1.2 Speed and Velocity

If you have been a passenger in a car or are taking driving lessons, speed is something you have thought about. Knowing the speed at which a vehicle is moving is important for safety. Excessive speed is a contributing factor in many collisions.

Speed can be measured in different ways. Police use laser speed devices to detect the speed of moving vehicles (**Figure 1**). In the laboratory, scientists and engineers can use electronic devices such as motion sensors to measure speed.

Figure 1 A laser speed device can accurately measure the speed of an oncoming vehicle.

Average Speed

The **average speed** of a moving object is the total distance travelled divided by the total time elapsed. You are probably familiar with the speedometer of a passenger vehicle, which tells the speed of the vehicle in kilometres per hour (km/h). However, the SI unit for speed is metres per second (m/s).

average speed (v_{av}) the total distance travelled divided by the total time taken to travel that distance

You do not need a special device like a police speed device to measure speed. If you know the distance travelled and the time it took an object to travel that distance, you can calculate the average speed of the object using the equation

$$v_{av} = \frac{\Delta d}{\Delta t}$$

where v_{av} is the average speed, Δd is the distance travelled, and Δt is the change in time. Like distance, speed is a scalar quantity. In the following Tutorial, we will determine the average speed of an object using this equation.

Investigation **1.2.1**

Watch Your Speed (p. 46)
In this investigation you will use the average speed equation to determine average speed in a study of vehicles passing an observation point.

Tutorial 1 Calculating Average Speed

The following Sample Problems will demonstrate how to use the equation for average speed.

Sample Problem 1: Determining Average Speed

Your dog runs in a straight line for a distance of 43 m in 28 s. What is your dog's average speed?

Given: $\Delta d = 43$ m; $\Delta t = 28$ s

Required: v_{av}

Analysis: $v_{av} = \frac{\Delta d}{\Delta t}$

Solution:
$$v_{av} = \frac{\Delta d}{\Delta t} = \frac{43\text{ m}}{28\text{ s}}$$
$$v_{av} = 1.5\text{ m/s}$$

Statement: Your dog's average speed is 1.5 m/s.

Sample Problem 2: Determining the Distance Travelled by a Ball Moving at Constant Speed

A baseball rolls along a flat parking lot in a straight line at a constant speed of 3.8 m/s. How far will the baseball roll in 15 s?

Given: $v_{av} = 3.8$ m/s; $\Delta t = 15$ s

Required: Δd

Analysis: $v_{av} = \dfrac{\Delta d}{\Delta t}$

$$\Delta d = v_{av}\Delta t$$

Solution: $\Delta d = v_{av}\Delta t$

$$= \left(3.8\,\frac{\text{m}}{\cancel{\text{s}}}\right)(15\,\cancel{\text{s}})$$

$$\Delta d = 57\text{ m}$$

Statement: The ball will roll 57 m in 15 s.

Practice

1. A paper airplane flies 3.7 m in 1.8 s. What is the airplane's average speed? T/I [ans: 2.1 m/s]
2. A cheetah can run at a maximum speed of 30.0 km/h, or 8.33 m/s. How far can a cheetah run in 3.27 s? T/I [ans: 27.2 m]
3. How long does it take a rock to fall through 2.8 m of water if it falls at a constant speed of 1.2 m/s? T/I [ans: 2.3 s]

LEARNING **TIP**

Rounding in Calculations
As a general rule, round final answers to the same number of significant digits as the given value with the fewest significant digits. Take extra care when rounding digits with multiple parts. You will see in this book that extra digits are carried in intermediate calculations. For more help with rounding, refer to the Skills Handbook.

Research This

Searching for Speeders

Skills: Researching, Analyzing, Communicating, Identifying Alternatives, Defending a Decision

SKILLS HANDBOOK A5

A laser speed device is used by police officers to measure the speed of moving vehicles. This device sends a pulse of infrared laser light at the speed of light (3.0×10^8 m/s) toward a moving vehicle. The laser pulse reflects off the vehicle and returns to a sensor on the speed device. A computer chip in the speed device determines the time it took for the pulse to travel to and from the moving vehicle. The speed device uses one half of this very short time and the speed of light to calculate the distance to the moving vehicle. The speed device's computer uses multiple distance readings to determine how the vehicle's distance is changing with time and then calculates the vehicle's speed. Modern speed devices send thousands of pulses of light each second, providing a high level of accuracy.

1. Conduct research to investigate how common laser speed devices are in the region where you live.
2. Investigate how speed affects the number of automobile collisions and fatalities in Canada.
3. Investigate alternative methods the police could use to determine the speed of a vehicle.

A. Does the use of laser speed devices have an impact on the number of automobile collisions and fatalities in Canada? K/U

B. Do you feel that the use of laser speed devices is the preferred way for police to monitor the speed of automobiles? C

C. Laser speed devices and video recorders can now be used to capture the speed of a moving vehicle, the vehicle's licence plate number, the date, and the time in the same image. If these devices are set in a fixed position, they can operate without the need for a police officer to be present. Data can be collected electronically and speeders can be sent a ticket through the mail. Do you support the use of devices like these in Ontario? Justify your decision. C A

GO TO NELSON SCIENCE

Average Velocity

average velocity ($\vec{v}_{av}$) the total displacement, or change in position, divided by the total time for that displacement

position–time graph a graph describing the motion of an object, with position on the vertical axis and time on the horizontal axis

slope (*m*) a measure of the steepness of a line

rise vertical change between two points on a line

run horizontal change between two points on a line

The **average velocity** of an object in motion is its total displacement, or change in position, divided by the total time taken for the motion. Velocity describes change in position over time. For instance, a cyclist travelling east at a constant speed of 11 m/s has a velocity of 11 m/s [E]. Since it has direction and magnitude, average velocity is a vector quantity. The SI unit for velocity is metres per second (m/s). The symbol for average velocity is $\vec{v}_{av}$.

A **position–time graph** is a graph that describes the motion of an object, with position on the vertical axis and time on the horizontal axis. **Figure 2** shows a position–time graph for the motion of a rolling ball measured by students during an experiment. Notice that the points on the graph form a straight line that moves upward from left to right. Whenever an object is moving at a constant velocity, the position–time graph of that motion is a straight line.

You may recall from your mathematics studies that the **slope** of a line describes its steepness. The symbol for slope is m. Slope is determined, as shown in Figure 2, by comparing the magnitude of the **rise** (the change between points on the y-axis) and the magnitude of the **run** (the change between the same points on the x-axis). You can use this technique whether the graph passes through the origin or not; for example, in **Figure 3** the motion begins at a position of 10 m [E] when $t = 0$ s.

For an object moving at a constant velocity, so that its position–time graph is a straight line, the key relationship is this:

> The slope of a position–time graph gives the velocity of the object.

The steeper the graph, the greater is the object's displacement in a given time interval, and the higher is its velocity. This can be confirmed using the information in Figure 2. Since the y-axis shows change in position, $\Delta\vec{d}$, and the x-axis shows change in time, Δt, the formula for the slope of this graph can be rewritten as follows:

$$\text{slope} = \frac{\text{rise}}{\text{run}}$$

$$m = \frac{\vec{d}_2 - \vec{d}_1}{t_2 - t_1}$$

$$\text{or} \quad m = \frac{\Delta\vec{d}}{\Delta t}$$

LEARNING TIP

Rates of Change
Average speed and average velocity are examples of rates of change—an important concept in science that describes how quickly a quantity is changing. Velocity is the rate of change of position, which means that the more rapidly an object's position is changing, the greater is the magnitude of its velocity.

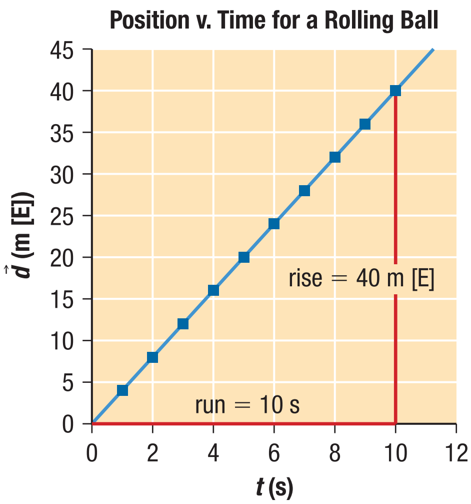


Figure 2 Calculating the slope of a position–time graph

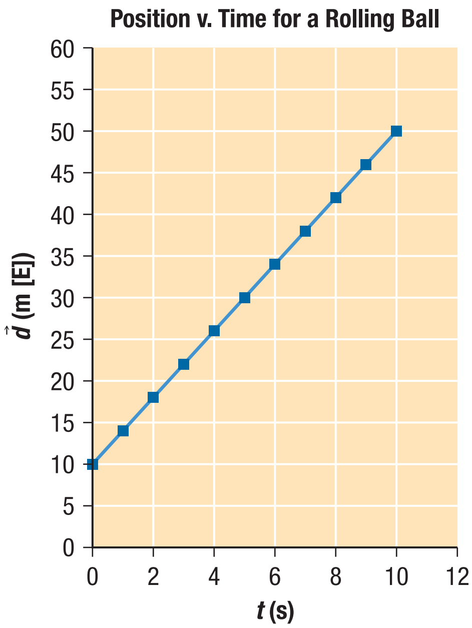


Figure 3 A position–time graph with non-zero initial position

The (average) velocity of a moving object is given by the equation

$$\vec{v}_{av} = \frac{\Delta\vec{d}}{\Delta t}$$

To determine the slope—the average velocity—from the zero point to the final data point for the *x*-axis and *y*-axis for the motion shown in Figure 2, substitute the initial and final displacement and time values into the equation we just derived:

$$\vec{v}_{av} = \frac{\Delta\vec{d}}{\Delta t}$$

$$m = \frac{\vec{d}_2 - \vec{d}_1}{t_2 - t_1}$$

$$= \frac{40 \text{ m [E]} - 0 \text{ m}}{10 \text{ s} - 0 \text{ s}}$$

$$m = 4 \text{ m/s [E]}$$

The velocity of the rolling ball is 4 m/s [E]. Note that the slopes of the graphs shown in Figure 2 and Figure 3 are the same, 4 m/s [E]. The two motions are different in that the motion described by Figure 2 started 0 m away from the observer, whereas the motion graphed in Figure 3 had an initial position of 10 m [E] from the observer. Calculating average velocity from the slope of a position–time graph is a very useful technique because average velocity is often difficult to measure directly. However, position can be easily measured with equipment such as tape measures, motion sensors, and laser speed devices.

Velocity (a vector quantity) is to speed (a scalar quantity) as displacement (a vector quantity) is to distance (a scalar quantity). The equation for average velocity should therefore look similar to the equation for average speed, except that velocity and displacement are vectors:

$$\vec{v}_{av} = \frac{\Delta\vec{d}}{\Delta t}$$

where $\Delta\vec{d}$ is the change in position and Δt is the change in time during the given time interval. This is the same equation as the one we just derived using the slope of a position–time graph.

Note that Δt can also be described by the equation $\Delta t = t_2 - t_1$. Often, we can simplify this equation by considering t_1, the start time, to be 0 s. In the following Tutorial, we will use the average velocity equation to determine unknown values.

LEARNING TIP

Calculations with Vectors
In general, you cannot divide one vector by another, as dividing a direction has no meaning. However, if the directions of both vectors are the same, you can disregard the direction and divide one magnitude by the other.

Tutorial 2 Solving Problems Using the Equation for Average Velocity

The equation for average velocity can be used to solve for any of the three variables in the average velocity equation when the other two are known. In the following Sample Problems, we will review solving equations for an unknown variable using the equation for average velocity.

Sample Problem 1: Calculating the Average Velocity of an Object

On a windy day, the position of a balloon changes as it is blown 82 m [N] away from a child in 15 s. What is the average velocity of the balloon?

Solution

We are given the change in time and the change in position of the balloon, so we can solve for average velocity.

Given: $\Delta\vec{d} = 82 \text{ m [N]}$; $\Delta t = 15 \text{ s}$

Required: $\vec{v}_{av}$

Analysis: $\vec{v}_{av} = \frac{\Delta\vec{d}}{\Delta t}$

Solution:

$$\vec{v}_{av} = \frac{\Delta\vec{d}}{\Delta t}$$

$$= \frac{82 \text{ m [N]}}{15 \text{ s}}$$

$$\vec{v}_{av} = 5.5 \text{ m/s [N]}$$

Statement: The average velocity of the balloon is 5.5 m/s [N].

Sample Problem 2: Calculating the Time for a Displacement to Occur

A subway train travels at an average velocity of 22.3 km/h [W]. How long will it take for the subway train to undergo a displacement of 241 m [W]?

Given: $\vec{v}_{av} = 22.3 \text{ km/h } [\text{W}]; \Delta\vec{d} = 241 \text{ m } [\text{W}]$

Required: Δt

Analysis: $\vec{v}_{av} = \dfrac{\Delta\vec{d}}{\Delta t}$

Since we are given the average velocity and the displacement of the subway train, we can rearrange the average velocity equation to solve for the change in time.

Solution: Before we solve this problem, we must first make sure that all of the given values are converted to SI metric units. This will require us to convert 22.3 km/h to metres per second. We will do this by multiplying 22.3 km/h by a series of ratios equal to 1. We will use these ratios so that the units that we do not want (kilometres and hours) will cancel, and we will be left with the units we do want (metres and seconds).

$$\vec{v}_{av} = \left(22.3 \frac{\cancel{\text{km}}}{\cancel{\text{h}}} [\text{W}]\right)\left(\frac{1 \cancel{\text{h}}}{60 \cancel{\text{min}}}\right)\left(\frac{1 \cancel{\text{min}}}{60 \text{ s}}\right)\left(\frac{1000 \text{ m}}{1 \cancel{\text{km}}}\right)$$

$$= \left(\frac{22.3 [\text{W}] \times 1000 \text{ m}}{60 \times 60 \text{ s}}\right)$$

$$\vec{v}_{av} = 6.1944 \text{ m/s } [\text{W}] \text{ (two extra digits carried)}$$

Now that we have converted units, we can use the average velocity equation to determine the change in time.

$$\vec{v}_{av} = \frac{\Delta\vec{d}}{\Delta t}$$

$$\Delta t = \frac{\Delta\vec{d}}{\vec{v}_{av}}$$

$$= \frac{241 \text{ m } [\text{W}]}{6.1944 \text{ m/s } [\text{W}]}$$

$$\Delta t = 38.9 \text{ s}$$

Statement: It takes the subway train 38.9 s to be displaced 241 m [W] from its starting point.

Practice

1. What is the average velocity of a soccer ball that is kicked and travels 2.17 m [E] in 1.36 s? T/I [ans: 1.60 m/s [E]]
2. How long will it take a cat to run 8.2 m [N] at an average velocity of 3.7 m/s [N]? T/I [ans: 2.2 s]

Motion with Uniform and Non-uniform Velocity

motion with uniform or constant velocity motion of an object at a constant speed in a straight line

motion with non-uniform velocity (accelerated motion) motion in which the object's speed changes or the object does not travel in a straight line

Motion with uniform or constant velocity is motion at a constant speed in a straight line. It is the simplest type of motion that an object can undergo, except for being at rest. Note that both requirements (constant speed and straight line) must be met for an object's velocity to be uniform. In contrast, **motion with non-uniform velocity** is motion that is not at a constant speed or not in a straight line. Motion with non-uniform velocity may also be called **accelerated motion**. **Table 1** shows some examples of motion with uniform velocity. You will learn more about accelerated motion in Section 1.3.

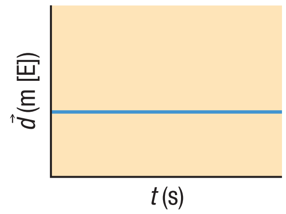
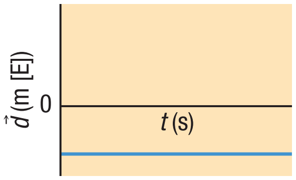
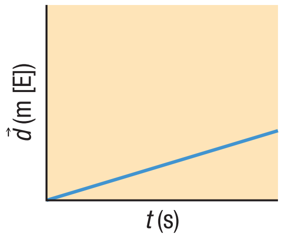
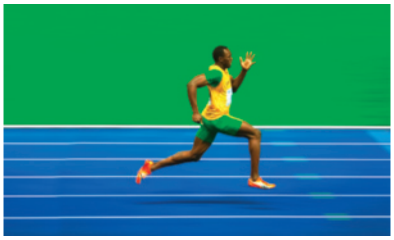
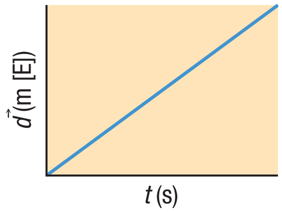
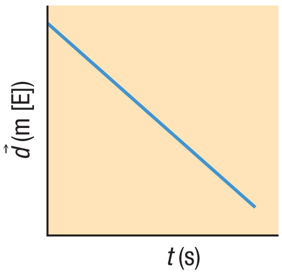
Table 1 Examples of Uniform and Non-uniform Velocity

Example	Uniform velocity	Non-uniform velocity	Explanation
A car travels down a straight highway at a steady 100 km/h.	✓		The car is travelling at a constant speed in a straight line.
A passenger on an amusement park ride travels in a circle at a constant speed of 1.2 m/s.		✓	The passenger is travelling at a constant speed but not in a straight line. She is travelling in a circle.
A parachutist jumps out of an aircraft.	✓ (after parachute opens)	✓ (before parachute opens)	Before he opens the parachute, the speed of the parachutist will increase due to gravity. Once the parachute is opened, his speed will become constant due to air resistance. He will then fall at a constant speed in the same direction (downwards).

Determining Types of Motion from Position–Time Graphs

Recall that the slope of a position–time graph gives the velocity of an object. A position–time graph that describes constant velocity must be a straight line because motion with constant velocity is motion at a constant speed. Therefore, the slope of the position–time graph must also be constant. **Table 2** shows five position–time graphs that represent commonly occurring types of motion. You will see these types of motion frequently in investigations. By the end of this unit, you should be able to identify the type of motion from the characteristics of its position–time graph.

Table 2 Interpreting Position–Time Graphs

Position–time graph	Type of motion	Example
Graph A 	• graph is a horizontal straight line • the slope of a horizontal straight line is zero • the object has a velocity of zero • the object is ***at rest*** • the object is at a constant positive position relative to the reference position • the object is stationary at a location to the east of the reference position	
Graph B 	• graph is a horizontal straight line • the slope of a horizontal straight line is zero • the object has a velocity of zero • the object is ***at rest*** • the object is at a constant negative position relative to the reference position • the object is stationary at a location to the west of the reference position	
Graph C 	• graph is a straight line with positive slope • straight lines with non-zero slopes always represent ***constant*** **(non-zero)** ***velocity*** • from the *y*-axis, we know the object is moving eastward • the object's velocity can be determined from the slope of the graph (rise divided by run)	
Graph D 	• graph is a straight line with positive slope, which represents ***constant*** **(positive)** ***velocity*** • from the *y*-axis, we know the object is moving eastward • the object's velocity can be determined from the slope of the graph • since graph D has the steeper slope, we can conclude that this object has a greater velocity than the object described by graph C	
Graph E 	• graph is a straight line, which represents ***constant velocity*** • the slope of the graph is negative • the object's velocity can be determined from the slope of the graph • note that the direction for position on the *y*-axis is given by a vector with direction [E] • the negative slope indicates that the object is moving westward	

Mini Investigation

Bodies in Motion

Skills: Performing, Observing, Analyzing

SKILLS HANDBOOK A6.2

Motion sensors are devices that send out ultrasonic wave pulses. When some of these waves reflect off an object, the waves return to the motion sensor. A computer can then analyze the data from the returning waves and generate real-time position–time graphs. Using motion sensors can help you understand position–time graphs.

Equipment and Materials: motion sensor; computer or computer interface; graph paper; pencil

1. Connect the motion sensor to a computer or computer interface.
2. Place the motion sensor on a lab bench. Make sure that you have about 4 m of free space in front of the motion sensor.
3. You will be using your body to generate position–time data with the motion sensor. Before you begin, sketch position–time graphs to show the overall shape and features of the graphs that you predict the motion sensor will generate for each of the following scenarios:
   - slow constant speed
   - speeding up
   - fast constant speed
   - slowing down
4. Using the motion sensor, generate real-time position–time graphs for each scenario in Step 3 using body motions.

A. Compare your predictions with the results. Explain any differences. T/I C

B. If there is time, use the motion sensor to generate graphs that resemble as many letters of the alphabet as you can. T/I C

1.2 Summary

- Average speed is equal to the total distance travelled divided by the time taken for the motion.
- A position–time graph describes motion graphically. The slope of the position–time graph gives the velocity of an object.
- Average velocity is equal to the total displacement divided by the time taken for the motion. In other words, velocity describes change in position over time.
- Motion with uniform or constant velocity is motion at a constant speed in a straight line.
- Objects that are undergoing constant velocity have a position–time graph that is a straight line.

1.2 Questions

1. When you are solving a problem, how do you know if you are given a speed value or a velocity value? K/U
2. Define motion with uniform velocity in your own words. K/U C
3. Give two real-life examples each of motion with uniform velocity and motion with non-uniform velocity. A
4. Determine the velocity for the motion described by the graph in **Figure 4**. T/I

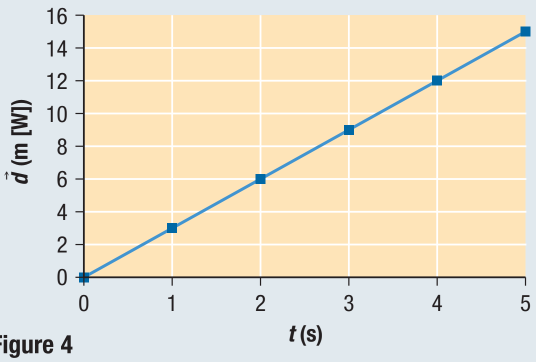


Figure 4

5. Copy and complete **Table 3** in your notebook. T/I

Table 3

$\vec{v}_{av}$	$\Delta\vec{d}$	Δt
	12.6 m [S]	16.3 s
2.0×10^3 m/s [E]	25 m [E]	
40 m/s [N]		0.25 s

6. What is the displacement of a horse that runs at a velocity of 3.2 m/s [S] for 12 s? T/I
7. How many seconds would it take a car travelling at 100.0 km/h to travel a distance of 16 m? T/I
8. What is the velocity (in metres per second) of a Canadian Forces CF-18 fighter jet that travels 8.864 km [S] in 0.297 min? T/I