Accuracy of speed measurements using the LSMD in crash testing applications

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Introduction

The LSMD (Laser Speed Measurement Device) is a device for measuring speed in vehicle crashworthiness testing. It was specifically designed to satisfy the requirements of pedestrian sub-system impact testing, and it is also suitable for any application requiring highly accurate speed measurement such as full scale crash tests or component sled tests.

The Centre for Automotive Safety Research has operated its own pedestrian impact test lab for 10 years conducting research on pedestrian safety and providing testing services for government, Australian NCAP and industry. This experience is built in to the design of the LSMD.

The LSMD operates on the simple principle of measuring the time required for the object being measured to traverse a set distance. While the LSMD system is very precise when used with normal care, uncertainties can arise from several sources, and the most significant of these affect the set distance used in the speed measurement. With care, uncertainty from these sources are easily minimised.

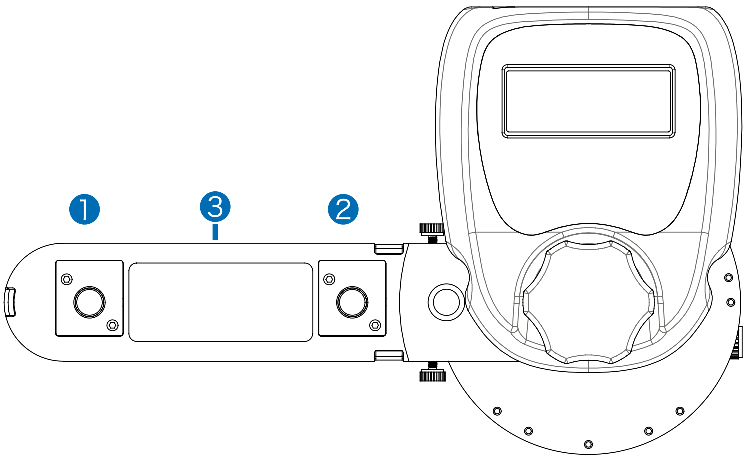
This paper explains how these sources contribute to the uncertainty in the measurement and quantifies the uncertainty in two typical applications

About the LSMD

The principle of operation of the device is relatively simple: The speed of a projectile is given by measuring the time interval for the projectile to pass between two lasers beams. Each laser beam is aimed at an optical receiver, such that the beams and the plane that is defined by the two beams are orthogonal to the trajectory of the projectile. When the projectile interrupts one of the beams the output from the associated optical receiver triggers an input on a timer. The speed is calculated by dividing the distance between the lasers by the time interval.

2.1 Source module

There are two modules that make up the LSMD: The source module is the one that contains the two laser units (Figure 1). The angle of the laser arm may be varied according to the application. The nominal distance between the laser units is 100 mm.



❶ Laser unit 2

❷ Laser unit 1

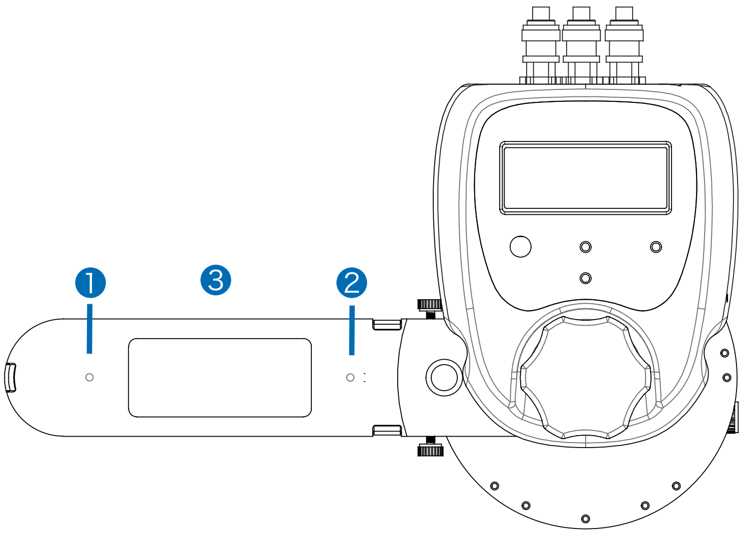
❸ Laser arm

Figure 1 Source module

2.2 Receiver module

The receiver module contains the laser receiver units and it is where the calculation of speed occurs. The module detects each laser beam and, once armed, will time the interval between each laser being interrupted and calculate the speed, displaying it on an LCD screen.

To achieve optimum accuracy, the distance between the lasers is measured once the source and receiver modules have been aligned. This is done by using a height gauge (or similar) that has been aligned with the projectile's trajectory. The gauge is used to measure the laser separation distance by sequentially breaking each beam. The measured distance is then entered into the LSMD for the calculation of speed.



❶ Receiver unit 2 ❸ Receiver arm

❷ Receiver unit 1

Figure 2 Receiver module

Sources of uncertainty in the speed measurement

Uncertainty in the speed measurement come largely from the uncertainty in the measured laser separation distance. There is also uncertainty in the time interval, but, in the LSMD, this contributes little to the overall uncertainty.

Uncertainties in the measurement of time in the LSMD come from three sources:

- errors in the timing oscillator,
- the resolution of the oscillator,
- and characteristics in the receiver circuitry, which are dominated by the fibre optic circuit.

The characteristics of the timing circuit are such that the uncertainty due to its resolution and accuracy is less than 225 ns or 2.25x10-4 milliseconds (ms).

At 40 km/h, the time between each laser being broken is nominally 9.009 ms. Therefore, at this speed, the uncertainty in the time is less than 0.0025%. For most applications, this level of uncertainty is about two orders of magnitude less than the uncertainty in the laser separation distance. Uncertainty in the measurement of time will therefore be ignored for the remainder of this discussion.

Uncertainties in the laser separation distance

Far more influential on the uncertainty in the speed measurement, is the difference between the measured laser separation distance and the effective separation distance. The effective separation distance can be thought of as the true speed of the projectile multiplied by the time interval measured on the device. The influence on the overall measurement is such that the uncertainty in the laser separation distance is a good approximation of the uncertainty in the velocity measurement itself.

There are several contributors to the uncertainty in the laser separation distance. These are:

- uncertainty in the measurement of the distance between the lasers
- angular misalignment between the trajectory of the device and the trajectory in which the distance is measured (or assumed), and
- for some projectiles, an added error from the angular misalignment and any offset, due to the curvature/slope of the projectile's face.

Consider the situation shown in Figure 3.

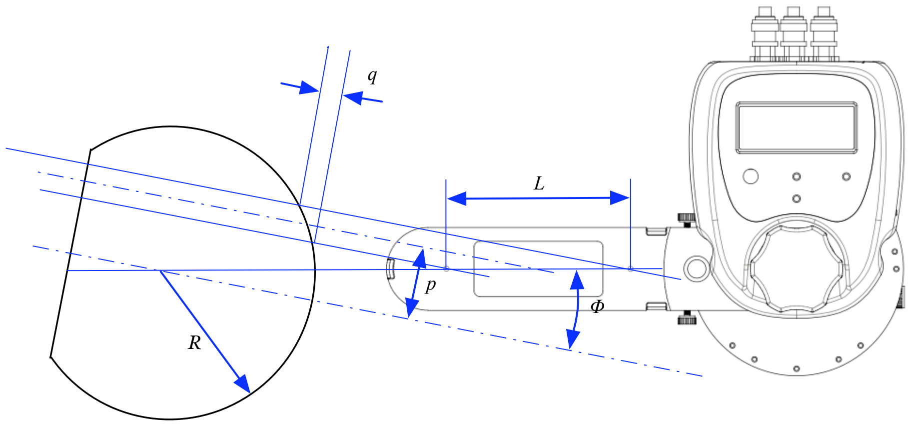


Figure 3 Potential misalignments between the trajectory of the object being measured and that assumed for the measurement.

For the case presented in Figure 3, the effective laser distance can be expressed as:

$$L^* = L\cos(\phi) + q$$

where:

L^* is the effective laser distance,
L is the measured laser distance,
ϕ is the angular misalignment between the assumed trajectory and the actual trajectory,
q is the error introduced by the combination of misalignments p and ϕ

The quantity q is zero for all objects that have a measurement profile that is straight and perpendicular to the object's trajectory. For spherical impactors with radius R, and for small values of ϕ, it can be shown that the the quantity q is closely approximated by

$$q \approx L\phi p/R$$

q may be positive or negative, however the the tendency of the cosine term is to make L^* smaller than L.

This has two important implications: First, the expected (mean) value of L^* will usually be less than L, meaning that, in certain situations, a first order correction to L may be warranted. Second, the distribution of possible values of L^* will not be normally distributed (i.e non-Gaussian) even if the possible values for ϕ and p are Gaussian. This is due to the presence of the cosine term.

The fundamental question that an operator of the LSMD (or similar device) must ask is: how accurately must the trajectory of the object be known to ensure an acceptably accurate estimate of the velocity is obtained? The answer to this question will depend on the application, as the application will determine the size of q. Typical levels of uncertainty can be determined by assuming a Gaussian uncertainty function for ϕ , L and p, and determining the effect of the uncertainty in these terms. Two examples are given below.

Examples: Uncertainty in the velocity measurement of a straight edge (e.g. a sled) and of a circular edge (e.g. the EEVC WG17 child headform impactor)

For the purposes of this example, we will assume that L can be measured with a device that has an expanded uncertainty of ±0.02 mm (corresponding to the 5th and 95th percentile values of the measurement). The standard uncertainty in this case is ±0.01 mm. As L is the difference between two measurements, the standard uncertainty of L in this case is the RMS value of the uncertainty of the two measurements: ±0.028 mm.

For guided impacts where the object whose speed is being measured has a straight edge (such as sled tests), this may be the only uncertainty in L. For free flight tests, such as EEVC-style pedestrian headform impact tests, p and ϕ are non-zero. The effect of gravity is usually taken into account in free flight testing, because of the tolerance required on the impact point on the vehicle being tested. However, we will assume, for the purpose of this example, a rather pessimistic standard uncertainty in the angle of the trajectory of ±0.02 radians (1.15°).

The EEVC WG17 pedestrian child headform impactor has a radius of 57.5 mm. Because the radius is small, the quantity q has a greater potential to affect the uncertainty in L than most other applications. It is now possible to simulate, using Monte Carlo techniques, the uncertainty in L for different values of p for this headform. The results of such a simulation are shown in Figure 4. This simulation assumed a Gaussian distribution for the uncertainties in ϕ and L, using the values mentioned above, and varied the standard uncertainty in p. Figure 4 also shows the result for the measurement of a straight edge (for which $q = 0$).

In general, measurement accuracy should be smaller that 10% of the tolerance allowable in the test. So a level of uncertainty of 0.2% is usually acceptable for EEVC-style pedestrian tests that have a speed tolerance of ± 0.2 m/s (or about 2%).

The results show that the standard uncertainty in p must be at least 7.5 mm before the standard uncertainty in L exceeds 0.2 mm (or 0.2 %). This corresponds to a trajectory known to within ±15.0 mm.

Readers who regularly perform pedestrian sub-system tests may already recognise that uncertainties in the trajectory of the headform that have been discussed here are unlikely, and undesirable for other reasons, and would be likely to lead to impacts outside EEVC WG17 (and similar) testing requirements.

For the straight impactor, the standard uncertainty is fixed at ±0.028%, for all values of *p*.

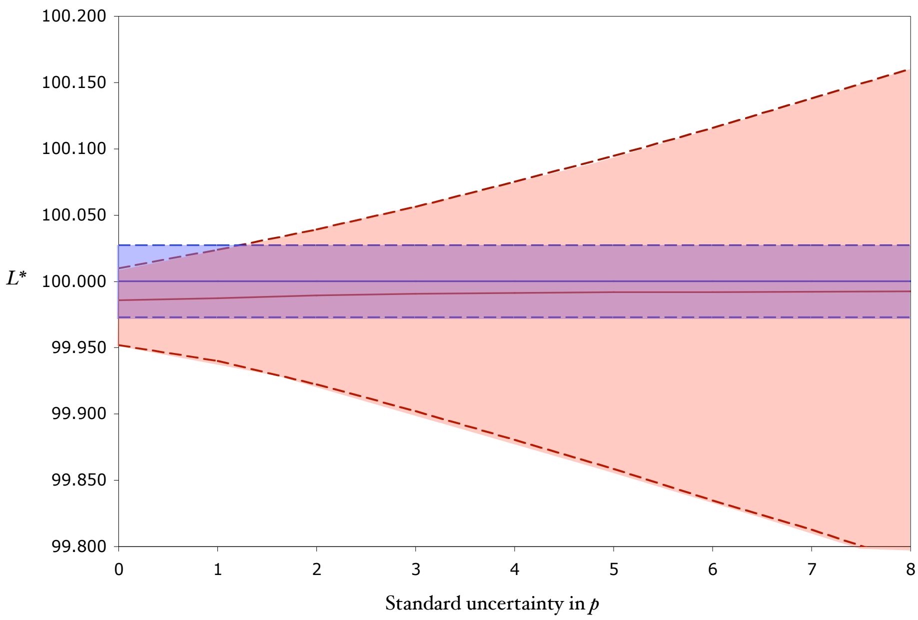


Figure 4 Value of L as a function of the standard uncertainty in p , given a standard uncertainty in Φ of ± 0.02 radians, for the EEVC WG17 child headform impactor (R = 57.5 mm; red) and a straight impactor(R = ∞; blue). The solid lines are the mean values and the dashed lines represent the 16th and 84th percentile values (equivalent to ± one standard uncertainty)*

Discussion

With due care, the LSMD operator can achieve a high level of speed measurement accuracy. Where the trajectory of the object being measured in highly controlled, a standard uncertainty of less than 0.03% is achievable. Such tests include sled tests, drop tests, or guided impact tests.

In free motion tests, such as pedestrian headform tests, the potential uncertainty is greater due to uncertainties in the object's trajectory. However, in normal testing environments, these uncertainties are unlikely to contribute unacceptable uncertainty to the overall measurement.

In all applications, for all devices similar to the LSMD, the uncertainty in the laser separation distance is important. A feature of the LSMD is that this distance can be measured and used in the calculation, rather than simply assumed. This greatly reduces the uncertainty in the laser separation distance and consequently the uncertainty in the speed measurement.

Further reading

Centre for Automotive Safety Research 2005, "Laser Speed Measurement Device: User's manual" (available on request from the author)

National Institutes of standard and Technology 2000, "Essentials of expressing measurement uncertainty", online: http://physics.nist.gov/cuu/Uncertainty/index.html, accessed 11/10/05.

National Institutes of standard and Technology, "NIST/SEMATECH e-Handbook of Statistical Methods", http://www.itl.nist.gov/div898/handbook/, accessed 11/10/05.

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