A REVIEW OF SPEEDOMETERS AND THE CRITERIA TO BE CONSIDERED BEFORE ACCEPTING 'FROZEN' READINGS AND OTHER MARKS.

Christopher Goddard BSc IEng MIET – Collision Science.
info@collisionscience.co.uk

and

David Price B.Tech MITAI – Forensic Accident Investigation Services Ltd.
info@forensic-ai.co.uk

Abstract

Various mechanisms have been used to drive speedometers and other instrument gauges. This paper reviews the mechanisms used; in particular stepper motors which have become the most common type in the last decade or so.

Stepper motors require power to drive the needle to any indicated position, including to return it to zero. Hence if power to the instrument is lost as a result of a collision there is no power to move the needle and it should be left at the reading shown at the moment the power was lost. However, not all stepper motor instruments are the same and before accepting the reading a number of criteria need to be considered to give a level of confidence in the result.

Keywords
Collision Investigation, Stepper Motor, Speedometer

Introduction

Speedometers have been essential instruments since cars started to travel above walking-speed. As well as having an instrument to inform the driver of their speed, in some countries early cars were required to have a large external speedometer to inform other road users (and most notably the police) of the speed of the car. Not surprisingly, those external speedometers were soon abandoned!

In the vast majority of instruments since introduced, the speedometer and other main instruments have been of the analogue type, having a circular dial with a centre-mounted needle (or 'pointer'). There have been many types of mechanism used to drive the needle but the greatest change has been in the last decade during which there has been an almost universal adoption of instruments driven by stepper motors.

The types of instruments that are likely to be encountered are described in this paper and the likelihood that residual ('frozen') readings are representative of the pre-impact reading is considered.

Types of instrument

There have been many types of mechanisms used to drive speedometers as well as those of other analogue instruments, such as rev. counters (tachometers), water temperature and fuel gauges.

The instruments fall into two main groups: mechanically-driven types, and electronic/electrical types.

i. Early speedometers were mechanically-driven. Initially, complex chronometric (clock-type) movements were used. However, for many years up until the 1990s, an eddy-current type of instrument was used, based on a design by Otto Schulze dating from 1905. Many instruments of that type are still in use today. They are mechanically driven via a cable that is turned by the transmission, or by the front wheel in the case of many motorcycles. At the other end of the cable, within the instrument, is a magnet (generally housed within a steel cup). The magnet rotates within an aluminium ('reactor') cup which is attached to the needle's spindle. The eddy-currents created by that rotation cause the aluminium cup to rotate against the resistance of a hair-spring. The faster the magnet rotates, the greater the rotational force applied to the cup and hence the reading increases.

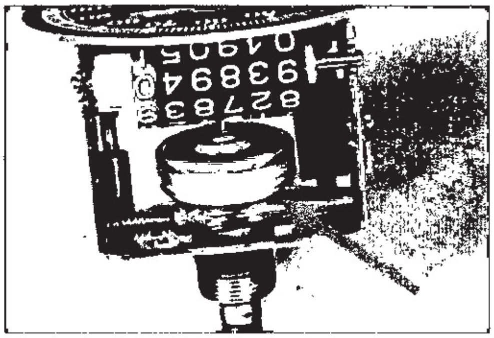

Fig 1 – Eddy-current mechanical speedometer, showing the magnetic coupling (arrowed)

ii. In more recent times, electronic/electric powered instruments have been used instead of mechanically-driven units. In the transition period, some manufacturers used cross-coil air-core instruments. In that type, sensors in the transmission provide information to the instrument which in turn causes current to flow through fixed electrical coils that surround the central rotor, creating magnetic flux. The central rotor shaft is fitted with a small magnet which reacts to the flux and turns, against the resistance of a hair-spring. Cross-coil air-core instruments can easily be distinguished from stepper motors by their partly exposed copper coils that surround the central rotor, there are two coils which cross over each other. Stepper motors have their coils situated to one side of the rotor.

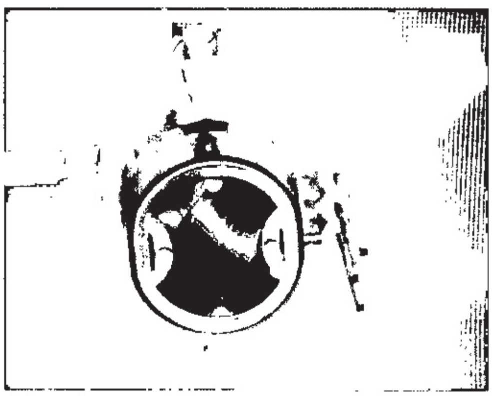

Fig 1 – Eddy-current mechanical speedometer, showing the magnetic coupling (arrowed)

Cross-coil instruments were used by some vehicle manufacturers around the 1990s but have since been superseded by instruments powered by miniature stepper motors. In fact many manufacturers by-passed the use of cross-coil instruments and changed directly from eddy-current to stepper motor instruments around the 1990s, at least for the speedometer and rev. counter. The design of stepper motors is considered in detail below.

Stepper motors

A stepper motor is an electromechanical device which converts electrical current into discrete mechanical movements. It is a permanently powered device that constantly corrects the position of the needle when in use. The needle is powered to its rest position when the ignition is switched off and is held there, hence the power is maintained to the instrument to allow the instruments to return to the zero position even after the ignition is turned off
(albeit some instrument panels remain permanently 'live' whereas others are programmed to be switched off automatically after several seconds).

Stepper motors comprise a shaft bearing a permanent magnet, called the rotor, surrounded by a number of electromagnets on the stationary portion, called the stator. The electromagnets are energized by an external control circuit.

The output shaft of a stepper motor rotates in discrete step increments when electrical command pulses are applied to it in the proper sequence, unlike an AC or DC motor which rotates continuously. This makes the motor suitable as a digitally controlled device. An integer number of steps makes a full rotation. The number of full steps depends on the number of external coils and the number of magnetic poles within the rotor. To make the motor shaft turn, first one electromagnet is given power, which makes the rotor's magnet align to the stator's magnetic field. Further motion is created when the next electromagnet is turned on and the first is turned off, at which time the rotor rotates to align with the next magnet, and from there the process is repeated (Fig 3). In this way, the motor can be turned by a precise angle, although only to an angle that corresponds to one or more steps. In the example shown in Fig 3 there are 4 steps to one full rotation. This disadvantage is overcome by the use of 'micro-steps' which will be discussed later in this paper.

A common design of stepper motor found in automotive instrument clusters uses a rotor with 5 magnetic pole pairs and 4 electromagnetic stator poles giving 20 incremental steps for a full rotation. This results in a single step angle of 18° of the motor shaft. The 4 poles are created by using only 2 electromagnetic coils. If the current is reversed in either coil, then the polarity of the magnetic field is also reversed.

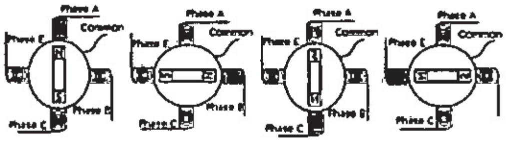

Fig 3 – Diagram showing how a stepper motor rotates[1].

While the principle of all stepper motors is the same, the design of the linkage to the instrument needle varies considerably. The output shaft from the motor may form the spindle on which the needle is fitted, or the output may pass through a reduction gearbox.

The design of the gearbox or the absence of it has a significant impact on the 'static torque' of the needle. The 'static torque' is the torque required to move the needle when the instrument is un-powered, i.e. as we would expect to find in a post collision vehicle. However, when power is connected to the motor and the electromagnets are energised the torque is much higher, because the magnetic flux adds resistance to the movement. That torque is known as the 'holding torque'. For example, in a Sonceboz motor the holding torque is over 4 times greater than the static torque.

The common methods of linking the motor to the needle are described below.

a) A number of vehicles have non-geared stepper motors. In these the needle is mounted directly on the rotor shaft. Such instruments are manufactured by NMB/Minebea (Thailand) and are used in Magneti-Marelli instrument clusters. Since there is no intermediate gearbox, the needle has little resistance to movement in the event of external forces being applied when there is no power to the instrument to hold the reading (i.e. such instruments have low 'static torque').

b) Currently, by far the most common method of linking the motor to the needle is to incorporate a small gearbox within the body of the motor (Fig 3) that has a series of spur gears and typically provides a reduction of around 36:1. Coupled with a 20-step motor, gearing of that ratio produces a 0.5 degree step angle resolution of the needle. Compared to the non-geared type, there is greater resistance to free movement of the needle when not powered (see later). Examples of this type are made by Sonceboz, Switec, Fraen and JST (Juken).

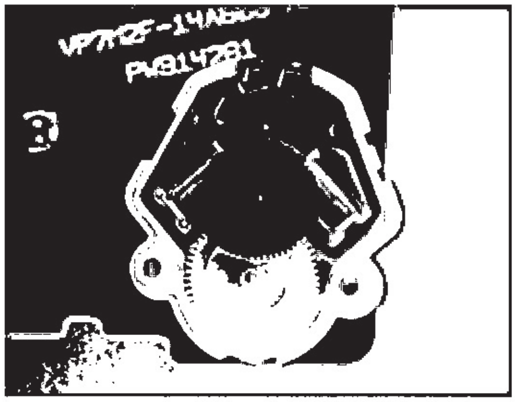

Fig 4 – A spur-geared stepper motor manufactured by Sonceboz (with black, blue and white gears), typical of group 'B'
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c) Another type of stepper motor is currently used for a number of vehicles, currently mainly within the Volkswagen/Audi Group. It utilises a motor and gearbox manufactured by Continental Automotive (formerly Siemens VDO). This arrangement has a worm gear connecting the rotor shaft to the needle (Fig 5). Employing a worm gear results in a high static torque and so provides a high degree of resistance to free movement of the needle when the instrument is not powered.

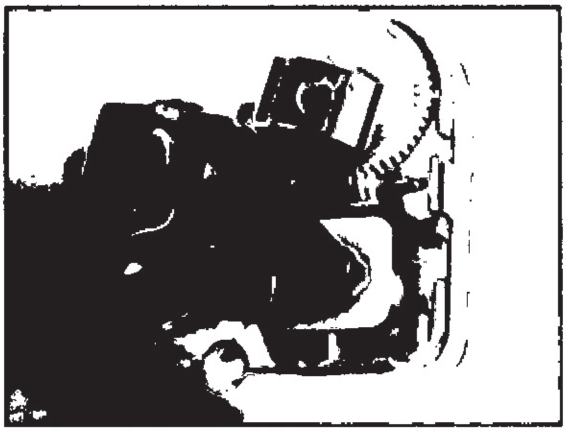

Fig 5 – A Continental (Siemens VDO) motor driving a worm gear

A few instrument panels, such as those of various models of Mercedes, do not have a central needle. Instead the pointer is part of a large ring that surrounds the dial face. These rings are driven by stepper motors fitted with a spur gear on the spindle. This engages with gear teeth on the outer edge of the ring.

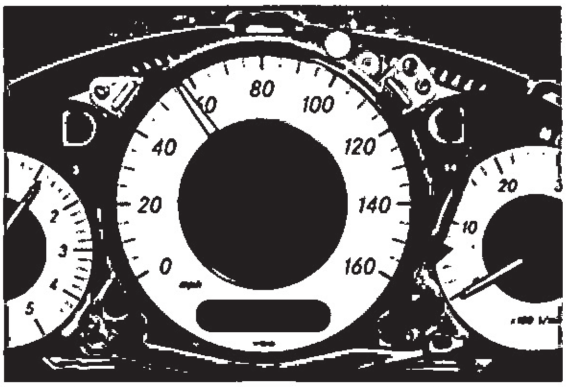

Fig 6 – Ring-style pointer (motor position arrowed)

As indicated earlier, irrespective of the type of motor, the single step angles are still too coarse for smooth needle movement and much finer changes of angle are required in practice; these finer steps are termed 'micro-steps'. They are achieved by operating both electromagnets at the same time. By altering the strength of each of the magnetic fields it is possible to produce a combined field that is mid way between a full step; for example the Siemens SM2 motor uses 128 micro steps between each full step. The introduction of the micro-steps is not just for improved accuracy but to produce smooth movement of the needle throughout its range.

The needle is generally mounted directly on the output shaft of the gearbox. The needle is a tight press-fit onto the spindle with a slight taper within the needle's hole which provides grip. Some have a hexagonal-shaped hole to provide extra grip.

Larger needles may have balance weights fitted to the base of the needle (Fig 7). This has the effect of also reducing the rotational torque during deceleration. Such counterweights were commonly used for mechanically-driven instruments but are less common for stepper motor instruments.

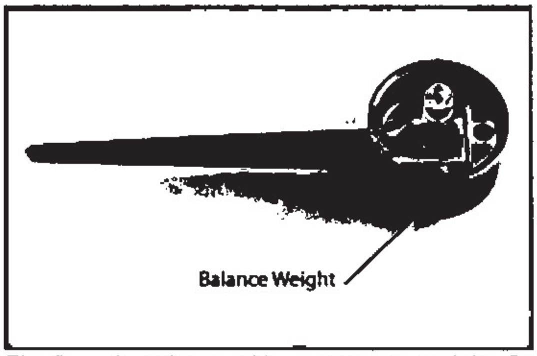

Fig 7 – A pointer with a counter weight fitted (arrowed)

Although normally a secure fit, the possibility of slippage of a needle on its spindle under impact conditions must be considered. Owing to the zero rotational force encountered under frontal impacts, and low rotational force encountered under near frontal impacts, slippage in these instances is highly improbable. However, slippage under violent side impact conditions is more likely. It cannot be detected on eddy-current or cross-coil instruments, as these incorporate a hair-spring and end-stop system to return the needle to its rest position, but slippage can be detected on stepper motor instruments. To do so requires the instrument cluster to be powered up, which results in the needle motor moving from its end stop or rest position to the zero position.
This can be seen on many vehicles when the ignition is turned on and the speedometer needle can be seen to move from its rest position to the zero.. If the needle had slipped on the shaft it would no longer align with the zero position when powered. Obviously this would alter the post-collision condition of the instrument and so the benefit of doing this should be balanced against the need to preserve evidence.

Sources of electrical power

Electrical power to an instrument cluster is normally provided by the alternator or battery. Power is required even in the event of momentary loss, for example in the event of a poor contact that is disturbed when the vehicle receives a severe jolt. In order to allow for this type of power loss, the instrument panel PCB (Printed Circuit Board) has a number of capacitors fitted. These devices are typically of the order of 500 µF and are intended to provide power for no more than 20 – 30 milliseconds[2]. A typical crash impulse during a NCAP test is between 40 – 70 ms [9]. It is not known where during a crash event the power is lost. This is dependent on amongst other factors the model of vehicle.

If there is a change of speed while power is lost beyond the 20 – 30 milliseconds then the instrument will not adjust for the change of speed during the loss of power. Conversely if the input signal is lost and power is maintained, then some instruments are programmed to hold their position for a few seconds and then return to zero.

The reliability of impact marks and 'frozen' reading of instruments

A technique that was used in the examination of crashed aircraft for many years (and probably still is for some small aircraft) was to examine the dial face of the instrument for a 'witness mark'. A similar technique can be used for speedometers. Old-style folded aluminium needles were flexible and could easily strike the dial face, even in road traffic crashes. However, moulded plastic needles used nowadays are much more rigid and, in our experience, marks from these are only rarely encountered.

Fig 7 – Witness mark made by the needle (arrowed)

For many years there has been the question of whether 'frozen' readings are a reliable indication of the pre-impact value. Some research on this matter was carried out on eddy-current instruments by MIRA (Motor Industry Research Association) on behalf of the Home Office Forensic Science Service in the 1980s; one of the authors of this paper was involved in this research[2]. Unfortunately this work was never published but the findings supported the view of many workers in this field i.e. speedometer readings frequently could not to be relied upon. The problem stemmed from distortion and contact between the parts of the magnetic coupling, which could cause the needle to be moved by direct rotational contact between the parts of the magnetic coupling, rather than only be eddy-currents. Equally damage, distortion, or debris trapped elsewhere were able to affect the reading significantly.

In recent years, instances of 'frozen' readings have become much more frequent. Most of these are now associated with instruments driven by stepper motors. It is known that the needle in this type of instrument should not move when all power is lost. The forces encountered in a collision that has resulted in the wiring loom or the batteries being damaged are very severe and so could potentially cause the needle to move.

In an attempt to put 'frozen' readings into a real-world context, a study was undertaken by one of the authors[3] whilst employed by TRL. The study was very limited and involved cars that had been crashed at known speeds (as a result of other types of research studies that had been carried out).

Most vehicles in this study did not have 'frozen' speedometer readings, either as a result of the power not having been lost in the impact or no power having been present during the test. None had their engines running at the time of the crash and so did not display any 'frozen' rev. counter reading. However, seven cars were found to have residual readings. Of these, two were off-scale but were of the mechanically-driven (eddy-current) type. The others appeared to be of the stepper-motor driven type, but it was not permitted to completely dismantle the units to investigate further. It was noted, however, that the readings of all the electronic units with 'frozen' readings were within the legally permitted tolerance of the instrument (see later), based on the known crash speed; this was reported via a letter to ITAI 'Contact'[4]. One further vehicle was identified from subsequent crash tests and again its reading was within the permitted tolerance.

In more recent times, other instances of 'frozen' readings have been encountered as part of ongoing casework where validation of the speed was available from other means (data recorders, tyre marks, crush damage calculations, etc). Amongst these, many instances have been encountered where both the speedometer and the rev. counter have 'frozen' readings which enables self-validation to occur. To do so, the make, specific model must be identified, and the information about the gearing must be obtained (from published vehicle tests, from the manufacturer), or tests carried out on an identical vehicle as part of the investigation. In most of those instances, the 'frozen' speeds and rpm for the known gear (or likely gear) have been corroborated. The limitations are discussed below.

Factors affecting the reading

If the cover has been smashed, the needle(s) will have been exposed and direct contact with the needle is then possible, either in the crash or in subsequent recovery, removal, or transit. The ease by which the needle might have been moved should be considered and evidence of rotational or other scuff marks on the dial face should be looked for.

In the event of there being rotational scuff marks, or scuff marks on the underside of the needle, the reading is not likely to be reliable.

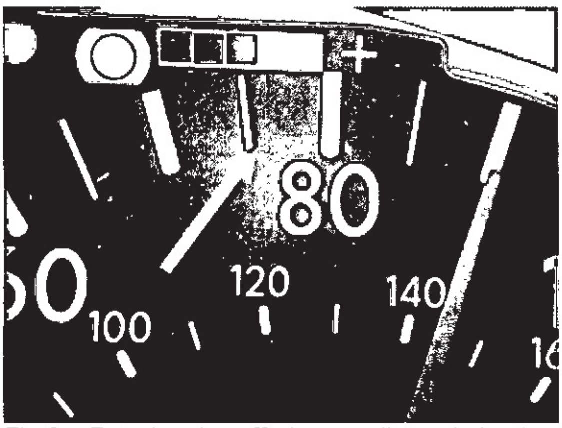

Fig 8 – Rotational scuffs (arrowed), made by the tip of the needle


Fig 9 – Worn tip of needle from Fig 8 (underside of needle reflected using a scalpel blade inserted between the dial face and needle

Similarly, if the needle or its spindle has damage, the reading is not likely to be reliable. Such damage could include displacement of the spindle and distortion of the centre hole of the dial face.

The presence of pieces of debris trapped between the dial face and the needle, or within the drive mechanism, is likely to render the reading unreliable because it may have either prevented movement of the speedometer or as it became trapped it may have caused movement of the needle.

Distortion of the magnetic coupling of an eddy-current type of mechanically-driven speedometer or rev. counter is likely to render the reading unreliable. This is because there could have been alteration of the eddy-currents or even direct mechanical coupling of the two parts.

Where the instrument cluster is mounted predominantly vertically, as in most cars or larger vehicles, the force acting on the instrument in a fontal collision is along the axis of the spindle, rather than a lateral force that will try to deflect the needle to one side or the other. If, however, the impact is to the side of the vehicle, such as the vehicle sliding broadside into a tree, there may be a force acting on the needle that will try to change the reading. The force will be greatest if the needle is vertical and least if it is horizontal.

Impact tests using eddy-current instruments carried out in the MIRA investigation, and separately[5], found that there was almost no change in reading in a violent frontal impact. Those instruments have a very low static torque but normally have balanced needle assemblies.

The un-geared stepper motor type of instrument has such a low 'static torque' that the needle can move even by tilting the panel, irrespective of it being subjected to a violent impact with some lateral component to the force. As identified by Anderson[6] un-geared stepper motors seem to be used more commonly in USA than in Europe.

Without further work, it cannot be determined if the needle of a stepper motor of the spur geared type is likely to suffer movement as a result of a violent impact. Based upon the cars involved in the TRL tests, stepper motors with spur gears with a high gear-ratio (e.g. around 40:1) are unlikely to be disturbed in a longitudinal impact configuration, although no impact tests have yet been carried out specifically to verify this. In addition to the TRL tests, anecdotal evidence from casework suggests that speedometer readings can often be successfully corroborated with rev counter readings. .

In addition to our investigations so far, it is hoped that testing will be carried out using instruments of this spur-gear type, mounted both laterally and longitudinally, and subjected to a representative collision envelope of force. It is envisaged that such tests may resolve this issue and provide criteria for investigators to accept or reject 'frozen' readings.

Stepper motors of the VDO Siemens worm-drive type were tested by Kuranowski[7]. The VDO/Siemens instruments have a high level of static torque as identified previously. When mounted with the needle aligned along the longitudinal and the lateral directions relative to the impact, he found that the needle did not move even when the vehicle was subjected to high impulsive forces.

Speedometer accuracy

In the EU at least, speedometers have legal tolerances defining their accuracy. Rev. counters, and other instruments do not have such tolerance requirements, other than that specified by the vehicle manufacturer. The tolerance for speedometers is specified in EEC Directive EC 75/443/EEC 75. The permitted tolerance is not simple and is expressed as:

$$0 \le V_1 - V_2 \le \frac{V_2}{10} + 4\text{km/h}$$

(*where V_1 is the indicated speed and V_2 is the true speed*)

Expressed in a simpler form, the speedometer is not permitted to under-read but may over-read by 10% + 4km/h (*equivalent to 10% + 2.5mph*).

The calibration of stepper motors is far more precise than the mechanically driven types for which the legislation was introduced. Most of the instruments are quoted as achieving accuracy of 1.5% or better.

In addition to the inherent accuracy of the instrument, the size of tyre and wheel fitted to the drive axle can influence the accuracy, as can the degree of wear of those tyres. Consequently, whenever speedometer readings are being considered evidentially, the size of tyre should be checked against the manufacturer's recommendation. However, so long as the overall diameter of the tyre is close to that of the manufacturer's intended fitment, a larger but squatter tyre may be acceptable. As a rough guide, a car tyre worn to the legal limit will typically affect the reading by about 2%.

We and the equipment manufacturers Visteon and Continental consider that where both the speedometer and rev. counter have 'frozen' readings, and they can be matched to the known, or likely gear ratio of the vehicle (using information obtained from tests of identical model vehicles or obtained from manufacturers), the readings can be considered to be reliable. This is of course dependent on them being of the same type of instrument, as is usually the case nowadays.

Instruments that have a low static torque and are fitted with a hair-spring to return the needle to its rest position are likely to be of the eddy-current mechanical type, a cross-coil type, or an un-geared stepper motor type. For such instruments any 'frozen' reading is likely to have resulted from damage to the instrument or from un-restrained lateral movement. For these instruments, the reading is likely to be unreliable, although laboratory examination can often help resolve this.

Un-geared stepper motors have a very low static torque. In use the motor is driven and the 'holding' torque is considerably greater than the static torque when no power is present (i.e. disruption of power following severance of wiring or damage to the battery). The reading can then change if the instrument is tilted, hence it is likely to be unreliable. These instruments can be identified by the spindle being central and/or by the name NMB/Minebea on the metal casing.

Results to determine the static torque of various stepper motors

Testing of various motors has been carried out by the authors[8] to try to determine the static torque of geared stepper motors. The method used was similar to that used by Anderson [7]. An instrument cluster was positioned with a needle in a horizontal position, a weight was added at a known distance from the centre of the needle. The weight was gently increased until it caused the needle to move. The torque was then calculated from the final weight being applied at a known distance with the following results.

Motor Type	Motor Step angle	Gearbox ratio	Needle step angle	Typically found in	Static Torque mNm	Motor Type
Continental MW2000	90°	1:50	1.8°	VW / Audi	22	A
Sonceboz 6405	18°	1:36	0.5°	Ford/SAAB	1.1	B
Fraen FRSM 6405	18°	1:36	0.5°		1.1	B
Continental SM2	90°	1:43.2	2.08°	VW	1.2	B
Switec MS X15 / JUKEN X27	60°	1:180	0.3°	Jaguar, Vauxhall	0.37	C
Denso	45°	1:24	1.8°	Toyota	0.47	C
Nippon Seiki	180°	1:4	45°	Land Rover	0.047	D
NMB PM20S-020	18°	N/A	18°	Fiat		D

The motors in the above table fell into four distinct groups. For reference, these groups have been designated with the letters A to D.

Group A, currently only consists of the Continental MW200 motor, which has a very high static torque. Needle movement is actually the force required to cause slippage of the needle on the shaft, rather than the force required to rotate the motor.

Group B are motors that have a static torque of around 1 mNm. Tests on those makes with gear ratios of between 1:50 and 1:36 showed significant static torque of around 1 mNm. In our experience, those form a large percentage of the instruments currently in use in the UK.

Group C consists of motors with a torque value below 0.5 mNm. As these Instruments have lower gearing ratios, they have lower static torque values than those in the previous two groups, as might be expected. Denso instrument fall into this category as do the Switec units despite the latter having a high gear ratio they exhibit very low static torque.

Group D motors have negligible resistance to movement of the needle. They were instruments manufactured by Nippon Seiki and they showed little resistance to movement. The low static torque approached that of the un-geared instrument.

As can be seen, there is a huge variation in the static torque between motor designs. This clearly helps explain the inconsistencies in the confidence of frozen speedometer readings and those highlighted by Anderson as being inconsistent with the actual crash speeds.

Criteria for a 'frozen' reading to be considered acceptable

Before a reading can be considered to be reliable the conditions below should be considered as a precursor to further investigation:

i. The instrument must be examined in detail to determine the motor type. The motor type should be either of type A or B stepper motors, as described above

ii. The vehicle should have experienced a predominantly frontal impact

iii. There should be no evidence of multiple impacts

iv. There should be no evidence of vehicle roll over

v. There should be an obvious cause of power loss identified and the loss of power should have been instantaneous.

Our preliminary view is that:

i. 'Frozen' readings on the Continental Automotive worm-drive instruments are likely to be reliable, unless extremely high lateral forces disturbing the needle on its spindle may have been experienced in the collision.

ii. 'Frozen' readings on instruments with gear ratios within the 1:50 to 1:36 range may well be reliable unless high lateral forces may have be experienced in the collision. It is hoped that impact testing will resolve this.

iii. 'Frozen' readings on instruments with gear ratios below 1:24 may, or may not, be reliable depending on the level of lateral force experienced in the collision. It is hoped that impact testing will resolve this.

iv. 'Frozen' readings on un-geared stepper motors, or those of the low-ratio geared Nippon Seiki type, are unlikely to be reliable if any lateral forces have been experienced in the collision.

Conclusions

Most speedometers up until the 1990s were mechanically-driven, eddy-current instruments. Previous investigations have shown that 'frozen' readings on this type of instrument are often unreliable although laboratory examination can often help resolve this.

Most instruments from around the 1990s have used miniature stepper motors.

Stepper motors are constantly powered when in use and they continuously correct the position of the needle. When switched off, the needle is powered down to zero. However, in the event of the wiring being severed or the battery is smashed in a collision, there is nothing to move the position of the needle other than external forces.

In Europe, most, but not all, stepper motors used for speedometer and rev. counters are fitted with reduction gearing within the instrument body.

The gearing ratio and type of gearing used with stepper motors varies widely between instrument manufacturers. That influences considerably the 'static torque', which is the resistance to movement when not powered.

The needles of instruments having worm-gearing are highly unlikely to move in a collision.

The needles of instruments that have high gearing ratios are less likely to move on impact and so any 'frozen' readings following a collision may well be reliable, as demonstrated in limited research undertaken so far. However, it is our intention that laboratory-based realistic impact testing will be carried out in order to help resolve this issue.

The needles of instruments that are either not geared or have low ratio gearing can move easily and so any 'frozen' readings are likely to be unreliable in the event of lateral forces having been experienced in a collision.

When both the speedometer and rev. counter have 'frozen' readings following a collision, and are of the same type of stepper motor, the speed can be compared with expected readings for given revs in different gears. That information may be obtained either from published information or from comparison tests using an identical vehicle. Readings that correspond provide a considerable degree of confidence in the speed reading.

In all cases, investigators should be wary of accidents in which the vehicle has skidded or left the road prior to collision, as the readings are likely to change during these events. Additionally, the size of tyres on the monitored axle should be checked to see that they are those specified by the vehicle manufacturer and have a rolling circumference similar to that specified.

Acknowledgements

We would like to extend our sincere thanks for the advice and knowledge provided by the following;

Mike Lees, Visteon Ltd
Martin Ebenter, Continental, Switzerland
Dr Heinrich-Jochen Blume, Continental, Germany
Helmuth Mohr, Continental, Switzerland
Asger Jurgensen, Continental, Switzerland
Stefan Rupp, Continental, Switzerland
Betinna Zahnd-Sinzig, AXA Research Centre, Winterthur
Christian Planting, ACtronics Ltd
Bob Russell, HG Brunner Ltd

We would also like to extend our thanks for helpful discussions held with:

Peter Jennings (TCRI, Worcester)
Jon Neades (AiTS, South Cerney)

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