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Road vehicles — Road load —

Part 1:
Determination under reference atmospheric conditions

Véhicules routiers — Résistance sur route —

Partie 1: Détermination dans les conditions atmosphériques de référence

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 10521-1 was prepared by Technical Committee ISO/TC 22, *Road vehicles*, Subcommittee SC 5, *Engine tests*.

This first edition, together with ISO 10521-2, cancels and replaces ISO 10521:1992, which has been technically revised.

ISO 10521 consists of the following parts, under the general title *Road vehicles — Road load*:

— *Part 1: Determination under reference atmospheric conditions*

— *Part 2: Reproduction on chassis dynamometer*

Introduction

It is known that wind gives much influence to vehicle road-load measurement on test roads. Therefore, no international standards or national standards/regulations allowed conducting on-road tests under windy (e.g. 3 m/s or more) conditions in terms of measurement accuracy. In this standard, wind effect correction methodology is newly introduced into the conventional coastdown method and torquemeter method, and it offers wider (up to wind speed of 10 m/s) opportunity of on-road tests. In addition, more realistic road load can be simulated even under lower wind conditions.

This part of ISO 10521 also adopts the off-road road-load measurement method as the comparable alternative. The method is based on the separation of the total road load into two components, aerodynamic drag and rolling resistance, where the former is measured in a wind tunnel and the latter with a chassis dynamometer. This alternative enables the standard users to carry out road-load measurement regardless of atmospheric conditions or other requirements necessary for the on-road test. It is not the scope of this standard to define all requirements of wind-tunnel design or test practice. Nevertheless, the standard users are encouraged to conduct the measurement with state-of-the-art wind-tunnel technologies and to respect the highest quality management standards such as ISO 17025, so as to secure the measurement reliability and repeatability.

In view of accessibility of the standard, International Standard ISO 10521 is divided into two parts in this second edition in order to provide two separate standards for the two different technical aspects, determination of road load and reproduction of road load on chassis dynamometer.

Road vehicles — Road load —

Part 1: Determination under reference atmospheric conditions

1 Scope

This part of ISO 10521 specifies methods of determining the road load of road vehicles for subsequent test purposes, for example, fuel consumption tests or exhaust emission measurements. This determines the road load of a vehicle running on a level road under reference atmospheric conditions. It is achieved by either the coastdown method, the torquemeter method or the wind-tunnel/chassis-dynamometer method.

This part of ISO 10521 is applicable to motor vehicles, as defined in ISO 3833, up to a gross vehicle mass of 3 500 kg.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 3833, *Road vehicles — Types — Terms and definitions*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 3833 and the following apply.

3.1
total resistance
total force-resisting movement of a vehicle, measured either by the coastdown method or by the wind-tunnel/chassis-dynamometer method, including the friction forces in the drive-train

3.2
running resistance
torque-resisting movement of a vehicle, measured by the torquemeter installed in the drive-train of a vehicle, including the friction torque in the drive-train downstream of the torquemeter

3.3
road load
general meaning of the force or torque which opposes the movement of a vehicle, including total resistance and/or running resistance

3.4
aerodynamic drag
resistance of the air to the motion of a vehicle

3.5
rolling resistance
opposing force in the drive-train, axles and tyres to the motion of a vehicle

3.6
reference speed
a vehicle speed at which a chassis-dynamometer load is verified

3.7
reference atmospheric conditions
atmospheric conditions of the following values, to which the road-load measurement results are corrected:

a) atmospheric pressure: p_0 = 100 kPa, unless otherwise specified by regulations;

b) atmospheric temperature: t_0 = 293 K, unless otherwise specified by regulations;

c) dry air density: ρ_0 = 1,189 kg/m^3, unless otherwise specified by regulations;

d) wind speed: 0 m/s.

3.8
stationary anemometry
measurement of wind speed and direction with an anemometer at a location and height above road level alongside the test road where the most representative wind conditions will be experienced

3.9
onboard anemometry
measurement of wind speed and direction with an anemometer appropriately installed to the test vehicle

3.10
wind correction
correction of the effect of wind on road load, which is achieved either by stationary or by onboard anemometry

3.11
aerodynamic stagnation point
point on the surface of a vehicle where the wind velocity is equal to zero

4 Required overall measurement accuracy

The required overall measurement accuracy shall be as follows:

a) vehicle speed: ± 0,5 km/h or ± 1 %, whichever is greater;

b) time: ± 50 ms or ± 0,1 %, whichever is greater;

c) wheel torque: ± 3 N·m or ± 0,5 %, whichever is greater;

d) wind speed: ± 0,3 m/s;

e) wind direction: ± 3°;

f) atmospheric temperature: ± 1 K;

g) atmospheric pressure: ± 0,3 kPa;

h) vehicle mass: ± 10 kg;

i) tyre pressure: ± 5 kPa;

j) product of aerodynamic coefficient and frontal projected area (SCd): ± 2 %;

k) chassis-dynamometer roller speed: ± 0,5 km/h or ± 1 %, whichever is greater;

l) chassis-dynamometer force:

Category 1 chassis dynamometer: ± 6 N, or

Category 2 chassis dynamometer: ± 10 N or ± 0,1 % of full scale, whichever is greater.

NOTE The Category 2 chassis dynamometer usually has a greater load capacity, e.g. 130 kW or more.

5 Road-load measurement on road

5.1 Requirements for road test

5.1.1 Atmospheric conditions for road test

5.1.1.1 Wind

The average wind speed over the test road shall not exceed 10 m/s, nor wind gusts exceed 14 m/s. Relevant wind correction shall be conducted according to the applicable type of anemometry specified in Table 1. In order to decide the applicability of each anemometry type, the average wind speed shall be determined by continuous wind speed measurement, using a recognized meteorological instrument, at a location and height above the road level alongside the test road where the most representative wind conditions will be experienced.

NOTE Wind correction may be waived when the average wind speed is 3 m/s or less.

Table 1 — Applicable anemometry depending on average wind speed and cross-wind component

Wind speed in metres per second (m/s)

Type of anemometry	**Average wind speed**		
	Absolute wind speed $v \le 5$		Absolute wind speed $5 < v \le 10$
	Cross-wind component (v_c) $v_c \le 3$	Cross-wind component (v_c) $3 < v_c \le 5$	
Stationary anemometry	Applicable	Not applicable	Not applicable
Onboard anemometry	Applicable	Applicable	Applicable
NOTE The stationary anemometry is recommended when the absolute wind speed is less than 1 m/s.			

5.1.1.2 Atmospheric temperature

The atmospheric temperature shall be within the range of 274 to 308 K, inclusive.

5.1.2 Test road

The road surface shall be flat, dry and hard, and its texture and composition shall be representative of current urban and highway road surfaces. The test-road longitudinal slope shall not exceed ± 1 %. The local inclination between any points 3 m apart shall not deviate more than ± 0,5 % from this longitudinal slope. The maximum cross-sectional camber of the test road shall be 1,5 %.

5.2 Preparation for road test

5.2.1 Vehicle preparation

5.2.1.1 Vehicle condition

The test vehicle shall be suitably run-in for the purpose of the subsequent test. The tyres shall be suitably broken-in for the purpose of the subsequent test, while still having a tread depth of not less than 50 % of the initial tread depth.

Unless any particular purpose is intended, the vehicle shall be in normal vehicle conditions, as specified by the manufacturer. That is, tyre pressure (see 5.2.1.2), wheel alignment, vehicle height, lubricants in the drive-train and wheel-bearings, and brake adjustment to avoid unrepresentative parasitic drag.

During the road test, the engine bonnet/hood and all windows shall be closed so that they will not influence the road-load measurement. Any covers of the air ventilation system, headlamps, etc., shall be closed, and the air-conditioning switched off.

The vehicle mass shall be adjusted to meet the requirement of the intended subsequent test, including the mass of the driver and instruments.

5.2.1.2 Tyre-pressure adjustment

If the difference between the ambient and soak temperature is more than 5 K, the tyre pressure shall be adjusted as follows.

Soak the tyres for more than 4 h at 10 % above the target pressure. Just before testing, reduce the pressure down to the manufacturer's recommended inflation pressure, adjusted for difference between the soaking-environment temperature and the ambient test temperature at a rate of 0,8 kPa per 1 K using the following formula:

$$\Delta P_t = 0{,}8 \times \left(T_{\text{soak}} - T_{\text{amb}}\right)$$

where

ΔP_t is the tyre pressure adjustment, in kilopascals (kPa);

0,8 is the pressure adjustment factor, in kilopascals per kelvin (kPa/K);

T_{soak} is the tyre-soaking temperature, in kelvins (K);

T_{amb} is the test ambient temperature, in kelvins (K).

5.2.2 Installation of instruments

Any instruments, especially for those installed outside the vehicle, shall be installed on the vehicle in such a manner as to minimize effects on the operating characteristics of the vehicle.

5.2.3 Vehicle preconditioning

Prior to the test, the vehicle shall be preconditioned appropriately, until stabilized and normal vehicle operating temperatures have been reached. It is recommended that the vehicle should be driven at the most appropriate reference speed for a period of 30 min. During this preconditioning period, the vehicle speed shall not exceed the highest reference speed.

5.3 Measurement of total resistance by coastdown method

The total resistance shall be determined by either the multi-segment method (5.3.1), the average deceleration method (5.3.2) or the direct regression method (5.3.3).

5.3.1 Multi-segment method

5.3.1.1 Selection of speed points for road-load curve determination

In order to obtain a road-load curve as a function of vehicle speed, a minimum of four speed points, V_j (j = 1, 2, etc.) shall be selected. The highest speed point shall not be lower than the highest reference speed, and the lowest speed point shall not be higher than the lowest reference speed. The interval between each speed point shall not be greater than 20 km/h.

5.3.1.2 Data collection

During the test, a) and b) shall be measured and recorded at a maximum of 0,2 s intervals, and c) and d) at a maximum of 1,0 s intervals.

a) elapsed time;

b) vehicle speed;

c) wind speed;

d) wind direction.

NOTE The wind speed and the wind direction are measured by the stationary anemometry.

5.3.1.3 Vehicle coastdown

5.3.1.3.1 Following preconditioning, and immediately prior to each test measurement, drive the vehicle at the highest reference speed for, at most, 1 min, if necessary. Then accelerate the vehicle to 5 km/h more than the speed at which the coastdown time measurement begins ($V_j + \Delta V$) and begin the coastdown immediately.

5.3.1.3.2 During coastdown, the transmission shall be in neutral, and the engine shall run at idle. In the case of vehicles with manual transmission, the clutch shall be engaged. Movement of steering-wheel shall be avoided as much as possible, and the vehicle brakes shall not be operated until the end of the coastdown.

5.3.1.3.3 Repeat the test, taking care to begin the coastdown at the same speed and preconditions.

5.3.1.3.4 Although it is recommended that each coastdown run be performed without interruption, split runs are permitted if data cannot be collected in a continuous fashion for the entire speed range. For split runs, care shall be taken so that the vehicle condition be constant as much as possible at each split point.

5.3.1.4 Determination of total resistance by coastdown time measurement

5.3.1.4.1 Measure the coastdown time corresponding to the speed V_j as the elapsed time from the vehicle speed ($V_j + \Delta V$) to ($V_j - \Delta V$). It is recommended that ΔV be 10 km/h when the vehicle speed is more than 60 km/h, and 5 km/h when the vehicle speed is 60 km/h or less.

5.3.1.4.2 Carry out these measurements in both directions until a minimum of three consecutive pairs of figures have been obtained which satisfy the statistical accuracy p, in percent, defined below.

$$p = \frac{ts}{\sqrt{n}} \times \frac{100}{\Delta T_j} \leq 3\ \%$$

where

n is the number of pairs of measurements;

ΔT_j is the mean coastdown time at speed V_j, in seconds (s), given by the formula:

$$\Delta T_j = \frac{1}{n}\sum_{i=1}^{n} \Delta T_{ji}$$

in which

ΔT_{ji} is the harmonized average coastdown time of the ith pair of measurements at speed V_j, in seconds (s) given by the formula:

$$\Delta T_{ji} = \frac{2}{\left(1/\Delta T_{jai}\right) + \left(1/\Delta T_{jbi}\right)}$$

and in which

ΔT_{jai} and ΔT_{jbi} are the coastdown times of the i^{th} measurement at speed V_j in each direction, respectively, in seconds (s);

s is the standard deviation, in seconds (s), defined by the formula:

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\Delta T_{ji} - \Delta T_j\right)^2}$$

t is the coefficient given in Table 2.

Table 2

n	t	$\frac{t}{\sqrt{n}}$
3	4,3	2,48
4	3,2	1,60
5	2,8	1,25
6	2,6	1,06
7	2,5	0,94
8	2,4	0,85
9	2,3	0,77
10	2,3	0,73
11	2,2	0,66
12	2,2	0,64
13	2,2	0,61
14	2,2	0,59
15	2,2	0,57

5.3.1.4.3 If, during a measurement in one direction, the driver is forced to change the vehicle direction sharply, this measurement and the paired measurement in the opposite direction shall be rejected.

5.3.1.4.4 The total resistances, $F_{j\text{a}}$ and $F_{j\text{b}}$ at speed V_j in each direction, in newtons, are determined by the formulae:

$$F_{j\text{a}} = -\frac{1}{3{,}6} \times (m + m_\text{r}) \times \frac{2 \times \Delta V}{\Delta T_{j\text{a}}}$$

$$F_{j\text{b}} = -\frac{1}{3{,}6} \times (m + m_\text{r}) \times \frac{2 \times \Delta V}{\Delta T_{j\text{b}}}$$

where

m is the test vehicle mass including the driver and instruments, in kilograms (kg);

m_r is the equivalent effective mass of all the wheels and vehicle components rotating with the wheels during coastdown on the road, in kilograms (kg); m_r should be measured or calculated by an appropriate technique. As an alternative, m_r may be estimated as 3 % of the unladen vehicle mass;

$\Delta T_{j\text{a}}$ and $\Delta T_{j\text{b}}$ are the mean coastdown times in each direction, respectively, corresponding to speed V_j, in seconds (s), given by the formulae:

$$\Delta T_{j\text{a}} = \frac{1}{n} \sum_{i=1}^{n} \Delta T_{j\text{a}i}$$

$$\Delta T_{j\text{b}} = \frac{1}{n} \sum_{i=1}^{n} \Delta T_{j\text{b}i}$$

5.3.1.4.5 The total-resistance curve shall be determined as follows. Fit the following regression curve to the data sets (V_j, $F_{j\text{a}}$) and (V_j, $F_{j\text{b}}$) corresponding to all the speed points V_j (j = 1, 2, etc.) and direction (a, b) to determine f_0, f_1 and f_2:

$$F_\text{a} = f_{0\text{a}} + f_{1\text{a}}V + f_{2\text{a}}V^2$$

$$F_\text{b} = f_{0\text{b}} + f_{1\text{b}}V + f_{2\text{b}}V^2$$

where

F_a and F_b are the total resistances in each direction, in newtons (N);

$f_{0\text{a}}$ and $f_{0\text{b}}$ are the constant terms in each direction, in newtons (N);

$f_{1\text{a}}$ and $f_{1\text{b}}$ are the coefficients of the first-order term of the vehicle speed in each direction, in newtons hour per kilometre (N·h/km); f_1 may be assumed to be zero, if the value of f_1V is no greater than 3 % of F at the reference speed(s); in this case, the coefficients f_0 and f_2 shall be recalculated;

$f_{2\text{a}}$ and $f_{2\text{b}}$ are the coefficients of the second-order term of the vehicle speed in each direction, in newtons hour squared per kilometre squared [(N·(h/km)^2];

V is the vehicle speed, in kilometres per hour (km/h).

Then calculate the coefficients f_0, f_1 and f_2 in the total-resistance equation using the following formulae:

$$f_0 = \frac{f_{0a} + f_{0b}}{2}$$

$$f_1 = \frac{f_{1a} + f_{1b}}{2}$$

$$f_2 = \frac{f_{2a} + f_{2b}}{2}$$

where f_0, f_1 and f_2 are the average coefficients in the following average total-resistance equation:

$$F_{avg} = f_0 + f_1 V + f_2 V^2$$

and in which F_{avg} is the average total resistance, in newtons (N).

NOTE As a simple alternative to the above calculation, the following formula may be applied to compute the average total resistance, where the harmonized average of the alternate coastdown time is used instead of the average of alternate total resistance.

$$F_j = -\frac{1}{3{,}6} \times (m + m_r) \times \frac{2 \times \Delta V}{\Delta T_j}$$

where ΔT_j is the harmonized average of alternate coastdown time measurements at speed V_j, in seconds (s), given by the formula:

$$\Delta T_j = \frac{2}{\left(1/\Delta T_{ja}\right) + \left(1/\Delta T_{jb}\right)}$$

and in which ΔT_{ja} and ΔT_{jb} are the coastdown time at speed V_j in each direction, respectively, in seconds (s).

Then, calculate the coefficients f_0, f_1 and f_2 in the total-resistance equation with the regression analysis.

5.3.2 Average deceleration method

As an alternative to the determination in 5.3.1, the total resistance may also be determined by the procedures described in 5.3.2.1 to 5.3.2.4.

5.3.2.1 Selection of speed points for road-load curve determination

Speed points shall be selected as specified in 5.3.1.1.

5.3.2.2 Data collection

Data shall be measured and recorded as specified in 5.3.1.2.

5.3.2.3 Vehicle coastdown

Vehicle coastdown shall be conducted as specified in 5.3.1.3.

5.3.2.4 Determination of total resistance by coastdown measurement

5.3.2.4.1 Record the speed-versus-time data during coastdown from vehicle speed ($V_j + \Delta V$) to ($V_j - \Delta V$), where ΔV is more than 10 km/h.

5.3.2.4.2 Fit the following function to the group of data by polynomial regression to determine the coefficients A_0, A_1, A_2 and A_3:

$$V_\mathrm{a}(t) = A_{0\mathrm{a}} + A_{1\mathrm{a}}t + A_{2\mathrm{a}}t^2 + A_{3\mathrm{a}}t^3$$

$$V_\mathrm{b}(t) = A_{0\mathrm{b}} + A_{1\mathrm{b}}t + A_{2\mathrm{b}}t^2 + A_{3\mathrm{b}}t^3$$

where

$V_\mathrm{a}(t)$, $V_\mathrm{b}(t)$	is the vehicle speed, in kilometres per hour (km/h);
t	is the time, in seconds (s);
$A_{0\mathrm{a}}$, $A_{1\mathrm{a}}$, $A_{2\mathrm{a}}$, $A_{3\mathrm{a}}$, $A_{0\mathrm{b}}$, $A_{1\mathrm{b}}$, $A_{2\mathrm{b}}$ and $A_{3\mathrm{b}}$	are the coefficients.

5.3.2.4.3 Determine the deceleration, γ_j, in metres per second squared, at the speed V_j as follows:

$$\gamma_j = \frac{1}{3{,}6} \times \left(A_1 + 2 \times A_2 t_j + 3 \times A_3 t_j{}^2 \right)$$

where t_j is the time at which the vehicle speed given by the function in 5.3.2.4.2 is equal to V_j.

5.3.2.4.4 Repeat the measurements in both directions, until a minimum of four consecutive pairs of the data have been obtained which satisfy the statistical accuracy p, in percent, below. The validity of the data shall be decided in accordance with 5.3.1.4.3.

$$p = \frac{ts}{\sqrt{n}} \times \frac{100}{\Gamma_j} \leq 3\ \%$$

where

n is the number of pairs of measurements;

Γ_j is the mean average deceleration at the speed V_j, in metres per second squared (m/s^2), given by the formula:

$$\Gamma_j = \frac{1}{n} \sum_{i=1}^{n} \Gamma_{ji}$$

in which

$$\Gamma_j = \frac{1}{2} \times \left(\gamma_{j\mathrm{a}i} + \gamma_{j\mathrm{b}i} \right)$$

and in which

$\gamma_{j\mathrm{a}i}$ and $\gamma_{j\mathrm{b}i}$	are the decelerations of the ith measurement at the speed V_j defined in 5.3.2.4.3 for each direction, respectively, in metres per second squared (m/s^2);
s	is the standard deviation, in metres per second squared (m/s^2), defined by the formula:

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\Gamma_{ji} - \Gamma_{j}\right)^2}$$

t is the coefficient given in Table 2.

5.3.2.4.5 Determine the total resistance F_j at the speed V_j by the following formula, using m and m_r as defined in 5.3.1.4.4.

$$F_j = \left(m + m_r\right)\Gamma_j$$

5.3.2.4.6 Total-resistance curve determination

Determine the total-resistance curve as specified in 5.3.1.4.5.

5.3.3 Direct regression method

As an alternative to the determination in 5.3.1.4.5, the total resistance may also be determined by the following mathematical approach.

5.3.3.1 Selection of speed range for road-load curve determination

The test speed range (i.e. the maximum speed and the minimum speed) shall be so determined that it covers the range of the reference speeds, over which total resistance is measured. If the test is carried out in a manner of split runs, each split speed range shall be determined accordingly.

5.3.3.2 Data collection

Data shall be measured and recorded as specified 5.3.1.2.

5.3.3.3 Vehicle coastdown

Vehicle coastdown shall be conducted as specified in 5.3.1.3.

5.3.3.4 Determination of total resistance by coastdown measurement

The coefficients f_0, f_1 and f_2 shall be calculated by approximating the relation between V and t to tangent with Equation (4), of which the mathematical process is as follows.

5.3.3.4.1 Express F using Formulae (1) and (2):

$$F = f_0 + f_1 V + f_2 V^2 \quad (1)$$

$$F = -\frac{1}{3{,}6} \times \left(m + m_r\right) \times \frac{\mathrm{d}V}{\mathrm{d}t} \quad (2)$$

where

F is the total resistance, in newtons (N);

f_0 is the constant term, in newtons (N);

f_1 is the coefficient of the first-order term, in newtons hour per kilometre [N·(h/km)];

f_2 is the coefficient of the second-order term, in newtons hour squared per kilometre squared [N·(h/km)^2];

m is the test vehicle mass including the driver and instruments, in kilograms (kg);

m_r is the equivalent effective mass of all the wheels and vehicle components rotating with the wheels during coastdown on the road, in kilograms (kg); m_r should be measured or calculated by an appropriate technique; as an alternative, m_r may be estimated as 3 % of the unladen vehicle mass;

V is the vehicle speed, in kilometres per hour (km/h).

5.3.3.4.2 Equation (3) is derived from Equations (1) and (2).

$$-\frac{3{,}6 \times \mathrm{d}t}{m + m_r} = \frac{\mathrm{d}V}{f_0 + f_1 V + f_2 V^2} \tag{3}$$

5.3.3.4.3 Yield Equation (4) from Equation (3).

$$V = \frac{\sqrt{4 \times f_0 f_2 - f_1^2}}{2 \times f_2} \tan\left(-\frac{3{,}6 \times \sqrt{4 \times f_0 f_2 - f_1^2}}{2 \times (m + m_r)} \times t - C_0 \right) - \frac{f_1}{2 \times f_2} \tag{4}$$

where

t is the time, in seconds (s);

C_0 is the integration constant.

5.3.3.4.4 Replace Equation (4) with (5).

$$V = A \tan(Bt + C) + D \tag{5}$$

5.3.3.4.5 Calculate A, B, C and D in the approximate Equation (5) by the least-squares method, and then determine the coefficients f_0, f_1 and f_2 by the following formulae:

$$f_0 = -\frac{1}{3{,}6} \times (m + m_r) \times \frac{B}{A} \times (A^2 + D^2)$$

$$f_1 = \frac{1}{3{,}6} \times (m + m_r) \times \frac{2 \times BD}{A}$$

$$f_2 = -\frac{1}{3{,}6} \times (m + m_r) \times \frac{B}{A}$$

NOTE If coastdowns are carried out in the manner of split runs, the total resistance, F, can be calculated as follows. Calculate the road-load force for each reference speed included in the actual coastdown speed range. Then put each split data into one set, and calculate one road-load force equation for respective directions.

5.3.3.4.6 Total-resistance curve determination

Determine the total-resistance curve as specified in 5.3.1.4.5.

5.4 Onboard-anemometer based coastdown method

As an alternative to the determination in 5.3.1, 5.3.2 or 5.3.3, the total resistance may also be determined by the procedure described in 5.4.1 to 5.4.5. This method is applicable to a wind speed range up to 10 m/s on a test road as given in Table 1.

5.4.1 Selection of speed range for road-load curve determination

Select the test speed range as specified in 5.3.3.1.

5.4.2 Data collection

The following data shall be measured and recorded at a maximum of 0,2 s intervals during the test.

a) elapsed time;

b) vehicle speed;

c) wind speed and direction.

NOTE The wind speed and the wind direction are measured by the onboard anemometry.

5.4.3 Vehicle coastdown

Vehicle coastdown shall be conducted as specified in 5.3.1.3.1 to 5.3.1.3.4 with an onboard anemometer installed on the vehicle. The anemometer shall be installed in a position such that the effect on the operating characteristics of the vehicle is minimized. It is recommended to install the anemometer at the aerodynamic stagnation point of the vehicle's front and approximately 2 m in front of it. Before the coastdown, the anemometer shall be installed on the vehicle and calibrated appropriately, as specified by the manufacturer. An example of the anemometer calibration procedure is given in Annex A.

5.4.4 Determination of coefficients

Calculate each coefficient by the following equation with multi-regression analysis, using coastdown time and wind data.

$$-\frac{1}{3{,}6}\times\left(m+m_{\text{r}}\right)\times\frac{\mathrm{d}V}{\mathrm{d}t}=a_{\text{mech}}+b_{\text{mech}}V+c_{\text{mech}}V^{2}+\frac{1}{2}\times\rho S V_{r}^{2}\times\left(a_{0}+a_{1}\theta+a_{2}\theta^{2}+a_{3}\theta^{3}+a_{4}\theta^{4}\right)$$

where

m	is the test vehicle mass including driver and instruments, in kilograms (kg);
m_{r}	is the equivalent effective mass of all the wheels and vehicle components rotating with the wheels during coastdown on the road, in kilograms (kg); m_{r} should be measured or calculated by an appropriate technique; as an alternative, m_{r} may be estimated as 3 % of the unladen vehicle mass;
$\mathrm{d}V/\mathrm{d}t$	is the acceleration, in kilometres per hour per second [(km/h)/s];
a_{mech}	is the coefficient of mechanical drag, in newtons (N);
b_{mech}	is the coefficient of mechanical drag, in newtons per kilometre per hour [N/(km/h)];
c_{mech}	is the coefficient of mechanical drag, in newtons per kilometre squared per hour squared [N/(km/h)^2];
V	is the vehicle speed, in kilometres per hour (km/h);
V_{r}	is the relative wind speed, in kilometres per hour (km/h);
ρ	is the air density, in kilograms per cubic metre (kg/m^3);

S is the projected frontal area of the vehicle, in square metres (m^2);

a_n (n = 0 to 4) is the coefficient for aerodynamic drag as a function of yaw angle, in degrees^{-n};

θ is the yaw-angle apparent wind relative to the direction of vehicle travel, in degrees.

NOTE If the wind speed is close to 0, the equation theoretically cannot separate c_{mech} and $(1/2) \times a_0 \ \rho \ S$ appropriately. Therefore, a contrained analysis, where a_0 is fixed if it is previously determined, for example in a wind tunnel, or c_{mech} is assumed to be zero, may be employed.

5.4.5 Determination of total resistance

Calculate the total resistance, F, where all the wind effects are eliminated, by the following equation with the coefficients obtained in 5.4.4.

$$F = a_{mech} + b_{mech} V + \left(c_{mech} + \frac{1}{2} \times a_0 \rho S \right) V^2$$

5.5 Measurement of running resistance by torquemeter method

As an alternative to the coastdown methods, the torquemeter method may also be used, in which the running resistance is determined by measuring the torque as described in 5.5.1 to 5.5.3.

5.5.1 Installation of torquemeter

The torquemeter(s) shall be installed on the drive-train of the test vehicle. It is preferable to have wheel torquemeters on each driven wheel.

5.5.2 Vehicle running and data sampling

5.5.2.1 Start of data collection

The data collection may be started following preconditioning and stabilization of the vehicle at the speed V_j, where the running resistance is to be measured.

5.5.2.2 Data collection

Record at least 10 data sets of speed, torque and time over a period of at least 5 s.

5.5.2.3 Speed deviation

The speed deviation from the mean speed shall be within the values in Table 3.

Table 3

Time period s	Speed deviation km/h
5	± 0,2
10	± 0,4
15	± 0,6
20	± 0,8
25	± 1,0
30	± 1,2

5.5.3 Calculation of mean speed and mean torque

5.5.3.1 Calculation process

Calculate the mean speed $V_{j\mathrm{m}}$, in kilometres per hour (km/h), and mean torque $C_{j\mathrm{m}}$ in newton metres (N·m), over a time period, as follows:

$$V_{j\mathrm{m}} = \frac{1}{k}\sum_{i=1}^{k} V_{ji}$$

and

$$C_{j\mathrm{m}} = \frac{1}{k}\sum_{i=1}^{k} C_{ji} - C_{j\mathrm{s}}$$

where

V_{ji} is the vehicle speed of the i^{th} data set, in kilometres per hour (km/h);

k is the number of data sets;

and

C_{ji} is the torque of the i^{th} data set, in newton metres (N·m);

$C_{j\mathrm{s}}$ is the compensation term for the speed drift, in newton metres (N·m), which is given by the following formula; $C_{j\mathrm{s}}$ shall be not greater than 5 % of the mean torque before compensation, and may be neglected if α_j is no greater than ± 0,005 m/s^2:

$$C_{j\mathrm{s}} = (m + m_{\mathrm{r}}) \times \alpha_j r_j$$

in which

m and m_r are the test vehicle mass and the equivalent effective mass, respectively, both in kilograms (kg), defined in 5.3.1.4.4;

r_j is the dynamic radius of the tyre, in metres (m), given by the formula:

$$r_j = \frac{1}{3{,}6} \times \frac{V_{j\mathrm{m}}}{2 \times \pi N}$$

and in which

N is the rotational frequency of the driven tyre, in revolutions per second (s^{-1});

α_j is the mean acceleration, in metres per second squared (m/s^2), which shall be calculated by the formula:

$$\alpha_j = \frac{1}{3{,}6} \times \frac{k\sum_{i=1}^{k} t_i V_{ji} - \sum_{i=1}^{k} t_i \sum_{i=1}^{k} V_{ji}}{k\sum_{i=1}^{k} t_i^{\,2} - \left(\sum_{i=1}^{k} t_i\right)^2}$$

and in which t_i is the time at which the i^{th} data set was sampled, in seconds (s).

5.5.3.2 Accuracy of measurement

Carry out these measurements in both directions until a minimum of four consecutive figures have been obtained which satisfy accuracy p, in percent (%), below. Calculate the mean speed V_{jm}, in kilometres per hour (km/h), and mean torque C_{jm} in newton metres, over a time period as follows. The validity of the data shall be decided in accordance with 5.3.1.4.3.

$$p = \frac{ts}{\sqrt{k}} \times \frac{100}{\overline{C}_j} \leq 3\ \%$$

where

k is the number of data sets;

$\overline{C}_j$ is the running resistance at the speed V_j, in newton metres (N·m), given by the formula:

$$\overline{C}_j = \frac{1}{k}\sum_{i=1}^{k} C_{jmi}$$

in which C_{jmi} is the average torque of the i^{th} pair of data sets at the speed V_j, in newton metres (N·m), given by the formula:

$$C_{jmi} = \frac{1}{2} \times \left(C_{jmai} + C_{jmbi}\right)$$

and in which

C_{jmai} and C_{jmbi} are the mean torques of the i^{th} data sets at the speed V_j determined in 5.5.3.1 for each direction respectively, in newton metres (N·m);

s is the standard deviation, in newton metres (N·m), defined by the formula:

$$s = \sqrt{\frac{1}{k-1}\sum_{i=1}^{k}\left(C_{jmi} - \overline{C}_j\right)^2}$$

t is the coefficient given by replacing n in Table 2 with k.

5.5.3.3 Validity of the measured average speed

The average speed V_{jmi}, shall not deviate by more than ± 2 km/h from its mean, $\overline{V}_j$, V_{jmi} and $\overline{V}_j$ shall be calculated as follows:

$$\overline{V}_j = \frac{1}{k}\sum_{i=1}^{k} V_{jmi}$$

and

$$V_{jmi} = \frac{1}{2} \times \left(V_{jmai} + V_{jmbi}\right)$$

where V_{jmai} and V_{jmbi} are the mean speeds of the i^{th} pair of data sets at the speed V_j determined in 5.5.3.1 for each direction respectively, in kilometres per hour (km/h).

5.5.4 Running resistance curve determination

The following regression curve shall be fitted to all the data pairs (V_{jm}, C_{jma}) and (V_{jm}, C_{jmb}) for both directions at all speed points V_j (j = 1, 2, etc.) described in 5.3.1.1, to determine c_{0a}, c_{0b}, c_{1a}, c_{1b}, c_{2a} and c_{2b}:

$$C_a = c_{0a} + c_{1a}V + c_{2a}V^2$$

$$C_b = c_{0b} + c_{1b}V + c_{2b}V^2$$

where

C_a and C_b are the running resistances in each direction, in newton metres (N·m);

c_{0a} and c_{0b} are the constant terms in each direction, in newton metres (N·m);

c_{1a} are c_{1b} are the coefficients of the first-order term in each direction, in newton metres hour per kilometre [N·m(h/km)]; c_1 may be assumed to be zero, if the value of c_1V is no greater than 3 % of C at the reference speed(s); In this case, the coefficients c_0 and c_2 shall be recalculated;

c_{2a} and c_{2b} are the coefficients of the second-order term in each direction, in newton metres hour squared per kilometre squared [N·m(h/km)^2];

V is the vehicle speed, in kilometres per hour (km/h).

Then calculate the coefficients c_0, c_1 and c_2 in the total torque equation using the following formulae:

$$c_0 = \frac{c_{0a} + c_{0b}}{2}$$

$$c_1 = \frac{c_{1a} + c_{1b}}{2}$$

$$c_2 = \frac{c_{2a} + c_{2b}}{2}$$

where

c_0, c_1 and c_2 are the average coefficients in the following average total torque equation:

$$C_{avg} = c_0 + c_1V + c_2V^2$$

and in which C_{avg} is the average running resistance, in newton metres (N·m).

5.6 Correction to standard atmospheric conditions

5.6.1 Correction factors

5.6.1.1 Determination of correction factor for air resistance

Determine the correction factor for air resistance K_2 as follows:

$$K_2 = \frac{T}{293} \times \frac{100}{\rho}$$

where

T is the mean atmospheric temperature, in kelvins (K);

ρ is the mean atmospheric pressure, in kilopascals (kPa).

5.6.1.2 Determination of correction factor for rolling resistance

The correction factor, K_0, for rolling resistance, in reciprocal kelvins, may be determined, based on the empirical data for the particular vehicle and tyre test, or may be assumed as follows:

$$K_0 = 8{,}1 \times 10^{-3} \times \mathrm{K}^{-1}$$

5.6.1.3 Wind correction

Wind correction, for absolute wind speed alongside the test road, shall be made by subtracting the difference that cannot be cancelled by alternate runs from the constant term f_0 given in 5.3.1.4.5, or from c_0 given in 5.5.4. This wind correction shall not apply in the onboard-anemometer-based coastdown method (5.4) as the wind correction is made during the series of data sampling and subsequent analysis. The wind correction resistance w_1 for the coastdown method (5.3) or w_2 for the torquemeter method shall be calculated by the formulae:

$$w_1 = 3{,}6^2 \times f_2 v_w^2$$

or

$$w_2 = 3{,}6^2 \times c_2 v_w^2$$

where

w_1 is the wind correction resistance, in newtons (N);

f_2 is the coefficient of the aerodynamic term determined in 5.3.1.4.5;

v_w is the average wind speed alongside the test road during the test, in metres per second (m/s);

or

w_2 is the wind correction resistance, in newtons (N);

c_2 is the coefficient of the aerodynamic term determined in 5.5.4.

5.6.2 Road-load curve correction

5.6.2.1 The fitting curve determined in 5.3.1.4.5, 5.3.2.4.6 or 5.3.3.4.6 shall be corrected to reference conditions as follows:

$$F^* = \{(f_0 - w_1) + f_1 V\} \times \{1 + K_0 (T - 293)\} + K_2 f_2 V^2$$

where

F^* is the corrected total resistance in newtons (N);

f_0 is the constant term, in newtons (N);

f_1 is the coefficient of the first-order term, in newtons hour per kilometre [N·(h/km)];

f_2 is the coefficient of the second-order term, in newtons hour squared per kilometre squared [N·(h/km)^2];

K_0 is the correction factor for rolling resistance, as defined in 5.6.1.2;

K_2 is the correction factor for air resistance, as defined in 5.6.1.1;

V is the vehicle speed, in kilometres per hour (km/h);

w_1 is the wind correction resistance, as defined in 5.6.1.3.

5.6.2.2 The fitting curve determined in 5.4.5 shall be corrected to reference conditions as follows:

$$F^* = \left(a_{\text{mech}} + b_{\text{mech}}V + c_{\text{mech}}V^2\right) \times \left\{1 + K_0 \times \left(T - 293\right)\right\} + \frac{1}{2} \times K_2 a_0 \rho S V^2$$

where

F^* is the corrected total resistance, in newtons (N);

a_{mech} is the coefficient of mechanical drag, in newtons (N);

b_{mech} is the coefficient of mechanical drag, in newtons per kilometre per hour [N/(km/h)];

c_{mech} is the coefficient of mechanical drag, in newtons per kilometre squared per hour squared [N/(km/h)^2];

ρ is the air density, in kilograms per cubic metre (kg/m^3);

S is the projected frontal area of the vehicle, in square metres (m^2);

a_0 is the coefficient for aerodynamic drag, as a function of yaw angle;

K_0 is the correction factor for rolling resistance, as defined in 5.6.1.2;

K_2 is the correction factor for air resistance as defined in 5.6.1.1;

V is the vehicle speed, in kilometres per hour (km/h).

5.6.2.3 The fitting curve determined as decribed in 5.5.4 shall be corrected to reference conditions as follows:

$$C^* = \left\{\left(c_0 - w_2\right) + c_1 V\right\} \times \left\{1 + K_0 \times \left(T - 293\right)\right\} + K_2 c_2 V^2$$

where

C^* is the corrected total running resistance, in newton metres (N·m);

c_0 is the constant term, in newton metres (N·m);

c_1 is the coefficient of the first-order term, in newton metres hour per kilometre [N·m (h/km)];

c_2 is the coefficient of the second-order term, in newton metres hour squared per kilometre squared [N·m·(h/km)^2];

K_0 is the correction factor for rolling resistance as defined in 5.6.1.2;

K_2 is the correction factor for air resistance as defined in 5.6.1.1;

V is the vehicle speed, in kilometres per hour (km/h);

w_2 is the wind correction resistance as defined in 5.6.1.3.

6 Road-load measurement by wind tunnel/chassis dynamometer

6.1 Aerodynamic drag measurement in wind tunnel

6.1.1 Requirements for wind tunnel

The wind-tunnel design, the test methods and the corrections shall be sufficient to provide a SCd [(see 4j)] representative of the on-road SCd value.

6.1.2 Testing procedure

6.1.2.1 The test vehicle shall be positioned according to the specifications of the wind-tunnel laboratory, so as to ensure that the air stream is parallel to the longitudinal axis of the test vehicle. The test-vehicle ground clearance shall be checked according to the vehicle manufacturer's specification, and shall be adjusted if required. The engine bonnet/hood, all windows, any covers of the air ventilation system, headlamps, etc., shall be closed. The test vehicle shall be immobilized in a way that minimizes the effect on the airflow.

6.1.2.2 The measurement shall be conducted according to the specification of the wind-tunnel laboratory. It is recommended to use the test section wind speed of 140 km/h, but the lowest wind speed shall be 80 km/h.

Two measurements shall be conducted. If the difference in the resultant SCd values is greater than 1 %, the test vehicle set-up and the wind-tunnel set-up shall be checked and corrected if necessary. Two further tests shall then be performed. This procedure shall be repeated until a difference of no more than 1 % between two values is obtained.

6.1.3 Test result

Determine the test result (SCd), in square metres, by averaging a pair of the measurement values.

6.2 Rolling resistance determination with chassis dynamometer

6.2.1 Testing device

The chassis dynamometer shall have the following characteristics:

— single roller (double single rollers for permanent four-wheel-drive vehicles);

— roller diameter: no less than 1,2 m;

— roller surface: smooth steel, or other equivalent materials, or textured and shall be kept clean. In cases where a textured surface is used, this fact shall be noted in the test report, and the surface texture shall be 180 µm deep (80 grit).

The external vehicle-cooling fan shall have the following characteristics:

— blower nozzle area: surface: greater than 0,4 m^2;

— cooling wind speed: ± 2 km/h of roller speed.

6.2.2 Testing procedure

The rolling resistance of the front and rear wheels shall be measured separately. When a double-single-axis-type chassis dynamometer is used for a permanent four-wheel-drive vehicle, the resistance of both axles may be measured simultaneously. During the test, the vehicle shall be cooled with an external cooling fan.

NOTE This procedure is based on force measurement at several steady speed points and not under deceleration.

6.2.2.1 Adjust the vehicle conditions as specified in 5.2.1.1.

6.2.2.2 Adjust the test room temperature to 293 K $^{+6}_{-2}$ K. Warm up the chassis dynamometer according to the chassis-dynamometer specification. Measure the chassis-dynamometer running losses.

6.2.2.3 Place the non-driving wheels in the normal front-driving direction on the chassis dynamometer first;

a) restrain the vehicle, taking care not to apply an abnormal load on the measured axle;

b) warm up the axle until the chassis-dynamometer force is stabilized, or up to a maximum of 30 min at the highest reference speed;

c) measure the axle rolling resistance for this speed;

d) decrease the speed to the immediate lower reference speed;

e) measure the axle rolling resistance for this new speed;

f) repeat c) to e) for each reference speed;

g) once the loads have been measured for each reference speed, repeat the entire measurement procedure from c) to f);

h) if the difference is greater than 4 % at any reference speed, the test vehicle set-up and the chassis-dynamometer set-up shall be checked and corrected, if necessary. Two further tests shall then be performed. This procedure shall be repeated until a difference of no more than 4 % between two values, at any reference speed, is obtained;

i) once two satisfactory measurements have been obtained, the final result shall be the average of the two measurements for each reference speed.

6.2.2.4 Place the driving axle on the chassis dynamometer;

a) restrain the vehicle, taking care not to apply an abnormal load on the measured axle;

b) adjust the chassis-dynamometer load to an appropriate value;

c) warm up the axle until the chassis-dynamometer force is stabilized, or up to a maximum of 30 min at the highest reference speed, running the engine on the appropriate gear;

d) return the engine to idle, shift the transmission into neutral, and re-engage the clutch in the case of a manual transmission vehicle;

e) stabilise the speed at the highest reference speed;

f) measure the axle rolling resistance for this speed;

g) decrease the speed to the immediate lower reference speed;

h) measure the axle rolling resistance for this new speed;

i) repeat e) to h) for each reference speed;

j) once the loads have been measured for each reference speed, repeat the entire measurement procedure from e) to i);

k) if the difference is greater than 4 % at any reference speed, the test vehicle set-up and the chassis-dynamometer set-up shall be checked and corrected, if necessary. Two further tests shall then be performed. This procedure shall be repeated until a difference of no more than 4 % between two values at any reference speed is obtained;

l) once two satisfactory measurements have been obtained, the final result shall be the average of the two measurements for each reference speed.

6.2.3 Test results

For each reference speed V_j, calculate the total rolling resistance using the following formula:

$$Rr_{\mathrm{t},j} = Rr_{\mathrm{f},j} + Rr_{\mathrm{r},j} - 2 \times Rr_{\mathrm{loss},j}$$

where

$Rr_{\mathrm{t},j}$ is the total rolling resistance, in newtons (N);

$Rr_{\mathrm{f},j}$ is the rolling resistance of the front wheel, in newtons (N);

$Rr_{\mathrm{r},j}$ is the rolling resistance of the rear wheel, in newtons (N);

$Rr_{\mathrm{loss},j}$ is the loss of the chassis dynamometer, in newtons (N).

The $Rr_{\mathrm{t},j}$ result should be corrected. Examples of the correction procedures are given in Annex B.

6.3 Total-resistance calculation

The total road-load resistance is calculated for each reference speed V_j by the following formula, using SCd obtained in 6.1 and $Rr_{\mathrm{t},j}$ in 6.2:

$$F_j = \frac{1}{3{,}6^2} \times \frac{\rho SCdV_j^2}{2} + Rr_{\mathrm{t},j}$$

where

F_j is the total road-load resistance, in newtons (N);

ρ is the air density, in kilograms per cubic metre (kg/m^3);

S is the projected frontal area of the vehicle, in square metres (m^2);

Cd is the aerodynamic coefficient;

V_j is the vehicle speed, in kilometres per hour (km/h).

6.4 Total-resistance curve determination

If necessary, the total-resistance curve shall be determined by fitting the following regression curve with the least-squares method:

$$F = f_0 + f_1 V + f_2 V^2$$

where

F is the total resistance, in newtons (N);

f_0 is the constant term, in newtons (N);

f_1 is the coefficient of the first-order term, in newtons hour per kilometre (N·h/km);

f_2 is the coefficient of the second-order term, in newtons hour squared per kilometre squared [(N·(h/km)^2];

V is the vehicle speed, in kilometres per hour (km/h).

Annex A
(informative)

Examples of onboard-anemometer calibration procedure

A.1 Introduction

This annex gives an example of a calibration procedure for a type of onboard-anemometer to be used in 5.4. The onboard-anemometer-based coastdown method requires instrumentation that measures the apparent relative air speed and apparent yaw angle encountered by the vehicle during a coastdown test. The method described below requires that the calibration data collection assume a minimum variation in the true wind speed and true wind attack angle, during each pair of opposite direction drives.

A.2 Instrumentation and theory

A meteorological anemometer is installed on a mast, approximately 2 m in front of the vehicle at the approximately aerodynamic stagnation height, level with the vehicle front bumper. Typically, this device produces an anemometer-propeller rotational signal which is proportional to the apparent relative air speed, as well as a static signal that indicates the angular direction of the anemometer vane with respect to some reference position. These signals are assumed to correlate with the observed changes in vehicle deceleration, such that the coefficients S, a_0, a_1, a_2, a_3 and a_4 can be determined in the following aerodynamic drag (F_{aero}) equation, which is consistent with that described in 5.4.4.

$$F_{aero} = \frac{1}{2} \times \rho S V_r^2 \times \left(a_0 + a_1\theta + a_2\theta^2 + a_3\theta^3 + a_4\theta^4 \right)$$

A “zero yaw offset” must be calculated by a method described in this Annex, because the aerodynamic centre-line of the anemometer may not be assumed to coincide exactly with the aerodynamic centre-line of the vehicle.

The following procedure outlines a method by which the anemometer signals can be correlated to vehicle deceleration.

A.3 Assumptions and procedural suggestions

A.3.1 Symbols

Symbols and the meanings in A.3 are as follows:

V is the vehicle speed, in kilometres per hour (km/h);

Va is the apparent air speed, in the direction of the vehicle movement without respect to wind, in kilometres per hour (km/h);

Vw is the true wind speed, in kilometres per hour (km/h);

α is the true direction of the wind, with respect to the direction of the track, in degrees;

θ_0 is the zero yaw offset angle, in degrees;

θ_{true} is the true yaw angle, in degrees;

$\theta_{apparent}$ is the apparent yaw angle, in degrees;

Vr_{true} is the true relative air speed, in kilometres per hour (km/h);

$Vr_{apparent}$ is the apparent relative air speed, in kilometres per hour (km/h);

ky is the yaw correction coefficient;

ka is the coefficient relating Vr_{true} to $Vr_{apparent}$;

$ka*$ is the coefficient relating V to Va;

kr is the minimum velocity at which the anemometer will respond, in kilometres per hour (km/h);

ku is a unitless coefficient relating yaw angle to relative air speed.

A.3.2 Graphical description of the pertinent parameters

The apparent air speed (Va) is lower than the vehicle speed (V) due to the presence of the vehicle. Because of this retardative effect, the measured relative air speed ($Vr_{apparent}$) and the true relative air speed (Vr_{true}) are shown graphically in Figures A.1 and A.2.

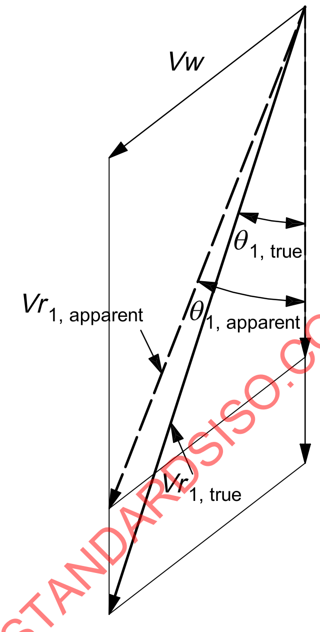

Figure A.1 — Direction against the wind

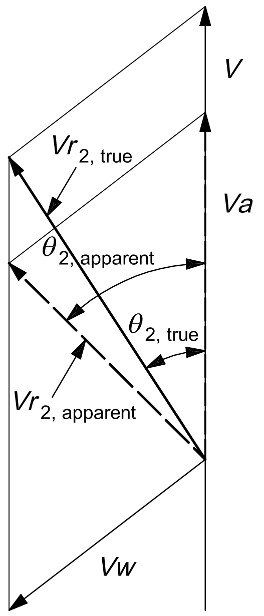

Figure A.2 — Direction with the wind

A.3.3 Equation assumption

When it is assumed that the variation in the true wind attack angle during each pair of opposite direction drives is a minimum, Va can be calculated with $Vr_{apparent}$ and $\theta_{apparent}$ as follows.

$$Va = \frac{Vr_{1,apparent}\cos\theta_{1,apparent} + \left(Vr_{1,apparent}\sin\theta_{1,apparent} / Vr_{2,apparent}\sin\theta_{2,apparent}\right)\times Vr_{2,apparent}\cos\theta_{2,apparent}}{1+\left(Vr_{1,apparent}\sin\theta_{1,apparent} / Vr_{2,apparent}\sin\theta_{2,apparent}\right)}$$