to show the position of a vehicle at a given time, whereas changes between the vehicle's successive positions can indicate its speed. Tetra radios, which are used by the emergency services, can be used in a similar manner, identifying the position of the user of the radio, who may be in a vehicle that is not equipped with a fleet data recorder.

These devices are generally based on a GPS system to identify position, although mobile phone networks can also be used by some systems. Velocity data can also be calculated (via the change of position with time) but acceleration, where it is recorded, is based on on-board accelerometers. Speeds are often calculated each second but will generally be displayed as an average speed over minute intervals. If that is what is made available, it will be of minimal assistance in assessing what the speed profile of a vehicle was in the seconds before a collision.

The sophistication of the systems varies greatly and can be expected to change quickly with time as new systems are developed. Because of the variety of systems available it is not possible to give a generic assessment of accuracy. Unfortunately, many manufacturers or distributors do not publish details of how speeds are calculated, or what smoothing of data is applied before calculations are made before the data are presented. For these reasons data should be examined in some detail before a court accepts an interpretation of them.

Insurance companies are increasingly encouraging private motorists to have 'black boxes' fitted to their cars. These are generally similar to fleet data recorders, and will always record acceleration data with a view to rewarding, or penalising, driving styles.

The accuracy of these devices is highly variable. In normal driving the speeds are likely to be accurate, usually being based on GPS data. However, in the event of sudden and harsh steering and braking, the accelerometers used may not have sufficient accuracy to record faithfully the events as they unfold. It will be important to identify the steps that have been taken to ensure the accuracy of the data before they are relied on in any detail. This may prove difficult if the device has been imported from another country and the manufacturer declines to clarify the data accuracy.

A.3.1.2 Car satellite navigation and 'infotainment' recordings

Many vehicles are fitted with a satellite navigation system of some description, either via a portable device, such as TomTom, Garmin or Mio products, or via a navigation system incorporated into the so-called infotainment system. All systems use GPS data to locate the vehicle. The typical accuracy of a GPS coordinate is a few metres, although there are various specialised technologies which circumvent that limitation (eg when using a dedicated electronic total station, a theodolite for measuring purposes, the accuracy is within millimetres).

Depending on the specific system, the user's favourite locations can be identified as well as the routes they have used and their phone records (if it is paired to a mobile phone); journey information can be recorded by way of track logs, allowing an investigator to identify where a journey started, the route taken and where the journey finished, as well as to find the vehicle's speeds. On portable mounted systems, acceleration as well as velocity are generally recorded using GPS data rather than by way of accelerometers. With built-in systems the velocity and acceleration may be provided by GPS data or via the speed signal from the vehicle's controller area network (which is like the nervous system of a vehicle), enabling information to be passed between all the sources of electronic data in the vehicle.

It is becoming more common for vehicles to be fitted with complex infotainment systems that combine the more traditional in-car audio with other information and entertainment systems such as a Bluetooth-linked mobile phone, music players, vehicle data and navigation. Data gathering by investigators from infotainment systems is in its infancy but is a developing area. Acquisition of the data from these systems can provide listings of paired mobile telephones, call logs, contact lists and text (SMS) for each phone, as well as the recording of events such as lights on/off, door opening/closing, gear selection and periods of harsh acceleration, harsh braking and traction control intervention. Some, but not all, of these events can include a time-stamp, as well as the latitude and longitude coordinates, for where they occurred. Whether it is appropriate for personal data, such as text messages, to be gathered as a matter of course by investigators is not considered in this primer.

The data currently available vary vastly between the systems, and this is an emerging field where improvements in compatibility and levels of data acquisition are continually evolving. The resolution of the data is not as fine as that from an incident data recorder, nor of a specific nature such as from a crash data recorder, and therefore it is recommended that caution is exercised with all data, and specifically those that have not been validated.

A.3.1.3 Mobile phone data

The direction of travel of a vehicle can often be identified by examining a record of radio masts it has linked to over a period of time. Whether or not a phone has been used for making or receiving calls at a particular time can also be identified from the records, but of course the record cannot identify which vehicle occupant was using the phone when the call was made.

Modern smartphones have a functionality whereby the user can download a large variety of specialised programs or ‘apps’ which utilise the phone’s hardware to record positional data, calculated either from GPS or from mobile phone antennae. The supplier of the app will store and analyse the data, providing graphical or tabular output of it to the user. Such apps are commonly used by runners or cyclists to assess their own performance.

Considerable care must be exercised in interpreting such data in the circumstances of a collision. The frequency with which the original data were captured depends upon both the app and the smartphone. The data will usually have been filtered and smoothed before being made available, to eliminate fluctuations due to momentary reflection or loss of a GPS signal, such as may occur when passing a tall building or passing through a tunnel. The detailed algorithms used for such smoothing are often confidential and may not be made available to the public or to police investigators. This processing of the data can mask the rapid changes of real speed that can occur as a result of a collision, such that the effects of the collision or even the existence of it can be eliminated from the final data available to the user.

A.3.2 Data recorders

A.3.2.1 Incident data recorders

This term is used to describe systems which are generally always 'active'. Most emergency service vehicles are fitted with devices generally known as incident data recorders. These will typically take recordings from several accelerometers, a measurement of vehicle speed from the vehicle's own electronic systems and possibly also a steering wheel position sensor. Most modern systems will also have data from a GPS sensor, so speed may be calculated from more than one data source.

During normal driving the data will be overwritten after a short while. In the event of a collision severe enough to be regarded as 'noteworthy' the data for several seconds before and after the collision will automatically be saved from being overwritten. Manual activation of a switch by the driver can also trigger the saving of data for a period extending a number of seconds before and after the switch has been operated.

If the system is interrogated after an accident or incident, the output data are normally very detailed with a resolution much better than 1 second, but the accuracy will depend ultimately on how well the device has been calibrated and on the software within the system.

Many of the devices fitted to emergency service vehicles and personal radios can also be tracked over extended periods in a manner similar to fleet data recorders, giving information over a longer period of time but with a lower resolution than the incident data recorder.

A.3.2.2 Event data recorders

The fitting of event data recorders is not mandatory in the UK, although they are often fitted currently. They are due to become mandatory in the EU within the next 2 – 3 years (EU General Safety Regulations, 2019). At the time of writing, it remains to be seen whether similar provisions will be adopted into UK law.

Where such recorders are fitted, some currently do not have a continual recording of driving data extending beyond a short period (sometimes a second or so) but triggering of a switch, such as an airbag sensor, in a violent incident will cause data to be recorded for a short period, varying from a few tenths of a second to several seconds. This may include seat belt usage, whether the brakes have been activated, vehicle speed and possibly the direction and severity of a sudden acceleration, such as would be due to a collision.

The availability of these data varies significantly between vehicle manufacturers and with how recently the vehicle was designed. The data may be recorded in an encrypted form, which manufacturers may be reluctant to decrypt. Access to these data, where they are available, requires specialist electronic tools and a trained operator. A common tool for this which is supported by several manufacturers is the 'Bosch CDR Tool', but the data from several other makers are only accessible using bespoke equipment available exclusively to the agents of the vehicle manufacturer and not law enforcement agencies.

Where such data are available, it is essential to review their relevance in relation to the circumstances of the case in question. For example, if a car goes out of control and strikes a pedestrian before striking a large tree, the activation of the data storage may have commenced when the tree was struck and not when the pedestrian was struck. The speed of the vehicle at each of those events may be very different if the vehicle was first being braked.

Further confusion can arise if the vehicle is subjected to more than one collision in quick succession. Depending on the level of detail within the data, it may or may not be possible to identify which of the two collisions initiated the recording.

If a crash data recorder is interrogated and shows vehicle speed, it will be important to assess how that speed was measured. It is likely that the speed was recorded from sensors which measure the rate at which the road wheels are rotating. When a car is moving forwards with only modest braking or acceleration, the wheel rotational speed will provide an accurate measure of the speed of the vehicle. But if a car has one or more driven wheels off the road, such as when rolling over, or the vehicle is starting to slide sideways or some wheels are locked under heavy braking, then the wheel rotational speed will not be related to the speed of the vehicle along the road. Such effects may be identifiable on the output of an incident recorder, which may show many seconds of data prior to the collision but may not be easily identifiable from a crash data recorder if the data contain little or no information about the motion of the vehicle prior to the device being triggered.

The EU regulations will require that several seconds of comprehensive pre-impact data be stored. The extent of the data set, which will include a record of what electronic safety devices (such as autonomous braking and lane departure warning) were active immediately prior to the accident, should enable an investigator to overcome many of the above problems.

A.3.2.3 Fault recorders

The on-board electronics of modern cars generally record, for the benefit of vehicle servicers and repairers, data about faults in the vehicle's systems. Sometimes the data recorded will include information about the timing of when the fault occurred, how many times the fault has occurred and occasionally what the speed of the vehicle was when the fault was recorded. A vehicle examiner may be able to retrieve these data if appropriate equipment is used. The time the data were generated is unlikely to be in a straightforward date format but may be shown in terms of elapsed time since the system was last reset.

If it is available, the information about several faults each occurring at the same time, and of a nature that would be expected in a collision, such as sudden cessation of the wheel speed information from a wheel that was damaged in the crash, may therefore be used to infer the speed of the vehicle at the time of the collision.

Considerable caution must be exercised with such data. Some of the faults can be generated during a period extending over several seconds, during which the vehicle speed is changing. If the car has an extended post-impact motion, such as sliding across a road and then tumbling into a field, some of the faults can be generated after the initial collision and potentially at a time when the wheel speed is wholly unrepresentative of the actual speed of the vehicle along the road. Furthermore, some of the functions of the car may only be monitored infrequently (such as a function which increases the volume of the radio above a pre-set speed); when a fault code for that function is stored, the speed information associated with it is 'out of date', representing the speed when the system was last monitored before the fault occurred.

A.3.2.4 eCall

From April 2018 all new cars and light commercial vehicles are fitted with a device called eCall. In the event of a severe collision, usually meaning sufficient to activate airbags, this automatically initiates a telephone call to a public service answering point, which contains at least a minimum set of data including the identification number of the vehicle (VIN), its location and its direction of travel and also enables voice communication. The minimum data set does not identify the speed of the vehicle either at impact or on approach to impact, nor does it identify the route the vehicle was following prior to impact. Information within the eCall data concerning the number of passengers in the vehicle, seat belt usage and possibly speed is optional, not mandatory.

Appendix B: Estimation of speed from tyre marks

B.1 Vehicles except motorcycles

Measuring the distance travelled by a test vehicle when it is braked firmly from a known speed is one method used to assess the deceleration undergone by a vehicle involved in a collision ('the target vehicle') on a particular road surface. More commonly electronic accelerometers are mounted securely either in the target vehicle, if it is still driveable, or, more commonly, in a test vehicle to record the peak and average deceleration. For those cases where the wheels of the target vehicle have locked, brake and skid tests will be conducted with the ABS of the test vehicle deliberately disabled (where possible) so that its wheels can lock and slide. The average deceleration will then be used for the deceleration of the target vehicle. Although this is not ideal, the peak deceleration is sometimes used for cases where the target vehicle has ABS. Rather better is a brake test in a vehicle with functioning ABS. In ABS tests it is the mean acceleration which should be applied to an ABS target vehicle.

Vehicles can accelerate, decelerate and corner because there is friction between the tyres and the road surface. The coefficient of friction is the maximum force which friction acting on the tyres can exert divided by the mass of the vehicle. In an idealised circumstance, the coefficient of friction can be estimated as the ratio of the maximum braking deceleration of a vehicle obtained in a brake test to the acceleration due to gravity (9.8 m/s^2). However, the measured braking deceleration may require adjustment to allow for unbalanced vehicle brakes, the incline of the road, whether the vehicle is spinning, etc.

Unless freshly laid, the coefficients of friction of dry roads vary only by a small amount, owing to variations in the road surface temperature and polishing. Roads which are wet, or even damp, can vary to a much greater extent, depending on their texture and how wet or damp they were at the time of the incident.

In general, wet roads (Sabey *et al.*, 1970) and also some kinds of freshly laid dry roads (Bullas and Hounsell, 2005) exhibit a speed dependence in their friction characteristics. To investigate this fully, the test skids should be undertaken at a speed similar to that suspected for the target vehicle. Where this is impractical, mathematical adjustments based upon published research will need to be applied when calculating vehicle speed.

Although the coefficient of friction can be very similar between vehicles, there can be modest differences when the test vehicle tyres are not closely similar to those fitted to the collision vehicle (Goudie *et al.*, 2000; Leiss *et al.*, 2013). Occasionally circumstances may also require the tests to be been carried out on a different road surface.

There are differences between the tyres fitted to cars and large commercial vehicles (trucks and buses), and also to motorcycles (see Appendix B.2). Tyres on large vehicles, such as lorries, tend to provide somewhat lower effective coefficients of friction than car tyres over the same surface. Ideally deceleration rates should be assessed for the type of vehicle in question, although skid tests with car tyres are often the only values available.

Regulations govern a minimum depth of tread on a tyre. In dry conditions a tyre with no tread will generally perform as well as a tyre with a good depth of tread. The tread depth is far more important in vehicles which are braking on a very wet road, as it is the tread pattern which to a greater or lesser extent dispels the water, allowing the tyre to make contact with the road.

A skidding vehicle will often generate tyre marks of considerably different lengths. In particular the rear wheels may not generate any marks at all. If all the wheels can be shown to be contributing fully to the braking effort, then it is reasonable to assume that the vehicle was braking fully throughout. In that case the longest tyre mark is often used to define the length of the skid. But this does not take into account the distance before the start of the tyre mark where the vehicle is braking but not generating a visible tyre mark. Even when a brake pedal is pushed very firmly and rapidly, it can take several tenths of a second for the brake pressure at the wheels to approach the maximum value. During this period, the tyre slip, and therefore the likelihood of producing a visible mark, increases progressively so a vehicle may lose a few miles per hour before a tyre mark becomes visible. If the subject vehicle has poorly balanced brakes then an allowance must be made in the method of calculating its speed from the skid marks.

In general coefficients of friction can be estimated by dragging the object to be tested over the surface, as has been discussed in Section 3.5.3. However, it should be noted that this is not a reliable method for measuring tyre/road friction because the friction of rubber on a roadway is more complex than simple classical friction theory might suggest; different test methods can give different results (Bartlett *et al.*, 2006).

B.2 Motorcycles

Motorcycles can also leave sliding tyre marks. These are usually generated by the rear wheel for the reason that, if the front wheel locks, the machine tends to capsize very quickly. The brakes on motorcycles are such that the front and rear brakes are usually operated independently, although there are exceptions known as linked brake systems. This means that, if there is a rear tyre mark only, it is often not known whether the front brake was being used at all. However, an effective coefficient of friction which assumes that only the rear wheel had been braked might lead to a result which substantially underestimates the actual speed of the motorcycle. Investigators will sometimes present a range of results corresponding to full braking and only rear wheel braking.

Some high-performance motorcycle tyres intended for road use may provide higher coefficients of friction than car tyres on a particular road surface, especially when the tyre is hot. As previously mentioned, deceleration rates should ideally be assessed for the type of vehicle in question, although skid tests with car tyres will often be the only values available.

B.3 Brake assist systems

Brake assist systems (BAS), also known as emergency brake assist (EBA), have been an increasingly common fitment since about 2000, and between 2011 and 2015 they have progressively become mandatory on all new cars and light commercial vehicles. BAS measure the force and/or speed at which the brake pedal is depressed by the driver; if an emergency rate is detected, the additional braking is applied. If the driver then reduces their braking effort, the increased BAS brake pressure is also reduced.

BAS are combined on some vehicles with a collision avoidance system, also known as autonomous emergency braking (AEB). AEB systems will become mandatory on all new cars and light commercial vehicles from 2022, but they already exist in some vehicles. If an impending collision is detected, the system usually warns the driver audibly and visually. If the driver fails to take action soon enough by braking, or does not brake hard enough, the collision avoidance system can then automatically apply braking. AEB systems which react to the presence of car-sized objects has been a mandatory fitment to new large goods vehicles since November 2015.

B.4 Calculating the speed and accounting for speed remaining at the end of a period of braking

The calculation which will usually be presented for the speed lost by a vehicle while braking or otherwise slowing to a halt will have the form:

$$u = \sqrt{2\mu g s}$$

where (by convention) u is the speed at the start of the braking or slowing, μ is the actual or effective coefficient of friction, g is the acceleration due to gravity and s is the distance over which it was braked. (The factor μg is the deceleration of the vehicle, and some may instead use the single letter a in its place.)

However, if the vehicle did not come to a halt at the end of the period of braking, perhaps because it crashed or the driver simply released the brakes, the equation becomes

$$u = \sqrt{v^2 + 2\mu g s}$$

where v is the speed at the end of the braking/slowing.

But sometimes the first, simpler, equation will be used, with the speed remaining at the end being mentioned afterwards. In that circumstance it would not be correct to simply add the remaining speed (v) to the speed (u) calculated from the first equation. Instead, to calculate the true initial speed (u_0) the correct procedure is to add the squares of the two speeds, u and v, and take the square root of the sum, thus:

$$u_0 = \sqrt{u^2 + v^2}$$

Glossary

These definitions are presented in the context of road collisions.

Angular momentum: A body possesses angular momentum when it is rotating or spinning. It is its moment of inertia (*q.v.*) multiplied by its angular velocity. The latter usually has units of degrees, or else radians, per second. It is conserved in collisions between objects. (The concept of angular velocity is rarely used in simple collision reconstructions.)

Centre of gravity: When the motion of a complex object like a vehicle is modelled mathematically it is convenient to treat it as a point at which all the vehicle mass is located. That point is its centre of gravity.

Energy: Energy is the capacity to do mechanical work. Energy cannot be created or destroyed – it can only be converted from one form into another. A vehicle in motion has kinetic energy, equal to half its mass multiplied by the square of its speed. It comes from the chemical energy in its fuel or electrical energy in its battery. When it slows down by braking, its energy is conserved because the kinetic energy it loses is converted to heat within its brakes. In a collision energy is likewise conserved, but some of the kinetic energy of the vehicles is used up in bending or crushing their structures. For that reason the sum of the kinetic energies of the vehicles after an impact is less than the sum of their kinetic energies before. To apply the conservation of energy to a collision to calculate the vehicles' speeds, either before or after they collide, requires an estimate of the energy lost in deforming the vehicles.

Force: A force is what brings about a change in the velocity of an object or what deforms an object. In Newtonian mechanics it is defined as the rate of change of momentum of an object.

Friction and coefficient of friction: Friction is what resists one surface sliding against another and is quantified as the coefficient of friction for the two surfaces in question. The coefficient of friction is a plain number, and does not have any units. If, for example, the engine of a vehicle is turned off while the vehicle is moving it will eventually come to a stop because friction together with air resistance act on the vehicle. The principal source of this friction is between the components of the drive train. Elsewhere, provided the wheels are rotating and not locked, friction between the tyres and the road enables vehicles to be steered. It also enables a vehicle to brake. The coefficient of friction between the tyres and the road is equal to the ratio of the force required to drag the vehicle with its wheels locked and unable to rotate at a constant speed on the road, to the weight of the vehicle. The coefficient of friction depends on the nature and state of the road surface, in particular whether it is wet, icy or dry, and to a lesser extent on the tyres. On dry surfaces it is generally independent of the sliding speed, but in other conditions it will tend to become less as the speed increases.

Linear momentum: The linear momentum of a vehicle is its mass multiplied by its velocity. It has the same direction as the velocity. In a collision between two vehicles the sums of their momenta immediately before and after they collide are equal. This is known as the conservation of linear momentum, or just the conservation of momentum. In vehicle collision reconstructions it is a more useful conservation principle than the conservation of energy.

Mass and weight: In common speech mass and weight have the same meaning, but in science and engineering they are different. Mass is a measure of how much material there is in a body, and does not depend on location or other circumstances. Weight is properly the force experienced by a body in a gravitational field: over the surface of the earth, where gravity does not vary significantly, the weight of a body remains the same, but where gravity is less (eg on the moon) its weight will be less; where there is no gravity the body is 'weightless'.

Materials science: This is the science of materials used in everyday objects and all technologies. It is concerned with the properties and failure of vehicle parts, the absorption of energy of an impact by vehicle bodies, flammability of materials in vehicles, etc.

Moment of inertia: This applies to a body which is rotating about a particular axis, and expresses the distribution of its mass around that axis. A compact object will have a smaller moment of inertia than an object with the same mass which is more spread out. The greater the moment of inertia a body has, the greater will be the torque required to set it rotating.

m/s and m/s^2: Abbreviations of, respectively, metres per second (speed) and metres per second per second (acceleration).

Newtonian mechanics: This is the science of the motion of large objects, such as vehicles, as determined by Newton's three laws. The first law states that the velocity of a vehicle changes only when there is a net force acting on it. The second law states that when there is a constant net force on a vehicle, and its mass remains constant, it has a constant acceleration. The mass of a vehicle is its inertia, which is its resistance to a change of velocity. The greater the mass the larger the net force required to achieve a given acceleration. The third law states that when two objects collide they exert equal and opposite forces on each other.

Percentile: The level below which a given percentage of data points in a sample falls. For example, an 85th percentile walking speed means that 85% of the people considered would walk more slowly than the value given.

Principal direction of force (PDOF): When two vehicles collide they exert a complex pattern of forces on each other. In most circumstances the collision forces are very much greater than the forces which may be generated by the tyres, but persist for only a very short time, sometimes referred to as the 'impact phase'. The PDOF acting within that very short time is the direction of the resultant force one vehicle exerts on the other, and it is used to simplify the calculation of the energy that goes into deforming the vehicles during the collision. If the overall contact between the vehicles is prolonged, such as when one vehicle pushes another along a road after the impact phase, tyre forces may alter the subsequent motion of the vehicles. This must be borne in mind when reconstructing the events, although that prolonged phase of the collision will generally be insufficient to substantially alter the damage pattern to the vehicles and is not taken into account when specifying a PDOF.

Resolution: A measure of the fineness of detail, for example in a photograph.

Speed and velocity: Speed is the distance travelled in a specified time interval. For example, 2.5 metres per second, or 2.5 m/s, means the distance travelled in 1 second is 2.5 metres, and in 15 seconds the distance travelled would be 15 × 2.5 = 37.5 metres. Speeds are commonly expressed in miles per hour (mph), kilometres per hour (km/h) and metres per second (m/s). A speed expressed in one set of units may be converted into another set of units. For example, 1 mph = 1.609 km/h, 1 m/s = 2.24 mph = 3.6 km/h. There are 3600 seconds in 1 hour and 5280 feet in 1 mile, so the distance travelled by a vehicle with a speed of 30 mph in 1.5 seconds will be 30 × (1.5/3600) = 0.0125 miles = 0.0125 × 5280 feet = 66 feet = 66 × 0.3048 metres = 20.12 metres = 0.0201 km. The velocity of an object is both its speed and the direction in which it is moving. Its speed is a number like 30 mph. To specify its velocity we might say 30 mph due north.

Traction control system: An electronic system that automatically reduces engine power and may also apply anti-lock braking to reduce the likelihood of a car going out of control because of excessive acceleration, usually on a slippery surface.

Yaw: Yaw is the rotation of a vehicle about a vertical axis passing through its centre of gravity. When a vehicle turns it undergoes a yaw rotation. There are three axes about which the vehicle may rotate. Rotations about its other two axes are referred to as pitch and roll.

Bibliography

Asher, L., Aresu, M., Falaschetti, E., & Mindel, I. J. (2012). Most older pedestrians are unable to cross the road in time: a cross sectional study. Age and Ageing **41**(5), 690 – 694. https://doi.org/10.1093/ageing/afs076

Ashton, S. (1982). Vehicle design and pedestrian injuries. In Pedestrian Accidents, eds. Chapman, A. J., Wade, F. M. and Foot, H. C., Chapter 6. Wiley and Co. ISBN: 978-0471100577

Ashton, S., & Mackay, M. (1979). Some characteristics of the population who suffer trauma as pedestrians when hit by cars and some resulting implications. Proc. 4th IRCOBI International Conference, Gothenburg. https://tinyurl.com/4ry67r2w

Bartels, S., & Erbsmehl, C. (2014). Bewegungsverhalten von Fußgängern im Straßenverkehr: Teil 1. Forschungsvereinigung Automobiltechnik e.V. FAT 267 (Pedestrian movement behaviour in road traffic, Part 1. Research Association Automobiltechnik e.V.)

Bartlett, W., Baxter, A., Livesay, E., Schmidt, B., Stanard, T., & Wright, W. (2006). Comparison of drag-sled and skidding vehicle drag factors on dry roadways. SAE Transactions **115**, 1345. https://www.jstor.org/stable/44667839

Becke, M., & Marten, N. (2009). Status quo in the pedestrian accident reconstruction. Verkehrsunfall und Fahrzeugtechnik **111**(2), 52. https://tinyurl.com/dwcywzk

Brun-Cassan, F., Vincent, J., Tarriere, C., Fayon, A., Cesari, D., Cavallero, C., & Mauron, G. (1984). Comparison of experimental car-pedestrian collision performed with various modified side-impact dummies and cadavers. SAE Transactions **93**, 905–915. https://www.jstor.org/stable/44467198

Bullas, J. C., & Hounsell, N. B. (2005). Slippery when DRY? Low dry friction and binder rich road surfaces. In Safer Roads Conference, May 2005, Christchurch, New Zealand. https://tinyurl.com/7z48nnms

Cairney, P., & Catchpole, J. (1996). Patterns of perceptual failure at intersections of arterial roads and local streets. In Vision in Vehicles, V, ed. Gale, A. G., p. 87. Elsevier Science. https://tinyurl.com/yysg428d

Cliff, W. E., Lawrence, J. M., Heinrichs, B. E., & Fricker, T. R. (2004). Yaw testing an instrumented vehicle with and without braking. SAE Technical Paper 2004-01-1187. https://doi.org/10.4271/2004-01-1187

Cole, B. L., & Jenkins, S. E. (1984). The effect of variability of background elements on the conspicuity of objects. Vision Research **24**, 261. https://doi.org/10.1016/0042-6989(84)90129-9

Coley, G. D., de Olivera, P., Neal-Sturgess, C., & Happee, R. (2001). Pedestrian human body validation using detailed real-world accidents. Proc. 1st IRCOBI Conf., Isle of Man. https://tinyurl.com/m7xvm99d

Crabtree, M., Lodge, C., & Emmerson, P. (2014). A review of pedestrian walking speeds and time needed to cross the road. TRL PPR700. https://tinyurl.com/sfhh4bd9

Cuerden, R., Richards, D., & Hill, J. (2007). Pedestrians and their survivability at different impact speeds. Proc. 20th International Technical Conference on the Enhanced Safety of Vehicles, Lyon, France, paper no. 07-0440. https://tinyurl.com/n7bc37em

Dettinger, J. (1997). Methods of improving the reconstruction of pedestrian accidents: development differential, impact factor, longitudinal forward trajectory, position of glass splinters. Verkehrsunfall und Fahrzeugtechnik **35**, 25 – 30.

Dunbar, G., Holland, C., & Maylor, E. (2004). Department for Transport Road Safety Research Report No. 37. Older Pedestrians: A Critical Review of the Literature. https://tinyurl.com/4r3yuypw

Elliott, J. R., Augy, S., Simms, C. K., & Wood, D. P. (2010). Statistical prediction of pedestrian pre-impact speed based on post-accident vehicle damage. Proc. 10th IRCOBI Conf., Hanover. https://tinyurl.com/thdu9br7

Enns, J. T. (1990). Three dimensional features that pop out in visual search. In Visual Search, ed. Brogan, D., pp 37 – 45. Taylor and Francis. ISBN 978-0850667738.

EU General Safety Regulation. (2019). Regulation (EU) 2019/2144 of the European Parliament and of the Council of 27 November 2019. https://eur-lex.europa.eu/eli/reg/2019/2144/oj

Eubanks, J.J., & Hill, P.F. (1999). Pedestrian accident reconstruction and litigation (Cdr edition). Lawyers and Judges Publishing Co. ISBN: 0-913875-56-2

Evans, A. K., & Smith, R. (1999). Vehicle speed calculation from pedestrian throw distance. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering **213**, 441. https://doi.org/10.1243/0954407991527008

Forensic Science Regulator (2020). Codes of Practice and Conduct Appendix: Digital Forensics – Video Analysis FSR-C-119 Issue 2. https://tinyurl.com/yypezqe6

Fricke, L. B. (2010). Traffic Crash Reconstruction, 2nd edn. Northwestern University Center for Public Safety.

Fugger, T., Randles, B., Wobrock, J., & Eubanks, J. (2002). Pedestrian throw kinematics in forward projection collisions. SAE Technical Paper 2002-01-0019. https://doi.org/10.4271/2002-01-0019

Fugger, T., Randles, R., Stein, A., Whiting, W., & Gallagher, B. (2000). Analysis of pedestrian gait and perception/reaction time at signal controlled crosswalk intersections. Transportation Research Record **1705**, 20. https://doi.org/10.3141/1705-04

Ghazizadeh, M., & Boyle, L. N. (2009). Influence of driver distractions on the likelihood of read-end, angular and single-vehicle crashes in Missouri. Transportation Research Record **2138**, 1. https://doi.org/10.3141/2138-01

Glynn, C., & Wood, D. (2015). Pedestrian speed from vehicle damage. EVU Conference, paper no. 09.

Goddard, C. H., & Price, D. (2017). Speedometers and collision reconstruction. SAE Technical Paper 2017-01-1412. https://doi.org/10.4271/2017-01-1412

Goudie, D. W., Bowler, J. J., Brown, C. A., Heinrichs, B. E., & Siegmund, G. P. (2000). Tire friction during locked wheel braking. SAE Technical Paper 2000-01-1314. https://www.jstor.org/stable/44687012

Granlund, J. (2017). Contaminated road surfaces – diesel spillage and loose gravel on bare asphalt. WSP Sverige AB Project 10249784. https://doi.org/10.13140/RG.2.2.29956.22407

Hague, D. J. (2001). Calculation of impact speed from pedestrian slide distance. Proc. 5th ITAI International Conference, York, pp. 101 – 108.

Hague, D. (2005). Frontal generic stiffness coefficients and CRASH3 analysis. Proc. 7th ITAI International Conference, Dunblane, pp. 155 – 180. https://trid.trb.org/view/1156484

Han, I., & Brach, R. M. (2001). Throw model for frontal pedestrian collisions. SAE Technical Paper 2001-01-0898. https://www.jstor.org/stable/44730964

Hight, P. V., Wheeler, J. B., Reust, T. J., & Birch, N. (1990). The effects of right side water drag on vehicle dynamics and accident causation. SAE Technical Paper 900105. https://doi.org/10.4271/900105

Hills, B. L. (1980). Vision, visibility and perception in driving. Perception **9**, 183. https://doi.org/10.1068/p090183

Hole, G., & Langham, M. (1997). Some factors affecting drivers' reaction times. Proc. 3rd ITAI International Conference, Telford, pp. 7 – 38.

Horne, W. B. (1984). Predicting the minimum dynamic hydroplaning speed for aircraft, bus, truck and automobile tyres rolling on flooded pavements. ASTM Committee E-17, Texas.

Horne, W.B., & Dreher, R. C. (1963). Phenomena of pneumatic tire hydroplaning. NASA Technical Note TND-2056. https://tinyurl.com/y6qu3do2

Imms, F. J., & Edholm, O. G. (1981). Studies of gait and mobility in the elderly. Age and Ageing **10**, 147. https://doi.org/10.1093/ageing/10.3.147

Kasanický, G., & Kohut, P. (2009). New partial overlap pedestrian impact tests. Proc. 18th EVU Conference & 9th ITAI Conference, Hinckley, pp. 107 – 126.

Krauss, D. A. (2015). Forensic Aspects of Driver Perception and Response, 4th edn. Lawyers & Judges Publishing Co. ISBN 978-1936360338.

Lambourn, R. F. (1989). The calculation of motor car speeds from curved tyre marks. Journal of the Forensic Science Society **29**, 371. https://doi.org/10.1016/S0015-7368(89)73284-9

Lambourn, R. F. (1991). The calculation of motorcycle speeds from sliding distances. SAE Technical Paper 910125. https://www.jstor.org/stable/44632025

Lambourn, R. F., & Viner, H. E. (2006). Friction tests on contaminated road surfaces. TRL Published Project Report PPR073. https://trid.trb.org/view/1156479

Leiss, P. J., Becker S., & Darien, G. (2013). Tire friction comparison of three tire types. SAE Technical Paper 2013-01-0783. https://doi.org/10.4271/2013-01-0783

Lennard, J., Hurley, B., & Thomas, P. (1998). The accuracy of Crash3 for calculating collision severity in modern European cars. Proc. 16th International Technical Conference on the Enhanced Safety of Vehicles, p. 1242. Enhanced Safety of Vehicles Conference 98-S6-08. https://tinyurl.com/y35bd6gz

Liangliang, S., Han, Y., Huang, H., Li, Q., Wang, B., & Mizuno, K. (2018). Analysis of pedestrian-to-ground impact injury risk in vehicle-to-pedestrian collisions based on rotation angles. Journal of Safety Research **64**, 37. https://doi.org/10.1016/j.jsr.2017.12.004

Martin, D. P. & Schaefer, G. F. (1996). Tire-road friction in winter conditions for accident reconstruction. SAE Technical Paper 960657. https://www.jstor.org/stable/44720793

McKnight, A. J. (1972). The application of systems/task analysis to the identification of driver perception and decision making processes. Proc. OECD Symposium on Road User, Perception and Decision Making, Rome, 13 – 15 November.

Medwell, C. J., McCarthy, J. R., & Shanahan, M. T. (1997). Motorcycle slide to stop tests. SAE Technical Paper 970963. https://www.jstor.org/stable/44731321

Meuwissen, J., & Spätjens, J. (2013). Sliding decelerations of lightweight scooter models. Proc. EVU Conference, Florence, p. 27. https://www.mvoa.nl/files/pdf/.pdf

Meyers, D., & Austin, T. (2012). Dry pavement friction reductions due to sanding applications. SAE Technical Paper 2012-01-0603. https://doi.org/10.4271/2012-01-0603

Monk, M. W., & Guenther, D. A. (1983). Update of crash 2 computer model damage tables. NHTSA HS-806-446. https://trid.trb.org/view/199837

Muttart, J. W. (2019). Drivers' responses in emergency situations: a quick reference. IPTM Publications, Jacksonville, Florida. https://crashsafetysolutions.com/home

Navin, F. (1995). Hydroplaning and accident reconstruction. SAE Technical Paper 950138. https://doi.org/10.4271/950138

Neades, J. (2011). Developments in road vehicle crush analysis for forensic collision investigation. PhD thesis, De Montfort University. https://tinyurl.com/yxm7mj7r

Neades, J., & Shephard, R. (2009). Review of measurement protocols applicable to speed from damage programs. Impact **17**(11), 4.

Neale, W. T., Danaher, D., Donaldson, A., & Smith, T. (2021). Pedestrian impact analysis of side-swipe and minor overlap collisions. SAE Technical Paper 2021-01-0881. https://doi.org/10.4271/2021-01-0881

Otte, D. (2004). Use of throw distances of pedestrians and bicyclists as part of a scientific accident reconstruction method . SAE Technical Paper 2004-01-1216. https://doi.org/10.4271/2004-01-1216

Perchonok, K., & Pollack, L. (1981). Luminous requirements for traffic signs. Federal Highways Administration, USDOT Report FHWA/RD-81/158

Randles, B. C., Fugger, T. F., Eubanks, J. J., & Pasanen, E. (2001). Investigation and analysis of real-life pedestrian collisions. SAE Technical Paper 2001-01-0171. https://doi.org/10.4271/2001-01-0171

Ravani, B., Brougham, D., & Mason, R. T. (1981). Pedestrian post-impact kinematics and injury patterns. SAE Technical Paper 811024. https://www.jstor.org/stable/44724965

Richards, D. (2010). Relationship between speed and risk of fatal injury: pedestrians and car occupants. Road Safety Web Publication 16. https://tinyurl.com/zfsm92hs

Rohm, M., & Schimmelpfennig, K. (1995). Einfluβ der Bewegungsgeschwindigkeit beim Pkw-Fuβgänger Unfall. (Influence of the speed of car on pedestrian accidents.) Verkehrsunfall und Fahrzeugtechnik. https://tinyurl.com/53n2vxxd

Rose, N. A., Beauchamp, G., & Asay, A. F. (2018). Rollover Accident Reconstruction R-475. SAE International. https://www.sae.org/publications/books/content/r-475/

Rumar, K. (1990). The basic driver error: late detection. Ergonomics **33**, 1281. https://doi.org/10.1080/00140139008925332

Sabey, B. E., & Staughton, G. C. (1975). Interacting roles of road environment vehicle and road user in accidents. Proc. 5th International Conference of the International Association for Accident Traffic Medicine, London. https://trid.trb.org/view/46132

Sabey, B. E., Williams, T., & Lupton, G. N. (1970). Factors affecting the friction of tyres on wet roads. SAE Transactions **79**, 1203 – 1218. https://www.jstor.org/stable/44644490

SAE Ground Vehicle Standard. (2017). Use of the critical speed formula. SAE J2969_201701. https://www.sae.org/standards/content/j2969_201701/

Searle, J. (2009). The application of the throw distance formulae. Road Accident Analysis, Institute of Police Technology and Management, Special Problems in Traffic Crash Reconstruction Conference, Orlando, FL.

Simms, C., & Wood, D. (2009). Pedestrian and Cyclist Impact: A Biomechanical Perspective. Springer. ISBN: 978-9048127429

Simms, C., & Wood, D. (2010). Effect of pre-impact pedestrian position and motion on kinematics and injuries from vehicle and ground contact. International Journal of Crashworthiness **11**, 345. https://doi.org/10.1533/ijcr.2005.0109

Stannard-Baker, J. (1953, 1957, 1963, 1975). Traffic Accident Investigation Manual. Northwestern University, Illinois. ISBN: 978-0912642062

Sturtz, G., Suren, E., Gotzen, L., Behrens, S., & Richter, K. (1976). Biomechanics of real child pedestrian accidents. SAE Technical Paper 760814. https://doi.org/10.4271/760814

Toor, A., Araszewski, M., Johal, R., Overgaard, R., & Happer, A. (2002). Revision and validation of vehicle/pedestrian collision analysis method. SAE Transactions **111**, 697 – 708. https://www.jstor.org/stable/44719248

Treisman, A. (1986). Features and objects in visual processing. Scientific American **255**, 114B. https://www.jstor.org/stable/24976089

Tumbas, N. S., & Smith, R. A. (1988). Measuring protocol for quantifying vehicle damage from an energy basis point of view. SAE Technical Paper 880072. https://doi.org/10.4271/880072

Vaughan, R., & Bain, J. (2000). Acceleration and speeds of young pedestrians: Phase II. SAE Transactions **109**, 1264 – 1287. https://www.jstor.org/stable/44686970

Vomhof, D. (2011). 4NX6XPRT Stifcalcs manual. http://www.4n6xprt.com/

Wach, W. (2013). Uncertainty in calculations using Lambourn's critical speed procedure. SAE Technical Paper 2013-01-0779. https://doi.org/10.4271/2013-01-0779

Wang, Q., & Gabler, H. C. (2007). Accuracy of vehicle frontal stiffness estimates for crash reconstruction. Proc. 20th Enhanced Safety of Vehicles Conference, paper no. 07-0513. NHTSA. https://tinyurl.com/8kn4aemn

Wiacek, C., Nagabhushana, V., Rockwell, T., Summers, S., Zhao, L., & Collins, L. (2015). Evaluation of frontal crash stiffness measures from the US New Car Assessment Program. Proc. 24th Enhanced Safety of Vehicles Conference, paper no. 15-0257. NHTSA. https://tinyurl.com/wcw7yz2f

Williams, A., & Evans, M. (1983). Influence of tread wear irregularity on wet friction performance of tyres. In Frictional Interaction of Tire and Pavement. https://doi.org/10.1520/STP793-EB

Windisch, M., & Senatli, E. (2015). Analysing the moving speeds of 2 to 3 year old children – new results. Proc. 24th EVU Congress, Edinburgh, paper no. 13. https://www.evuonline.org/index.php/hu/component/content/article?id=1193&Itemid=101

Wood, D. P., Simms, C. K., & Walsh, D. G. (2005). Vehicle–pedestrian collisions: validated models for pedestrian impact and projection. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering **219**, 183. https://doi.org/10.1243/095440705X6703

Wood, D. P., Alliot, R., Glynn, C., Simms, C. K., & Walsh, D. G. (2008). Confidence limits for motorcycle speed from slide distance. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering **222**, 1349. https://doi.org/10.1243/09544070JAUTO731

Wulf, G., Hancock, P. A., & Rahimi, M. (1989). Motorcycle conspicuity: an evaluation and synthesis of influential factors. Journal of Safety Research **20**, 153. https://doi.org/10.1016/0022-4375(89)90025-X

Zębala, J., Ciępka, P., & Reza, A. (2013). Pedestrian speeds and acceleration – results of research on contemporary population. Impact **Summer**, 4 – 11.

Acknowledgements

The members of the groups involved in producing this primer are listed below. The members acted in an individual and not organisational capacity and declared any conflicts of interest. They contributed on the basis of their own expertise and good judgement. The Royal Society and the Royal Society of Edinburgh gratefully acknowledge their contribution.

Primer leads
Mrs Justice Amanda Yip DBE
Professor Adrian P Sutton FRS

Editorial board
Professor David Cebon FREng
Professor John Duncan FRS FBA
His Honour Judge Jeremy Freedman
Professor Anthony J Kinloch FREng FRS
Sir Alastair Muir Russell KCB FRSE
Sir David J Wallace CBE FRS FRSE FREng
Sheriff Alistair Watson

Writing group
Mr Peter Jennings
Dr Richard Lambourn
Dr Martin Langham
Dr Jon Neades

Assistant to the Editorial board
Mr Chris Gutteridge

Primer steering group
Dame Anne Rafferty DBE
Lord Hughes of Ombersley
Professor Dame Sue Black DBE FRSE
Sir Charles Godfray CBE FRS
Lord Justice Peter Jackson
Dr Julie Maxton CBE
Professor Dame Angela McLean DBE FRS
Professor Niamh Nic Daéid FRSE
Professor Sarah Skerratt
Lord Beckett
Mr Justice Wall
Lord Weir
Mrs Justice Yip

The Royal Society is a self-governing Fellowship of many of the world's most distinguished scientists drawn from all areas of science, engineering, and medicine. The Society's fundamental purpose, as it has been since its foundation in 1660, is to recognise, promote, and support excellence in science and to encourage the development and use of science for the benefit of humanity.

The Society's strategic priorities are:

- Promoting excellence in science
- Supporting international collaboration
- Demonstrating the importance of science to everyone

For further information
The Royal Society
6 – 9 Carlton House Terrace
London SW1Y 5AG

T +44 20 7451 2571
E law@royalsociety.org
W royalsociety.org/science-and-law

Registered Charity No 207043

The Royal Society of Edinburgh (RSE), Scotland's National Academy, is a leading educational charity which operates on an independent and non-party-political basis to provide public benefit throughout Scotland. Established by Royal Charter in 1783 by key proponents of the Scottish Enlightenment, the RSE now has around 1600 Fellows from a wide range of disciplines. The work of the RSE includes awarding research funding, leading on major inquiries, informing public policy and delivering events across Scotland to inspire knowledge and learning.

For further information
The Royal Society of Edinburgh
22 – 26 George Street
Edinburgh EH2 2PQ

T +44 131 240 5000
E info@theRSE.org.uk
W rse.org.uk

Scottish Charity No SC000470

ISBN: 978-1-78252-571-4
Issued: January 2022 DES7309