Pavement Skid Resistance Measurement and Analysis in the Forensic Context

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ABSTRACT

Skid resistance measurement and analysis is now a routine procedure in motor vehicle crash analysis. In fact it was one of the earliest investigative and analytical tools used for this work. Many different measurement methods are in common use, including: visual estimation assisted by friction tables; various dragged devices with friction force measurement and instrumented vehicle skid-to-rest testing, the last having become the preferred alternative for many investigators over the past decade or so.

The skid resistance measurement devices at present commonly used by traffic engineers for pavement condition monitoring and maintenance intervention, such as SCRIM, ROAR, Griptester and the British Pendulum, are only rarely used for forensic purposes in New Zealand although in some other countries these may be applied as a routine procedure during crash-scene investigations.

The interpretation and analysis of the results obtained by skid resistance measurement in the forensic context may seem to be an obvious process but it is not always straightforward. Uncertainties exist and there is considerable scope for fundamental error. The latter is of significant concern, given the potential adverse consequences of an analyst presenting flawed expert testimony in Court.

This paper examines the most common skid resistance measuring methods used for forensic purposes and discusses the interpretation and analysis of the results obtained, the uncertainties involved and the expression of expert opinion in Court. It contrasts the differing needs of the forensic analyst and the traffic engineer in this area. It emphasises the need for crash analysts to have a thorough understanding of the physics involved, the empirical data obtained and the relationship between the analysis subsequently performed and the skid resistance measurement method used.

1. INTRODUCTION

Over the past fifty or more years, an enormous amount of knowledge has been accumulated in relation to motor vehicle crash analysis and reconstruction. The research required to achieve this has drawn upon a broad range of scientific disciplines, ranging across theoretical and empirical aspects of physics, bio-mechanics, psychology and engineering at least. This has resulted in the analytical methods and mathematical/physical models currently and commonly used by motor vehicle crash analysts. It has long reached the stage where many such analyses of available crash evidence are performed by simply plugging numbers into commonly accepted and used formulae to obtain estimates for parameters of interest. Acceleration and braking distances, vehicle speeds and the scope for crash avoidance are common examples. The purpose behind this is most often to assist the determination of cause and/or culpability, typically for insurance managers, Judges, Juries or Coroners, by advising them through formal reporting or giving expert evidence.

Performing such analyses and giving such advice is an important and serious responsibility. The outcome can have an immense effect upon the lives of those involved. It is essential that the analysis be performed correctly with a declared level of accuracy and reliability. That means being careful and thorough as well as thinking through the analysis with proper understanding of the physical processes involved. That in turn means knowledge of the inherent limitations of the methods used, together with a full understanding of the logical relationships and sequences involved, in order to progress from the available evidence to the reported opinions in a clear and unambiguous manner, so that the results and their limitations can be understood by the person being advised and will assist them in their task.

One of the most common tasks confronting the motor vehicle crash analyst is the interpretation and analysis of tyre-mark evidence on the road and other surfaces traversed. This evidence is used frequently to identify the path(s) taken by the vehicle(s) involved, to estimate vehicle speeds at different stages of the crash sequence, to assess the likely actions of the driver(s) involved and the scope for collision avoidance. Much of this requires estimation of the likely range of forces that were generated between the vehicle tyres and the road surface. That in turn requires estimation of the most likely pavement skid resistance range operating at the time of the crash. This may be undertaken in a variety of ways ranging from visual estimation to physical measurement. However, each of the available estimation methods has limitations that lead to uncertainty associated with the data obtained and may place significant constraints upon the manner in which it can be used if appropriate accuracy and reliability are to be achieved and declared.

2. THE FORENSIC CONTEXT

An expert fulfils a unique function in Court by assisting the Trier of Fact to understand technical matters not commonly known to a lay person [1]. Exclusion rules operate that determine whether their evidence is admissible at trial. In essence, to be admissible, the expert evidence must be relevant to the issues at trial, helpful in assisting the decision, beyond common knowledge and within the expert’s sphere of expertise. To be admissible, expert opinion must be based upon proven facts and/or the results of expert investigation and analysis. Virtually anyone can be an expert by suitably qualifying themselves. The extent of the expertise so established ultimately determines the weight given to the expert’s evidence by the Trier of Fact. The expert is responsible to the Court in that the evidence given must be complete, impartial and unbiased. However it does not have to be objective. All opinions based upon experience are subjective, although no doubt based upon sound information and reasoning. Such opinions are admissible as evidence from expert witnesses.

As well as avoiding the common knowledge exclusion rule, expert evidence must meet other criteria affecting admissibility and weight. These are intended to exclude so-called “bad science” from the courtroom. Since 1923, the Courts have relied upon a principle established in Frye v United States, 293 Federal Reports 1st Series 1013, 1014 CA. This required that “*the things from which the deduction is made must be sufficiently established to have gained general acceptance in the particular field in which it belongs.”* This is in addition to the normal requirements of relevance and helpfulness. In 1993 the Frye test for expert evidence admissibility was eclipsed in the United States by a Supreme Court decision in Daubert v Merrell Dow Pharmaceuticals, 113 S Ct 2786, in which it was decided that United States Federal Rule of Evidence 702 should be applied instead. Rule 702 requires that “*if scientific, technical or other specialised knowledge will assist the Trier of Fact to understand the evidence or to determine a fact in issue, a witness qualified as an expert by knowledge, skill, experience, training or education, may testify thereto in the form of an opinion or otherwise.”*

Some key guidelines were listed to assist in the interpretation of this Rule when applied to scientific knowledge. None were intended to determine admissibility. The objective was to determine scientific validity and reliability of the evidence and thus go to its weight. These guidelines, that may or may not be considered in any given case, and the application of Rule 702 for *"engineering and other experts who are not scientists"* were confirmed by the 1999 United Sates Supreme Court decision Kumho Tire Company v Carmichael et al. The guidelines are:

a) Whether the theory or technique could be and has been tested.
b) Whether the technique has been published or subject to peer review.
c) Whether the actual or potential error rates have been considered.
d) Whether the technique is widely accepted within the relevant scientific community.

Clearly, these guidelines give much more specific definition to the criteria that should be applied by the courts when considering expert evidence and allow much more opportunity for new methods to be utilised when preparing such evidence than available under the Frye test.

In other jurisdictions it is open to question whether the Frye test has been superceded in common law because the United States Federal Rules of Evidence apply only in that country. In New Zealand, in R v Calder T154/94, HC Christchurch 1995 for example, Tipping J reviewed the criteria used to determine the admissibility of novel scientific evidence. He cited Frye, Daubert and several other relatively recent decisions at that time as examples and then decided to admit the questioned expert evidence on the basis of its relevance, helpfulness and probative versus prejudicial balance. The Judge used the word helpful to mean "*reliable"* rather than "*to assist the Court's understanding".* Thus in New Zealand Law, expert evidence is given a rather more flexible environment in which to operate than in the United States. Nonetheless, the factors listed for the Daubert case remain important tests of the weight which might be accorded to expert evidence, especially if it involves a novel analysis or test method. More importantly in the context of this paper, the emphasis is upon establishing and declaring the accuracy and inherent uncertainties that might exist in the expert evidence affecting its reliability.

3. LEGAL TESTS AND EXPRESSING EXPERT OPINION

When Court decisions are made various legal tests may be applied. In the area of vehicle accident analysis the most common relate to careless, dangerous and reckless driving. In the case of careless driving, sometimes termed negligent driving, the test is legally objective, in other words solely dependent upon the proven facts. There is no intent or mens rea element in this. The test most commonly applied, that appears to have its origins in Simpson v Peat 1952, 2QB 24, 27, is whether or not the driver was exercising the degree of care that a reasonable prudent driver would exercise in the circumstances. Although legally objective, the application of this test is highly subjective in the hands of the Court. In the case of dangerous driving the test, in New Zealand at least, is whether or not the driving was or might be dangerous to the public or a person in the circumstances. This too is a legally objective test that has subjective consequences in Court. The test for reckless driving includes a mens rea component. In essence the driver must have had knowledge of the danger to the public or to a person but continued to drive in that manner. All of these tests form a datum against which a motor vehicle crash analyst's evidence must be considered and effectively define its application.

It is not the expert's task to decide the case before the Court. The so-called ultimate-issue exclusion rule was aimed at preventing this by barring evidence on the issue being tried. In practice this exclusion has become more relaxed. It is possible for experts to give evidence that embraces the ultimate-issue and by inference, if their evidence is accepted by the Trier of Fact, effectively decide the case without actually saying so. Nonetheless, the expert evidence must be couched in terms that are acceptable to the Courts and do not usurp judicial prerogatives. This requires identification of the inferred or suspected culpable act, the actus reus, and of the issues that may have influenced it. It is the analysis of the facts in relation to those issues and presentation of the results with consequent conclusions that is the focus of the expert evidence. In doing this, the actions of the driver or other parties involved cannot be overtly stated as being culpable or non-culpable. However, the expectations and limits of vehicle and human performance in the circumstances are proper areas for experts to address and these may establish boundaries that effectively exclude one or the other of these when compared with the requirements of the relevant legal test.

The burden of proof of culpability is always with the Prosecution or the Plaintiff. In the Criminal Jurisdiction that means the inferred or suspected culpable act must be shown to have been committed beyond reasonable doubt. In the Civil Jurisdiction the proof is on balance of probability. These criteria require the uncertainty that surrounds the relevant facts to be determined as far as possible. Although it is up to the Trier of Fact to decide what is reasonable doubt or balance of probability, expressions of the uncertainty associated with each element of the evidence before the Court will assist this process. Clearly that does not trespass into the inadmissible areas of the ultimate-issue exclusion rule and is likely to be both relevant and helpful. Therefore, quite separately from the Frye and Daubert criteria, it is essential that the evidence of motor vehicle accident analysts be couched in simple and easily understood terms that permit this.

The most logical method to use involves consideration of the probabilities associated with the relevant facts. The expert can then state the opinion he or she has on the certainty associated with the occurrence of any event or driver action that has been analysed. The Court can then make its own inferences accordingly. This should not be confused by obscure statistical methods and terminology. Expert evidence containing such references runs a great risk of being unintelligible to the lay person and therefore being ignored or at least discounted by the Trier of Fact. A further issue is the logical justification for the use of many so-called classical statistical methods. There is a substantial body of knowledge relating to this type of statistical analysis that has been challenged severely. [2] Consequently, Bayesian statistical methods and expressions of expert opinion have now become preferred amongst most if not all forensic scientists. [3] The Bayesian approach also assists the expert to follow a logical approach and more often than not permits qualitative opinion to be derived from the available evidence when quantitative data is absent. The same should be said for motor vehicle crash analysis but appropriate acknowledgment of uncertainty has been slower to develop in this field. It has now achieved some currency in the literature and in practice but is restricted by the lack of appropriate test data for quantification. A Bayesian approach has not been used in most cases. [4 to 9]

4. THE APPLICATION OF TYRE MARK EVIDENCE

There are two common circumstances in which tyre-mark evidence might be significant when analysing the physical evidence of a vehicle accident for forensic purposes. The first is wheels-locked braking such as may occur when a driver brakes to avoid a collision. The second is loss of directional control on bends. In both cases tyre-marks may be left on the road that may permit an estimation of vehicle speed, in the first case from the braking skid mark length and in the second case from the resultant centrifugal yaw-mark radius of curvature. In both cases this involves measurement of a specific length-feature of the tyre-mark at the scene, the use of a simplified physical model for the process that produced the tyre-marks and an estimation of a so-called road/tyre coefficient of friction value appropriate for the circumstances. The formulae for the simple and commonly used physical models are:

$v^2 = 2gfs$ for brake skid-marks, and $v^2 = gfr$ for yaw-marks,

where: g is the acceleration due to gravity; f is the estimated road/tyre coefficient of friction; s is the measured braking skid-mark length and r is the measured centrifugal yaw-mark radius of curvature. The objective is to estimate the vehicle speed at the start of the tyre-mark.

In the case of directional control loss on bends an additional assumption is required, stipulating a balance between the maximum available road-tyre lateral friction forces and the required total radial accelerating force lateral to the curved path followed by the vehicle when the yaw-mark was produced. This assumption is not necessarily correct simply because a curved tyre-mark was present at an accident scene. In some circumstances, especially with heavy vehicles, curved tyre-marks can be produced at far lower speeds than required to demand the maximum available road-tyre friction for the path radius followed.

Much study and data gathering has been done in relation to this over many years. Rather than using the term skid resistance, the concept of road/tyre friction has been emphasised. Countless skid-to-stop tests have been done with the aim of verifying wheels-locked braking analysis and quantifying the appropriate values of road/tyre friction to use under varying circumstances. [10 to 21, for example] Similarly, many yaw-mark producing curved-path speed tests have been done in conjunction with road/tyre friction testing to verify or otherwise assess the accuracy of the above-quoted so-called critical speed formula for estimating vehicle speed from the radius of turning yaw-marks. [22 to 24, for example]

A variety of measurement devices have been used for this purpose. They fall into two major groupings: those that purport to measure the available road/tyre friction directly and those that measure the deceleration to rest from a known speed of a vehicle under wheels-locked braking. In the former group are a variety of tyre rubber-shod drag sleds or wheels of known mass for which the drag-force is measured as they are pushed or pulled over the pavement. In the latter group are recording and integrating accelerometers, bumper-guns for marking the road surface at the moment of braking commencement and fifth-wheels with a revolution recorder and timer. Tables of recommended road-tyre friction values for motor vehicle crash analysis obtained by such testing have been around for over half a century. They are often used for visual estimation of the available road-tyre friction, particularly when testing has not been done or is not feasible. Two examples are given in Table 1. Although not giving exactly the same values, they are generally similar and consistent within their uncertainty range.

Despite this, although the general features of the results of such tests are consistent, there are no firmly identified preferences in relation to measurement devices or even of what precisely is being measured. A very recent voluntary survey of measurement device preference amongst an international internet news-group of about 600 motor vehicle crash analysts resulted in a response from 86 individuals [25]. Their preferences were: 30% for drag-sleds; 21% for skid tests not using an accelerometer; 27% for skid tests using an accelerometer and 20% for the use of friction tables, with 2% stating a preference for some other undeclared method. A relatively recent measurement protocol, SAE Recommended Practice J2505 [26] does not resolve these issues although it does state that friction measurement methods not involving vehicle skid-to-rest testing are not recommended. Scant consideration appears to have been given as to how the results should be used in motor vehicle crash analysis, the uncertainties involved, what exactly is being measured in each case and whether what has been measured is appropriate for that use.

COEFFICIENTS OF FRICTION OF VARIOUS ROADWAY SURFACES								
DESCRIPTION	DRY				WET			
OF	Less than		More than		Less than		More than	
ROAD SURFACE	30 mph		30 mph		30 mph		30 mph	
	From	To	From	To	From	To	From	To
PORTLAND CEMENT								
New, Sharp	.80	1.20	.70	1.00	.50	.80	.40	.75
Travelled	.60	.80	.60	.75	.45	.70	.45	.65
Traffic Polished	.55	.75	.50	.65	.45	.65	.45	.60
ASPHALT or TAR								
New, Sharp	.80	1.20	.65	1.00	.50	.80	.45	.75
Travelled	.60	.80	.55	.70	.45	.70	.40	.65
Traffic Polished	.55	.75	.45	.65	.45	.65	.40	.60
Excess Tar	.50	.60	.35	.60	.30	.60	.25	.55
GRAVEL								
Packed, Oiled	.55	.85	.50	.80	.40	.80	.40	.60
Loose	.40	.70	.40	.70	.45	.75	.45	.75
CINDERS								
Packed	.50	.70	.50	.70	.65	.75	.65	.75
ROCK								
Crushed	.55	.75	.55	.75	.55	.75	.55	.75
ICE								
Smooth	.10	.25	.07	.20	.05	.10	.05	.10
SNOW								
Packed	.30	.55	.35	.55	.30	.60	.30	.60
Loose	.10	.25	.10	.20	.30	.60	.30	.60

Reproduced from: Baker, J.S., Traffic Accident Investigation Manual. The Traffic Institute, Northwestern University, 1975.

Average Sliding and Peak Friction Coefficients For Passenger Car Tires		
Surface Condition	Sliding Friction	Peak Friction
Concrete/Asphalt, polished to new, dry	0.65 – 0.90	0.80 – 1.00
Concrete/Asphalt, polished to new, wet	0.45 – 0.70	0.60 – 0.75
Gravel, loose to packed	0.40 – 0.70	---
Gravel, some grass	0.35 – 0.40	0.40 – 0.50
Meadow, wet	0.15 – 0.20	0.20 – 0.25
Meadow, dry, firm, short grass	0.35	0.45
Off-road shoulder, firm dry	0.35	0.45
Soil, loose, moist, Tires sink down appr. 2 in.	0.60	0.70
Asphalt, wet leaves	0.60	0.70
Road, snow covered	0.30	0.30
Ice	0.15	0.15
Mud on wet pavement	0.2 – 0.3	---
Diesel fuel on wet asphalt	0.25 – 0.3	---
Diesel fuel on wet, polished asphalt	0.05 – 0.12	---

Reproduced from: Motor Vehicle Accident Reconstruction and Cause Analysis. 5th Edition. Rudolf Limpert.

TABLE 1.

The results produced by these measurement devices have been compared. [27 to 29] It has become clear that they do not produce the same result for the purported road tyre friction when used on the same pavement surface under the same surface conditions. Consequently, speed estimates obtained from their results differ, depending upon which device is used. This has resulted in closer examination of the friction measuring process according to its intended use. [30, 31 for example] It has become obvious that the common practice of inferring a coefficient of friction value from such tests can introduce significant error when applied to the simple uniform linear deceleration models used for pre-braking speed estimation. It has become obvious also that contradictory information was being obtained in relation to the appropriate resultant friction value to use for speed estimation from yaw-marks. That in turn led to testing aimed at resolving those issues. [32 to 37, for example] Most of these studies have been based upon the results of instrumented vehicle skid-to-rest testing. They disclosed the need for much more thorough understanding of the physics involved, the need for much more careful testing procedures and some limitations of the commonly used simple mathematical models when applied to the results obtained.

5. SKID RESISTANCE TESTING

There is a well established interest amongst Traffic Engineers in the condition of pavement surfaces and the manner in which it affects vehicle performance and safety. That has resulted in the development of routine and standardised testing of the pavement surface in order to monitor its skid resistance. This can now be quantified and specified in relation to the International Friction Index (IFI) or its European equivalent. The variety of devices used to obtain pavement skid resistance has led to a need for standardised comparison and translation of their respective results. Although useful, the comparisons are not particularly precise. In New Zealand the uncertainty introduced by translating from British Pendulum Number, Grip Number and Norsemeter Mu to SCRIM Sideways Force Coefficient is quoted as ± 0.08 at a 95% confidence level. [38] This is equivalent to a coefficient of variation of about 6% and introduces about ± 12% spread of results.

It is interesting to compare these results with those published by Viner et al [29]. The devices compared were skid cars (skid-to-rest testing with accelerometer and bumper-gun), Portable Skid Resistance Tester (British Pendulum), SCRIM and the Pavement Friction Tester (a proprietary locked-wheel trailer fitted with an ASTM standard smooth tyre). Four test pavements were used under both wet and dry conditions: hot-rolled asphalt, brushed concrete, un-chipped mastic asphalt and a semi-permeable thin surfacing (Safepave). Their statistical analysis showed quite high correlation between the skid-to-rest accelerometer and bumper-gun results but much lower correlations between these and the other devices except for the Pavement Friction Tester in dry conditions. In their conclusions they stated that *"In this study, the agreement between the Pavement Friction Tester and skid cars was generally good on dry surfaces. However, substantial differences were observed between the measured coefficients of friction on brushed concrete. The SCRIM results on dry surfaces were uniformly high and did not correspond well with the results of the other devices"*.

Efforts have been made to use these measurement techniques for accident analysis purposes. Indeed SCRIM or equivalent testing is a routine matter at accident sites in some countries. In New Zealand, studies of the scope for using the IFI to predict actual vehicle braking performance have been made. [39] While these investigations have identified many useful factors for accident analysts, they do not yet appear to have grappled fully with the fundamental issue of how the skid resistance measuring devices and their results can be appropriately applied in the forensic context. Further, the logical basis for relating the results to the issue of interest, namely estimating vehicle speed, and for incorporating the influence of scene and vehicle factors is by no means clear. It is well known that the pavement surface type and condition together with its weather and traffic history can make a substantial difference to the road/tyre friction that was available in any particular motor vehicle crash. Similarly, the vehicle tyre characteristics and condition also exert a substantial influence upon this. These factors appear not to have been expressly considered.

In contrast to the Traffic Engineer, the motor vehicle crash analyst is usually not very interested in pavement condition monitoring results, although sometimes they can be relevant, extremely helpful and, in the absence of at-scene measurement, may be the best information that is available. [40] On most occasions, the crash analyst is interested in the friction available at the time of the crash being investigated on the path followed by the crash vehicle. Therefore, the results of routine skid resistance testing are not necessarily useful for forensic purposes because they are more likely to represent the pavement condition at a time well removed from that of the crash, with all of the uncertainty that this implies.

Thus, the crash analyst has a fundamental need for at-scene road/tyre friction testing to be performed on the path followed by the crash vehicle. Depending upon whether a skid-mark from wheels-locked braking or a yaw-mark from limit-speed cornering is being considered, there may be a need to measure the available friction in either a longitudinal or lateral direction respectively, depending upon the measurement method used. Also, many of the skid resistance measuring machines used are quite bulky. This introduces a practical question of whether they can be operated at an accident scene on the appropriate part of the road. Compact portable measuring devices appear to have an advantage in that regard.

6. ERRORS AND UNCERTAINTIES IN CURRENT PRACTICE

Accelerometer-instrumented vehicle wheels-locked skid-to-rest testing is now routinely performed at accident scenes, particularly in New Zealand where it is commonly the method of choice. Instruments are available that are easy to use. The results appear easy to interpret. This may use the actual vehicle involved but more often is either an exemplar vehicle of the same brand and model or a Police vehicle with its ABS disabled. The tests may be conducted on the same part of the road as that traversed by the crash vehicle when the tyre marks were produced but often that is impracticable because of the presence of debris and rescue services or other safety issues.

Contrary to commonly encountered statements of the test results, such tests do not measure the road-tyre friction coefficient. They measure the test vehicle deceleration. The friction is then inferred from the results. The deceleration may be sampled many times per second during the skid-to-rest test and then expressed as a mean equivalent constant deceleration. The mere fact that the results are expressed to several significant figures should not be taken to indicate equivalent accuracy. That, in conjunction with skid-mark length measurement in the case of braking or yaw-mark radius of curvature in the case of directional control loss, is then used to estimate the speed of the vehicle involved in the crash being investigated when at the start of the tyre mark.

A typical graph of vehicle deceleration to rest plotted against time when measured with an accelerometer during a wheels-locked braking test is shown in Figure 1. It is immediately apparent that the deceleration is not uniform. An initial rapid increase from zero as the brakes start to take effect reaches a peak and then quickly diminishes to a level that varies about a constant or slightly rising trend for most of the remaining time followed by a rapid decrease to zero as the vehicle comes to rest. The typical range of visible braking skid-mark commencement is shown by a superimposed ellipse. This varies according to pavement type and colour and according to tyre tread compound hardness. The range for this reported in the literature is quite wide. It appears that the factors determining the skid-mark and yaw-mark onset have not yet been subject to a full and systematic study.

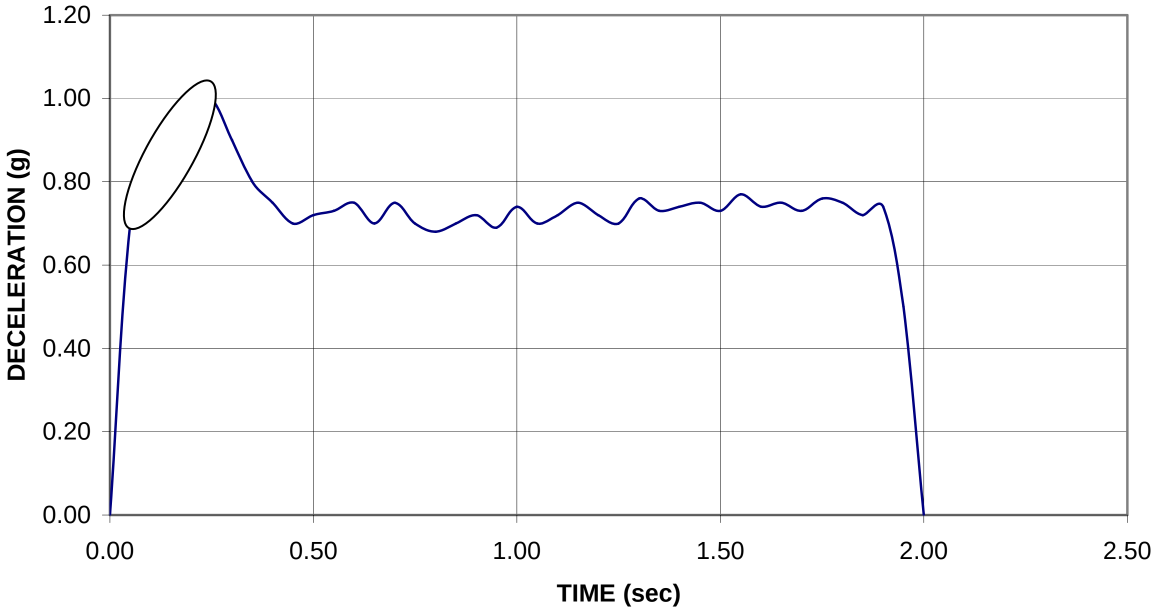

Figure 1: Typical Deceleration vs Time Result of Skid-To-Rest Test

If the acceleration vs time graph is integrated with respect to time a corresponding speed vs time graph is produced. A typical example is shown in Figure 2.

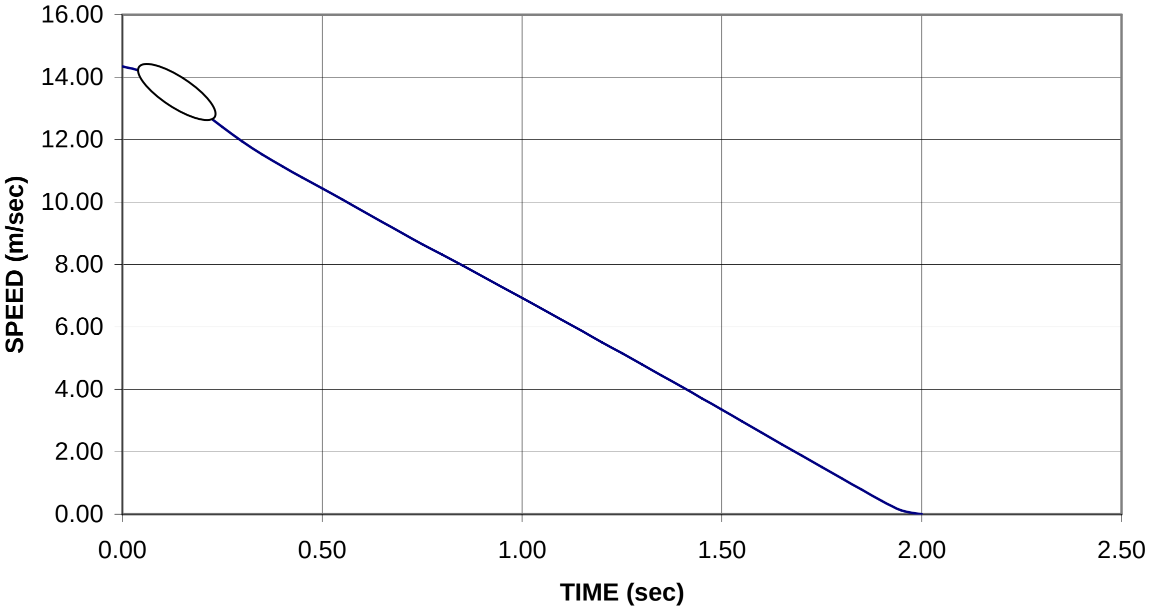

Figure 2: Typical Speed vs Time Result of Skid-To-Rest Test

It may be seen that the plotted slope very rapidly becomes nominally linear and uniform. This shows that the effective deceleration is usually very close to constant for most of the braking time. The mean slope in the nominally uniform portion of the graph may also be very easily measured and is the mean vehicle deceleration during that period.

However, it is clear that if this is applied to a uniformly decelerated linear physical model as is usually the case two sources of error exist. The first arises from the delayed onset of the visible skid-marks which understates the distance over which entire deceleration existed, thereby leading to underestimation of the pre-braking speed. The second arises because the deceleration rises from zero, peaks and then reduces prior to the nominally uniform level and then reduces to zero. If the uniform deceleration level is applied to the entire braking time, the pre-braking speed may be in error. While this is most likely when analysing skid-mark evidence because the actual commencement location of braking prior to the skid-mark would be indeterminate, it could also easily occur during testing if bumper gun pavement marking was used as the braking commencement point. It would then result in an error of the actual mean deceleration achieved in the test with a resultant further error of the crash vehicle pre-braking speed estimate. The nett effect is that significant uncertainty is introduced by the limitations of the simple physical model used to adequately represent the variation of deceleration with time and by the delay in skid-mark commencement after significant braking deceleration has started. Clearly, a workable physical model that better represents the actual braking deceleration variation with time would be an improvement. Neptune et al proposed such a model in1995 [32] but it has not been widely adopted if at all.

The most commonly used recording and integrating accelerometers incorporate an integrating algorithm for speed and distance and also report a mean braking deceleration for the test. The latter is usually the principal result of interest and its value is used for the vehicle speed estimation. The basis of the integrating and the mean deceleration algorithms are not stated and it is not at all clear whether they should be applied in that way. In essence, to be used for that purpose, the algorithm should return a mean deceleration that is equal to $v^2/2gs$, where v is the vehicle speed at the skid-mark commencement obtained by integration and s is the skid-mark length. That would then compensate for the most significant measurement error arising from the non-uniform part of the initial deceleration. In the absence of a declared algorithm that does this or produces an equivalent result, an inherent uncertainty remains that is almost impossible to satisfactorily quantify.

A very common source of error with such testing arises from failure to recognise that the mean deceleration result obtained is not the maximum available road/tyre friction. It is simply the mean wheels-locked deceleration calculated by the accelerometer algorithm from which the underlying maximum available road/tyre friction may be estimated. The recorded deceleration variation with time upon which it is based is referenced to the test vehicle, not to the gravitation vector. Figure 3 shows the gravitation force components acting on the accelerometer when a skid-to-rest test is conducted on a down-slope with the vehicle pitching nose-down under the heavy braking. The pavement longitudinal gradient introduces a force component proportional to the sine of the gradient angle relative to horizontal that must be eliminated in order to obtain the effective underlying road-tyre friction estimate.

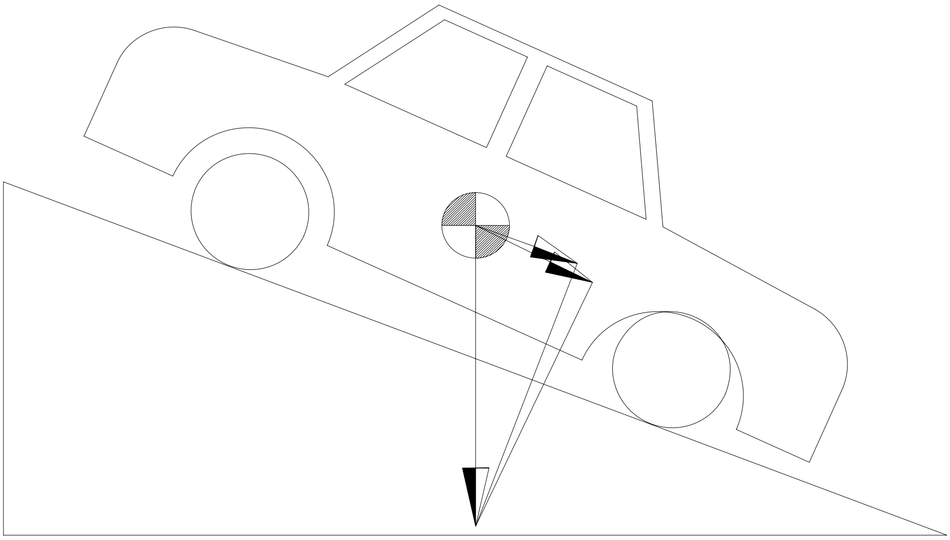

Figure 3: Gravity Force Components Acting Along Slope Planes

Of course, if the test is conducted along the braking path followed by the crash vehicle, the longitudinal gradient effect would have been the same for it and thus not affect the direct applicability of the test result. However, if the test result is to be used for directional control loss speed estimation, the test result must be corrected for longitudinal gradient to obtain the underlying effective road/tyre friction and that in turn must be corrected for lateral road gradient before use in the yaw-mark formula.

Similarly and independently from the longitudinal road gradient, the change in pitch angle of the test vehicle in which the accelerometer is mounted due to the heavy braking introduces an added longitudinal gravitation force component that causes the mean deceleration result to overstate the actual mean deceleration achieved and thus both the maximum available road/tyre friction and the pre-braking speed. Some accelerometer-based devices include a constant or operator-entered nominal value for this but it is of limited benefit because the wheels-locked braking pitch angle of vehicles can vary greatly. Thus, further experimental uncertainty is introduced.

The most frequently claimed advantage of skid-to-rest testing is that it uses a vehicle and thus models the behaviour of vehicles. Implicit in this are the characteristics of the suspension, the brakes and the tyres as well as weight distribution and centre of mass height. These factors vary considerably between vehicle types and according to the vehicle condition. Therefore, in order to realise this claimed advantage, the characteristics of the crash vehicle should be duplicated in the testing. That is often extremely difficult to achieve with any certainty because very often the crash vehicle is unusable and a sufficiently similar exemplar vehicle not available. The uncertainties that this introduces are effectively indeterminate. Little research appears to have been performed in this area.

Despite the regular occurrence of errors arising from failure to include the appropriate corrections for road gradient and vehicle pitching under braking in crash analysis results using skid-to-rest testing, the cited references show that there is significant awareness of these limitations in the results of such testing amongst researchers at least. That is evident in the recent and on-going road-tyre friction testing that has been and continues to be conducted. There is greater realisation that inferences used in Court made from the test results must include statements of uncertainty. The research objective has been to refine the testing procedure for better accuracy and identification of uncertainty sources. Despite this, in some cases significant experimental errors have remained. In particular, the effect of the change in pitch angle of the test vehicle in which the accelerometer is mounted is mentioned in some cases but the research results appear not to have been compensated for it.

Quite apart from these sources of experimental error and uncertainty, skid-to-rest testing has other limitations affecting the reliability of its results that are likely to be significant but are almost never mentioned in Court. Frequently, issues of accessibility and safety dictate that the testing be done at a location adjacent to that traversed by the crash vehicle, either longitudinally or laterally. If the tests are not conducted on the same part of the road, the pavement surface condition may be different from that actually encountered by the crash vehicle. If the road was dry at the time of the crash, this usually has a relatively small effect upon the maximum available road-tyre friction, but for a wet road this effect may be quite high because, if a significant time elapses between the crash and the test, the maximum available road-tyre friction may have changed substantially and sometimes this can occur extremely quickly. Consequently, the test vehicle’s measured deceleration may not characterise the road-tyre friction that was available to the crash vehicle and the common inferences made may be in error. Also, the research shows that an at least contentious issue is whether the maximum available road-tyre sliding friction estimate obtained in this way is appropriate for use when estimating the loss of directional control speed from yaw-marks.

Drag-sled or drag-wheel/tyre testing is often used when it is impracticable to use skid-to-rest testing. This measures the drag force required to move a known mass along the pavement under test and thus enables a coefficient of friction to be calculated directly. Provided that the pull or push force being measured is parallel to the road surface and does not introduce unknown moments or vertical force components that interfere with the normal forces acting between the sled or wheel and the road, repeatable results can be obtained. The major reservation about this method is its fidelity in returning the effective road/tyre friction acting on a motor vehicle when under emergency braking or at the limits of directional control. It is a subject of great controversy amongst motor vehicle crash analysts and, despite its wide current use, the method is not recommended in SAE Recommended Practice J2505 [26]. Obviously, the loads, pressures and relative speeds between the sled shoe and the road surface are about an order of magnitude lower than those acting between the tyres and the road with a vehicle and this could influence the fidelity of the test result. However, provided the steady sliding drag force is measured and not the peak static friction, drag-sled test results on many pavement types are comparable to and thus consistent with those obtained by skid-to-rest testing with a vehicle. The same influence of road gradient upon the drag force exists as for skid-to-rest testing, requiring correction to obtain the underlying friction.

The pre-braking speed of a vehicle and the expected directional control loss speed on a curve are proportional to the square-root of the road/tyre friction estimate obtained by testing when applied to the simple physical models used. Therefore, the influence of such errors is effectively halved in the respective resultant speed estimates. Further, because visible skid-marks are the source of the braking distance for pre-braking speed estimation and these commence after some significant deceleration has occurred, it is more likely than not for the pre-braking speed estimate based upon the test result to be biased low. Consequently, despite the acknowledged errors and uncertainties associated with estimation of the available road-tyre friction, the existing test procedures have persisted for forensic purposes. Clearly, that is less than ideal from the uncertainty declaration viewpoint. The best that can be said is that the result is very likely to be conservative, provided the friction measurement errors have been minimised or the results have been corrected for known errors.

A further issue in the case of braking skid-mark evidence analysis is the assumption that the crash vehicle driver actually or should have applied the brakes to the maximum possible extent when avoiding collision. Two aspects of the evidence and the test results frequently encountered emphasise these points. First, the evidence often consists of just two tyre marks of different length from the locked wheels. Thus, there is no reliable evidence that the brakes were working at full efficiency on the unlocked wheels. In the absence of testing with the crash vehicle, the issue of its actual braking efficiency is then significant. Support for this is contained at pp 248 to 251 of “Motor Vehicle Reconstruction and Cause Analysis” Fifth Edition, by Dr Rudolf Limpert [41]. Second, when the skid-to-rest tests are conducted, the first one or two deceleration results are often lower than the others. One commonly given reason for this is that the test driver required practice to ensure that the brakes were applied hard enough to produce an all-wheels-locked test. Given that most drivers never or only rarely experience the need for maximum emergency braking, it is not unreasonable to infer that the crash driver might not have achieved a braking deceleration at the maximum available level and that failure to have done so is an acceptable performance. [42, 43] Thus, the common assumption that skid-to-rest testing produces reliable pre-braking speed estimates for the vehicle involved is not always justified. Of greater concern is that this is not often considered or even questioned when such expert evidence is presented in Court.

7. ESTIMATING VEHICLE SPEEDS FROM TYRE MARK EVIDENCE

It is useful to consider the logical relationships implicit in the use of tyre mark evidence for the estimation of vehicle speed. If the ultimate objective of tyre-mark interpretation and analysis in the forensic context is estimation of vehicle speed as has been described, this and the mathematical models involved must be considered an integral part of the estimation process. The variables of interest in such situations are continuous. The basic Bayesian expression of the analysis for continuous variables may be considered as follows:

$$f(v|e,i) = \frac{f(e|v,i)f(v|i)}{\int[f(e|v,i)f(v|i)]dv}$$

This states that the result of interest on the left side, namely the probability density function of the vehicle speed v, given the relevant physical accident evidence e and the background information i, is equal to the probability density function of the relevant physical accident evidence being observed, given the vehicle speed and the background information, multiplied by the probability density function of the vehicle speed, given the background information, all divided by the probability of the evidence, over the entire range of possible speeds and the background information. The denominator can be deleted and the relationship becomes a proportionality involving the numerator only on the right side.

The fundamental scene evidence is either the length of the braking skid-mark s, or the radius of the turning yaw-mark r, either of which can be denoted by a length l. The Bayesian relationship then becomes:

$$f(v|l,i) \propto f(l|v,i)f(v|i)$$

If speed was a direct function of l alone, the likelihood function could be obtained by repeated testing with a vehicle being driven at a known speed and either braked or turned to produce the relevant type of tyre-mark that could be measured. This could then be applied directly to the accident scene evidence l and the posterior probability distribution of the speed obtained. However speed is not a direct function of l alone. A further set of parameters is involved. Repeating the commonly used simple physical models that relate vehicle speed to the tyre-mark length or radius measured at the scene:

$v^2 = 2gf^*s$ for brake skid-marks, and $v^2 = gf^*y$ for yaw-marks.

The parameter f^* has replaced the commonly used coefficient of friction or friction factor f. It is simply the g-multiple of the braking deceleration or radial acceleration respectively. It is specific to this simple physical model as well as the measurement method used. It is not necessarily the same as the underlying road/tyre coefficient of friction. It relates the speed to the length measurement and cannot be inferred from the length measurement alone. It must be measured at the scene. The value of the parameter f^* is influenced by the pavement surface characteristics, condition and the immediate past weather and traffic history together with tyre characteristics and condition. These characteristics may be represented by further collective parameters p for the pavement, t for the tyres, b for the vehicle braking and d for the driver, the individual components of which must also be characterised by measurement. They are continuous random variables and may be incorporated into the Bayes' relationship as conditional probability density functions as follows:

$$f[v|l,f(f^*|p,t,b,d),i] \propto f[l,f(f^*|p,t,b,d)|v,i]f(v|i)$$

The Bayes' relationship is now in a useful form that can assist in establishing the logical status of each of the parameters that might be measured, the means of measuring the parameters and the requirements for tests that might be performed to relate the parameters to the variables of interest. The probability density function of primary interest is $f(f^*|p,t,b,d)$. It is apparent that two alternative approaches to the speed estimation might be considered. One is to establish detailed likelihood relationships for f* given joint variations of each conditional parameter. That is likely to be a mammoth research task and in the end might not produce easily applied results. The other is to use a physical model of greater fidelity that would enable a value for the underlying road/tyre friction as measured at the crash scene to be applied directly, thereby greatly reducing the range of likelihood testing necessary. Clearly, the latter is likely to be more practicable than the former. Nonetheless, significant further research would be required to establish the specific relationships between the at-scene measurement method used and the uncertainty associated with the speed estimate.

It is immediately apparent from the foregoing discussion that these relationships are very likely to be measurement device specific, although it may be possible to establish conversions with reasonably acceptable uncertainties. It shows also that the same restriction applies to existing measurement methods. In other words, the uncertainty relationship between a particular measurement method and the speed estimation produced from its results will differ from those relating to a different measurement method. Therefore, it appears that it is possible to choose any suitable well-behaved at-scene skid-resistance or road/tyre friction measurement method and to apply it to vehicle speed estimation that includes declarable uncertainty limits, provided the relationship between its measurement results and the consequent speed estimate has been validated by testing. That is no different from all other types of forensic testing. The validation establishes the likelihood function between the result of interest and the evidence upon which it is based. That is obtained by observing the tyre-marks produced when a vehicle is either skidded-to-rest or tuned sharply at speed. The results can then be presented in the form of the likelihood function f(l|v,f,p,t,b,d) for a range of pavement, vehicle and tyre types, where f is the measured road/tyre coefficient of friction. The same measurement method can then be used at a crash scene and the speed of interest can be estimated in the form f(v|l,f,p,t,b,d) which enables the uncertainty limits to be declared, based upon quantitative data.

8. CONCLUSIONS

The review and discussion in this paper has highlighted the need for more research aimed specifically at establishing the statistical relationships between the data produced by friction measurement methods suitable for use at crash scenes and the resultant estimates of vehicle speed. This requires careful test design to ensure that the necessary data is obtained and the experimental errors are minimised. In addition, this paper has emphasised the need for a thorough understanding of the physics involved by crash analysts and investigators who perform forensic friction measurement testing and speed estimation in order to avoid the experimental and methodological errors that have an inherent potential to occur. This extends to knowledge of the limitations of the methods used and the specificity of their results when assessing their respective reliabilities. The major emphasis that then follows is the need for the crash analyst to consider the uncertainties involved in the process with care and to declare them as far as possible when giving expert evidence in Court.

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