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Heavy commercial vehicles and buses — Centre of gravity measurements — Axle lift, tilt-table and stable pendulum test methods

Véhicules utilitaires lourds et autobus — Mesure du centre de gravité — Méthode d'essais du plateau incline, levage d'un essieu et pendule stable

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ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Fax: +41 22 749 09 47
Email: copyright@iso.org
Website: www.iso.org

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Contents

Page

Foreword

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This document was prepared by Technical Committee ISO/TC 22, *Road vehicles*, Subcommittee SC 33, *Vehicle dynamics and chassis components*.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Methods are presented for measuring the location of the centre of gravity of an individual vehicle unit in the horizontal, lateral and vertical planes. Location of the longitudinal and lateral centre of gravity positions are obtained through successive use of wheel or platform scales. Three different methods are described for measurement of the vertical centre of gravity – the axle lift method, the tilt-table method, and the stable pendulum method. The selection of the method to use depends on the facility and resource availability, as well as constraints imposed by the vehicle design. Knowledge of a vehicle unit's centre of gravity supports vehicle modelling work, design validation and planning for other dynamic tests yet to be performed.

Heavy commercial vehicles and buses — Centre of gravity measurements — Axle lift, tilt-table and stable pendulum test methods

1 Scope

This document describes a standard method for measuring a vehicle's longitudinal and lateral (horizontal plane) centre of gravity (CG) positions and three methods for estimating a vehicle's vertical CG position, the axle lift, tilt-table, and stable pendulum methods. It applies to heavy vehicles, that is commercial vehicles and buses as defined in ISO 3833 (trucks and trailers with maximum weight above 3,5 tonnes and buses and articulated buses with maximum weight above 5 tonnes, according to ECE and EC vehicle classification, categories M3, N2, N3, O3 and O4). CG measurements are performed separately for each single unit.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 612, *Road vehicles — Dimensions of motor vehicles and towed vehicles — Terms and definitions*

ISO 8855, *Road vehicles — Vehicle dynamics and road-holding ability — Vocabulary*

ISO 15037-2, *Road vehicles — Vehicle dynamics test methods — Part 2: General conditions for heavy vehicles and buses*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 8855, ISO 15037-2 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
scale
instrument or device used to measure total vehicle, axle, track or individual wheel weights

3.2
crane
device used to lift one end of the test vehicle, with sufficient lift capacity

3.3
load cell
device for measuring force along a single axis

3.4
axle hoist
device used to lift an individual axle with the *crane* (3.2) and safety provisions to prevent the axle from leaving the hoist once lifted

3.5
tilt-table
apparatus for supporting a vehicle on a nominally planar surface and for tilting the vehicle in roll by rotating that surface about an axis nominally parallel to the x-axis of the vehicle

Note 1 to entry: A tilt-table is composed of (1) a single structure supporting all tyres of the vehicle on a contiguous surface, or (2) multiple structures supporting one or more axles on separated, but nominally coplanar surfaces.

3.6
wheel dummy
surrogate solid wheel used to remove tyre compliance

3.7
trip rail
rail or kerb fixed to the *tilt-table* (3.5) surface and oriented longitudinally beside the low-side wheel dummies to prevent the vehicle from sliding sideways

3.8
tilt angle
Φ_T
angle between the ground plane and a vector that is in the plane of the *tilt-table* (3.5) surface and is perpendicular to the tilt axis

3.9
tilt angle variance
differences between the *tilt angles* (3.8) observed at each vehicle axle due to *tilt-table* (3.5) compliance, twist or misalignment of multi-platform tilt-tables

3.10
critical wheel lift
first moment when one or more wheels lifts from the table surface, following which stable roll equilibrium of the vehicle cannot be maintained

3.11
critical tilt angle
Φ_{Tc}
tilt angle at *critical wheel lift* (3.10)

3.12
tilt-table ratio
TTR
tan (Φ_{Tc}), as shown in Formula (1)

$$\mathrm{TTR} = \tan(\Phi_{Tc}) \qquad (1)$$

Note 1 to entry: It can also be expressed as tan (Φ_T) at the occurrence of *critical wheel lift* (3.10).

Note 2 to entry: See Figure 5.

3.13
central axis
axis defined as the intersection of the longitudinal median plane of the vehicle, Xv-Zv, and the ground plane

3.14
stable pendulum
pendulum apparatus for supporting a vehicle on a nominally planar surface where the combined vehicle and pendulum centre of gravity is below the pivot point

3.15
unstable pendulum
pendulum apparatus for supporting a vehicle on a nominally planar surface where the combined vehicle and pendulum centre of gravity is above the pivot point

3.16
platform
nominally planar surface of the pendulum on which the vehicle unit or trailer is parked

3.17
vehicle restraint
means to constrain the vehicle unit or trailer in the longitudinal direction on the pendulum *platform* (3.16)

4 Principles

This document specifies a method to determine the longitudinal and lateral centre of gravity coordinates in the horizontal plane and three common methods to determine the vertical centre of gravity coordinate. The longitudinal and lateral centre of gravity coordinates, x_{CG} and y_{CG}, are determined in the horizontal plane using scales. Individual scales can be used at each wheel or axle location, or the vehicle wheels or axles can be moved across a single scale successively. The vertical centre of gravity coordinate (z_{CG}) is determined using either the axle lift, tilt-table or stable pendulum method.

The accuracy of the vertical centre of gravity measurements is dependent on the vehicle condition during measurement, measurement equipment accuracy and potential movement of heavy sprung or unsprung masses within the vehicle – such as engine and transmission assemblies and suspensions –, during the measurement process. Methods involving tilting the vehicle or lifting the vehicle axles are prone to movement of suspended components. Consequently, the required accuracy of the vertical centre of gravity measurement should be considered when selecting a measurement method. In general, the pendulum method results in less movement of suspended components, and does not require that the suspension be locked-out vertically.

5 Variables

5.1 Reference system

The reference system specified in ISO 15037-2 shall apply.

5.2 Variables to be measured

5.2.1 Variables to be measured for location of x_{CG} and y_{CG} coordinates of centre of gravity in horizontal plane

With the vehicle at rest on the ground plane and prepared with the load condition specified for the test, the following shall be measured and recorded in accordance with the dimensions given in ISO 612 and ISO 8855.

- F_z the total vehicle load (or weight);
- n_a number of axles;
- F_{zi} ith axle load (F_{z1} is the front axle load);
- $F_{zi,left}$ ith axle, left wheel track load;
- $F_{zi,right}$ ith axle, right wheel track load;
- $F_{z,left}$ total left track load;

— $F_{z,right}$ total right track load;

— l vehicle average wheelbase of 2-axle vehicle;

— l_{right} right track wheelbase of 2-axle vehicle;

— l_{left} left track wheelbase of 2-axle vehicle;

— l_{i-1} average axle distance (left and right track) from front axle to axle i;

— b_i ith axle track (b_1 is at the front axle).

5.2.2 Variables to be measured using the axle lift method for location of z_{CG} coordinates

In addition to the relevant variables listed above, measure and record the following.

— F_{zi}' ith axle load after lifting is initiated;

— $F_{zi}'_{,left}$ left track axle load on the ith axle after lifting is initiated;

— $F_{zi}'_{,right}$ right track axle load on the ith axle after lifting is initiated;

— θ vehicle pitch angle change in the $X\,Z$ plane, relative to the initial orientation on the ground plane before lifting occurs;

— r_{stat} average static loaded radius of all tyres; see Annex A;

— $r_{stat\ i}$ the average static loaded radius on the ith axle; see Annex A.

5.2.3 Variables to be measured using the tilt-table method for location of z_{CG} coordinates

In addition to the relevant variables listed above, measure and record the following.

— l_c longitudinal distance between the contact centres of the two axles contacting the trip rail;

— y_{mi} half-width across wheel dummy trip edges on ith axle;

— $r_{stat,\ dummy}$ average static radius of the wheel dummies;

— Φ_{Tc} critical tilt angle;

— Z_s height of the centre of gravity with the wheel dummies.

NOTE See Figure 7 for a description.

5.2.4 Variables to be measured using the stable pendulum method for location of z_{CG} coordinates

In addition to the relevant variables listed above, measure and record the following.

— h pivot height from the platform surface;

— h_p platform's CG distance below the pivot axis;

— W_p load of the platform including the restraint components;

— W_A applied load;

— θ_p tilt angle of the platform relative to the gravity vector (positive for the front of the vehicle pitched down);

— X longitudinal displacement of the vehicle relative to the platform (positive for forward vehicle displacement);

— h_A vertical distance from the pivot axis to the location of the applied load;

— l_A horizontal distance from the pivot axis to the location of the applied load.

NOTE See Figure 8 for a description.

6 Measuring equipment

The measuring equipment, transducer installation and data processing shall be in accordance with ISO 15037-2.

Typical operating ranges of the variables to be determined for this document are shown in Tables 1 and 2 and in ISO 15037-2.

Table 1 — Variables, typical operating ranges and recommended maximum errors of variables not listed in ISO 15037-2 for the longitudinal and lateral centre of gravity measurements

Variable	Typical operating range	Recommended maximum errors of the combined transducer and recorder system
Vehicle, axle or track load:	Up to 40 000 kg (392 400 N)	0,2 %
Distance:	≤2 000 mm	±1 mm
	>2 000 mm	±0,05 %

Table 2 — Variables, typical operating ranges and recommended maximum errors of variables not listed in ISO 15037-2 for the vertical centre of gravity measurement

Method	Variable	Typical operating range	Recommended maximum errors of the combined transducer and recorder system
All	Suspension air-spring inflation pressure:	500–1 000 kPa	15 kPa
	Vehicle, axle or track load:	Up to 40 000 kg (392 400 N)	0,2 %
	Distance:	≤2 000 mm	±1 mm
		>2 000 mm	±0,02 %
Axle Lift	Angles:	±30°	±0,05°
Tilt-table	Angles:	±60°	±0,1°
	Tilt angle variance:	±0,2°	±0,05°
	Heading angle error:	±1,0°	±0,05°
	Tilt rate:	Up to 0,1°/s	0,2 %
	Lateral deflections:	±50 mm	±1 mm
Stable Pendulum	Angles:	±7°	±0,01°
	Applied mass (weight):	Up to 2 500 kg (24 525 N)	±0,2 %
	Distance X:	±20 mm	±1,0 mm

7 Test conditions

7.1 General

The limits and specifications indicated below shall be maintained during the test. Any deviations shall be identified in the test report.

7.2 Ambient conditions

The surface shall be clean and dry, especially if the test is performed outdoors, and the ambient wind speed is recommended to be less than 1 m/s. Since in certain cases the temperature of vehicle components may influence test results, the ambient temperature shall be reported.

7.3 Test surface

The test surface, when applicable, should be in accordance with ISO 15037-2 and the surface should be hard enough to avoid surface deformation when measuring the vehicle.

7.4 Test vehicle

The load condition shall be reported as described in ISO 15037-2. Tyre pressures and the suspension setting (if applicable) shall be recorded.

On vehicles with multiple adjustable seats or other device such as beds, adjust the items to a mid-travel position (longitudinal and vertical) and adjust the seat back torso angle to the manufacturers' designated specification or as close as possible to 15°. The positions shall be reported.

On vehicles with steering wheel reach and rake, the position shall be reported.

7.5 Operating and other liquids

The fuel tanks shall be completely full or empty, including the urea tanks. Fuel motion within an unfilled fuel tank can have an adverse effect on the results. If the displacement of other liquids carried on the vehicle (operating and otherwise), such as engine oil, is expected to influence the results, precautions should be taken to fill the fluid tanks, drain the fluids or note the potential issue. Tank conditions (empty or full) and locations shall be reported. Occurrences of leaking fluid when the vehicle is inclined should be noted.

7.6 Loading conditions, suspension and mechanical parts

Vehicle payload shall be held in place to avoid displacement due to inclination of the vehicle.

If the vehicle has a suspended cab or semi-suspended cab, the cab shall be locked at its standard height when the vehicle is in a horizontal plane with no driver in the cab. Once the vehicle payload is set, the wheel suspension shall be locked or constrained to avoid deflection during vehicle inclination or pitching. Other components with flexible mounting may need to be constrained as well, if deflection will adversely influence the results. It may not be necessary to lock out these components if the stable pendulum method is used to measure the vertical centre of gravity.

Immediately prior to each test event, all self-regulating suspensions shall be adjusted such that they are at the proper ride height or, in the case of the suspensions for certain auxiliary axles, at the prescribed inflation pressure. The initial ride height of each suspension shall be reported.

When lifting or inclining the vehicle during the axle lift method test, the gearbox shall be in neutral, any lockable differential shall be released, and the parking-brake shall be released with no longitudinal constraints applied. Any steerable wheel shall be steered straight ahead.

Tyre condition and pressure shall be in accordance with the vehicle manufacturer's recommendations and ISO 15037-2. In case a range is specified for tyre pressure, the highest pressure value should be selected to minimize tyre deflection.

Suspended components such as the engine, gearbox and axles can move laterally and/or longitudinally when lifting or tilting the vehicle. Such displacements can influence measurement accuracy and should be noted accordingly.

8 Determination of the centre of gravity in the horizontal plane

8.1 General

When using scales for wheel and axle load measurements, care should be taken to ensure scales are used in a common plane with an inclination less than 1 % grade within the wheelbase of the vehicle. Permissible deviation of any scale from the common plane is based on engineering judgement to minimize measurement error. Considerations include tyre and suspension spring rates. The vehicle or axles should be parked over the scales with light brake application, the vehicle transmission should be shifted to neutral, and the brakes shall be released before measurements are recorded.

8.2 x_{CG} position of the centre of gravity in the horizontal plane

8.2.1 Two axle vehicles

The horizontal distance between the centre of the front axle and the longitudinal centre of gravity, x_{CG}, in millimetres, is determined by Formulae (2) to (4):

$$x_{CG} = \frac{F_{z2}}{F_z} \times l \tag{2}$$

where

F_{z2} is the rear axle load;

F_z is the total vehicle load;

l is the average wheelbase.

$$F_{z2} = F_{z2,left} + F_{z2,right} \tag{3}$$

$$l = 0{,}5 \times (l_{left} + l_{right}) \tag{4}$$

8.2.2 More than two axles

The horizontal distance between the centre of the front axle and the longitudinal centre of gravity, x_{CG}, in millimetres, is determined by Formulae (5) and (6):

$$x_{CG} = \frac{\sum_{i=2}^{n_a} F_{zi} \times l_{i-1}}{F_z} \tag{5}$$

$$l_{i-1} = 0{,}5 \times (l_{i-1,left} + l_{i-1,right}) \tag{6}$$

where n_a is the number of axles as defined in 5.2.

With mutli-axle vehicles, a single large platform scale is often used. Each axle or track is successively rolled onto the platform and the combined axle loads are recorded. Continue until the entire vehicle is on the platform scale. Repeat measurements in the reverse directions. To determine individual axle loads, successively subtract the first axle load from the combined first and second axle load, and so on. Then apply the above equations to determine the x_{CG}.

8.3 y_{CG} position of the centre of gravity in the horizontal plane

8.3.1 Two axle vehicles

The horizontal distance between the longitudinal median plane of the vehicle and the centre of gravity (positive when centre of gravity is to the left of the Xv-Zv plane), y_{CG}, in millimetres, is determined by Formula (7):

$$y_{CG} = \frac{b_1 \times (F_{z1,left} - F_{z1,right}) + b_2 \times (F_{z2,left} - F_{z2,right})}{2 \times F_z} \quad (7)$$

where all symbols are as defined in 5.2.

8.3.2 More than two axles

The horizontal distance between the longitudinal median plane of the vehicle and the centre of gravity (positive when the centre or gravity is to the left of the longitudinal median plane), y_{CG}, in millimetres, is determined by Formula (8):

$$y_{CG} = \frac{\sum_{i=1}^{na} b_i \times (F_{zi,left} - F_{zi,right})}{2 \times F_z} \quad (8)$$

where all symbols are as defined in 5.2.

9 Determination of the centre of gravity height

9.1 General

Three methods are presented to determine the centre of gravity height in the vertical plane, the axle lift method, the tilt-table method, and the stable pendulum method. Prior to performing any of these methods, the vehicle shall be prepared as described in Clause 7.

9.2 Axle lift method

9.2.1 General guidance

The vehicle is lifted by either the front axle or the rearmost axle, as shown in Figures 1 and 2, while the axle farthest away from the lifted axle remains in contact with the ground plane. One of two measurement configurations may be used to perform this test:

— Configuration 1. The vehicle is lifted by a crane with a load cell between the crane hook and the axle hoist (Figure 3). The load cell measures the lifted axle load at several inclination angles. The hoist shall be designed to ensure that the vehicle is stable during the lift and that the axle cannot roll off the hoist (or other supporting platform). The load of the hoist (or other platform) and the cables and clevis shall be subtracted from the load cell measurement.

— Configuration 2. The vehicle is lifted by some other means and the load on the axle remaining on the ground plane is measured with a scale. The means used to lift the vehicle shall be applied to ensure that the vehicle is stable during lifting.

To enable a sufficiently large inclination angle for accurate results, while avoiding any contact of the vehicle extremities with the ground, it may be necessary to utilize a spacer block, as shown in Figure 4, under the tyres of the non-lifted axle. The spacer shall be dimensioned such that the tyres of the non-lifted axle cannot roll off during lifting. Any steering linkages shall be locked to avoid steer motion during lifting.

Measurements are made at multiple vehicle inclinations. Begin measurements when the vehicle inclination is at least 10° and only one axle remains in contact with the ground plane. For subsequent measurements, increase the inclination angle in steps (no more than 5° per step is recommended). The maximum inclination angle depends on the vehicle geometry, lifting apparatus limitations, safety considerations, fluid spillage and the range of the scale used at the ground plane. A maximum inclination angle of 30° is normally adequate.

If a scale is used, the crane position shall be adjusted during the lifts to keep the axle over the scale centre. The orientation of the crane and hoist cabling shall be vertical, perpendicular to the ground plane, at each lifting step. At each step, ensure that the vehicle is free of motion and that the load measurement from the load cell or scale is steady.

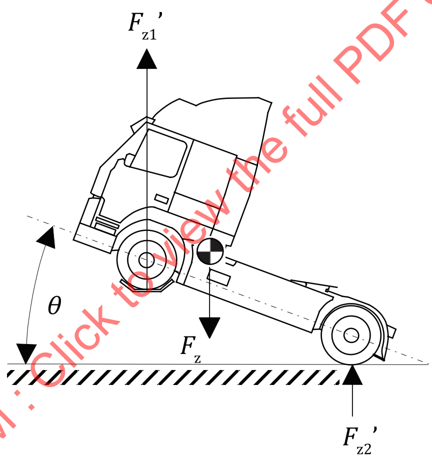


Figure 1 — Two-axle truck lifted at the front axle

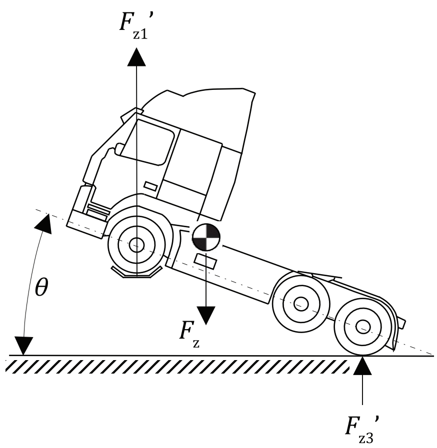


Figure 2 — Three-axle truck lifted at the front axle

Figure 3 — Axle hoist example

Key

X overhang

Z height

Figure 4 — Example of spacer placement

9.2.2 Procedure

9.2.2.1 With the vehicle at rest on the ground plane, prior to any lifting, measure and record the average static loaded radius at each axle ($r_{stat,i}$), the total vehicle load (F_z), the axle loads (F_{zi}) and the axle spacing from the front to rearmost axle (l_{i-1}).

9.2.2.2 Lift the front or rearmost axle in steps (at least three steps are recommended), starting at no less than 10°, with no more than 5° between steps. After lifting is initiated, the load cell or scale measurement (F_{zi}') and inclination angle (θ) are recorded for each step when the vehicle is in a stable position. If a load cell is used, the load of the axle remaining on the ground during lifting is calculated by subtracting the load cell reading from the total vehicle load.

9.2.2.3 To account for hysteresis the vehicle shall be lowered in steps and the measurements of inclination angle and axle load recorded as described in 9.2.2.2.

9.2.2.4 It is recommended that the procedure is repeated, lifting the axle on the opposite end of the vehicle.

9.2.3 Determination of the axle load and inclination angle

9.2.3.1 General

Calculate the load transfer for each inclination step, and plot load transfer versus tan θ. Perform a linear curve fit of the results to obtain an averaged constant slope of the axle load transfer versus the inclination angle. The averaged constant slope, (load transfer)/tan θ, is used in Formulae (11) and (12).

9.2.3.2 Two-axle vehicle

If a load cell and hoist are used at the front axle, the load transfer is determined by (F_{z1} – F_{z1}'). If a scale is used at the axle remaining on the ground, the load transfer is determined by (F_{zi}' – F_{zi}), where i corresponds to the axle on the ground.

9.2.3.3 More than two axles

Determination of the load transfer for vehicles with more than two axles is complicated because intermediate axle loads are initially transferred to the axle being lifted and the axle remaining in contact with the ground. If a load cell and hoist are used at the front axle, the initial static axle load on the front axle (F_{z1}) as used for the load transfer calculation in 9.2.3.2 is replaced with Formula (9).

$$F_{z1} = F_z \times \left(1 - \frac{x_{CG}}{l_{i-1}} \right) \tag{9}$$

Similarly, if the front axle is lifted and a scale is used at the axle remaining on the ground, the initial static axle load on the scale (F_{zi}) as used for the load transfer calculation in 9.2.3.2 is replaced with Formula (10).

$$F_{zi} = F_z \times \left(\frac{x_{CG}}{l_{i-1}} \right) \tag{10}$$

9.2.4 Location of the centre of gravity above the ground plane with loaded tyre radius

9.2.4.1 Two axle vehicle

If the front axle is lifted, the height of the centre of gravity above the ground plane, z_{CG}, in millimetres, is determined by Formula (11):

$$z_{CG} = \frac{l \times (F_{z1} - F_{z1}')}{F_z \times \tan\theta} + r_{stat} \tag{11}$$

Alternatively, if a scale is used with the axle remaining on the ground, the height of the centre of gravity above the ground plane, z_{CG}, in millimetres, is determined by Formula (12):

$$z_{CG} = \frac{l \times (F_{zi}' - F_{zi})}{F_z \times \tan\theta} + r_{stat} \tag{12}$$

where l, F_z, F_{zi}, F_{zi}', θ, and r_{stat} are as defined in 5.2.

9.2.4.2 More than two axles

Formulae (11) and (12) are again used to determine the height of the centre of gravity above the ground plane, provided the substitutions given in Formulae (9) and (10) are utilized and l is replaced with l_{i-1}.

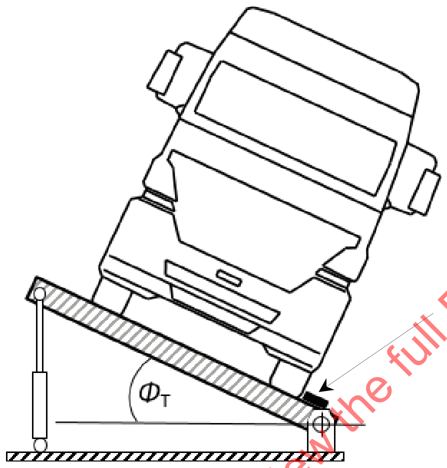
9.2.4.3 Data presentation

Measured data and test results shall be presented in a test report. An example report is shown in Annex B.

9.3 Tilt-table method

9.3.1 General guidance

The vehicle is positioned on a tilt-table and tilted until the upside wheels lift from the tilt-table platform. The process is illustrated in Figure 5. The critical tilt angle is recorded and used to calculate the vertical centre of gravity, z_{CG}.



Key

1 trip trail

Figure 5 — Tilt-table method

It is recommended that solid wheel dummies (see Figure 6) be used on the down slope track to remove vertical and lateral tyre compliance and improve measurement accuracy. The wheel dummies can be driveable or non-drivable (as shown in Figure 6). It is also recommended that the wheel dummy radius, $r_{stat,\ dummy}$, is the same as r_{stat} (see Annex A) and that standard wheels be kept on the upslope track to minimize mass property differences. If wheel dummies are used on the upslope track, the mass properties of the wheel dummies shall be consistent with the standard wheels. The wheel dummies shall be sufficiently stiff in bending to avoid deflections that would affect the CG height measurement accuracy.

The lower outboard edge of the wheel dummy is referred to as the trip edge. The trip edges are placed in contact with the tilt-table trip rail during tilting. It is recommended that the wheel dummies are fabricated such that the contact area between the trip edges and trip rail is as close to the table surface as practical. It is further recommended that the wheel dummies be fabricated such that the half-width across the wheel dummy trip edges, y_{mi} (see Figure 7), is consistent between axles when the wheel dummies are installed. If y_{mi} at one axle is wider than at other axles, solid spacers may be used between the narrower axle dummy wheels and the tilt-table trip rail during testing.

Tilt-angle variance at each vehicle axle during measurements shall not exceed ±0,1°.

It is recommended that safety straps be inspected regularly and replaced if any wear or damage is observed.

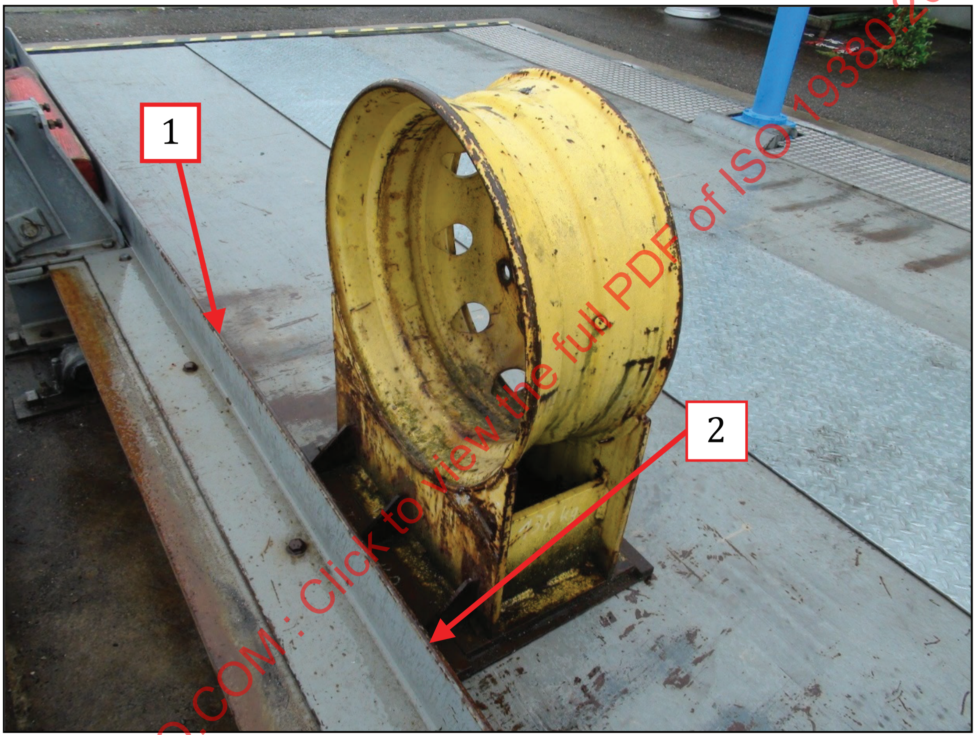
If the vehicle has a trailing axle, the axle can be raised and bound above the ground during testing, unless the centre of gravity height with the axle completely lowered on the ground is required. Less wheel dummies are necessary if the trailing axle is raised.

Some test units require auxiliary vertical support at the coupling joint. For example, a semitrailer coupled to a converter dolly requires support of the dolly drawbar at the pintle hitch. In such cases, a mechanism shall be provided that

a) provides the necessary vertical support in a manner representative of normal use;

b) maintains the lateral position necessary to achieve ±1° alignment of the vehicle unit and the tilt-table axis;

c) provides no significant roll coupling at the support point.

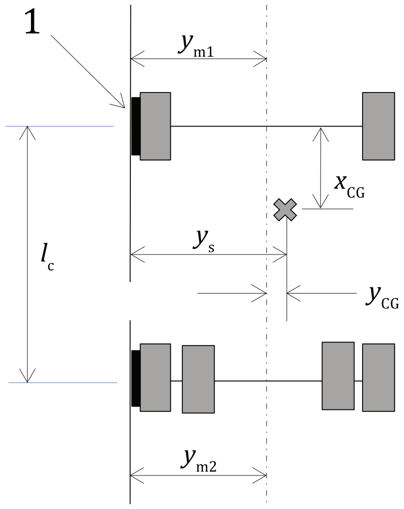


Key

1 tilt-table trip rail

2 wheel dummy trip edge

Figure 6 — Wheel dummy and tilt-table examples



Key

1 spacer

Figure 7 — Tilt-table horizontal plane measurements

9.3.2 Tilt-table procedures

9.3.2.1 With the vehicle at rest on the ground plane, prior to any tilting or installation of the wheel dummies, measure and record the average static loaded radius at each axle ($r_{stat,i}$) and the longitudinal and lateral centre of gravity results from Clause 8, x_{CG} and y_{CG}.

9.3.2.2 Position the vehicle (preferably with wheel dummies) on the tilt-table with the wheel trip edges against the tilt-table trip rail and the vehicle heading aligned to the tilt axis within ±1°. If a longitudinal constraint is required, it shall be applied to only one axle to avoid over-constraining the vehicle.

9.3.2.3 Record the longitudinal distances between axles equipped with wheel dummies, l_c, the static radius of the wheel dummies, r_{stat}, dummy, and the half-widths across the wheel dummy trip edges at each axle, y_{mi}.

9.3.2.4 Install an appropriate number of safety cables or straps between the vehicle and the tilt-table on the upslope side to prevent rollover. The vehicle straps are positioned and oriented to optimize their effectiveness.

9.3.2.5 Slowly and continuously raise the tilt-table from zero tilt angle until the vehicle is unstable and all upslope dummy or standard wheels lift from the platform. Record the critical tilt angle Φ_{Tc}. The vehicle tips up as the gravitational force vector moves outside the lower wheel track. A lower centre of gravity height will result in a higher tilt angle at the point of tip-up. The tilt rate near the expected tipping point should not exceed 0,05°/s. During a lift it is permissible to stop periodically to adjust safety cables or straps and to allow the vehicle to settle. However, once stopped do not decrease the tilt angle. Tilting should be stopped as quickly as possible following the critical wheel lift.

Some vehicle frames are more compliant than others, and the upslope tyres on different axles may lift from the platform at different angles. It is recommended to stop tilting momentarily when one axle lifts from the platform to inspect the safety straps. Restart tilting slowly until the critical tilt angle is reached. Measurement accuracy may be affected by twisting of the chassis.

A series of trial tilts are recommended prior to the measurement tilt to ensure proper adjustment of the safety restraints, establish the test sequence, determine when wheel lift and other significant events may occur, and test wheel lift indicator devices if used. A preliminary tilt shall be initiated with a very conservative safety restraint configuration, for example, one that shall not allow the full vehicle roll freedom required of the actual measurement tilt. The tilt shall be proceeded cautiously with several pauses, typically at wheel lift points for readjustment of safety restraints.

A simple method to indicate wheel lift utilizes thin sheets of metal placed between the upslope tires and the table surface. Elastic cords are attached to the plates so that the plates are pulled out from under the tyres when the tire normal force reaches zero.

9.3.2.6 The measurement tilt shall be repeated at least three times in each vehicle tilt direction.

9.3.3 Determination of the centre of gravity height z_{CG}

The tilt-table ratio (TTR), equal to tan Φ_{Tc}, shall be calculated for each measurement tilt. For each direction of tilt, the mean value of TTR and the 90 % confidence interval of the mean value shall be determined and reported.

For each tilt orientation of the vehicle, calculate the lateral offset of the CG from the trip rail, y_s, based on Formula (13) and Figure 7. Though the formula and diagram refer to a two-axle truck with y_{mf} and y_{mr} unequal, they apply equally well when all y_{mi} are equivalent or with multiple axle vehicle units (some engineering judgement may be required to adjust the formula to suit unique situations).

$$y_s = \frac{y_{m2} - y_{m1}}{l_c} \cdot x_{CG} + y_{m1} - y_{CG} \tag{13}$$

where

y_{m1} is the distance between the central axis and the tilting edge at the front axle;

y_{m2} is the distance between the central axis and the tilting edge at the second axle;

l_c is the longitudinal distance between the contact centres of the two axles contacting the trip rail, as defined in 5.2.

The height of the centre of gravity with the wheel dummies is calculated using Formula (14).

$$z_s = \frac{y_s}{\tan \Phi_{Tc}} \tag{14}$$

The height of the centre of gravity based on the static radius of the original wheels is calculated using Formula (15).

$$z_{CG} = z_s + r_{stat} - r_{stat,\,dummy} \tag{15}$$

The results from testing both sides of the vehicle unit upslope shall be averaged to give the final result of $z_{CG,}$ with relevant statistics reports (e.g. mean, standard deviation).

9.3.4 Data presentation

Measured data and test results shall be presented in a test report. An example report is shown in Annex C.

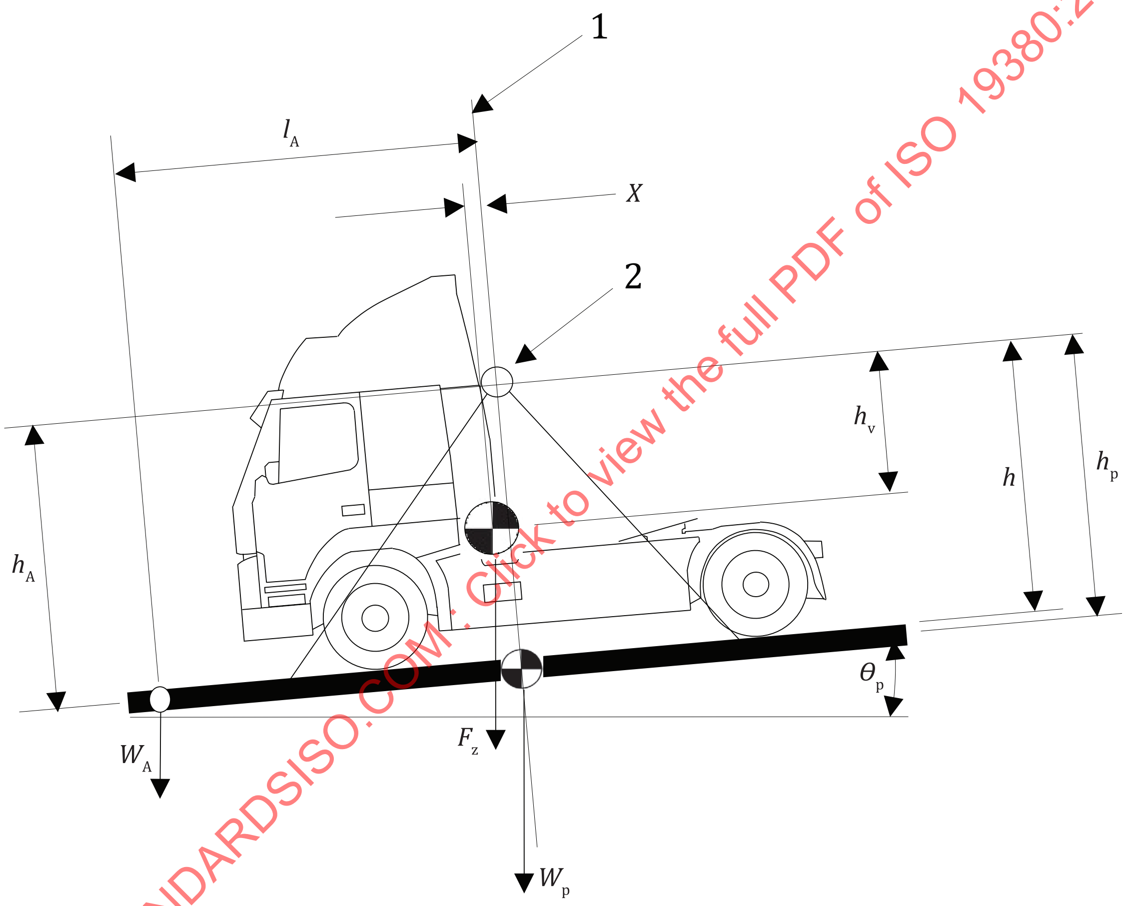
9.4 Stable pendulum method

9.4.1 General guidance

The vehicle is positioned longitudinally on a pendulum platform, as illustrated in Figure 8, where the pendulum pivot point is above the combined centre of gravity of the vehicle, platform and any vehicle restraints used. The stable pendulum method can also be performed using a vehicle roll configuration, where the vehicle longitudinal axis is aligned with the pendulum pivot axis.

The vehicle longitudinal CG is initially aligned with the platform longitudinal CG location. The vehicle parking brakes and parking pawl (if present) are enabled to restrain the vehicle. Additional restraint hardware may be installed at the discretion of the tester. A static disturbance torque is applied to the system to induce a steady-state inclination of the platform. A common means to apply the disturbance torque is by hanging known weights from the platform at a known distance from the pivot axis. Once the platform is stable, the inclination angle of the platform is measured and the CG height is determined as described below.

During testing, the maximum inclination angle shall not exceed 5°, thus minimizing the weight transfer across the axles. Because of this constraint, it may not be necessary to lockout the vehicle's suspension, the cab or any other suspended component prior to testing.



Key

1 centerline

2 pivot point

Figure 8 — Side view of stable pendulum method configuration

An unstable pendulum may also be used, where the pivot point is below the combined centre of gravity of the system. In this case, a static restoring force is applied throughout the test at a known distance from the pivot access to maintain system stability. The restoring force is measured with load cells or scales. The formulation of the equations for the unstable pendulum method is similar to the formulation presented below for the stable pendulum method and is omitted for brevity. Provided similar levels of accuracy are used for the required measurements and equipment specifications, the overall accuracy of the unstable pendulum method is similar to that of the stable pendulum method.

The platform structure shall be sufficiently stiff to support the test vehicle without significant vertical deflection. However, it is also recommended that the platform load (weight) be as light as possible for the intended vehicle class usage. Furthermore, for the stable pendulum method it is recommended that the pivot axis be as low as practical without sacrificing platform stability or the ability to test different vehicle classes. Measurement accuracy is generally improved with light platforms and low pivot heights, both of which enable the use of lighter ballast weights. It is recommended that the pivot height be no higher above the platform than the height of the vehicle.

9.4.2 Stable pendulum procedure

Position the vehicle, configured at the desired payload condition, on the pendulum platform such that the vehicle system longitudinal CG is aligned as closely as possible with the platform longitudinal centre of gravity location. The vehicle is restrained by the parking brakes, parking pawl or external restraints as required. The inclination angle of the platform and restrained vehicle should be less than 0,5° to start the test. Record the initial offset of the vehicle longitudinal CG with the platform longitudinal CG, and designate this offset X_{zero}. Measure and record the initial inclination angle of the platform, θ_{zero}.

Apply a known load, W_A, near the fore end of the platform at a known location defined by l_A and h_A (see Figure 8). The applied load should be such as to cause the platform to incline between three and five degrees. Repeat the procedure with a different applied load to cause the platform to incline to a different angle, but still no more than five degrees. Repeat this procedure for rearward inclination angles by applying loads near the aft end of the platform. Before any measurements are conducted, allow any platform motion caused by the load application to stop. Record θ, X, W_A, l_A, and h_A, for all test conditions.

9.4.3 Determination of platform properties

The restraint components, if used, are considered part of the platform. The total platform load W_p and the total platform CG height h_p are adjusted for the restraint components using Formulae (16) and (17):

$$W_p = W_{p(\text{Empty})} + W_{res} \tag{16}$$

$$h_p = \frac{(h - h_{res}) \cdot W_{res} + h_{p(\text{Empty})} \cdot W_{p(\text{Empty})}}{W_p} \tag{17}$$

where

W_{res} is the restraint hardware load;

h_{res} is the restraint CG distance above the platform surface.

9.4.4 Determination of the applied torque

The torque, T_A, applied to the system by the load, W_A, is:

$$T_A = W_A \left(l_A \cos\theta_p - h_A \sin\theta_p \right) \tag{18}$$

9.4.5 Consideration of platform deflection

Since the platform may deflect under the weight of the test vehicle, the height of the platform centre of gravity can be adjusted using Formula (19).

$$h_p' = h_p + \Delta h_p \tag{19}$$

The term Δh_p will normally have to be determined analytically.

9.4.6 Determination of the centre of gravity height, z_{CG}

The vehicle CG distance below the pivot axis, h_v, is computed by summing the moments acting about the pivot axis (Figure 8) following Formulae (20) to (22):

$$\sum M_{PIVOT} = 0 \tag{20}$$

$$0 = T_A - W_p \cdot h_p' \cdot \sin\left(\theta_p - \theta_{zero}\right) - \ldots$$

$$\ldots - F_z \cdot \left[h_v \cdot \sin\left(\theta_p - \theta_{zero}\right) - \left(X - X_{zero}\right) \cdot \cos(\theta_p - \theta_{zero})\right] \tag{21}$$

Calculating h_v with Formula (21):

$$h_v = \frac{T_A - W_p \cdot h_p' \cdot \sin\left(\theta_p - \theta_{zero}\right)}{F_z \cdot \sin\left(\theta_p - \theta_{zero}\right)} + \frac{X - X_{zero}}{\tan\left(\theta_p - \theta_{zero}\right)} \tag{22}$$

The vehicle centre of gravity above the ground plane, $z_{CG,}$ can now be calculated using Formula (23)

$$z_{CG} = h + D_z - h_v \tag{23}$$

where D_z is the deflection of the platform under the vehicle unit weight.

Once the centre of gravity heights from individual measurements are calculated, the results can be averaged to yield a final value of z_{CG}.

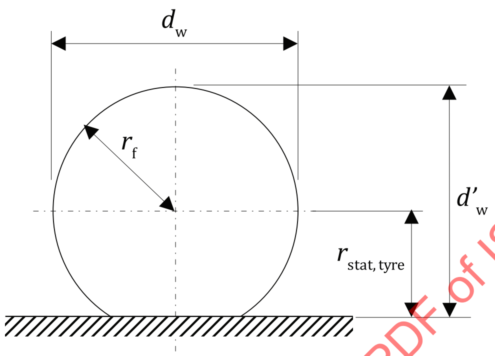
9.4.7 Data Presentation

Measured data and test results shall be presented in a test report. An example report is shown in Annex D.

Annex A
(informative)

Determination of static loaded radius, r_{stat}

The static loaded radius of an individual tyre $r_{stat,\ tyre}$ may be determined as shown in Figure A.1. Formula (A.1) is sufficiently accurate for the test procedure described in this document.



Key

d_w wheel diameter
d'_w loaded wheel diameter
r_f static free radius
$r_{stat,\ tyre}$ static loaded radius of an individual tyre
$r_{stat\ i}$ average static loaded radius of all tyres on axle i
r_{stat} average static loaded radius of all tyres

Figure A.1 — Determination of static loaded radius, r_{stat}

$$r_{stat,\ tyre} = d'_w - \frac{d_w}{2} \tag{A.1}$$

Annex B
(informative)

Test report — Axle lift method

B.1 Vehicle identification

B.1.1 Make:

B.1.2 Model:

B.1.3 Type:

B.1.4 Tyres

Size, first axle:	Size, second axle:
Size, third axle (if existing):	Size, fourth axle (if existing):
Pressure, first axle: bar	Pressure, second axle: bar
Pressure, third axle (if existing): bar	Pressure, fourth axle (if existing): bar

B.1.5 Suspension setting (if applicable):

B.2 Measurement data

B.2.1 Ambient conditions

Air temperature: °C

Relative humidity: %

Wind speed: $^{m}/_{s}$

B.2.2 Loading conditions (description of the seating positions, steering wheel reach and rake position, fuel tank condition, and loads, for example, dummies, luggage, etc., and their *X*, *Y*, and *Z* locations in the vehicle; if relevant, include cargo area dimensions):

B.2.3 Axle loads (vehicle)

First axle left:	N	First axle right:	N
Second axle left:	N	Second axle right:	N
Third axle left (if existing):	N	Third axle right (if existing):	N
Fourth axle left (if existing):	N	Fourth axle right (if existing):	N

Total vehicle: N

B.2.4	Track, first axle:	mm
	Track, second axle:	mm
	Track, third axle (if existing):	mm
	Track, fourth axle (if existing):	mm
B.2.5	Wheelbase, first to second axle:	mm
	Wheelbase, second to third axle (if existing):	mm
	Wheelbase, third to fourth axle (if existing):	mm
	Theoretical wheelbase:	mm

B.2.6 Static load radii

First axle left:	mm	First axle right:	mm
Second axle left:	mm	Second axle right:	mm
Third axle left (if existing):	mm	Third axle right (if existing):	mm
Fourth axle left (if existing):	mm	Fourth axle right (if existing):	mm

Average static load radius:	mm

B.2.7 Tyre

Tyre offset:	mm
Width of the rim:	mm

B.3 Test results

B.3.1	Longitudinal displacement between centre of front axle and CG, x_{CG}:	mm
B.3.2	Distance between the longitudinal median plan of the vehicle and the CG (positive to the left), y_{CG}:	mm

B.3.3 Height of the centre of gravity above the ground plane

B.3.3.1 Test with lifted front axle

Lifting angle:	deg
Axle in contact with the ground (axle number):	—
Axle in contact with the ground load (vehicle inclined):	N
Height of CG, front axle lifted:	mm

B.3.3.2 Test with lifted i axle

Lifting:	deg
Axle lifted (axle number):	—
Axle in contact with the ground load (vehicle inclined):	N
Height of CG, front axle lifted:	mm