14/19

14 Terminal Velocity

A falling object in the air, which is not influenced by wind or other sideways forces, has a maximum of two forces acting on it: weight and air resistance (also known as drag). The weight does not change. The air resistance is zero when the object is stationary but increases as the object speeds up.

The resultant (net) force the falling object experiences is equal to the force of gravity minus the air resistance. [$F = mg - Drag$]

Newton's Second Law states that the acceleration of the object is proportional to the resultant force on the object when its mass is constant.

- The longer the object falls for, the faster it travels (due to its acceleration),
- but then the greater the air resistance, which increases with speed.
- Eventually, however, the air resistance upwards will equal the force of gravity downwards.
- At this point, the resultant force is zero,
- hence, the velocity remains constant. This is called the terminal velocity of the object.

An object with a constant force acting on it in the direction it is travelling and a frictional force (related to the object's velocity) acting in the opposite direction, will reach terminal velocity given enough time. This is true for cars driving along a road or an anchor falling through water towards the seafloor.

14.1 A parachutist of mass 80 kg is falling to the ground at a steady vertical velocity of 10 m/s. What is the value of the total drag force acting on him?

14.2 A bicycle is ridden along a horizontal road with a driving force of 400 N. Its speed is constant at 12 m/s. What is the magnitude of the sum of the frictional forces acting on the bike and its rider?

14.3 Two identical bottles are dropped off a cliff, both falling with their bases downwards. One of them is full of water, while the other con-

tains air at atmospheric pressure. What can you say about the terminal velocities these two bottles will reach?

14.4 A car travelling at constant speed has a driving force of 2.1 kN acting on it. The driver presses the accelerator, and the driving force increases to 2.5 kN.

(a) Immediately after the driver presses the pedal, what is the total resistive force acting on the car?

(b) When the car again reaches a constant speed, what is the total resistive force acting on the car?

14.5 A care package has a mass of 150 kg. It is dropped from a helicopter 2 000 m above the ground.

(a) What is the weight of the care package?

(b) If the object is falling at terminal velocity, what is the value of the air resistance?

(c) The care package has a parachute built in, which opens automatically at 1 000 m. What happens to the air resistance as it opens?

(d) After a short time, the care package plus the open parachute begin to fall with their terminal velocity. How does this value qualitatively compare to the terminal velocity of the care package without the parachute?

(e) How does the air resistance of the care package falling at terminal velocity with the parachute open compare to the air resistance of the care package falling at terminal velocity without the parachute? Explain your answer.

(f) The care package falls off course and lands in a lake. Ignore the effect of buoyancy. The care package starts to sink and reaches terminal velocity once more. How does this value of terminal velocity qualitatively compare to the previous two values? Explain your answer.

(g) In (f), what is the value of the fluid drag through the water when the object sinks at its terminal velocity?

14.6 The online graph shows how the drag force on a $25\,000$ kg lorry depends on the lorry's speed.

(a) At one moment, the lorry is travelling at 20 m/s and the driving force acting on it is $80\,000$ N. What is the acceleration of the lorry at this instant?

(b) The lorry maintains a constant driving force of $80\,000$ N. What is its terminal velocity?

(c) While at the above terminal speed, the driver then halves the driving force to $40,000$ N. What is the initial acceleration of the lorry?

(d) After some time the lorry reaches a new terminal velocity. What is this new terminal velocity?

14.7 When an object is travelling through a fluid (liquid or gas), the resistive force will depend on the speed of the object. However, how this force changes with speed depends on whether the flow of the fluid past the object is smooth or turbulent.

(a) If the flow is smooth, the resistive force is proportional to the speed of the object moving through the fluid. If the driving force is multiplied by 5, by what factor does the terminal velocity of the object increase?

(b) If the flow is turbulent, the resistive force is proportional to the square of the speed of the object moving through the fluid. If the driving force is multiplied by 5 , by what factor does the terminal velocity of the object increase?

14.8 When a ship is moving through the water, the resistance to its motion is made up of a few different components. One of these comes from the fact that the ship will push water in such a way to make waves, so it is called the "Wave Making Resistance". The main part of the resistance is known as "Frictional Resistance". For one ship, this provides 80 % of the total resistance force. Give an equation for F_D , the driving force propelling the ship, in terms of the frictional resistance F_f , when the ship is travelling at its terminal velocity.