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Agricultural machinery and tractors — Safety of partially automated, semi-autonomous and autonomous machinery —

Part 4: Verification methods and validation principles

Tracteurs et matériels agricoles — Sécurité des machines partiellement automatisées, semi-autonomes et autonomes —

Partie 4: Méthodes de vérification et principes de validation

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 23, *Tractors and machinery for agriculture and forestry*, Subcommittee SC 19, *Agricultural electronics*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 144, *Tractors and machinery for agriculture and forestry,* in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

This first edition of ISO 18497-4 together with ISO 18497-1, ISO 18497-2 and ISO 18497-3, cancels and replaces ISO 18497:2018, which has been technically revised.

The main changes are as follows:

— verification methods and validation principles were made its own part (i.e. ISO 18497-4) and substantially revised to account for the wide range of functionality and use cases within agricultural machines and tractors.

A list of all parts in the ISO 18497 series can be found on the ISO website.

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

This document is a type-B1 standard as stated in ISO 12100:2010.

This document is of relevance, in particular, for the following stakeholder groups representing the market players with regard to machinery safety:

— machine manufacturers (small, medium and large enterprises);

— health and safety bodies (regulators, accident prevention organisations, market surveillance, etc.).

Others can be affected by the level of machinery safety achieved with the means of the document by the above-mentioned stakeholder groups:

— machine users/employers (small, medium and large enterprises);

— machine users/employees (e.g. trade unions, organizations for people with special needs);

— service providers, e.g. for maintenance (small, medium and large enterprises);

— consumers (in case of machinery intended for use by consumers).

The above-mentioned stakeholder groups have been given the possibility to participate at the drafting process of this document.

In addition, this document is intended for standardization bodies elaborating type-C standards.

The requirements of this document can be supplemented or modified by a type-C standard.

For machines which are covered by the scope of a type-C standard and which have been designed and built according to the requirements of that standard, the requirements of that type-C standard take precedence.

The structure of safety standards in the field of machinery is as follows:

— Type-A standards (basis standards) give basic concepts, principles for design, and general aspects that can be applied to machinery;

— Type-B standards (generic safety standards) deal with one or more safety aspects or one or more types of safeguards that can be used across a wide range of machinery:

  — Type-B1 standards on particular safety aspects (e.g. safety distances, surface temperature, noise);

  — Type-B2 standards on safeguards (e.g. two-hands controls, interlocking devices, pressure sensitive devices, guards);

— Type-C standards (machinery safety standards) deal with detailed safety requirements for a particular machine or group of machines.

The purpose of the ISO 18497 series is to establish general design principles for partially automated, semi-autonomous and autonomous (see ISO 18497-1:2024, Clause 3) functions of agricultural machinery and tractors.

Manual non-automated functions are addressed in existing agricultural machinery and tractor safety standards. Due to the potential number of different functions of agricultural machinery and tractors and the mixed type and mode to which these functions can exist, it is necessary to establish general design principles. In this way, the combination, operator location, and types of interaction of these functions can be guided so that further type-C safety standards can be developed consistently and explicitly to address the mitigation of risk of injury to operators and bystanders. This is the primary focus of safety standards. Attempting to specify risk mitigation requirements based on combinations of type and mode of functions alone cannot be accomplished accurately for all agricultural machinery and tractors due to the wide variety of the machinery and variety of functionality.

Therefore, the familiar representation of SAE J3016[1] with six levels of automation was deliberately not chosen as a basis for the ISO 18497 series and it is necessary to develop more specific type-C safety standards, using the general design principles of this document, to adequately account for the risks of agricultural machinery and tractors used in a specified way with various types of partially automated, semi-autonomous and autonomous functions.

When the requirements of the ISO 18497 series for partially automated, semi-autonomous and autonomous functions of agricultural machinery and tractors are different from those which are stated in a machine-specific type-C standard dealing with partially automated, semi-autonomous and autonomous functions of agricultural machinery and tractors, the requirements of the machine-specific standard take precedence over the requirements of the ISO 18497 series.

Agricultural machinery and tractors — Safety of partially automated, semi-autonomous and autonomous machinery —

Part 4: Verification methods and validation principles

1 Scope

This document specifies principles for verification methods and validation principles of agricultural machinery and tractors that are used in agricultural applications and that have partially automated, semi-autonomous and autonomous functions.

The purpose of this document is to assist in the provision of more specific safety requirements, means of verification and information for use to ensure an appropriate level of safety for agricultural machinery and tractors with partially automated, semi-autonomous and autonomous functions used in a specified way.

This document deals with the significant hazards relevant to agricultural machinery and tractors with partially automated, semi-autonomous and autonomous functions when used as intended and under the conditions of misuse reasonably foreseeable by the manufacturer during normal operation and service.

Applicability of the design principles and any additional requirements, for design, verification, validation or information for use are outside the scope of this document. When risk assessment concludes that hazards are not significant hazards, the principles of this document do not apply.

NOTE Safety requirements for specific non-automated functions of agricultural machinery and tractors can be available in machine-specific type-C standards.

This document is not applicable to:

— forestry applications;

— operations on public roads including relevant requirements for braking and steering systems.

This document is not applicable to agricultural machinery and tractors which are manufactured before the date of its publication, or to systems applied to agricultural machinery and tractors put into use before the date of its publication.

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 12100:2010, *Safety of machinery — General principles for design — Risk assessment and risk reduction*

ISO 13849-1:2023, *Safety of machinery — Safety-related parts of control systems — Part 1: General principles for design*

ISO 13849-2:2012, *Safety of machinery — Safety-related parts of control systems — Part 2: Validation*

ISO 18497-1:2024, *Agricultural machinery and tractors — Safety of partially automated, semi-autonomous and autonomous machinery — Part 1: Machine design principles and vocabulary*

ISO 18497-2:2024, *Agricultural machinery and tractors — Safety of partially automated, semi-autonomous and autonomous machinery — Part 2: Design principles for obstacle protective systems*

ISO 18497-3:2024, *Agricultural machinery and tractors — Safety of partially automated, semi-autonomous and autonomous machinery — Part 3: Autonomous operating zones*

ISO 25119-1:2018, *Tractors and machinery for agriculture and forestry — Safety-related parts of control systems — Part 1: General principles for design and development*

ISO 25119-1:2018/Amd 1:2020, *Tractors and machinery for agriculture and forestry — Safety-related parts of control systems — Part 1: General principles for design and development — Amendment 1*

ISO 25119-2:2019, *Tractors and machinery for agriculture and forestry — Safety-related parts of control systems — Part 2: Concept phase*

ISO 25119-3:2018, *Tractors and machinery for agriculture and forestry — Safety-related parts of control systems — Part 3: Series development, hardware and software*

ISO 25119-3:2018/Amd 1:2020, *Tractors and machinery for agriculture and forestry — Safety-related parts of control systems — Part 3: Series development, hardware and software — Amendment 1*

ISO 25119-4:2018, *Tractors and machinery for agriculture and forestry — Safety-related parts of control systems — Part 4: Production, operation, modification and supporting processes*

ISO 25119-4:2018/Amd 1:2020, *Tractors and machinery for agriculture and forestry — Safety-related parts of control systems — Part 4: Production, operation, modification and supporting processes — Amendment 1*

3 Terms and definition

For the purposes of this document, the terms and definitions given in ISO 18497-1:2024 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 https://www.electropedia.org/

4 Verification methods and validation principles

4.1 General

Design of machine systems, obstacle protective systems and systems (perception, supervisory or other) to prevent unintended excursions beyond the boundary of the autonomous operating zone of agricultural machinery and tractors with partially automated, semi-autonomous and autonomous functions (see Figure 1) shall be in accordance with ISO 18497-1:2024, ISO 18497-2:2024 and ISO 18497-3:2024, respectively.

For ensuring an appropriate level of safety, the verification methods of 4.2 and validation principles of 4.3 shall be applied for protective or risk reduction measures of significant hazards, as defined in ISO 12100:2010, 3.8, when used in the machine design.

<table>
<tr><th></th><th>Manual non-automated
(see ISO 18497-1:2024, 3.1)</th><th>Partially automated
(see ISO 18497-1:2024, 3.2)</th><th>Semi-autonomous
(see ISO 18497-1:2024, 3.3)</th><th>Autonomous
(see ISO 18497-1:2024, 3.4)</th></tr>
<tr><td rowspan="2">Functions
(see ISO 18497-1:2024, 3.5)</td><td colspan="3">Non-automated (see ISO 18497-1:2024, 3.6)</td><td></td></tr>
<tr><td></td><td colspan="3">Automated (see ISO 18497-1:2024, 3.7)</td></tr>
<tr><td rowspan="2">Modes</td><td colspan="2">Manual mode (see ISO 18497-1:2024, 3.9)</td><td></td></tr>
<tr><td colspan="2"></td><td colspan="2">Autonomous mode (see ISO 18497 - 1:2024, 3.10)</td></tr>
</table>

NOTE See ISO 18497-1:2024.

Figure 1 — Terms used for combinations of functions and modes

4.2 Verification methods

4.2.1 Verification shall be carried out by the collection of data and results from the verification methods listed in this clause. Table 1 provides the minimum verification methods for each part of the ISO 18497 series. Depending on the design and implementation of the protective or risk reduction measures, other verification methods may also be used. More detailed verification methods for a specific use case or type of machine may be given in type-C standards.

a) Inspection/observation – visual and/or audible evaluation without any specialized equipment.

b) Measurement – evaluation of physical values of components or systems of the machine to specified values or limits.

c) Test – evaluation of components or systems of the machine under normal and abnormal conditions:

   — Functional tests (e.g. fault injection testing);

   — Cyclic tests (e.g. endurance testing);

   — Performance tests (e.g. braking, steering, persons and/or obstacle detection tests).

d) Simulation – virtual evaluation of functions and performance of components or systems of the machine with anticipated environmental and operating stresses.

e) Analysis – evaluation of inspection/observation, measurement, test and simulation methods in addition to the design and its specifications through qualitative and quantitative means:

   — Failure modes and effects analysis (FMEA);

   — Fault tree analysis (FTA);

   — Estimation / prediction by simulation models (e.g. Markov models, reliability models);

   — Formal design review.

NOTE 1 Annex A gives information regarding physical properties of objects and humans for use in development of test and simulation verification methods.

NOTE 2 Annex B gives information regarding environmental influences for use in development of test and simulation verification methods.

NOTE 3 Annex C gives information regarding test objects for use in development of test and simulation verification methods.

NOTE 4 Annex D gives information regarding examples of test procedures.

Table 1 — List of required verification methods of protective or risk reduction measures

ISO 18497	Subclause	Inspection / observation	Measurement	Test	Simulation	Analysis
ISO 18497-1:2024	4.2.2.1; 4.2.2.2 a), b)	X		X		
ISO 18497-1:2024	4.2.3.1; 4.2.3.2 a), b)	X			X	
ISO 18497-1:2024	4.2.4.1 a)	X				
ISO 18497-1:2024	4.2.4.1 b)	X			X	
ISO 18497-1:2024	4.2.4.1 c), d)	X		X		
ISO 18497-1:2024	4.2.4.2 a)	X				
ISO 18497-1:2024	4.2.4.2 b), c), d), e), f), h)	X			X	
ISO 18497-1:2024	4.2.4.2 g)	X		X		
ISO 18497-1:2024	4.2.5.1 a)	X				
ISO 18497-1:2024	4.2.5.2 a), b), c), d)	X				
ISO 18497-1:2024	4.2.6.1 a)	X				
ISO 18497-1:2024	4.2.6.2 a), b), c), d)	X				
ISO 18497-1:2024	4.2.7.1 a), b)	X		X		
ISO 18497-1:2024	4.2.7.2 a), b)	X		X		
ISO 18497-1:2024	4.2.8.1 a), b), c)	X		X		
ISO 18497-1:2024	4.2.9.2 a)	X				
ISO 18497-1:2024	4.2.9.2 b)	X			X	
ISO 18497-1:2024	4.2.10.1; 4.2.10.2; 4.2.10.3; 4.2.10.4 a), b)				X	X
ISO 18497-1:2024	4.3.1; 4.3.2.2	X				
ISO 18497-1:2024	4.3.2.3; 4.3.2.4, 4.3.2.5	X	X			
ISO 18497-1:2024	4.3.3.2; 4.3.3.3; 4.3.3.4; 4.3.3.5	X				
ISO 18497-1:2024	4.4; 4.5	X				X
ISO 18497-2:2024	4.2.2 a)			X	X	
ISO 18497-2:2024	4.2.2 b)	X			X	
ISO 18497-2:2024	4.2.2 c)			X		X
ISO 18497-2:2024	4.2.3	X		X		
ISO 18497-2:2024	4.2.4; 4.2.5; 4.2.6.2	X				
ISO 18497-2:2024	4.2.7.1; 4.2.7.2; 4.2.7.3				X	X
ISO 18497-2:2024	4.3; 4.4	X				X
ISO 18497-3:2024	4.2.2.1 a)			X	X	
ISO 18497-3:2024	4.2.2.1 b)	X			X	
ISO 18497-3:2024	4.2.2.1 c)			X		X
ISO 18497-3:2024	4.2.2.2 a)			X	X	
ISO 18497-3:2024	4.2.2.2 b)	X			X	
ISO 18497-3:2024	4.2.2.2 c)			X		X
ISO 18497-3:2024	4.2.3.1; 4.2.3.2	X		X		

Table 1 *(continued)*

ISO 18497	Subclause	Inspection / observation	Measurement	Test	Simulation	Analysis
ISO 18497-3:2024	4.2.4	X				
ISO 18497-3:2024	4.2.5.1; 4.2.5.2; 4.2.5.3				X	X
ISO 18497-3:2024	4.3; 4.4	X				X

4.3 Validation principles

Validation shall be carried out by applying the validation principles listed in this subclause for the protective or risk reduction measures provided in the machine design.

a) Evaluation of used verification methods from 4.2.1:

- appropriate tests, test methods, setup, conditions and procedures;
- appropriate simulations, simulation methods, setup, conditions and procedures;
- appropriate analysis methods.

b) Evaluation of risk reduction level as intended per ISO 12100:2010.

c) Evaluation of functional safety performance level as intended per ISO 25119-1:2018, ISO 25119-1:2018/Amd 1:2020, ISO 25119-2:2019, ISO 25119-3:2018, ISO 25119-3:2018/Amd 1:2020, ISO 25119-4:2018 and ISO 25119-4:2018/Amd 1:2020, or ISO 13849-1:2023 and ISO 13849-2:2012.

d) Evaluation of information for use:

- found in ISO 18497-1:2024, 4.5;
- found in ISO 18497-2:2024, 4.4;
- found in ISO 18497-3:2024, 4.4.

Annex A
(informative)

Information regarding physical properties of objects and humans for use in development of test and simulation verification methods

A.1 Physical properties of objects

The physical properties of an object can include, but are not limited to:

— absorption (physical);
— absorption (electromagnetic);
— area;
— capacitance;
— colour;
— density;
— dielectric;
— ductility;
— elasticity;
— electric charge;
— electrical conductivity;
— electrical impedance;
— electric field;
— emission;
— flow rate;
— fluidity;
— frequency;
— hardness;
— inductance;
— intrinsic impedance;
— intensity;
— irradiance;
— length;
— location;
— luminance;

— luminescence;

— malleability;

— magnetic field;

— opacity;

— permeability;

— permittivity;

— radiance;

— reflectivity;

— strength;

— temperature;

— thermal conductivity;

— velocity;

— volume.

A.2 Human dimensions

The following are sources for human adult and child anthropometric data:

— ISO 7250 (all parts)[2] to [4];

— Japanese children size data[5];

— Physical characteristic of children[6].

NOTE 1 CEN/CENELEC Guide 14, Annex C and D[7] is a source of information on age specific behaviour and development which can be used to help determine appropriate ages of anthropometric data to use.

A.3 Human movement

The following are values which can be used for human movement:

— Velocity representing walking of adult persons: between 0 mm/s and 1 600 mm/s;

NOTE 1 1 600 mm/s for velocity is in accordance with intended use of an industrial environment as defined in ISO 13855[8].

— Acceleration of adult persons: between 0 mm/s^2 and 2 000 mm/s^2.

NOTE 2 2 000 mm/s^2 is the acceleration of an adult person initiating normal walking speed of 1 600 mm/s according to the Journal of Rehabilitation Research and Development[9].

A.4 Human forces

— ISO/TS 15066:2016, Annex A[10].

— ISO 13856-3:2013, Table 2[11].

Annex B
(informative)

Information regarding environmental influences for use in development of test and simulation verification methods

B.1 Environmental parameters

Environmental parameters and severities can include, but are not limited to:

— indoor and/or outdoor use (sheltered or not);

— stationary operation and/or mobile operation;

— temperature and humidity;

— precipitation (rain, hail or snow) and wind;

— pressure (of surrounding air, water, etc.);

— solar radiation and thermal radiation;

— condensation and icing;

— fog, dust, sand and salt mist;

— vibration and shocks;

— fauna and flora (e.g. mould growth);

— chemical influences;

— electrical and electromagnetic influences;

— mechanical load;

— sound.

IEC 60721 (all parts)[12] is a source for environmental parameters.

B.2 Specific standards containing environmental requirements

— IEC 60654-1[13].

— ISO 15003[14].

— EN 50125-1[15].

— ISO 19014-3[16].

— IEC 60721-3-3[17].

— IEC 60721-3-4[18].

— IEC 60721-3-5[19].

— IEC 60721-3-6[20].

B.3 Other standards containing environmental requirements

— IEC 60068 (all parts)[21].

— IEC 60529[22].

Annex C
(informative)

Information regarding test objects for use in development of test and simulation verification methods

C.1 Test object

The following defines a test obstacle (e.g. intended to represent a seated human, small human, animal):

a) the dimensions given by Figure C.1;

b) test obstacle can be filled with water to represent the composition of the human body;

c) test obstacle can be filled with water and warmed by a heater to represent the temperature of the human body;

d) material should be plastic, e.g. polyethylene with matte surface;

e) the colour should be olive green with matte surface.

NOTE "Olive green" is specified as 2.5 GY 3.5/3 by the Munsell Colour System or RAL 6003 by the German Institute for Quality Assurance and Certification (Deutsches Institut für Gütesicherung und Kennzeichnung e.V.). Olive green colour chosen to provide a challenging identification of the object in multiple field conditions (e.g. camouflage).

Dimensions in millimetres

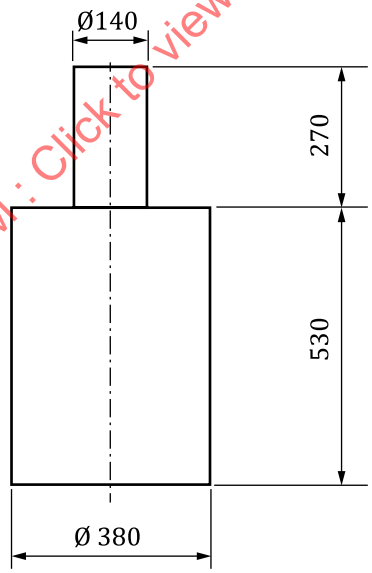


Figure C.1 — Test obstacle dimensions

C.2 Specific standards containing test objects

— ISO 19206-1[23].

— ISO 19206-2[24].

— ISO 19206-3[25].

— ISO 19206-4[26].

— ISO 3691-4[27].

— United States of America Code of Federal Regulations[28].

Annex D
(informative)

Information regarding examples of test procedures

D.1 Example test procedure for obstacle protective system (origin: test protocol ARPA 1 – INRAE[29])

NOTE Test procedures are applicable to obstacle protective systems which prevent contact with obstacles only. The test procedures have been consolidated for the purpose of listing in this document.

D.1.1 Manufacturer and machine information

Record the information from the manufacturer and machine under test:

— maximum mass;

— maximum velocity in working condition;

— dimension of the machine and its embedded implement to test;

— directions of travel of the machine (reverse, forward, etc.);

— list of the parameters that can be modified in the configuration environment of the machine involved in the function under test, as well as their values during testing;

— safe state of machine in case of failure;

— hardware and software version;

— hardware and software version of obstacle protective system and their components in charge;

— version of the operator manual;

— description of both the warning zone and hazard zone if existent;

— operating principle of the obstacle protective system if possible to find out impact factors that can disturb test results;

— information concerning tire/tracks system: brand, type and pressure usage;

— take photos of the machine and obstacle protective system;

— note the battery state of charge at the beginning of the test (if applicable);

— record the date/hour of the test;

— record weather conditions, describe soil state, check conditions are in compliance with the operator manual;

— record the position of perception system on the machine (if applicable) (e.g. orientation, height).

D.1.2 Test parameters

— Perform test in flat ground, allows test repetition.

— Perform test in ideal weather condition, without rain, fog, dust emission, dry soil, frozen ground etc. with external temperature in accordance with machine usage (operator manual).

— Run the test at the maximum permissible mass and maximum velocity.

— Run the test in conditions in accordance within machine dimensions and its implements to test (operator manual).

D.1.3 Test data to collect

— Record the machine velocity during test.

— Record the velocity and velocity standard deviation just before machine stop.

— Record the safe state of machine following stop before contact with test object.

D.1.4 Additional documents and support

— The presence of a manufacturer representative can be necessary to:

  a) configure the machine appropriately;

  b) check that it operates consistently;

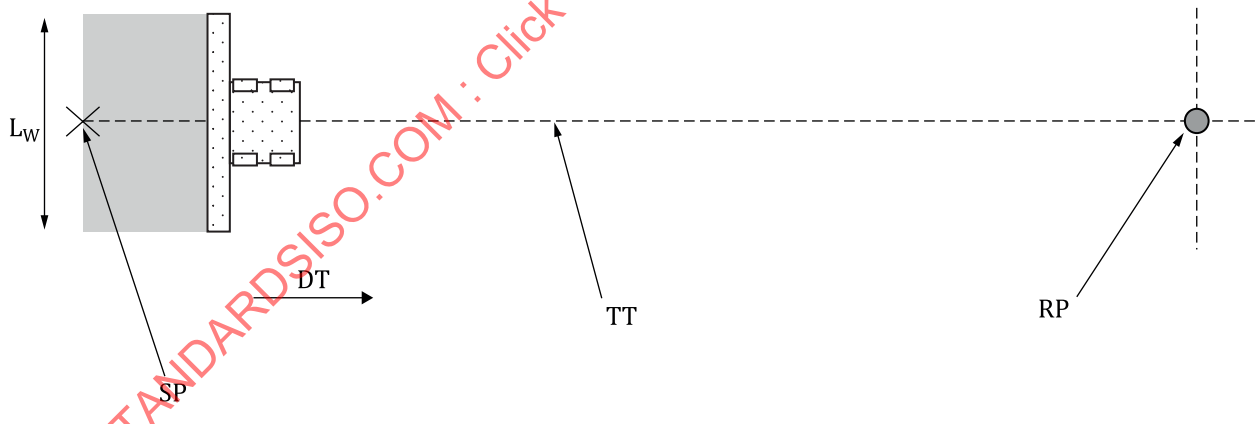
  c) allow checking hardware and software information;

  d) assist with tests;

— The machine's technical manual in addition to the operator's manual supplied by the manufacturer and/or any other documents specifying information needed to carry out tests.

D.1.5 Test description

The machine approaches the test obstacle and stops before contact is made between the test obstacle and the rigid parts of the machine or its implement. The reference test obstacle is described in C.1. The machine is set on a straight path to achieve its maximum speed at steady power (see Figure D.1). Path is learned or recorded or generated previously by machine.



Key

Lw working width
TT theoretical trajectory
SP starting point
RP reference point for test obstacle
DT direction of travel

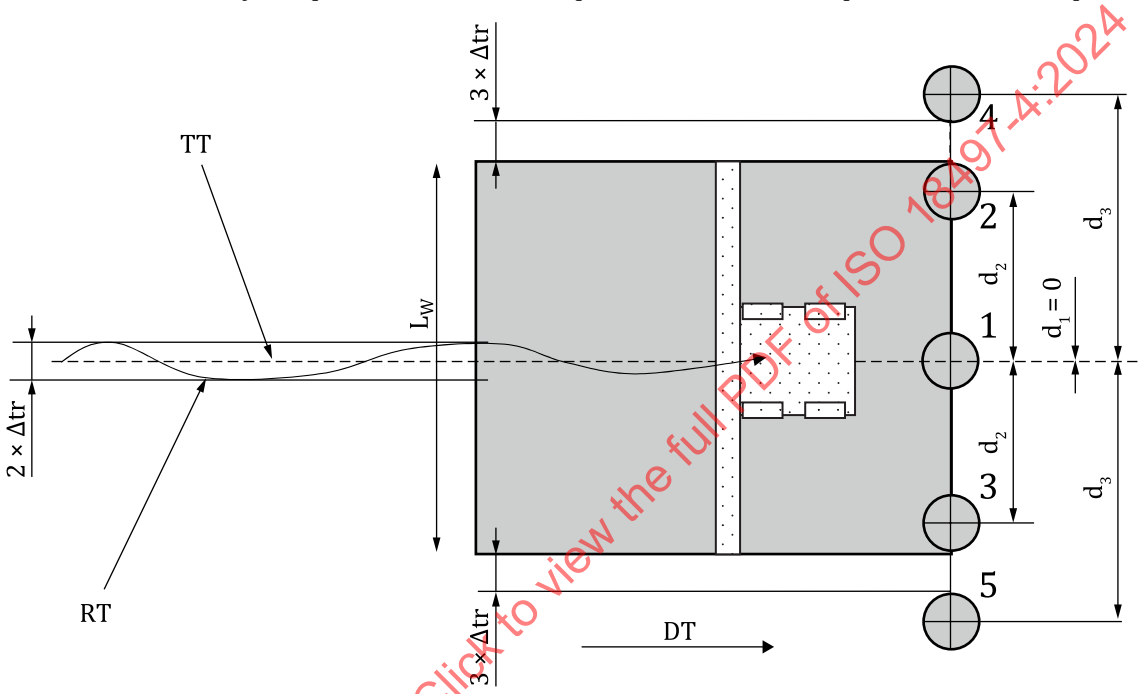
Figure D.1 — Example of obstacle located on a straight path to the machine

The test obstacle is placed successively at different lateral positions to check that the obstacle protective system function operates in those cases as shown in Figure D.2. Machine behaviour is observed at all times.

If a stop occurs before a contact between the test obstacle and the rigid parts of the machine, the minimum distance "obstacle – machine", D_{min}, is measured (see Figure D.3). It is a metric used to evaluate the machine stopping distance margin and to qualify its obstacle protective system.

The velocity is recorded during the test to check that it is compliant with a speed setpoint a few metres before the machine changes its stopping process. The average speed for each iteration is reported in the test report.

The actual path of the machine is a succession of positions close to the setpoint path induced by the path controller. These variations are described by standard deviation. This lateral deviation can set the machine on a trajectory with no clear detection of the test obstacle. Thus, to verify that the machine does not hit the test obstacle in those cases, position 4 and 5 in relation to the trajectory are set. Position 4 and 5 are optional positions, at manufacturer's request. The three-sigma rule of thumb is applied to cover 99,7 % of possible lateral deviations induced by the path controller. This parameter Δtr is computed from test repetition.



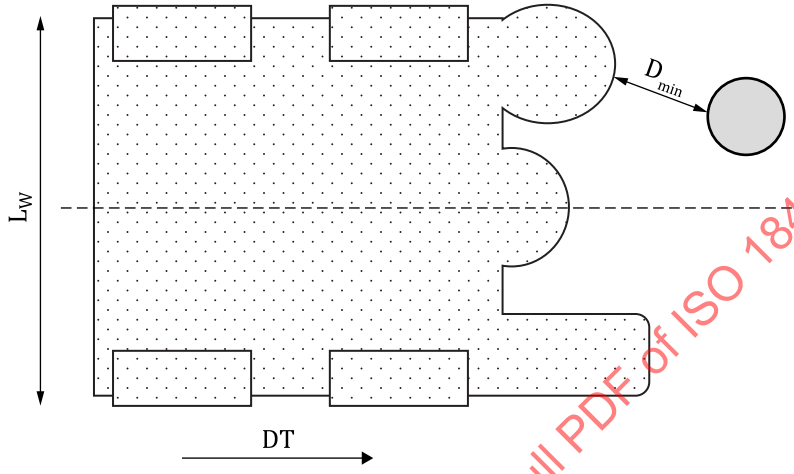
Key

Δtr	standard deviation of lateral position
DT	direction of travel
RT	real trajectory
Lw	working width
TT	theoretical trajectory
DT	direction of travel
d_1, d_2, d_3	test obstacle centre distance from TT
1, 2, 3, 4, 5	locations of test obstacles

Figure D.2 — Example of obstacles located in different lateral positions

Table D.1 — Different locations of test obstacles regarding Figure D.2

Location of test obstacle	Test obstacle centre located at a distance d_i to the theoretical trajectory and set on the axis passing through the reference test obstacle point and perpendicular to the theoretical trajectory
1	$d_1 = 0$
2 and 3	$d_2 = Lw/2 - R$
4 and 5	$d_3 = Lw/2 + 3\,\Delta tr + R$
With Δtr: standard deviation of lateral machine position in relation to theoretical trajectory; R: Test obstacle maximum radius	



Key

Lw working width

D_{min} minimum distance to test obstacle from machine outline

DT direction of travel

Figure D.3 — Measurement of minimum distance of machine and obstacle

D.1.6 Test preparation

The full information needed for the test shall be provided by the manufacturer (See D.1.1 and D.1.4). In case of an electrically driven machine, all batteries are charged to proceed to all tests. In case of a combustion driven machine, tanks should be full for mass and induced energy considerations. The machine should embark its maximum mass (an implement with maximum cantilever should be installed). The mass of the machine is measured before the test and is noted in the final test report. After setting the machine on the test track, a straight path trajectory shall be recorded or defined so that nominal velocity is reached during test and prior to test object contact.

D.1.7 Test procedure

For each obstacle position, the test is done at a minimum 7 times. These repetitions are needed to find the standard deviation of machine position in relation to theoretical trajectory: Δtr. In order to measure this parameter, the testing station shall use a measurement method with an accuracy level under manufacturer declared position accuracy.

Tests series are carried out on the other lateral side.

D.1.8 Measurement and devices

Velocity is measured from start to stop. Machine independent measuring system is used. Sensor technologies used should guarantee the quality of the measurements performed (e.g. laser measurement system).

Record the velocity and velocity standard deviation just before machine stop. Compare to the values fixed in the machine operator's manual.

After each test, measure the machine stop position in relation to the reference test obstacle. See Figure D.3. D_{min} is the minimum distance between test obstacle and machine outline. It is a target metric. Document the capabilities of the sensor used for the validation.

Measurement is done only after the machine is fully stopped. Start the distance sensor. Place it near the machine at the closest position to the object. Acquire the distance measurement.

Record the state of machine following a stop before contact with the test obstacle. Compare to the values fixed in the machine operator's manual.

D.1.9 Acceptance criteria

In addition to the performance criteria set by the manufacturer, the machine and its obstacle protective system should fulfil at a minimum the following conditions after completion of the tests:

a) Machine should not contact the test obstacle;

b) For all test obstacle positions except for position 4 and 5 (see Figure D.2), the machine should stop and reconfigure itself in safe state as described in the operator's manual;

c) For test obstacle positions 4 and 5; when the machine passes close by but does not stop or make contact with the test obstacle, the test result is considered as acceptable.

D.1.10 Optional test variations

At the manufacturer's request, tests may be redone in different conditions:

— test obstacle at position 2 and 3 (see Figure D.2);

— variable ground conditions;

— variable environment conditions.

EXAMPLE Perpendicular trajectory execution from the previous one, for instance, due to sun distress in relationship with some specific embedded perception sensors dedicated to obstacle detection.

D.2 Example test procedure for obstacle protective system under rain and fog environmental conditions (origin: test protocol ARPA 2 – INRAE[30])

NOTE The test procedures have been consolidated for the purpose of listing in this document.

D.2.1 Manufacturer and machine information

Record the information from the manufacturer and machine under test:

— maximum mass;

— maximum velocity in working condition;

— dimension of the machine and its embedded implement to test;

— directions of travel of the machine (reverse, forward, etc.);

— list of the parameters that can be modified in the configuration environment of the machine involved in the function under test, as well as their values during testing;

— safe state of machine in case of failure;

— hardware and software version;

— hardware and software version of obstacle protective system and their components in charge;

— version of the operator manual;

— description of both the warning zone and hazard zone if exist;

— operating principle of the obstacle protective system if possible to find out impact factors that can disturb test results;

— information concerning tire/tracks system: brand, type and pressure usage;

— take photos of the machine and obstacle protective system;

— note the battery state of charge at the beginning of the test (if applicable);

— record the date/hour of the test;

— record weather conditions, describe soil state, check conditions are in compliance with the operator manual;

— record the position of perception system on the machine (if applicable) (e.g. orientation, height).

D.2.2 Test parameters

— Perform the test in flat ground, allows test repetition.

— Perform the test with external temperature in accordance with machine usage (operator manual).

— Run the test at the maximum load and maximum velocity.

— Run the test in conditions in accordance within machine dimensions and its implements to test (operator manual).

D.2.3 Test data to collect

— Record the machine velocity during test.

— Record the velocity and velocity standard deviation just before machine begins to brake.

— Record the safe state of machine following stop before contact with test object.

D.2.4 Additional documents and support

— The presence of a manufacturer representative can be necessary to:

  a) configure the machine appropriately;

  b) check that it operates consistently;

  c) allow checking hardware and software information;

  d) assist with tests;

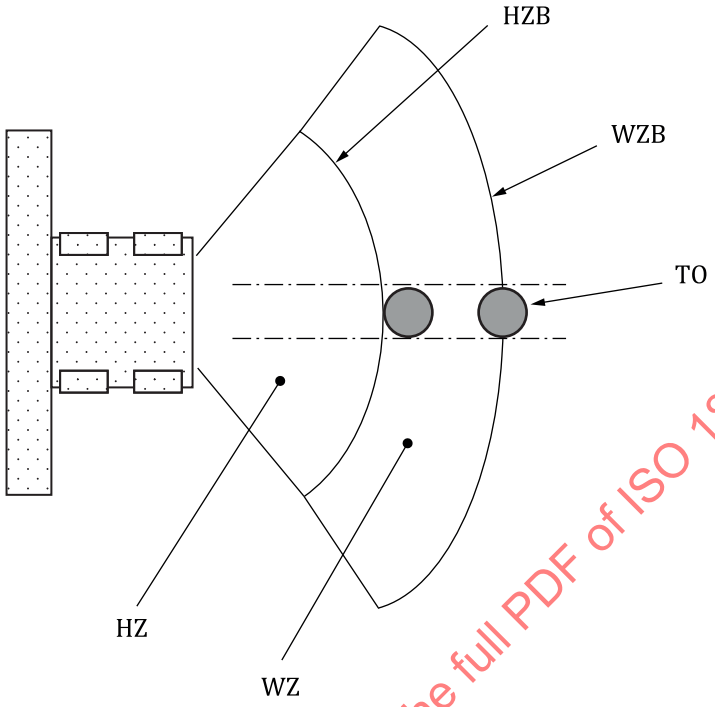
— The machine's technical manual in addition to the operator's manual supplied by the manufacturer and/or any other documents specifying information needed to carry out tests.

D.2.5 Test description

This test consists of a series of unit tests applied to a machine or an obstacle protective system in harsh environment conditions. Detection system submitted to test can estimate the distance to test obstacle in C.1 in function of various meteorological visibilities or densities (fog) and/or rainfall rates (rain). For each test, the test obstacle is set in front of the machine (or the obstacle protective system) in two steps as described in Table D.2 and in Figure D.4. Test order is always from closer to farther from the machine.

Table D.2 — Test obstacle positions along the machine longitudinal axis

Test	Test obstacle positions along the machine longitudinal axis
1	Edge of the object on the detection boundary
2	Object on the detection boundary



Key

HZ hazard zone
HZB hazard zone boundary
WZ warning zone
WZB warning zone boundary
TO C.1 test object

Figure D.4 — Test obstacle positions near boundary

Sequence of test follows this pattern for rain and fog distress:

— Blank test: without test obstacle;

— Hazard zone boundary test: edge of the test obstacle is positioned on the hazard zone boundary;

— Warning zone boundary test: test obstacle is positioned on the warning zone boundary.

D.2.6 Test preparation

The machine or obstacle protective system is set up inside a platform producing controlled fog and rain. The tests are carried out at a fixed position. When only the obstacle protective system is tested, its height position should meet its normal position when used mounted on the machine. Distances from the obstacle protective system to the hazard zone boundary and detection boundary limits are reported on the platform ground.

Manufacturers should make sure its obstacle protective system is correctly protected from water like it should be when used on the machine.

The platform dimensions should fit a complete machine in it, but the test can be conducted with only the obstacle protective system and its post-treatment computer unit. Platform length should be at least 15 m. This can allow any type of obstacle protective system with a rightful range of length detection. The platform

should provide a direct measurement of rainfall rate, rain and fog droplet size distribution and temperature measurement.

For rain and fog, the precipitation should be distributed evenly. Tests providing rain should be sized to allow at least 9 minutes test at the highest rainfall rate level.

Fog droplet size should be around 1 µm (up to 10 µm).

Rain droplet size ranges between 0,2 mm to 2,5 mm, depending on rainfall rate.

D.2.7 Test procedure

Five levels of rain are used:

— 20 ± 5 $mm \cdot h^{-1}$;

— 45 ± 5 $mm \cdot h^{-1}$;

— 75 ± 5 $mm \cdot h^{-1}$;

— 100 ± 5 $mm \cdot h^{-1}$;

— 165 ± 5 $mm \cdot h^{-1}$.

Once the platform valves are opened and level of rainfall rate stabilised, record state of perception: detection or no detection of test obstacle.

Proceed with each level likewise.

Fill the platform with fog to complete saturation (meteorological visibility < 10 m).

Perform either one kind of fog test:

— fog dissipation leading to a meteorological visibility variation from about 10 m to 500 m during 20 min;

— stabilized fogs at prescribed visibility levels between 10 m and about 100 m, without duration limitation for each level.

Fog and rain tests shall be repeated with increasing visibility levels (fog) or decreasing rainfall rate level (rain) up to target detection.

D.2.8 Measurement and devices

Rainfall rate is measured continuously. Sensor technologies used should guarantee the quality of the measurements performed (e.g. disdrometer).

If needed, droplet size distribution measurement devices can be controlled before tests with calibrated latex droplets. Meteorological visibility is usually measured via a transmissometer, according to the World Meteorological Organization. It is composed of two parts: a light emitter and a receiver, separated by a distance. The transmittance corresponds to the ratio of the luminous flux received over the luminous flux emitted by the source. The meteorological visibility is calculated from the measurement of this magnitude.

D.2.9 Acceptance criteria

In addition to the performance criteria set by the manufacturer, the machine and its obstacle protective system should, at a minimum, detect the test obstacle on edge of the hazard zone boundary, or before, for all fog and rain density conditions.

D.2.10 Test results

The manufacturer may change its settings to optimize its perception system. Any change can result in repetition of test. For each test, test obstacle position, observations and perception system settings are

reported in a results table. During fog test, the meteorological visibility is reported when system detects the test obstacle, and rainfall rate is reported for the rain tests.

D.3 Example test procedure for autonomous operating zone (origin: test protocol ARPA 3 – INRAE[31])

NOTE The test procedures have been consolidated for the purpose of listing in this document.

D.3.1 Manufacturer and machine information

Record the information from the manufacturer and machine under test:

— maximum mass;

— maximum velocity in working condition;

— dimension of the machine and its embedded implement to test;

— directions of travel of the machine (reverse, forward, etc.);

— list of the parameters that can be modified in the configuration environment of the machine involved in the function under test, as well as their values during testing;

— type of boundaries (digital, physical, etc.);

— method to make the acquisition of boundaries (e.g. registration of geographical landmarks by pointing and transfer by proprietary system);

— safe state of machine in case of failure;

— for edges: note the type needed and acquired method;

— hardware and software version;

— hardware and software version of obstacle protective system and their components in charge;

— version of the operator manual;

— description of both the warning zone and hazard zone if exist;

— operating principle of the obstacle protective system, if possible, to find out impact factors that can disturb test results;

— information concerning tire/tracks system: brand, type and pressure usage;

— take photos of the machine and obstacle protective system;

— note the battery state of charge at the beginning of the test (if applicable);

— the date/hour of the test;

— weather conditions, describe soil state, check conditions are in compliance with the operator manual;

— the position of perception system on the machine (if applicable) (e.g. orientation, height).

D.3.2 Test parameters

— Perform the test in flat ground, allows test repetition.

— Perform the test in weather conditions that allow a good repeatability of test (ground conditions) and without disruption of visibility (fog, rain, dust).

— Define a representative off-road soil for the evolution area.

— Run the test at the maximum load and maximum velocity.

— Define an area with varying evolution edges shapes.

— Perform test in flat evolution area to limit test condition.

— Define the evolution area regarding activities, if machine works with algorithm of structure detection or not.

— Run the test in conditions in accordance with machine dimensions and its implements to test (operator manual).

D.3.3 Test data to collect

— Record the machine velocity during test.

— If machine goes out of the evolution area, record behaviour of machine and safe state.

D.3.4 Additional documents and support

— The presence of a manufacturer representative can be necessary to:

  a) configure the machine appropriately;

  b) check that it operates consistently;

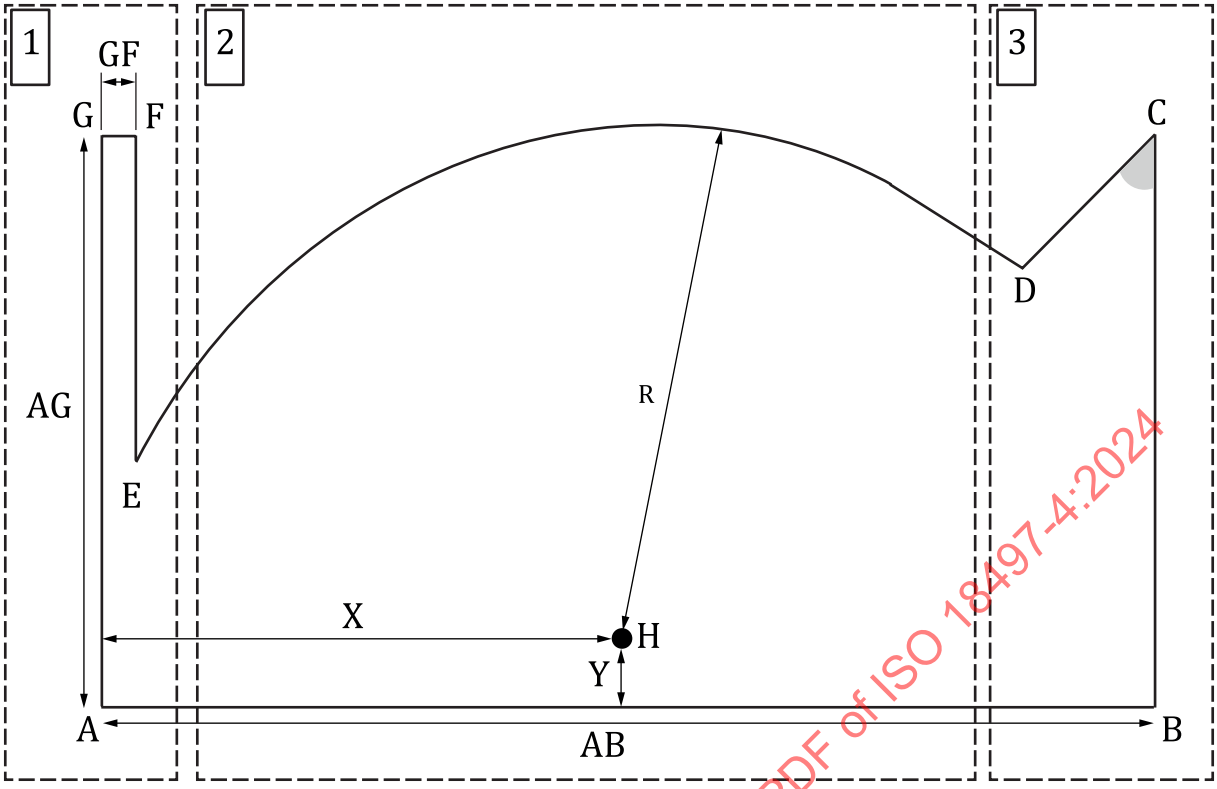
  c) allow checking hardware and software information;

  d) assist with tests;

— The machines technical manual in addition to the operator manual supplied by the manufacturer and/or any other documents specifying information needed to carry out tests.

D.3.5 Test description

This area is a level flat test area, on grassy, agricultural type soil, with an average ground grip coefficient [0,4 to 0,8]. The shape of the level test area, see Figure D.5, is a succession of obtuse and acute angles, in order to create a complex, artificial but realistic, geometry for testing the autonomous operating zone devices.



Key

AG	overall parcel width
AB	overall parcel length
GF	length of narrow parcel segment
X	middle point of AB
H	middle point of AB offset by Y
Y	offset height of H
R	radius of parcel arc
E	point created by intersection of parcel arc R and width segment E and F
D	point created by intersection of parcel arc R and segment C and D
A and G	width parcel segment
B and C	width parcel segment parallel to AG
A and B	length parcel segment
G and F	length parcel segment parallel to AB
E and F	width parcel segment parallel to AG
C and D	parcel segment with angle of 50 degrees from segment B and C
1, 2 and 3	areas of parcel

Figure D.5 — Shape of test area

In Figure D.5, the area 1 provides behaviour observations of the machine on a narrow path. Likewise, the area 2 provides behaviour observations of the machine on a circular arc-shaped edge, while the area 3 provides behaviour observations of the machine on a succession of obtuse and acute angles.

Parcel dimensions are as a function of machine's working width (Lw) and length (Long) dimensions, thus the test area remains at the machine's scale. The dimensions are described in Table D.3 as follows, expressed in metres:

Table D.3 — Geometry for shape of test area

Parcel dimension (see Figure D.5)	Calculation
AG	α x (Lw + Long) / 2
BC	AG
AB	β x (Lw + Long) / 2
GF	1,5 x Lw
Y	1/10 x AG
R, X	AB / 2
H	AB / 2

With α and β are shape and span factors (α =11, β=22) to adapt the dimensions of the parcel to the size of the machine and guarantee proportionality for all machines.

Point H is the middle of the AB segment offset by the height Y. The angle BCD is 50 degrees.

The arc of a circle can be considered as a succession of six segments of equal length to each other and to one sixth of the length of the arc.

D.3.6 Test preparation

The full information needed for the test should be provided from the manufacturer. See D.3.1 and D.3.3. In case of an electrically driven machine, all batteries are charged to proceed to all tests. In case of a combustion driven machine, tanks should be full for mass and induced energy considerations. The machine shall embark its maximum mass (implement with maximum cantilever should be installed). The measurement of machine weight is done before the test and is noted in final test report.

For the global validation test described in D.3.7.1:

— The machine is equipped to obtain the maximum mass (machine-implement system if applicable) described in the machine operator's manual while respecting the standard distribution of loads on the machine (identical distributions to maintain the same dynamic behaviour);

— Likewise, the test is carried out with a maximum working speed setting appropriate to the task and the implement, machine can automatically adapt its speed according to its assessment of the environment and working conditions in accordance with the software version tested;

— Thus, tests are performed under the most severe conditions of use to guarantee the machine's operation over its entire field of use;

— The weather conditions (for implementation) should be good (dry weather, no fog, no excessive dust);

— In this test, machine follows trajectory in nominal operating mode. Machine's trajectories should be defined in accordance with the operator's manual. In case of GPS based following, the tracks are recorded beforehand in accordance with the operator's manual. In case of structure based following, like vine, crop row, etc., an artificial structure can be installed in field by the manufacturer representative;

— Evolution edges definition and installation are done in accordance with the user manual procedures;

— Test is repeated at a minimum 3 times;

— Throughout the test, machine's position and its associated implements, if any, is recorded by a relative or absolute positioning system implemented by the testing station (aerial photos of the machine in relation to evolution edges, multiple GPS points, laser tracker, etc.).

For the edge crossing test described in D.3.7.2:

— The shape of the evolution area is recalculated with regard to the machine dimensions (see Figure D.5);

— Evolution area is implanted in an agricultural field. The GPS points of the evolution area can be shared with the test requester;

— Measurement devices are positioned near the evolution area;

— Paths trajectory are generated so that nominal velocity is reached during test from specific software in accordance with test specifications and established with manufacturer to be compatible;

— Import paths trajectory to machine information technology, set the machine on the test track, and check with first test(s) that machine works fine in accordance with test conditions;

— Run tests in autonomous condition.

D.3.7 Test procedure

D.3.7.1 Global validation test

The aim is to assess, in a standard operating situation, the autonomous operating zone feature of keeping the machine in its evolution area, in a level field with an edge of particular shape to create a range of machine approach angle to the edge (factor identified as potentially leading to exit the area, see Figure D.5). If necessary, the shape is adjusted to be in accordance with technical or operator's manual.

First, a trajectory following the parcel edge is generated. It simulates a field outline work in function of a machine working width, close to the one described in Figure D.6. This trajectory should minimize the non-worked surface between this path and the edge. On the other hand, in the narrow path, the aim is to observe the respect of the evolution edges despite the path narrowness and to subject the machine to difficult narrow strip. Strip width is: E = 1,5 × Lw.

Second, the machine evolves on a level test parcel. The trajectory should be defined to cover the working area as well as possible. Figures D.6 and D.7 show the two proposed modes of the machine's trajectories in the test parcel.

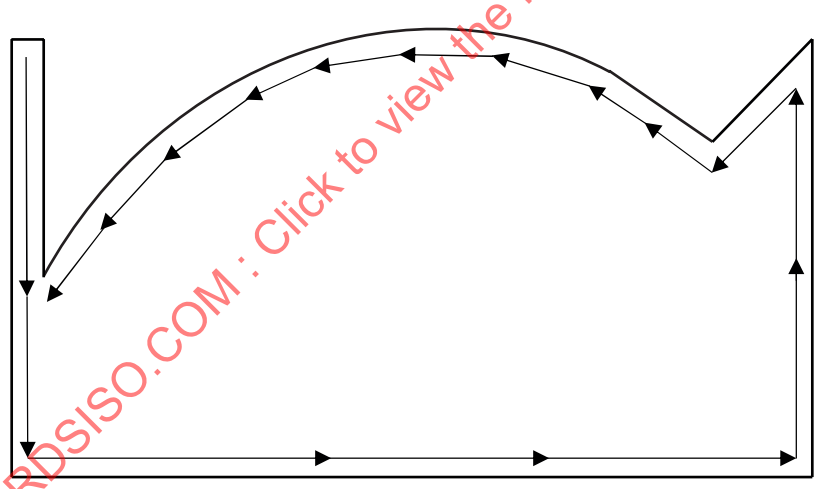
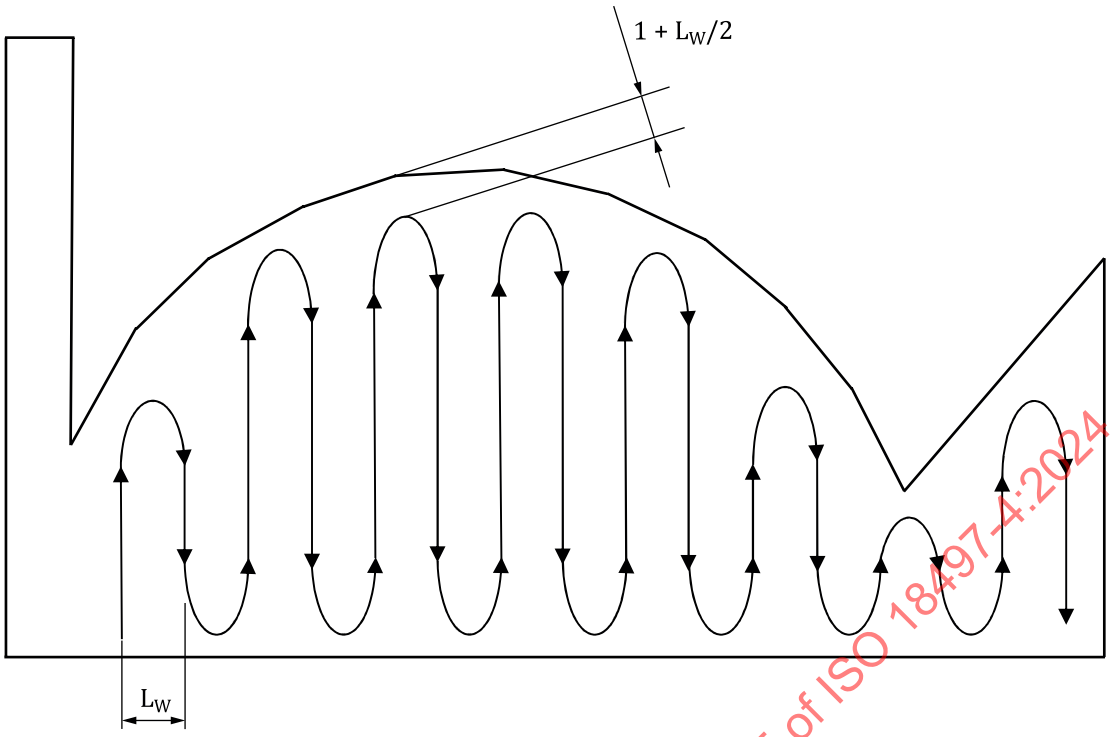


Figure D.6 — Trajectory type to simulate field outline work



Key

Lw working width

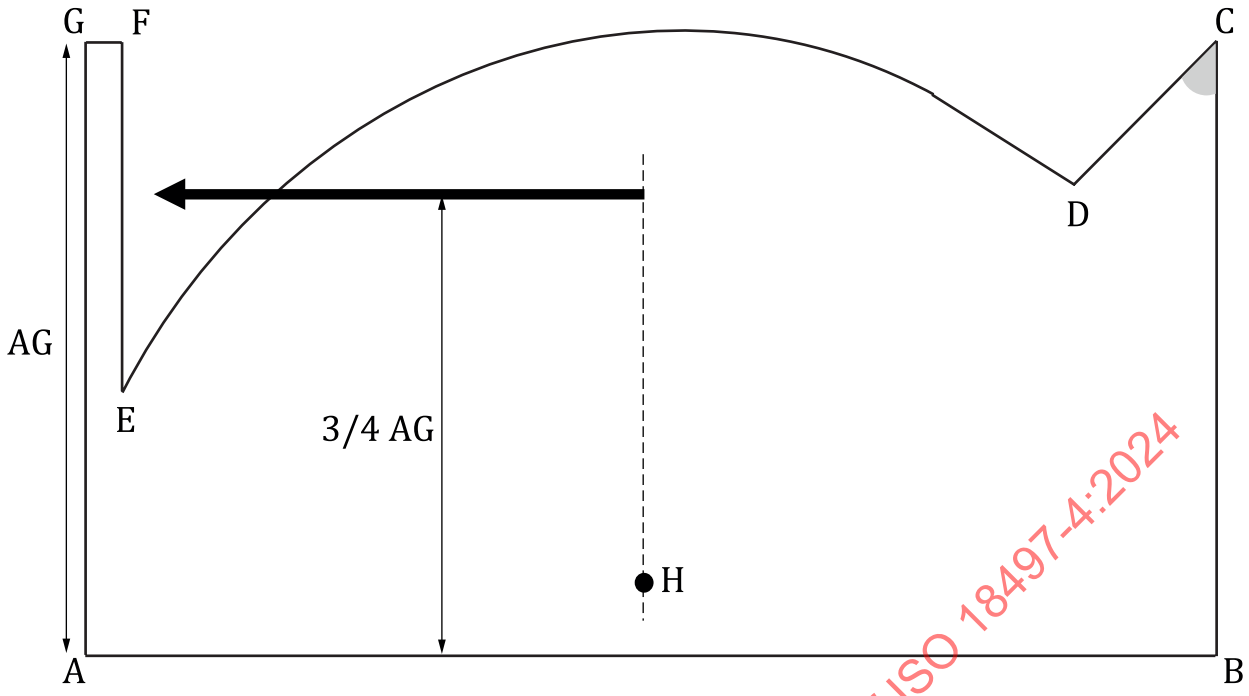
Figure D.7 — Trajectory type to cover the working area

These "basic" trajectories can be generated by the software associated with the machine and dedicated to this function. If no proprietary software exists, testing station generates these trajectories.

D.3.7.2 Edge crossing test

The aim is to assess the autonomous operation zone feature of keeping the machine in its working area when asked to proceed to follow a trajectory crossing the evolution edges. The trajectory type in this mode is shown in Figure D.8. First, assess the machine behaviour in regards to accepting the trajectory type.

Second, if the machine starts to follow trajectory, the testing station should record every event and machine behaviour.



Key

A, B, C, D, E, F, G, H	parcel characteristic points
AG	overall parcel width
←	trajectory type

Figure D.8 — Trajectory type for edge crossing tests

D.3.8 Measurement and devices

Velocity is measured from start to stop. Machine independent measuring system is used. Sensor technologies used should guarantee the quality of the measurements performed (e.g. laser measurement system).

Evolution edges position is measured before test with the same geographical reference than the one used to track machine.

D.3.9 Acceptance criteria

In addition to the performance criteria set by the manufacturer, the machine and its autonomous operating zone system should fulfil at a minimum the following conditions after completion of the two tests.

a) Machine should remain in the evolution area without ever crossing over any evolution edge. The whole machine is considered (including the implements) for non-crossing (at all points of the machine).

b) Machine should reconfigure itself in the safe state mode described in the machine operator's manual in case of losing control leading to cross over any evolution edge and exiting out of the evolution area (Example: uncontrolled slip as in the end of the edge crossing test, external system that keeps the machine from exiting).

c) For the edge crossing test the test result is considered as acceptable if:

   1) the machine stops before crossing over evolution edge;

   2) the machine and its information technology system reject the possibility to perform trajectory tracking after analysis and detection of a crossing between the theoretical trajectory and evolution edges.

D.4 Example test procedure for semi-autonomous and autonomous tractors (origin: NARO test methods[32])

NOTE Test procedure applicable for obstacle protective systems which prevent contact with obstacles only. The test procedures have been consolidated for the purpose of listing in this document.

D.4.1 Overview

The methods and criteria of this test are applied to an agricultural tractor (riding type) (hereinafter referred to as tractors) that autonomously operates in an agricultural field without an onboard operator but is subject to the supervision of the operator located in or near the field.

D.4.2 Test items

The test is conducted on the following inspection and test items:

a) structural inspection;

b) manual mode function test;

c) operation state indication function test;

d) person/obstacle detection function test;

e) other necessary safety function test;

f) operability test;

g) optional test: person/obstacle detection function test (on starting)

D.4.3 Test conditions

D.4.3.1 Measuring instrument

Measuring instruments shall be verified and corrected.

D.4.3.2 Discontinuation of test

The inspection and test shall be discontinued for the following occasions:

a) When the tractor to be inspected is different from its normal state (the state in which the tractor and its implement have been manufactured as designed and the quality is guaranteed), or when a proper inspection or test cannot be performed due to the occurrence of damage, abnormality, etc.

   Notwithstanding above, inspection and test can be continued when the inspecting agency recognizes that the reason for the damage/abnormality cannot be attributed to the applicant, or that the damage/abnormality is a minor, and by replacing parts, a proper inspection or test can be promptly continued.

b) An occasion the applicant requests to discontinue the inspection and/or test.

D.4.4 Inspections and test methods

D.4.4.1 Structural inspection

D.4.4.1.1 Purpose

This inspection checks the equipment required for autonomous operation.

D.4.4.1.2 Inspection and test items

a) Autonomous mode/manual mode switching device.

b) Indicator displaying the operation state (hereinafter referred to as the indicator).

c) System required for the autonomous operation.

d) Function to prevent exceeding the operation zone.

e) Other necessary equipment, etc.

D.4.4.1.3 Test acceptance

Equipment necessary for the autonomous operation is installed, and the equipment that requires operator's inputs for operation is positioned so that it can be safely and easily handled by the operator in the normal working position. In addition, the functions and operation methods of the equipment are indicated. Furthermore, the tractor shall have a function to remain inside the operation zone during autonomous operation including the implement attached to it.

D.4.4.2 Manual mode function test

D.4.4.2.1 Purpose

This test checks the tractor's behaviours in the autonomous operation disabled state.

D.4.4.2.2 Test conditions

a) The tractor shall be placed on a flat and paved surface.

b) The test shall be conducted with the tractor parked.

D.4.4.2.3 Test method

Check behaviours of the tractor in the manual mode when the operator instructs it to start autonomous operation.

D.4.4.2.4 Test acceptance

The autonomous operation cannot be started in manual mode.

D.4.4.3 Operation status indication function test

D.4.4.3.1 Purpose

This test checks that the indicators of the tractor's operation state clearly display the relevant information at the operator's position.

D.4.4.3.2 Test conditions

a) The tractor shall be placed on a flat and paved surface.

b) The test shall be performed on a parked or operating tractor in autonomous mode.

D.4.4.3.3 Test method

a) Check the indication when the tractor is in autonomous operation state.

b) Check the indication when the tractor is in autonomous operation enabled state.

c) Check the indication when the tractor is in autonomous operation disabled state.

D.4.4.3.4 Test acceptance

The state of the tractor is indicated correctly, and the operator can easily recognize the state of the tractor.

D.4.4.4 Person/obstacle detection function test

D.4.4.4.1 Purpose

This test checks that the tractor detects a person or an obstacle approaching without contact in autonomous operation. And warns people in the surroundings and stops autonomously.

D.4.4.4.2 Test conditions

a) The tractor shall be placed on a flat and paved, dry surface.

b) The test shall be performed with the tractor moving (permissible maximum speed) in autonomous mode.

c) The test obstacle shall conform with Annex C.1.

d) The test obstacle shall be placed, both in front or behind the tractor, on the centre line of the roll axis direction of the tractor (hereinafter referred to as the centre line) as well as the straight lines parallel to the centre line passing through the outermost side of the tractor including the implement that the applicant mounts (See Figure D.9).

D.4.4.4.3 Test method

a) Test in the warning zone

   1) With the test obstacle placed in front of the tractor, as the tractor moves forward, check behaviours of the tractor when the test obstacle enters the warning zone.

   2) With the test obstacle placed behind the tractor, as the tractor moves backward, check behaviours of the tractor when the test obstacle enters the warning zone.

b) Test in the hazard zone

   1) With the test obstacle placed in front of the tractor, as the tractor moves forward, check behaviours of the tractor when the test obstacle enters the hazard zone.

   2) With the test obstacle placed behind the tractor, as the tractor moves backward, check behaviours of the tractor when the test obstacle enters the hazard zone.

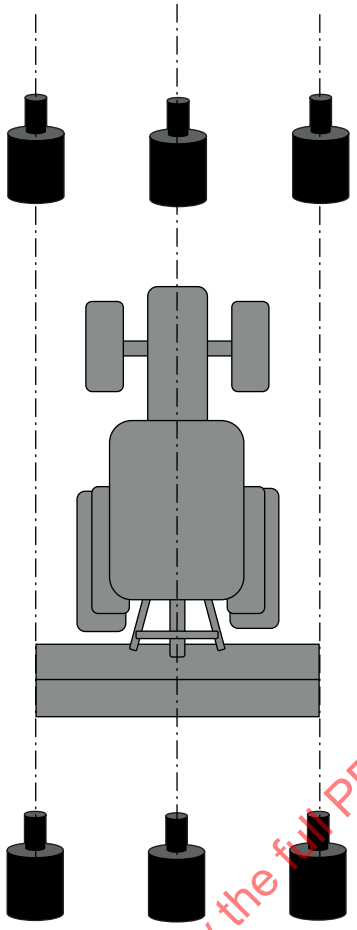


Figure D.9 — Relative positions of the tractor and test obstacle

D.4.4.4.4 Test acceptance

a) A warning signal shall be issued.

b) The tractor and its implement must not come into contact with the test obstacle. Also, the tractor and its implement shall stop.

D.4.4.5 Other necessary safety function check

D.4.4.5.1 Purpose

This test checks the operability of the pendant control device, etc., and safety functions in case of a communication failure.

D.4.4.5.2 Test conditions

a) The tractor shall be placed on a flat and paved surface.

b) The test shall be performed on the tractor in the autonomous mode, parked, and in operation.

D.4.4.5.3 Test method

a) Check the procedure to start the autonomous operation.

b) Check tractor's behaviours when the operator instructs the tractor in the autonomous operation to stop.