1 Introduction

A moving vehicle such as a bicycle, car or plane is subject to air resistance. The air exerts an opposing friction force. The greater this air friction, the greater the vehicle’s fuel consumption is. Or, in the case of cycling, the more effort you must make to stay in motion.

Air friction
While in motion at a constant speed, the resultant force on a vehicle is zero, as indicated in Figure 1. When we do not consider the other sources of friction (such as the friction between the wheels and road surface), the forward force on the vehicle equals the backward air friction. The greater the air friction, the greater the force needed to keep the vehicle moving at a constant speed. As the forward force becomes greater, so must the work done by the motor or your own body for covering a certain distance, resulting in a larger energy consumption. It is therefore important to reduce the air resistance on a vehicle as much as possible.

1 Reducing air resistance
In practice there are several ways of reducing air friction on a moving vehicle. Figure 2 shows some examples.

a What ways of reducing air friction are shown in Figure 2? Can you think of some other ways?

b What hypotheses can you make concerning the factors that influence the amount of air friction on a moving vehicle?

Figure 1 < At a constant speed the resultant force on a vehicle is zero: the forward force \( F_v \) equals the backward air friction force \( F_{w,l} \), provided the other backward frictional forces are small enough to be neglected.

Figure 2 – Examples of situations where the air friction force on a moving vehicle is made as small as possible.

To test these hypotheses is difficult in realistic traffic situations, not to mention measuring the forces on a moving vehicle. Checking the hypotheses is more easily done by measuring the air friction when the air is moving and the vehicle is stationary as in a wind tunnel. To carry out measurements on realistic vehicles, a wind tunnel needs to be large, which can be problematic. However, the research can also be done with model vehicles in a model wind tunnel. The next section describes the available equipment set-up and explains which variables can be adjusted and measured. After that you will be able to formulate the research questions, draw up a work plan, explore the measuring methods and conduct the investigation. Finally you will use the results to determine the air friction coefficient, and you will be able to check whether this
2  Equipment set-up

**Wind tunnel**
The wind tunnel is shown in Figure 3. It consists of a tunnel with a fan and a measuring platform. The fan is connected to a variable voltage source for regulating the number of fan revolutions, and thus the air speed in the tunnel. This air speed $v$ can be measured with an anemometer (air speed meter) at the end of the tunnel.

![Model wind tunnel for measuring the air friction force on a vehicle.](image)

The measuring platform can be fitted with a model vehicle. The platform floats on an air track to minimise the influence of other sources of friction. The air friction $F_{w,l}$ on the vehicle is measured by a force metre outside the tunnel.

**Frontal surface area**
The air friction on a vehicle depends, among others, on the *frontal surface area* of that vehicle: the cross-sectional area perpendicular to the direction of motion. A method for measuring the frontal surface area $A$ using a projection method is shown in Figure 4.

![The projection method for measuring the frontal surface area of a vehicle.](image)

The light source provides an almost parallel light beam. The vehicle’s shadow is visible on the screen with a millimetre-grid. After drawing the shadow’s shape on the screen, the frontal surface area can be determined by counting the number of mm$^2$ or cm$^2$.

3  Research questions and work plan

In the introduction you have formulated a number of hypotheses about the factors influencing the air friction on a moving vehicle. From the description of the equipment set-up you can devise a plan to test these hypotheses.

2  Research questions

Formulate the research questions for the investigation with the wind tunnel. Draw up a hypothesis for each research question.

3  Work plan

Draw up a work plan for the investigation with the wind tunnel. For each research question
Experiment 1-1: Air resistance

indicate which variables you are going to adjust and measure, and how this will enable you to test the hypothesis.

4 Model vehicles
Find out which model vehicles are available. Look for or make, if necessary, the required model vehicles (scale approximately 1:25).

4 Measuring method

Before doing the research following your work plan in Task 7, an understanding of the equipment set-up is necessary. In Task 5 you will do some preliminary measurements to get an idea whether a measurement of air friction is sufficiently reproducible. In Task 6 you will measure the frontal surface area of the model vehicles you are going to use in the investigation.

5 Air friction
An important characteristic of the equipment set-up is that the influence of friction other than air friction is as small as possible. However, these unwanted sources of friction can never be completely reduced to zero, and can cause variations in the measured air friction. In other words, the measurements may not be sufficiently reproducible. In this task, you check whether such variations occur, how big they are, and how they can be reduced.

- Measurement – Put a model vehicle on the measuring platform. Fix the variable voltage source at a particular setting. Measure the air speed \( v \) in the wind tunnel and the air friction \( F_{w,l} \) on the model vehicle. Switch off the fan, and let the equipment set-up ‘come to rest’. Repeat these measurements a number of times. What can you conclude? Are the measurements sufficiently reproducible?

- Measuring method – Think about how a measurement of ‘the’ air speed \( v \) and ‘the’ air friction \( F_{w,l} \) can be best carried out. How large (approximately) would the measurement error be in both measurements?

6 Frontal surface area
By using the projection method, determine, as accurately as possible, the frontal surface area \( A \) of the model vehicles you are going to use in your investigation.

5 Investigation

7 Research questions
Search for answers to your research questions with the help of the equipment set-up and according to your work plan, and check your hypotheses. Whenever possible, present your results in the form of a diagram.

6 Theory: flow mechanics

The research results can be checked by using the theory of flow mechanics. This theory describes, among others, how air friction on a moving vehicle depends on factors such as stream line, frontal surface area and vehicle speed.

8 Air friction force
According to the theory, air friction \( F_{w,l} \) on a moving vehicle is given by: \( F_{w,l} = \frac{1}{2} c_w A \rho v^2 \).
In this formula, \( F_{w,l} \) is the air friction force on the vehicle, \( \rho \) is the air density, \( A \) is the
frontal surface area, and \( v \) is the vehicle speed. The constant of proportionality \( c_w \) is called the air friction coefficient. This air friction coefficient represents the influence of the vehicle’s stream line: the better the stream line, the smaller the \( c_w \)-value.

a Check, if possible, whether the research results reflect this theory of flow mechanics.
b Indicate, if possible, the significance of the research results for realistic traffic situations.
So, answer questions such as ‘by what percentage does fuel consumption of a vehicle decrease if...’, or ‘by what percentage does the speed of a vehicle increase at constant power if...’, or a comparable question related to the research done.

9 Air friction coefficient
From the research results the air friction coefficient (or \( c_w \)-value) of one or more model vehicles can be determined. In practice, comparable measurements have been done on ‘real’ vehicles. A comparison might show the extent to which research on model vehicles in the wind tunnel relates to reality.

a Determine the air friction coefficient of the model vehicles used in the research.
b Search the literature for data about the air friction coefficient of comparable vehicles. Compare these data with the \( c_w \)-values found in your investigation. Do the research results for model vehicles in the wind tunnel also apply to real situations?

7 Report
Report about this investigation in the form of a written report or an oral presentation. Make sure that this report or presentation addresses the following: the research questions, the equipment set-up, the research results including answers to the research questions, the (additional) determination of the air friction coefficient, and the relevance of this kind of model research to practice.
Submit your report to your teacher together with the lab journal which you kept while preparing and conducting the investigation. For presentations, simply hand in the lab journal.