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The physics of traffic accidents

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Every motorist knows and dreads those moments when a sudden emergency causes him to brake hard possibly locking the car wheels and precipitating the vehicle into a dangerous and spectacular skid. Most times we escape from the situation with nothing more serious than an injured pride and a racing heart; what we may well fail to realize is that the behaviour of a car when braking is critically dependent on many factors. A slight change in the nature of the road surface or a delay in the driver's reaction could be all that is needed to turn a mere incident into a tragedy.

A motor car, like any moving body, is subject to physical law. At first sight it may well seem to be too complex a system for a quick and convenient analysis, but for several years the Highway Patrol in the United States has been using a knowledge of basic physics and mechanics to analyse traffic accidents (Stannard-Baker 1973). The quantitative information that has been obtained has proved invaluable not only in determining responsibility but also in evaluating and improving the design and construction of roads. Recently, similar techniques have been introduced in the United Kingdom and are being used in a number of police areas.

Skids and drag factors

The most pertinent information in accident analysis is the speed at which the vehicles were travelling at various times before impact. If a skid mark has been left by a vehicle only a simple application of classical mechanics is required to obtain a minimum value for the speed. The principle of the analysis can best be explained by an example. Suppose that a Mini is travelling along a straight dry asphalt country road at about 55 miles per hour (mph) (24.6 m s⁻¹). Suddenly, a cow steps into the road 183 ft (55.6 m) in front of the car. Faced with the prospect of having beef for lunch for the next six months if he hits the creature, the driver stamps on the brakes, locks all four wheels and skids to a halt. The skidding exerts a retarding force on the car and in accordance with Newton's second law the product of the mass of the vehicle and its deceleration will be directly proportional to the external force. In this case the external force is the frictional force between the locked wheels and the road surface. A force arising from skidding friction is equal to the product of the mass of the body and a coefficient that is a function of the nature of the two surfaces that are in sliding contact. It is independent of the area of contact. Consequently, when the car skids along the road the deceleration that it experiences is independent of its mass and is a function only of the nature of the surfaces of the tyre and the road. The deceleration is usually expressed as a proportion of the gravitational constant and is known as the coefficient of dynamic friction or, less pretentiously, the drag factor. The result that the drag factor is not a function of the mass of the vehicle implies that if the cow had appeared at the same distance in front of a ten ton truck doing 55 mph (24.6 m s⁻¹) instead of the Mini it would have had exactly the same chance of avoiding being hit. The idea that, all things being equal, a lorry should be able to skid to a stop in the same distance as a car seems to conflict with the experience of many motorists. Nevertheless the result can easily be confirmed experimentally, and after all the back cover of the Highway Code does not differentiate between cars and lorries when giving examples of shortest stopping distances.

In this brief analysis it has been assumed that the drag factor is not a function of the speed of the vehicle, so that the deceleration is uniform for the duration of the skid. This proves to be a reasonable assumption for speeds up to the legal maximum of 70 mph (31.4 m s⁻¹), and a typical deceleration curve is illustrated in figure 1. This represents a skid from 55 mph (24.6 m s⁻¹) to a halt with an average drag factor of 0.55 (dry traffic polished asphalt). The

Figure 1 A typical deceleration curve

![Deceleration Curve](image-url)
Figure 2: Compression of a car on impact. It is possible to estimate the impact velocity of a car involved in an accident from the amount of damage. The car on the right has been 'shortened' by about 60 cm. Naturally it is important to assess impact velocity at the end of a skid as this will increase the speed at the commencement of skidding.

The graph shows the change in the instantaneous value of the drag factor at various times in the skid. Point A represents the start of effective braking, when the road wheels are still rolling but an increasingly greater force is needed to maintain rolling contact. The drag factor reaches a peak at B, the position of maximum retardation; this is still determined by the complex conditions of rolling friction before the start of the skid. Close to point B the brake pressure will become sufficient to stop the wheels rotating and heat is then generated at the point where the tyre is in contact with the road. The tar in the road will then melt and as this happens the drag factors falls to C, the sliding value, as the wheel skids on a small pool of molten bitumen. It is here that the first evidence of skidding will be found. Under emergency conditions the sequence from A to C occurs in a very short time; usually only one or two revolutions of the wheel will have taken place between the onset of effective braking and the commencement of the skid.

From C to D the car decelerates at a uniform rate until its velocity is insufficient to provide the heat to maintain the molten interface between the tyre and the road. The drag factor starts to increase towards the rolling value and the car halts. It is this rise in the instantaneous drag factor that always makes the last few moments of a skid seem much more abrupt than

Figure 3: The abrupt change in the direction of the skid at the end marked the point of impact (other car not shown).
Different road surfaces have different drag factors and it is difficult to give a precise value for a particular surface. The main reason for this is that the drag factor is dependent on the roughness of the surface and this is a function of the amount of wear that the road has been subjected to. Figure 4 illustrates the range of drag factors for the common road surfaces at commencement of skidding speeds of about 40 mph (17.9 m s\(^{-1}\)) on a dry horizontal surface. Figure 5 gives similar information for a wet surface. The tables are based on data obtained initially by the Traffic Institute of Northwestern University, Illinois. The danger of wet roads is clearly shown. Not only is the variation of drag factor greater in the wet, but the values are considerably lower on most surfaces.

The *Highway Code* quotes braking distances of 45 ft (13.7 m), 125 ft (38.2 m) and 245 ft (74.5 m) for speeds of 30 mph (13.4 m s\(^{-1}\)), 50 mph (22.6 m s\(^{-1}\)) and 70 mph (31.4 m s\(^{-1}\)) respectively. These correspond to an assumed drag factor of 0.66, a value that is probably optimistic as it represents the maximum that could be achieved on dry traffic polished asphalt. Of course, motorists can always stop in a shorter distance by avoiding skidding and utilizing the higher drag factors that are available under conditions of rolling friction. The *Highway Code* rightly lays great emphasis on the shortest stopping distance; that is, the sum of the driver's reaction distance and the braking distance. The reaction time is the time that elapses from the moment that the driver first perceives the hazard to the onset of effective braking. Reaction time varies with the age and health of the individual. An average reaction time is 0.66 s which corresponds to a reaction distance of 1 ft for each 1 mph of assumed speed. At 55 mph (24.6 m s\(^{-1}\)) the reaction distance is 55 ft (16.8 m), and if we again consider the problem of the cow in the road 183 ft (55.6 m) in front of the car it is apparent that 55 ft (16.8 m) will be used up before braking starts. The car then skids the 128 ft (38.6 m) and hits the cow. The impact velocity can be found as it is only necessary to calculate the velocity 128 ft (38.6 m) into the 182 ft (55.4 m) skid mark at a drag factor of 0.55. This comes to 30 mph (13.4 m s\(^{-1}\)) at impact. Poor cow!

**Accident analysis**

The laws governing motoring are numerous and difficult to appreciate. Often there may be little argument that a motorist is in the wrong but it is important that the courts should be able to determine the degree of his wrongdoing. For instance if a motorist hits a pedestrian on a zebra crossing there are few defences but most people would agree that a distinction should be made between the man who is
travelling within the legal speed limit and carelessly allows his attention to wander and the hooligan who is doing 60 mph (26.8 m s\(^{-1}\)) in a 30 mph (13.3 m s\(^{-1}\)) area and mows down the pedestrian. The consequences for the pedestrian may be the same in both cases although the law recognizes a difference of degree. A driver who commits a momentary error that leads to an accident, even a fatal one, may well only be charged with driving without due care and attention (maximum penalty £100) whereas a man who was blatantly driving at more than the speed limit when he caused the accident could be charged with dangerous or reckless driving (maximum penalty £100 and/or 4 months jail). When the accident results in a death the most serious charge would be that of manslaughter (maximum life imprisonment). In practice this is now reserved for cases of particularly ruthless or callous driving. As juries were always reluctant to convict motorists on manslaughter charges a charge of causing death by dangerous driving (maximum 5 years jail) was introduced in the 1960 Road Traffic Act. So in any fatal accident a decision must first be taken to prosecute on causing death by dangerous driving or on driving without due care and attention (or both) and if the former course is decided upon evidence must be presented to the jury for them to decide what is dangerous and what is merely careless.

The actual procedure for accident analysis can best be illustrated by an example. Figure 6 shows a plan view of a dry asphalt road with a 24 ft (7.3 m) carriageway. The road forms a horizontal plateau at the top of a slight hill to the east. It is 11.30 at night and a saloon car is driven up the hill and along the road in a westerly direction; at position A it hits and fatally injures an elderly man who is crossing the road from between two parked cars. There are no witnesses of the impact although a man standing at point B says that he remembers that the car seemed to be going 'quite quickly'. The driver says that he was travelling at close to the legal limit (30 mph) (13.4 m s\(^{-1}\)) and just didn't see the old man until it was too late as his vision was obscured by the top of the hill. Is the driver's story reasonable? Several facts must be established:

1. The exact point of impact should be determined by looking for debris such as broken headlight glass or dirt falling off the chassis;
2. The lengths of skid marks must be measured and their relation to the point of impact established;
(3) By driving the saloon car up the hill the point on the brow of the hill where the pedestrian would have first become visible should be found. This is the first point of possible perception.

(4) The car should be driven behind a police car with a calibrated speedometer and skidded to a halt from various speeds. If the lengths of these skids are measured the drag factor of the road can easily be calculated. As a result of these experiments several facts have been established:

- Drag factor of dry asphalt = 0.65
- Total skid length = 130 ft (39.6 m)
- Length of skid after impact = 30 ft (9.1 m)
- Distance of impact from south pavement = 3 ft (0.9 m)
- Distance from impact to point of possible perception = 400 ft (122 m).

Figure 7 displays this information. It should now be possible to answer three questions:

(1) What was the speed of the car?
(2) Did the driver react immediately to the hazard?

(3) Are any improvements required in the design of the road?

The answer to the first question can be obtained easily as a skid length of 130 ft (39.6 m) on a road with a drag factor of 0.65 implies that the speed at the commencement of skidding was 50 mph (22.6 m s\(^{-1}\)). This is not necessarily the speed of the car, in that it could have been going faster but the driver avoided locking the wheels in the first moments of braking. He would then have been decelerating, but there would have been no evidence of it as there would not have been a skid mark until the wheels locked at 50 mph (22.6 m s\(^{-1}\)). In these circumstances only a minimum speed can be found.

Using the value of 50 mph (22.6 m s\(^{-1}\)) did the driver react quickly enough? Here we need to look at the sequence of the times at which the events occurred. Simple mechanics gives a value for the time \(T = \frac{0.046}{S/F}\).

In this case 3.54 s were occupied in the skid. Add to this a reaction time of 0.66 s and it is seen that the last time of possible reaction to avoid the accident was 4.2 s before impact. Had the pedestrian started walking across the road at this moment? From the time that he was visible from between the parked cars to the point of impact, the pedestrian covered 15 ft (4.6 m). Now when you start walking all the acceleration is achieved in your first stride so we can reasonably regard the pedestrian as moving with constant velocity at an average walking speed of 2 mph or 2.9 ft s\(^{-1}\) (0.9 m s\(^{-1}\)). It would have taken the pedestrian 5.2 s to cover the 15 ft (4.6 m) so the moment after the pedestrian started walking the driver could have wasted a second before reacting and still have avoided the collision. In fact the skid marks go 30 ft (9.1 m) beyond the collision and this would have occupied a further 1.8 s as the vehicle decelerated from 25 mph (11.3 m s\(^{-1}\)) impact velocity to a halt. So a total of 2.8 s elapsed during which the driver had the opportunity of reacting to the situation but took no action. The time locations of these events are illustrated in figure 8. Finally the question of the hill obscuring visibility can easily be answered when it is realized that the reaction distance at 50 mph (22.6 m s\(^{-1}\)) is 50 ft (15.2 m) giving a total stopping distance of 180 ft (55 m). This is 220 ft (67 m) past the point of possible perception.

**Physics in actions**

The case against the driver may seem to be strong: he was going too fast and he failed to anticipate a hazard. He would probably be charged with dangerous driving and if convicted he could face a fine of the order of £75 with 2 to 3 years disqualification. In
the absence of any analysis such as this the case becomes open, depending largely on the reliability of the witness. Obviously great care has to be taken in the preparation of evidence of this kind and every effort is made to ensure that any experimental error is biased in the favour of the defendant. It is obviously preferable to have some form of quantitative analysis available to a court rather than the vague expressions of opinion that so often characterize this type of offence. Unfortunately, there are human problems to be overcome before the system is generally accepted. Judges, recorders and barristers always seem to have had classical educations so that they experience considerable difficulty in following comparatively straightforward physical and mathematical arguments. This often means that they are reluctant to use this type of simple numerical analysis in court room arguments and hearings often commence with a heated discussion as to the admissibility of this evidence. Even if this is a problem at the moment, the techniques of accident analysis have already proved their worth in cases in coroner’s court and by showing that in some circumstances the motorist was not at fault or should only face a minor charge. However, it is unfortunate that innumeracy amongst the legal profession should impede the introduction of these quantitative methods.

It is not possible in a short article such as this to do any more than touch on some of the most common aspects of this rapidly developing subject. I have concentrated on a particular type of accident to illustrate the potential use of physics in this field. Other equally well established methods can be used to determine critical speeds on curves, behaviour of motor cycles and stability of articulated vehicles. A knowledge of the acceleration of motor cars from a halt can be applied to determine the visibility that is needed to make a minor road junction safe. Apart from analysing actual accidents calculations of this type can highlight potentially dangerous sections of roads. Perhaps schools may consider particularly notorious junctions in their own area and apply these methods to them. Such a project would not only present some of the more mundane aspects of mechanics in an acceptable way but would also indicate one aspect of the social relevance of physics.

REFERENCE

Books for schools
The next issue of Physics Education will be a special issue on 'Books for schools'.