IB Physics Topics A1 A2 A3; SL & HL

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1 Newton's Laws of Motion

1. N^{1st}: An object will remain at rest or in uniform motion unless acted upon by a net external force.

2. N^{2nd}: The acceleration of an object is directly proportional to the net force acting on it

3. N^{3rd}: For every action, there is an equal and opposite reaction.

2 The SUVAT Equations

$$
\begin{aligned}
v &= u + at \\
s &= ut + \frac{1}{2}at^2 \\
v^2 &= u^2 + 2as \\
s &= \frac{(u+v)}{2}t \\
s &= vt - \frac{1}{2}at^2
\end{aligned}
$$

where

- u is the initial velocity
- v is the final velocity
- a is the acceleration
- s is the displacement
- t is the time

N.b. these equations can only be used when the acceleration is constant!

3 Special Forces

3.1 Drag Force

The drag force in a fluid is given by:

$$F_d = 6\pi\eta r v$$

where:

- F_d is the drag force
- η is the viscosity of the fluid
- r is the radius of the object
- v is the velocity of the object

It is in the opposite direction of the velocity vector.

An explanation on the forces acting on a skydiver can be asked in exams; let us consider the scenario with respect to a velocity/time graph

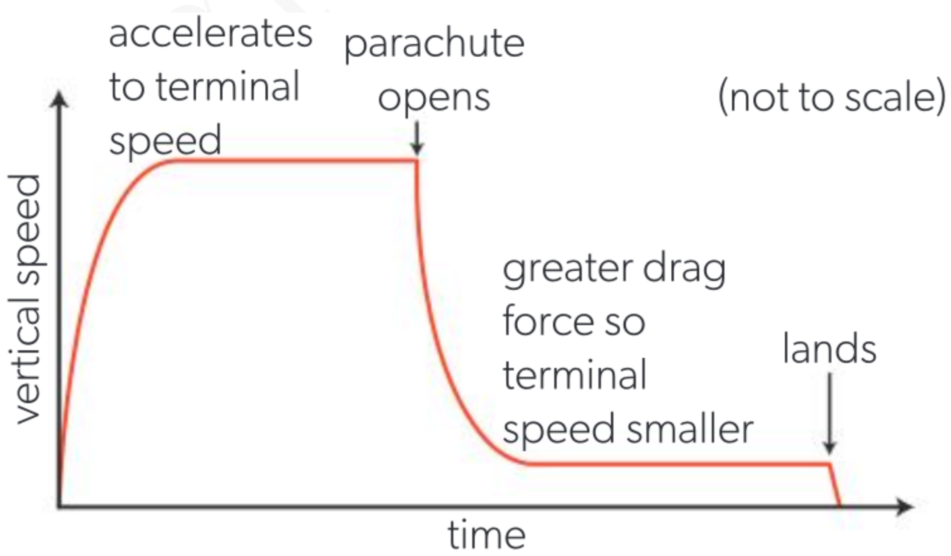

Figure 1: Velocity/time graph of a skydiver

1. When the skydiver jumps out of the plane, immediately there is a constant gravitational force acting on them, initially giving a downward acceleration of g.
2. As the skydiver accelerates downwards, the drag force opposing their motion increases because the velocity is increasing and the skydiver hits the air particles with more force (so greater resistance upwards, by N^{3rd}).
3. The drag force continues to increase until it is equal to the gravitational force, at which point the net force acting on the skydiver is zero, and a terminal velocity is reached.
4. The instant the skydiver opens their parachute, the drag force increases significantly, and the drag force now is much greater than the gravitational force, causing the skydiver to decelerate rapidly.
5. With decreasing velocity, the drag force also decreases until it is equal to the gravitational force again, at which point the skydiver reaches a new, lower terminal velocity.

3.2 Buoyancy Force

The buoyancy force exerted by a fluid on an object is given by:

$$F_b = \rho g V$$

where:

- F_b is the buoyancy force
- ρ is the density of the fluid
- g is the acceleration due to gravity
- V is the volume of the fluid displaced

This force is always directed upwards, against the force of gravity. It is worth noting that, when the object is fully submerged, the volume of the fluid displaced is equal to the volume of the object.

This allows us to find the terminal velocity v_0 of an object of volume V and density ρ_{obj} falling through a fluid of density ρ_{fluid}:

$$\begin{aligned} F_b + F_d &= F_g \\ \rho_{\text{fluid}} g V + 6\pi\eta r v_0 &= \rho_{\text{obj}} g V \\ v_0 &= \frac{(\rho_{\text{obj}} - \rho_{\text{fluid}})\, gV}{6\pi\eta r} \end{aligned}$$

3.3 Frictional Force

The frictional force is given by:

$$F_f = \mu F_n$$

where:

- F_f is the frictional force
- μ is the coefficient of friction
  - The static coefficient $\mu = \mu_s$ is used when the object is at rest relative to the surface.
  - The kinetic coefficient $\mu = \mu_d$ is used when the object is in motion relative to the surface.

It then follows that the maximum force along the surface before the object starts moving is given by:

$$F_{f,\max} = \mu_s F_n$$

Exerting a force greater than this limit will cause the object to start moving, in which case, the frictional force now must use the kinetic coefficient.

3.4 Spring Force

The spring force is given by:

$$F_s = -kx$$

where:

- F_s is the spring force
- k is the spring constant
- x is the displacement from the equilibrium position

The negative sign indicates that the force is always directed opposite to the displacement.

4 Circular Motion

The equations are

- Linear acceleration: $a = v\omega = \dfrac{v^2}{r} = \omega^2 r$ is the centripetal acceleration, directed inwards towards the center of the circle.
- Linear speed: $v = \dfrac{2\pi r}{T} = r\omega = 2\pi r f$
- Angular speed: $\omega = \dfrac{2\pi}{T}$
- Frequency: $f = \dfrac{1}{T}$

It must be noted that, when drawing free body diagrams, the centripetal force is not a type of force in itself, but rather a net force acting on the object, and so should not be drawn. We will practice with this in the Exam Questions section later on.

There are a few scenarios that we investigate in IB questions; below is the list identifying the force providing the centripetal force.

Scenario	**Centripetal Force**
Car at a roundabout	Frictional force
Object on a string rotating in a horizontal circle	Horizontal component of tension
Bicycle on a banked curve	Normal force
Satellites in orbit	Gravitational force
Rotor ride	Normal reaction force

4.1 Turning without Slipping

Consider a car turning around a corner, whose path is modelled by a circle of radius r.

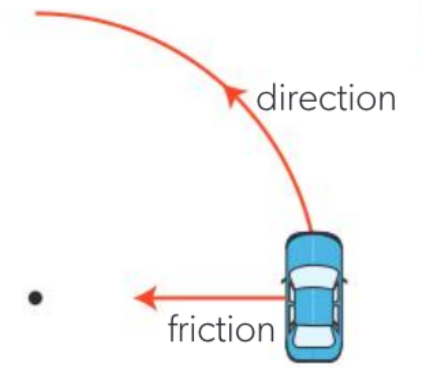

Figure 2: Car turning around a corner

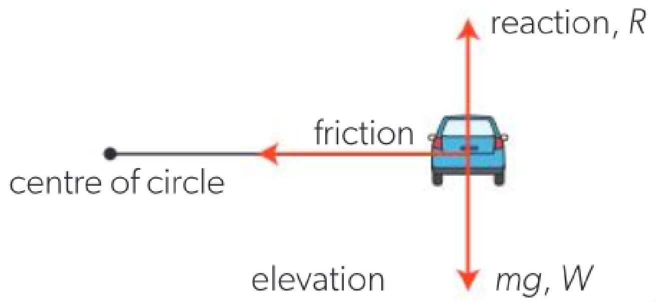

Figure 3: Forces acting on a car turning around a corner

Suppose road has a static friction coefficient μ_s and the car has a mass m. The car is moving with a speed v and the radius of the turn is r. The forces acting on the car are:

- Vertically: The weight of the car mg acting downwards and the normal force $F_n = mg$ acting upwards.
- Horizontally: The frictional force F_f acting towards the center of the circle.

The common problem in IB questions is to find the maximum speed at which the car can turn without slipping. This is where the frictional force does not surpass the maximum static frictional force. This means

$$\begin{aligned} F_c &\leq F_{\text{f, static}} \\ \frac{mv^2}{r} &\leq \mu_s mg \\ v^2 &\leq \mu_s gr \\ v &\leq \sqrt{\mu_s gr} \end{aligned}$$

4.2 Banking

Suppose an object travelling on a curved path with radius r banked at an angle θ to the horizontal. The free body diagram is as follows

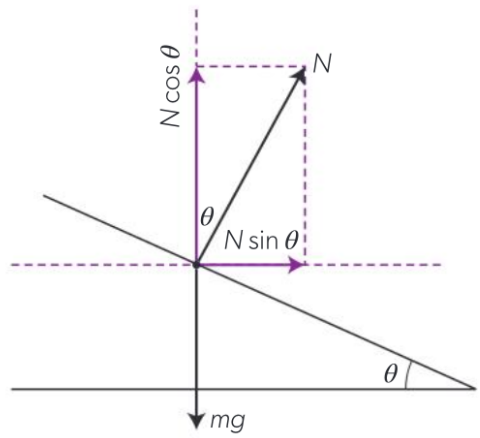

Figure 4: Free body diagram of a banked curve

- The vertical component of the normal force F_n is equal to the weight of the object mg, since the object is not accelerating vertically.
- The centripetal force is provided by the horizontal component of the normal force F_n, namely $N \sin \theta$.

4.3 Car over a Bridge/Hill

What is the maximum speed at which a car can go over a bridge/hill of radius r without losing contact with the road? The diagram is as follows.

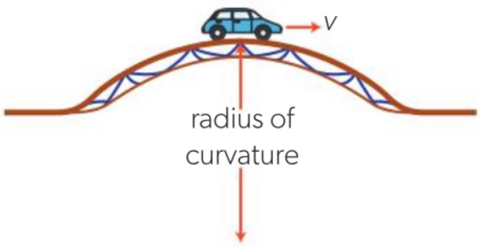

Figure 5: Car over a bridge

1. The forces acting on the car are

   - The weight of the car mg acting downwards, so its negative equivalent acts upwards on it.
   - The centripetal force $F_c = \dfrac{mv^2}{r}$ acting towards the centre of the circle (downwards).
   - The normal reaction force should be upwards and so is

   $$F_n - F_c = m\left(g - \frac{v^2}{r}\right)$$

2. If, at any point, this normal force is zero, then the car will lose contact with the road. For this to happen, the normal reaction force must be 0, giving

   $$g = \frac{v^2}{r}$$
   $$v = \sqrt{gr}$$

5 Energy

- Kinetic energy: $E_K = \frac{1}{2}mv^2 = \frac{p^2}{2m}$
- Gravitational potential energy: $E_P = mgh$
- Elastic potential energy: $E_E = \frac{1}{2}kx^2$
- Work done: $W = Fd\cos\theta$
- Power: $P = \frac{W}{t} = Fv\cos\theta$

5.1 Sankey Diagrams

They are used for both energy and power. The rules of a Sankey diagram are as follows:

- The diagram is drawn to scale with the width of the arrow being proportional to the amount of energy transfer it represents.
- Left to right: The energy input is on the left, and the energy output is on the right.
- Lost/wasted energy is directed downwards.

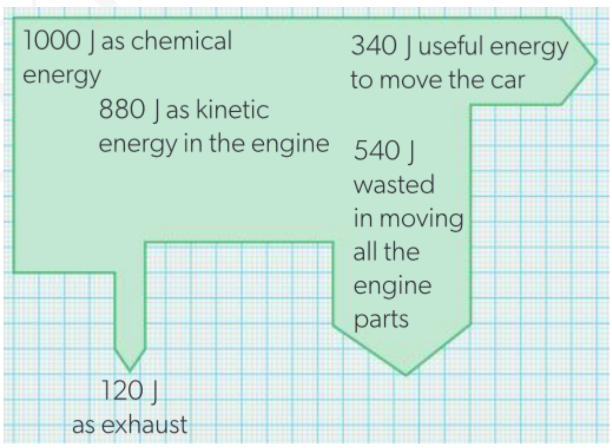

Figure 6: Sankey diagram of a car

6 Momentum

Momentum, as an attribute of a body, is given as

$$p = mv$$

where:

- p is the momentum
- m is the mass
- v is the velocity

The momentum of a system is given by the sum of the momenta of all objects.

The **impulse**, change in momentum, is given by:

$$\Delta p = F\Delta t = m(\Delta v)$$

The differential form (through the product rule) can be used when one or both of mass and velocity are changing:

$$\Delta p = \frac{\mathrm{d}(mv)}{\mathrm{d}t} = m\frac{\mathrm{d}v}{\mathrm{d}t} + v\frac{\mathrm{d}m}{\mathrm{d}t}$$

This is useful in situations such as rockets, where the mass is changing due to fuel consumption. When a rocket is travelling while expelling fuel, the total momentum of the fuel-rocket system is conserved. We will practice this later.

6.1 Collisions and Explosions

In these cases, the total momentum of the system is conserved only if the net force acting on the system is 0. Hence

$$\sum p_{\text{before}} = \sum p_{\text{after}}$$

Often times, these questions may involve looking at both components. It is important to know that the momentum is conserved in all directions, and so the momentum in the x-direction and y-direction are conserved separately, which can give us a system of equations to solve. We will practice later.

For it to be an elastic collision, the kinetic energy must also be conserved. This means that

$$\sum E_{K,\text{before}} = \sum E_{K,\text{after}}$$

In a lot of questions, you'd be ask to determine whether the collision is elastic or inelastic. This can be done by checking if the kinetic energy before and after the collision is equal. If it is, then it is elastic, otherwise it is inelastic.

7 Exam Questions