Physics outdoors: from the Doppler effect to *F* = *ma*

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Even rough-and-ready approaches outdoors can add greatly to the teaching of physics

This article uses two examples to show how physics can be demonstrated in a very practical and active way in or near school grounds. The first shows how to measure the speed of cars passing, using only recorded sound. The second describes the use of a mountain board to tackle Newton's laws – rough and ready but very effective at getting students involved!

Doppler effect speed measurement

It can be shown that if a source of sound is moving towards an observer, at a speed much less than the speed of sound, the frequency that the observer records will be higher than the source frequency. If the source is moving away from the observer, the frequency that the observer records will be lower than the source frequency.

The shift in frequency Δf, compared to f, is given by the equation:

$$\Delta f / f = v / c \qquad [1]$$

where v is the speed of the source relative to the observer and c is the speed of sound.

Further notes and explanation of this derivation can be found in most A-level textbooks and on the Web (see websites).

Equipment

A recording device – we use a laptop with a built-in microphone

ABSTRACT
Two fieldwork activities are described, which can be tried in most school environments. The first uses the sound of passing cars to measure speed, introducing the Doppler effect in a very active way. The second brings Newton's laws to life through using a mountain board.

Sound analysis software – we use *Amadeus*, but there are others, including the free *Audacity* (see websites)

Procedure

Stand by the side of the road (obviously take stock of the risk factors before going to a road), preferably one where cars will pass one at a time with some separation. It may be helpful to arrange to have a driver passing at a known speed, and possibly even sounding the horn. Record the sound. Analyse the sound on a computer to produce a sonogram (a frequency/time plot).

An alternative is to search the Web for audio recordings of cars passing. A *Google* search on '*cars passing audio files*' yields many results. So that readers can follow the procedure, I shall analyse one of these files here (see website for free download).

Looking at the sonogram (a frequency/time plot) of the file (Figure 1), we can see the change in frequency of engine harmonics. Analysis shows that the marked harmonic goes from 650 Hz to 440 Hz. We assume that the source frequency is halfway between these two, that is, 545 Hz. Δf, which is the maximum Doppler shift from the source frequency, is, in this case, 105 Hz. We can use this to calculate the car's speed.

Equation [1] can be rearranged to give:

$$v = c \Delta f / f$$

Assuming the speed of sound was 330 m s^{-1}, this gives:

$$v = 330 \times 105 / 545 = 64 \text{ m s}^{-1}$$

which translates to about 144 mph.

A similar analysis can be done for slower speeds. Readers might want to have a go at analysing the horn sound passing, also available on the website (see websites). I calculate that it has a speed of just over 10 m s^{-1}.

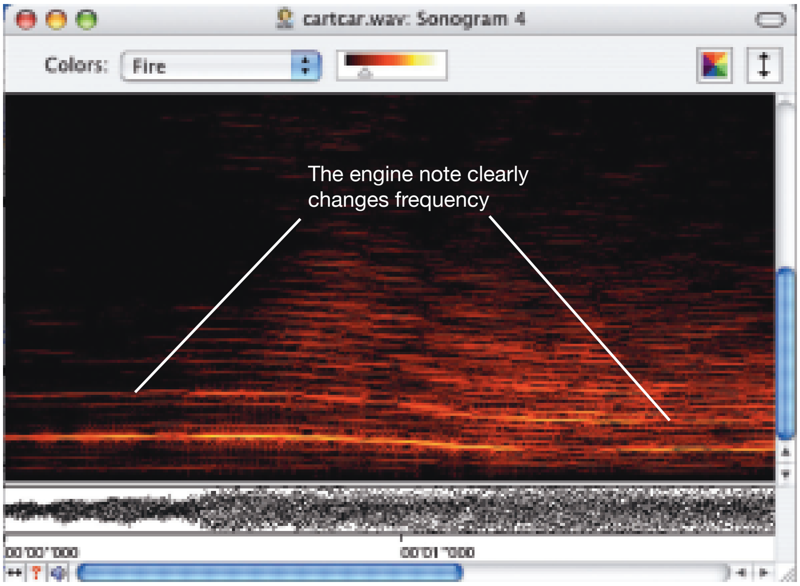

Figure 1 A sonogram (frequency/time plot) for a passing car.

Further discussion

It can be interesting, with a good group, to discuss what other information is presented by the sonogram. One can imagine that if the recording were taken from in front of the car, the frequency recorded would be unchanging until the time of impact. If the microphone is to the side, the frequency changes gradually, as the component of the car's speed towards the microphone decreases. The further away the microphone is, the more gradual the change. Indeed, one can analyse the gradient of the slopes on the sonogram to come up with a distance from the microphone to the car. Although the calculus involved in deriving this is a little difficult, I outline the resulting calculation below.

The gradient of the sonogram trace at the time of closest approach is at its steepest. If the distance of closest approach is r, then the gradient of the sonogram is given by:

$$\frac{df_{\text{observed}}}{dt} = \frac{f_{\text{source}} v^2}{rc}$$

Rearranging for r, we get

$$r = \frac{f_{\text{source}} v^2}{c} \times \frac{dt}{df_{\text{observed}}} \qquad [2]$$

In Figure 1, the change from 650 Hz to 440 Hz happens in the space of about 0.4 s, giving:

$$\frac{df_{\text{observed}}}{dt} = \frac{210}{0.4} = 525\ \text{s}^2$$

Substituting into [2] gives:

$$r = \frac{545 \times 64^2}{330 \times 525} \approx 13\ \text{m}$$

That is, the microphone was about 13 m from the passing car at its closest. Amazing what a sound can reveal!

F = *ma* is for life, not just the lab!

When teaching about Newton's laws, it is very easy to become bound up by experiments in the lab.

Figure 2 The basic set up for testing $F = ma$ (NB. rope should pull parallel with road, not sloping up, as shown here).

Figure 3 The mountain board minus footstraps. Cycle helmet should be worn.

Figure 4 Testing to see if the slope is friction-compensated.

Airtracks, runways, pulleys and masses are all useful teaching aids, but sometimes a more rough-and-ready approach sticks in the minds of students. Here I will describe how to test $F = ma$ using a mountain board and a large newtonmeter, a few metre rules and some stopclocks (Figure 2).

Apparatus

Mountain board (available from Argos for around £30); we took off the foot straps to allow the rider to sit (Figure 3)
Cycle helmet (you may also want elbow and knee pads)
Dynamometer/large newtonmeter (see websites for one around £60)
Metre rules/tape measure
Stopclocks
Rope
Slope

Procedure

First, we need to eliminate the effects of friction from the experiment. To do this we need a friction-compensated slope. Start with the rider on the mountain board with no rope attached and give him or her a push (Figure 4). Either by estimate, or by measurement of time taken over set distances, determine that they are travelling at a steady speed. If they are, you can see that the slope is allowing the weight to balance the force of friction. If your slope is too steep, try running obliquely across it until you find the correct angle.

Now you are ready to test $F = ma$. Attach a rope to the rider and get a fit volunteer to pull it with the dynamometer; they will have to run, whilst trying to maintain a steady force reading on the dynamometer. Starting from rest, they should pull the rider over a known distance whilst the time is taken. Repeat to check reliability of data.

Back in the lab, weigh the rider and board to determine their mass (Figure 5).

Sample calculation

Measured distance: 10 m
Time taken: 5 s (note that this is recorded to the nearest second only)
Average accelerating force: 50 N
Mass of rider and board: 70 kg

$F = ma$, rearranged, should give us a value for the expected acceleration:

$$a = \frac{F}{m} = \frac{50}{70} = 0.7 \text{ m s}^{-2} \qquad [3]$$

We can check this against the measured acceleration.

Advanced classes can leap in with *suvat* equations, thus:

$$s = ut + \tfrac{1}{2}at^2$$

$$10 = 0 + \tfrac{1}{2} \times 25 \times a$$

$$a = \frac{10}{12.5} = 0.8 \text{ m s}^{-2} \qquad [4]$$

Figure 5 Weighing the rider, board and helmet to determine mass.

However, I prefer to take less-able students through more carefully as follows:

What was the average speed over 10 m?

$$v = \frac{d}{t} = \frac{10}{5} = 2 \text{ m s}^{-1}$$

So, starting at 0 m s^{-1}, what final speed would give an average of 2 m s^{-1}?

4 m s^{-1}, as (0 m s^{-1} + 4 m s^{-1})/2 = 2 m s^{-1}

So if the final speed was 4 m s^{-1}, what is the acceleration?

$$a = \frac{\text{change in speed}}{\text{time taken}}$$

$$= \frac{4 \text{ m s}^{-1} - 0 \text{ m s}^{-1}}{5 \text{ s}}$$

$$= 0.8 \text{ m s}^{-2}\text{, as before in [4].}$$

We can see the agreement between [3] and [4] is quite good, and certainly within the uncertainty of the timing.

Further work

Film from a distance (to minimise parallax errors) and analyse the motion, both unaccelerated and accelerated, using video analysis packages such as *Videopoint* or *Multimedia Motion*.

Websites

For succinct derivation of the equation for the Doppler effect: http://hyperphysics.phy-astr.gsu.edu/hbase/sound/dopp.html

Good site on the Doppler effect, with wave animations and some spectacular movies: http://www.kettering.edu/~drussell/Demos/doppler/doppler.html

Sound analysis software – *Amadeus*: http://www.hairersoft.com/Amadeus.html; *Audacity*: http://audacity.sourceforge.net/

Audio recording of car passing: http://www.autospeak.com/grpsndc/cartcar.wav

Audio recording of horn sound passing: http://www.autospeak.com/grpsndb/horngoby.wav

Dynamometer/large newtonmeter: www.ascol.co.uk

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