Newton's First and Second Laws

In the 1660s, a chap called Isaac Newton worked out his dead useful Laws of Motion. Here are the first two.

A Force is Needed to Change Motion

This may seem simple, but it's important. Newton's First Law says that a resultant force (p.67) is needed to make something start moving, speed up or slow down:

> If the resultant force on a stationary object is zero, the object will remain stationary. If the resultant force on a moving object is zero, it'll just carry on moving at the same velocity (same speed and direction).

So, when a train or car or bus or anything else is moving at a constant velocity, the resistive and driving forces on it must all be balanced. The velocity will only change if there's a non-zero resultant force acting on the object.

1) A non-zero resultant force will always produce acceleration (or deceleration) in the direction of the force.
2) This "acceleration" can take five different forms: starting, stopping, speeding up, slowing down and changing direction.

Acceleration is Proportional to the Resultant Force

1) The larger the resultant force acting on an object, the more the object accelerates — the force and the acceleration are directly proportional. You can write this as $F \propto a$.
2) Acceleration is also inversely proportional to the mass of the object — so an object with a larger mass will accelerate less than one with a smaller mass (for a fixed resultant force).
3) There's an incredibly useful formula that describes Newton's Second Law:

Resultant force (N) Mass (kg)

$$\boxed{F = m \times a}$$

Acceleration (m/s²)

Large Decelerations can be Dangerous

1) Large decelerations of objects and people (e.g. in car crashes) can cause serious injuries. This is because a large deceleration requires a large force — $F = m \times a$.
2) The force can be lowered by slowing the object down over a longer time, i.e. decreasing its deceleration.
3) Safety features in vehicles are designed to increase collision times, which reduces the force, and so reduces the risk of injury. For example, seat belts stretch slightly and air bags slow you down gradually. Crumple zones are areas at the front and back of a vehicle which crumple up easily in a collision, increasing the time taken to stop.

EXAMPLE: Estimate the resultant force acting on a car stopping quickly from 15 m/s.

1) Estimate the deceleration of the car — you did that for this example on page 13.
   The car comes to a stop in ~1 s.
   $a = (v - u) \div t = (0 - 15) \div 1 = -15$ m/s²
2) Estimate the mass of the car.
   Mass of a car is ~1000 kg.
3) Put these numbers into Newton's 2nd Law.
   $F = m \times a$
   $= 1000 \times -15 = -15\ 000$ N

The force here is negative as it acts in the opposite direction to the motion of the car.

4) The brakes of a vehicle do work on its wheels (see p.66). This transfers energy from the vehicle's kinetic energy store to the thermal energy store of the brakes. Very large decelerations may cause the brakes to overheat (so they don't work as well). They could also cause the vehicle to skid.

Accelerate your learning — force yourself to revise...

Newton's First Law means that an object moving at a steady speed doesn't need a net force to keep moving.

Q1 Find the resultant force needed to accelerate an 80 kg man on a 10 kg bike at 0.25 m/s². [2 marks]

Weight and Circular Motion

Now for something a bit more attractive — the force of gravity. Enjoy...

Weight and Mass are Not the Same

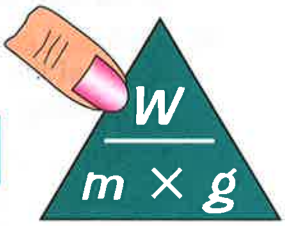
1) Mass is just the amount of 'stuff' in an object. For any given object this will have the same value anywhere in the universe.
2) Mass is a scalar quantity. It's measured in kilograms with a mass balance (an old-fashioned pair of balancing scales).
3) Weight is the force acting on an object due to gravity (the pull of the gravitational force on the object). Close to Earth, this force is caused by the gravitational field around the Earth.
4) Weight is a force measured in newtons. You can think of the force as acting from a single point on the object, called its centre of mass (a point at which you assume the whole mass is concentrated).
5) Weight is measured using a calibrated spring balance (or newton meter).

Gravity attracts all masses, but you only notice it when one of the masses is really big (like a planet).

Weight Depends on Mass and Gravitational Field Strength

1) You can calculate the weight of an object if you know its mass (m) and the strength of the gravitational field that it is in (g):

Weight (N) = mass (kg) × gravitational field strength (N/kg)



2) Gravitational field strength varies with location. It's stronger the closer you are to the mass causing the field (and more massive objects create stronger fields).
3) This means that the weight of an object changes with its location.

EXAMPLE: What is the weight, in newtons, of a 2.0 kg chicken on Earth (g = 10 N/kg)?

Calculate the weight on Earth using the equation for weight given above. $W = m \times g = 2.0 \times 10 = 20$ N

The chicken has a weight of 16 N on a mystery planet. What is the gravitational field strength of the planet?

1) Rearrange the weight equation for g. $g = W \div m$
2) Substitute the values in. $= 16 \div 2.0 = 8.0$ N/kg

Remember — the mass of the chicken is the same on every planet, it's the weight of the chicken that changes.

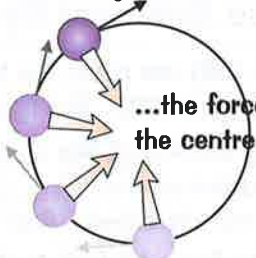
Circular Motion — Velocity is Constantly Changing

See p.59 for more on gravity causing circular motion.

1) Velocity is both the speed and direction of an object (p.12).
2) If an object is travelling in a circle (at a constant speed) it is constantly changing direction, so it is constantly changing velocity. This means it's accelerating.
3) This means there must be a resultant force (p.67) acting on it.
4) This force acts towards the centre of the circle.
5) This force that keeps something moving in a circle is called a centripetal force.

It's pronounced sen-tree-pee-tal.

The velocity's in this direction, but...



...the force is always towards the centre of the circle.

I don't think you understand the gravity of this situation...

Remember that weight is a force due to gravity and that it changes depending on the strength of the gravitational field the object is in. Gravity can cause circular motion (in things like moons and satellites — see page 59).

Q1 Calculate the weight in newtons of a 25 kg mass:
a) on Earth ($g \approx 10$ N/kg) b) on the Moon ($g \approx 1.6$ N/kg) [4 marks]

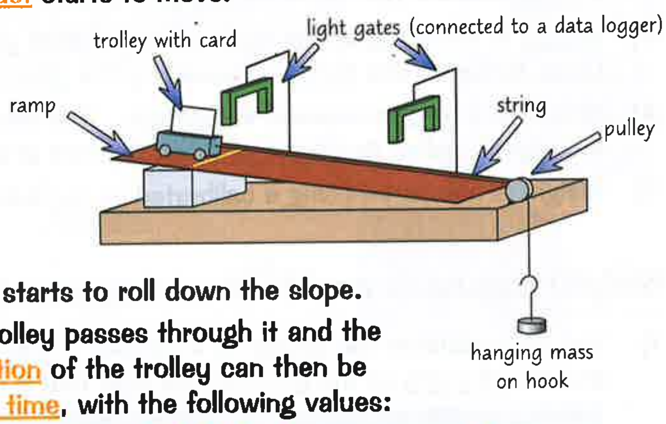
Investigating Motion

Doing an experiment for yourself can really help you to understand what's going on with $F = ma$ (p.16).

You can Investigate the Motion of a Trolley on a Ramp

PRACTICAL

1) Measure the mass of the trolley, the unit masses and the hanging hook. Measure the length of the piece of card which will interrupt the light gate beams. Then set up your apparatus as shown in the diagram below, but don't attach the string to the trolley.
2) Adjust the height of the ramp until the trolley just starts to move.
3) Mark a line on the ramp just before the first light gate — this is to make sure the trolley travels the same distance every time. The light gate will record the initial speed of the trolley as it begins to move.



4) Attach the trolley to the hanging mass by the string. Hold the trolley still at the start line, and then let go of it so that it starts to roll down the slope.
5) Each light gate will record the time when the trolley passes through it and the speed of the trolley at that time. The acceleration of the trolley can then be found using acceleration = change in speed ÷ time, with the following values:
   - the initial speed of the trolley as it passes through the first light gate (it'll be roughly 0 m/s),
   - the final speed of the trolley, which equals the speed of the trolley through the second light gate,
   - the time it takes the trolley to travel between the two light gates.

By changing the height of the ramp so that the trolley just begins to move, it means that any other forces that are applied (like the force due to gravity caused by the hanging mass) will be the main cause of the trolley accelerating as it travels down the ramp (page 16).
The size of this acceleration depends on the mass of the trolley and the size of the accelerating force.

- To investigate the effect of the trolley's mass: add masses one at a time to the trolley. Keep the mass on the hook constant (so the accelerating force is constant — where the force is equal to the mass on hook × acceleration due to gravity). Repeat steps 2-5 of the experiment above each time.
- To investigate the effect of the accelerating force: start with all the masses loaded onto the trolley and transfer the masses to the hook one at a time. Again, repeat steps 2-5 each time you move a mass.

You transfer the masses because you need to keep the mass of the whole system (the mass of the trolley + the mass on the hook) the same. This is because the accelerating force causes BOTH the trolley and the hanging masses to accelerate.

You should find that as the accelerating force increases, the acceleration increases (for a given trolley mass). So force and acceleration are proportional. As the mass of the trolley increases its acceleration decreases (for a given force) — mass and acceleration are inversely proportional.

You can use Different Equipment to Measure Distance and Time

Light gates (p.106) are often the best option for short time intervals. They get rid of the human error caused by reaction times (p.22). But light gates aren't the only way to find the speed of an object:

1) For finding something like a person's walking speed, the distances and times you'll look at are quite large. You can use a rolling tape measure (one of those clicky wheel things) and markers to measure and mark out distances. And for any times longer than five seconds, you can use a regular stopwatch.
2) If you're feeling a bit high-tech, you could also record a video of the moving object and look at how far it travels each frame. If you know how many frames per second the camera records, you can find the distance travelled by the object in a given number of frames and the time that it takes to do so.

My acceleration increases with nearby cake...

Make sure you know multiple methods for measuring the speed (distance travelled in a time) of an object.

Q1 Why is it better to use a light gate instead of a stopwatch to measure short time intervals? [1 mark]

Inertia and Newton's Third Law

Inertia and Newton's Third Law can seem simple on the surface, but they can quickly get confusing. Make sure you really understand what's going on with them — especially if an object is in equilibrium.

Inertia is the Tendency for Motion to Remain Unchanged

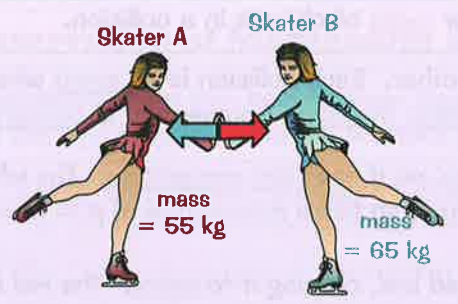
1) Until acted on by a resultant force, objects at rest stay at rest and objects moving at a constant velocity will stay moving at that velocity (Newton's First Law).
2) This tendency to keep moving with the same velocity is called inertia.
3) An object's inertial mass measures how difficult it is to change the velocity of an object.
4) Inertial mass can be found using Newton's Second Law of $F = ma$ (p.16). Rearranging this gives $m = F \div a$, so inertial mass is just the ratio of force over acceleration.

Newton's Third Law: Reaction Forces are Equal and Opposite

Newton's Third Law says:

> When two objects interact, the forces they exert on each other are equal and opposite.

1) If you push something, say a shopping trolley, the trolley will push back against you, just as hard.
2) And as soon as you stop pushing, so does the trolley. Kinda clever really.
3) So far, so good. The slightly tricky thing to get your head round is this — if the forces are always equal, how does anything ever go anywhere? The important thing to remember is that the two forces are acting on different objects.



When skater A pushes on skater B (the 'action' force), she feels an equal and opposite force from skater B's hand (the 'normal contact' force). Both skaters feel the same sized force, in opposite directions, and so accelerate away from each other.

Skater A will be accelerated more than skater B, though, because she has a smaller mass — remember $a = F \div m$.

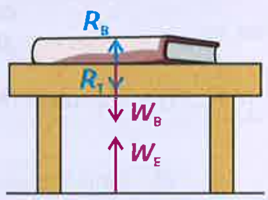
These equally-sized forces in opposite directions also explain the principle of conservation of momentum (see pages 20-21).

4) It's a bit more complicated for an object in equilibrium (p.68). Imagine a book sat on a table:

The weight of the book pulls it down, and the normal reaction force from the table pushes it up. These forces are equal to each other — the book is in equilibrium and doesn't move. This is NOT Newton's third law. These forces are different types and they're both acting on the book.

The pairs of forces due to Newton's third law in this case are:

- The book is pulled down by its weight due to gravity from Earth (W_B) and the book also pulls back up on the Earth (W_E).
- The normal contact force from the table pushing up on the book (R_B) and the normal contact force from the book pushing down on the table (R_T).



I have a reaction to forces — they bring me out in a rash...

Newton's 3rd law really trips people up, so make sure you understand exactly what objects the forces are acting on and how that results in movement (or lack of it). Then have a crack at this question to practise what you know.

Q1 A full shopping trolley and an empty one are moving at the same speed. Explain why it is easier to stop the empty trolley than the full trolley over the same amount of time. [1 mark]

Momentum

A large rugby player running very fast has much more momentum than a skinny one out for a Sunday afternoon stroll. It's something that all moving objects have, so you better get your head around it.

Momentum = Mass × Velocity

Momentum is a property that all moving objects have. (Think of it as how much 'oomph' something has.) It's defined as the product of the object's mass and velocity:

$$p = m \times v$$

momentum (kg m/s) = mass (kg) × velocity (m/s)

1) The greater the mass of an object, or the greater its velocity, the more momentum the object has.
2) Momentum is a vector quantity — it has size and direction.

EXAMPLE:

A 50 kg cheetah is running at 60 m/s. Calculate its momentum.

$p = m \times v = 50 \times 60$
$= 3000$ kg m/s

EXAMPLE:

A boy has a mass of 30 kg and a momentum of 75 kg m/s. Calculate his velocity.

$v = p \div m = 75 \div 30 = 2.5$ m/s

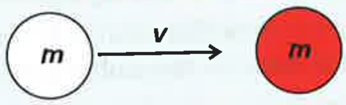
Total Momentum Before = Total Momentum After

A closed system is just a fancy way of saying that no external forces act.

In a closed system, the total momentum before an event (e.g. a collision) is the same as after the event. This is called conservation of momentum. You can use this to help you calculate things like the velocity or mass of objects in a collision.

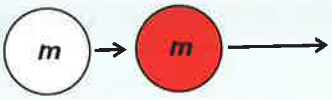
In snooker, balls of the same size and mass collide with each other. Each collision is an event where the momentum of each ball changes, but the overall momentum stays the same (momentum is conserved).

Before:



The red ball is stationary, so it has zero momentum. The white ball is moving with a velocity v, so has a momentum of $p = m \times v$.

After:



The white ball hits the red ball, causing it to move. The red ball now has momentum. The white ball continues moving, but at a much smaller velocity (and so a much smaller momentum).

The combined momentum of the red and white balls is equal to the original momentum of the white ball, $m \times v$.

EXAMPLE: A 1500 kg car, travelling at 25 m/s, crashes into the back of a parked car. The parked car has a mass of 1000 kg. The two cars lock together and continue moving in the same direction as the original moving car. Calculate the velocity that the two cars move with.

1) Calculate the momentum before the collision.
   $p = m \times v = 1500 \times 25 = 37\ 500$ kg m/s
   Total momentum before = total momentum after
2) Find the combined mass of the cars.
   New mass of joined cars = 2500 kg = M
3) Rearrange the equation to find the velocity of the cars.
   $v = p \div M = 37\ 500 \div 2500 = 15$ m/s

Learn this stuff — it'll only take a moment... um...

Conservation of momentum is incredibly handy — there's more on using it on the next page.

Q1 Calculate the momentum of a 60 kg woman running at 3 m/s. [2 marks]

Q2 Describe how momentum is conserved by a gun recoiling (moving backwards) as it shoots a bullet. [4 marks]

Changes in Momentum

A force causes the momentum of an object to change. A bigger force makes it change faster.

Forces Cause Changes in Momentum

1) When a resultant force acts on an object for a certain amount of time, it causes a change in momentum. Newton's 2nd Law can explain this:
   - A resultant force on an object causes it to accelerate: force = mass × acceleration (see p.16).
   - Acceleration is just change in velocity over time, so: force = $\frac{\text{mass} \times \text{change in velocity}}{\text{time}}$.
     This means a force applied to an object over any time interval will change the object's velocity.
   - Mass × change in velocity is equal to change in momentum, so you end up with the equation:

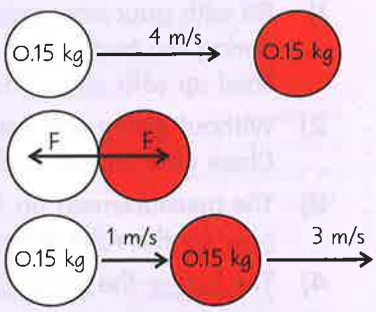
$$\text{force (N)} = \frac{\text{change in momentum (kg m/s)}}{\text{time (s)}} \quad \text{or} \quad F = \frac{(mv - mu)}{t}$$

2) The faster a given change in momentum happens, the bigger the force causing the change must be (i.e. if t gets smaller in the equation above, F gets bigger).
3) So if someone's momentum changes very quickly, like in a car crash, the forces on the body will be very large, and more likely to cause injury. There's more about this on p.16.
4) You can also think of changes in momentum in collisions in terms of acceleration — a change in momentum normally involves a change in velocity, which is what acceleration is (see p.13).
5) As you know, $F = ma$, so the larger the acceleration (or deceleration), the larger the force needed to produce it.

Conservation of Momentum Shows Newton's Third Law

The equation above can help to show Newton's Third Law (reaction forces are equal and opposite). Take the snooker balls from the previous page.

1) Before the collision, the white ball has a momentum of 0.15 × 4 = 0.6 kg m/s. The red ball has a momentum of zero.
2) The total momentum of the system is 0.6 kg m/s.
3) When the balls collide, the white ball exerts a force on the red ball. This force causes the red ball to start moving.
4) Due to Newton's 3rd Law, the red ball also exerts an equal but opposite force on the white ball. This force causes the white ball to slow down.
5) The collision lasts 0.1 s. After the collision, the white ball continues moving at 1 m/s. The red ball begins moving at 3 m/s.



6) The total momentum is (0.15 × 1) + (0.15 × 3) = 0.6 kg m/s. Momentum is conserved.
7) You can calculate the size of the force that caused this change of velocity (and so change of momentum) for each ball:
8) The force exerted on the white ball (by the red ball) is equal and opposite to the force exerted on the red ball (by the white ball). This shows Newton's Third Law.

white ball

$$F = \frac{(mv - mu)}{t} = \frac{(0.15 \times 1) - (0.15 \times 4)}{0.1} = \frac{-0.45}{0.1} = -4.5 \text{ N}$$

red ball

$$F = \frac{(mv - mu)}{t} = \frac{(0.15 \times 3) - (0.15 \times 0)}{0.1} = \frac{0.45}{0.1} = 4.5 \text{ N}$$

Homework this week — play pool to investigate momentum...

Sigh if only. Momentum is a pretty fundamental bit of physics — learn it well. Then have a go at this question.

Q1 Calculate the force a tennis racket needs to apply to a 58 g tennis ball to accelerate it from rest to 34 m/s in 11.6 ms. [3 marks]

Stopping Distances and Reaction Times

The stopping distance of a vehicle is the distance covered between the driver first spotting a hazard and the vehicle coming to a complete stop. It's made up of the thinking distance and the braking distance.

Stopping Distance = Thinking Distance + Braking Distance

The longer it takes a car to stop after seeing a hazard, the higher the risk of crashing. The distance it takes to stop a car (stopping distance) is divided into the thinking distance and the braking distance:

The thinking distance is the distance the car travels in the driver's reaction time (the time between noticing the hazard and applying the brakes). It's affected by two main factors:

1) Your reaction time — this is increased by tiredness, alcohol, drugs and distractions.
2) Your speed — the faster you're going, the further you'll travel during your reaction time.

The braking distance is the distance taken to stop once the brakes have been applied. It's affected by:

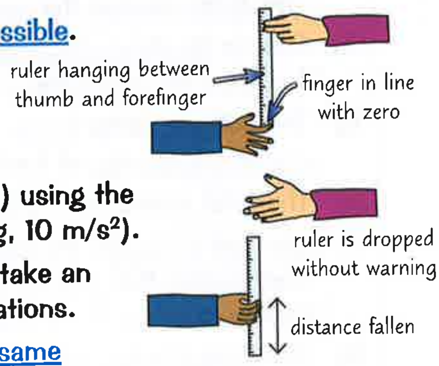
1) Your speed — the faster you're going, the longer it takes to stop (see next page).
2) The mass of the car — a car full of people and luggage won't stop as quickly as an empty car.
3) The condition of the brakes — worn or faulty brakes won't be able to brake with as much force.
4) How much friction is between your tyres and the road — you're more likely to skid if the road is dirty, if it's icy or wet or if the tyres are bald (tyres must have a minimum tread depth of 1.6 mm).

In the exam, you may need to spot the factors affecting thinking and braking distance in different situations. E.g. if a parent is driving her children to school early in the morning on an autumn day, her thinking distance could be affected by tiredness, or by her children distracting her. Her braking distance could be affected by ice, or by leaves on the road reducing the friction/grip.

The Ruler Drop Experiment Measures Reaction Times

Everyone's reaction time is different and many different factors affect it (see above).
One way of measuring reaction times is to use a computer-based test (e.g. clicking a mouse when the screen changes colour). Another is the ruler drop test:

1) Sit with your arm resting on the edge of a table (this should stop you moving your arm up or down during the test). Get someone else to hold a ruler so it hangs between your thumb and forefinger, lined up with zero. You may need a third person to be at eye level with the ruler to check it's lined up.
2) Without giving any warning, the person holding the ruler drops it. Close your thumb and finger to try to catch the ruler as quickly as possible.
3) The measurement on the ruler at the point where it was caught is how far the ruler dropped in the time it took you to react.
4) The longer the distance, the longer the reaction time.
5) You can calculate how long the ruler was falling for (the reaction time) using the equations on p.13 because its acceleration is constant (and equal to g, 10 m/s^2).
6) It's hard to do this experiment accurately, so do a lot of repeats and take an average of the distance the ruler fell. Use this average in your calculations.
7) Make sure it's a fair test — keep the variables you aren't testing the same every time, e.g. use the same ruler for each repeat and have the same person dropping it.
8) For an experiment like this, a typical reaction time is around 0.2-0.6 s.
9) A person's reaction time in a real situation (e.g. when driving) will be longer than that, though. Typically, an alert driver will have a reaction time of about 1 s.



Stop right there — and learn this page...

Bad visibility also causes accidents — if it's foggy, it's harder to notice a hazard, so there's less room to stop.

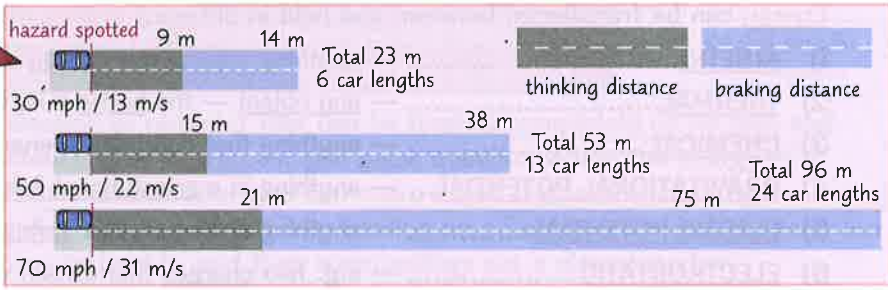
Q1 Drivers on long journeys should take regular breaks. Explain why, in terms of stopping distance. [3 marks]

Stopping Safely

So now you know what affects a car's stopping distance, let's have a look at the facts and figures.

Drivers Need to Leave Enough Space to Stop

1) These typical stopping distances are from the Highway Code.
2) To avoid an accident, drivers must leave enough space in front so they could stop safely — at least equal to the stopping distance for their speed.
3) Speed limits are really important because speed affects stopping distances so much. (Remember, weather and road conditions can affect them too.)
4) As speed increases, thinking distance increases at the same rate. This is because the driver's reaction time stays fairly constant, but the higher the speed, the further you go in that time ($d = st$, p.12).
5) However, braking distance and speed have a squared relationship — if speed doubles, braking distance increases by a factor of 4 (2^2), and if speed trebles, braking distance increases by a factor of 9 (3^2).



The brakes of a car do work on the car's wheels (see page 66). This transfers energy from the car's kinetic energy store to the thermal energy store of the brakes.
To stop a car, the brakes must transfer all of this energy, so:

There's more on these equations on pages 24 and 65.

Energy in the car's kinetic energy store = Work done by the brakes

$$\tfrac{1}{2} \times m \times v^2 = F \times d$$

mass of the car (m), speed of car (v), braking force (F), braking distance (d)

This means doubling the mass doubles the braking distance.

You can Estimate the Distances Involved in Stopping

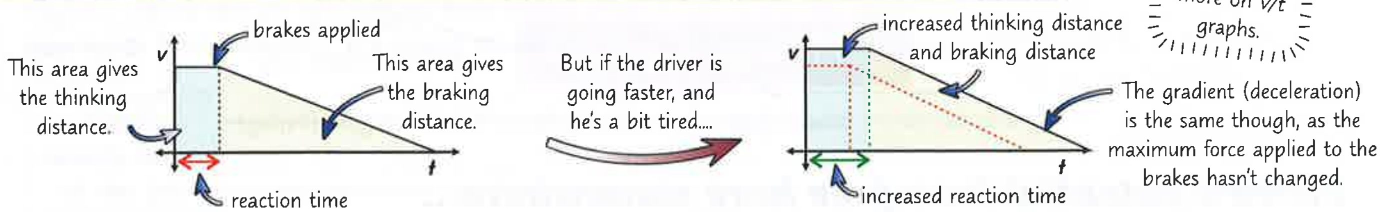
EXAMPLE: A car travelling at 25 m/s makes an emergency stop to avoid a hazard. The braking force applied to the car is 5000 N. Estimate the total distance taken to stop.

1) Estimate the driver's reaction time.
   Reaction time is ~1 s.
2) Calculate the thinking distance.
   $d = v \times t = 25 \times 1 = 25$ m
3) To work out the braking distance, rearrange the equation above for d, and estimate the mass of the car.
   $d = (\tfrac{1}{2} \times m \times v^2) \div F$
   Mass of a car is ~1000 kg
   $d = (\tfrac{1}{2} \times 1000 \times 25^2) \div 5000$
   $= 62.5$ m
4) Add the thinking distance and braking distance to give the stopping distance.
   $25 + 62.5 = 87.5$ m   Distance is ~90 m

Make sure you can estimate the mass of objects. A car's mass is ~1000 kg. A single decker bus is ~10 000 kg and a loaded lorry is ~30 000 kg.

Thinking and Braking Distance can be Seen on v/t Graphs

See p.15 for more on v/t graphs.



It's enough to put you off learning to drive, isn't it...

This is quite a tough page, but it's important, so head back to the top and read it again.

Q1 Estimate the size of the force needed to stop a lorry travelling at 16 m/s within 50 m. [4 marks]