

Road-testing of the braking performance of agricultural vehicles

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ABSTRACT

According to Delegated Regulation (EU) 2015/68, the braking performance of agricultural vehicles is determined through road tests. Trailer braking performance is evaluated based on either the braking of the entire combination with coupling force measurement or the trailer's individual braking. In the first case, the braking performance of the combination is influenced by driver behaviour and transient processes within the tractor and trailer braking systems (e.g., pressure values and pneumatic lag). The same applies when trailer brakes are engaged using a hand-brake valve. To reduce the impact of random factors, an innovative device has been developed that simulates the pneumatic control system of the tractor, allowing the trailer to brake independently of the tractor. Along with other measuring devices, this simulator forms the measuring and diagnostic system created by the authors for roadside vehicle testing. The simulator enhances the accuracy and repeatability of measurements. Sample results from road tests of a prototype trailer and tractor were included.

Keywords: agricultural vehicle, braking, performance, test, simulator.

INTRODUCTION

Agricultural vehicles are not principally designed for road transportation purposes [1], but are nevertheless often used on public roadways to transport goods from the farms to the markets or distributors [2]. On individual farms in Poland, the share of tractor-trailer combinations in transporting all goods is about 80% [3, 4]. The tractor-trailer combinations are the longest and relatively heavy combinations encountered in traffic, the passage of which does not require any permission from the road manager. In the case of a two-axle combination, the overall length can be up to 18.75 m, while in the case of a tractor with two trailers, it can be up to 22 m. The maximum gross vehicle weight of a four-axle tractor combination can be up to 32 t; with more axles, it can be up to 40 t [5, 6]. In addition, agricultural vehicles and machinery are characterised by their relatively high rigidity and incompatible design with other vehicles or road users [7]. The large length and weight of tractor-trailer combinations,

combined with their relatively slow speed and driving dynamics, pose several risks to the flow and safety of regular traffic, which can lead to risky situations and cause fatal crashes [1]. Recent studies in the United States suggest that severe crashes involving agricultural vehicles are nearly five times more common than the average for all road crashes [1, 8].

Dual-line pneumatic or hydraulic braking systems are typically used on trailers and towed agricultural machinery. Despite their disadvantages, pneumatic braking systems are technologically mature [9] and are used on recently manufactured trailers and towed farm machinery in many EU countries. Overrun (mechanical) brakes are also permitted on trailers and towed machinery with a gross vehicle weight of less than 8 tonnes, travelling at a speed of up to 40 km/h. At higher speeds, the weight of towed vehicles with overrun brakes is limited to 3.5 tonnes. Much greater variation in the design of friction brakes and brake control mechanisms is found in agricultural tractors, where mechanical, pneumatic and hydraulic

systems are used [10, 11]. Irrespective of the type of service brakes used, tractors are equipped with a pneumatic system [9] to actuate the air braking systems of towed trailers and agricultural machinery. Depending on how the service brakes of a tractor are actuated, a suitable trailer brake control valve [9] is used in the tractor pneumatic system.

For road safety reasons, the braking systems of farm vehicles must meet many requirements stipulated in the Delegated Regulation (EU) 2015/68 [12]. Before any tests can be conducted, the system must be checked for leaks, and the actuators as well as load-dependent brake regulators must be adjusted. The static and dynamic properties of the air braking system of the tractor and trailer, relevant to the interaction within the combination, shall be examined in stationary tests. For type-approval, the compressor capacity and air reservoir capacity of the tractor and trailer are tested [12]. These determine the operation of the trailer air supply unit and ensure sufficient efficiency for repeated braking. In the case of control units, the speed of their operation is checked by measuring the response time of the tractor control line and the response time of the trailer braking system. Inappropriate braking of the tractor-trailer combination caused by the longer reaction time of the air transmission can result in severe road accidents [13, 14].

In stationary tests, the assessment of the compatibility of the tractor and trailer braking systems can also be made by the determination of the braking characteristics on a roller brake tester by the brakes being applied successively on all axles and the pressure in the trailer brake control line being measured [15]. Regulation 2015/68/EU [12] requires the braking characteristics of the towing and towed vehicles (both laden and unladen) to fall within the prescribed tolerance zones, known as ‘compatibility bands’ or ‘compatibility corridors’. These zones are defined by the curve showing the relationship between braking rate and pressure at the control coupling head.

The braking performance of farm vehicles undergoing type approval is ascertained through road tests [16, 17]. The performance of the parking system is based on its ability to keep the vehicle stationary on gradients of 18% uphill and downhill. By contrast, the recommended effectiveness of service and emergency braking systems is based on either stopping distance or mean fully developed deceleration (MFDD), or both [12]. The stopping distance is the distance

travelled by the vehicle from the moment the driver presses the brake pedal until it comes to a complete stop from its initial speed. This distance is affected by the technical condition of the braking system, as well as by road and weather conditions. It should be noted that the successful implementation of type-approval activities involves several challenges and is rather difficult. The condition of the brakes depends, among other things, on the bedding procedure (lack of standardisation) and the accuracy of adjusting the stroke of brake chambers. A very important factor affecting the friction properties of brakes is the temperature of the brake mechanisms, which changes during testing. The critical issue in trailer testing is to ensure the correct interaction of the tractor-trailer brakes (compatibility) [15]. Furthermore, to ensure an adequate distribution of braking forces, the axle loads and the centre of gravity height must correspond to the permissible values set out in the technical specifications for the vehicle in question.

The braking performance of tractors can be described in terms of stopping distance and/or MFDD. The results of braking deceleration tests conducted on two farm tractors under different road conditions were described in [18]. The performance of trailer service and emergency braking systems is defined by a braking rate, calculated as the ratio of MFDD to ground acceleration expressed as a percentage. MFDD is calculated using the distance travelled when the vehicle brakes from 80% to 10% of its initial speed [12]. The braking rate of the tractor-trailer combination is then converted to that of the trailer alone, taking into account the force in the coupling or the masses of the tractor and trailer [12], depending on the measurement method.

In the first method, the braking rate of the trailer is determined by the braking rate of the combination, adjusted by the force in the coupling divided by the total normal road reaction on all the wheels of the towed vehicle. Both the tractor and the trailer are braked. A device for measuring the longitudinal force in the coupling between the vehicles is essential equipment here [19]. It should be noted that the performance of braking systems depends on many stochastic factors [20]. The intensity with which the driver presses the brake pedal as well as the pressure variations in the tractor and trailer braking systems affect the braking of the combination, causing discrepancies in the measurement results.

In the second method, only the towed vehicle is braked, and the braking rate is calculated from the measured braking rate of the combination, considering the ratio of the weight of the entire combination to the total static reaction of the towed vehicle on all wheels. The second method, being more universal and applicable to both trailers and semi-trailers, inspired the authors to develop a measurement and diagnostic system for performing braking tests on agricultural vehicles. To brake the trailer (towed agricultural machine) without using the tractor brakes, an innovative device was employed to simulate the control unit of the tractor pneumatic system [21]. The simulator guarantees the repeatability of the trailer brake control pressure waveform, thereby enhancing the precision and consistency of the braking process measurements in comparison with the first method. Furthermore, using a simulator to measure trailer braking performance removes the effects of the driver's behaviour as well as incompatibility between the tractor and trailer braking systems on the braking process. The computer programme for controlling the measurements and generating test reports facilitates the operation of the developed device. An advanced version of this device also allows stationary testing of the trailer braking system, including measuring leaks, checking response time and air reservoir capacity [22]. The methodology for carrying out such tests was described in [23]. Using a universal device for both stationary and road tests reduces the time taken for testing and lowers costs.

The advantage of the developed measurement and diagnostic device is the possibility of implementing various instruments for measuring the parameters of the braking process, including an optical Correvit sensor, a GPS converter, a fifth wheel, and an electronic decelerometer. The developed device is easy to operate, as the course and acquisition of measurements are controlled by a computer programme. The focus of this work was the description of the simulators that activate trailer brakes during road tests, as there are no existing reports on the design of such devices in the literature. This work may be useful for vehicle type approval test institutes, particularly for manufacturers of trailers and towed agricultural machinery with air braking systems.

BRAKING PERFORMANCE OF AGRICULTURAL VEHICLES

Determining braking performance indices

EU Delegated Regulation 2015/68 outlines the manner and conditions under which tests are to be conducted, as well as the minimum requirements for the performance of the braking system across various categories of agricultural vehicles. The performance of the braking system is assessed by determining the stopping distance of a vehicle from a given initial speed and/or MFDD achieved during the test. The stopping distance is the distance travelled by a vehicle from when the driver begins to engage the brakes to when the vehicle comes to a complete stop. The initial speed v_0 at which the driver begins to apply the brakes must be no less than 98% of the speed specified for the test.

As it is difficult to achieve an exact value of the initial speed during road tests, the corrected value of the stopping distance s_c can be calculated according to the relationship [24]:

$$s_c = s_m \frac{v_0^2}{v_m^2} \quad (1)$$

where: s_m – measured stopping distance [m], v_0 , v_m – required and measured initial speed before brake application [m/s].

The mean fully developed deceleration d_m [m/s^2] is given by the average reduction in speed from v_b to v_e divided by the distance travelled in that time (Figure 1a):

$$d_m = \frac{v_b^2 - v_e^2}{25.92(s_e - s_b)} \quad (2)$$

where: v_b – vehicle speed corresponding to $0.8 v_0$ [km/h], v_e – vehicle speed corresponding to $0.1 v_0$ [km/h], s_b – distance travelled between v_0 and v_b [m], s_e – distance travelled between v_0 and v_e [m].

Speed and distance shall be measured with instruments having an accuracy of $\pm 1\%$ at the speed prescribed for the test. The value of d_m may be determined using methods other than measuring speed and distance, in which case the accuracy of the d_m measurement shall be within $\pm 3\%$.

When measuring deceleration over time (Figure 1b), the average deceleration is calculated over the time interval from t_b to t_e , the limits of which are calculated according to ISO/TR 13487 [25]:

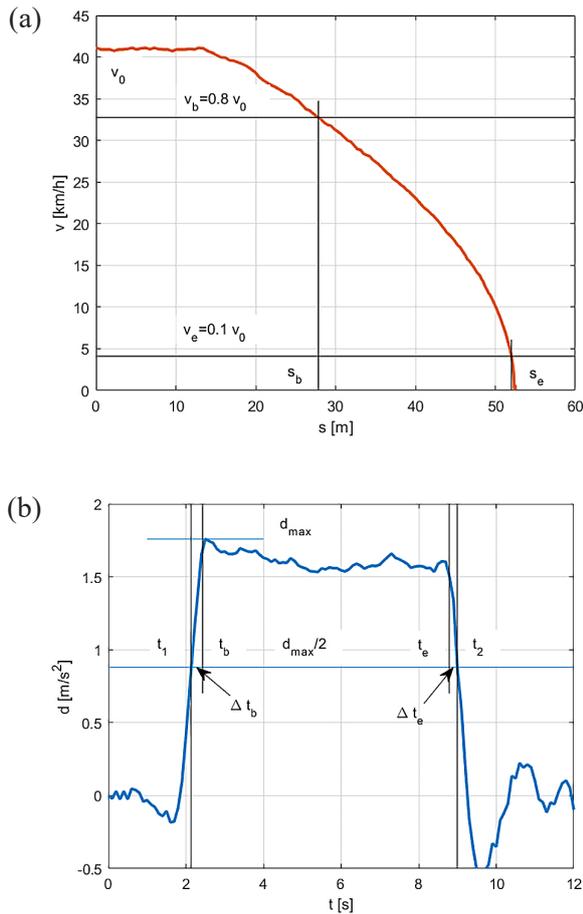


Figure 1. Methods for determining the MFDD:
 a) According to Delegated Regulation (EU) 2015/68 [12];
 b) According to ISO/TR 13487 [25]

$$t_b = t_1 \left(\frac{d_{max}}{2} \right) + \Delta t_b \quad (3)$$

$$t_e = t_2 \left(\frac{d_{max}}{2} \right) - \Delta t_e \quad (4)$$

where: t_1, t_2 – time at which the deceleration value is equal to half the maximum deceleration d_{max} (Figure 1b), Δt_b – time interval of 0.3–0.4 s, Δt_e – time interval of 0.1–0.2 s.

The braking deceleration in the time interval from t_e to t_b is calculated by numerical integration according to the formula given in the standard. In a simplified version, where the deceleration curve in the interval from t_b to t_e is replaced by a linear approximation, MFDD is estimated according to the following relationship:

$$d_m = 0.75 \cdot \frac{(d_e + d_b)^2}{2 \cdot d_e + d_b} \quad (5)$$

where: d_b – deceleration read from the linear approximation for time t_b , d_e – deceleration read from the linear approximation for time t_e .

From MFDD, a braking rate is calculated as the basis for evaluating the vehicle performance:

$$z = \frac{d_m}{g} 100\% \quad (6)$$

where: z – braking rate, g – gravitational acceleration.

EU Directive 2015/68 does not specify the required number of road test repetitions. According to the Polish standard PN-76/S-47000 [26], the result should be taken as the average of two consecutive measurements taken in both directions on the same section of road. However, it should be noted that increasing the number of measurements reduces error when assessing braking effectiveness. Due to the labour intensity and costs of road tests, it seems that four repetitions can be recommended as reasonable.

Braking performance requirements for agricultural vehicles

The requirements described in Delegated Regulation (EU) 2015/68 [12] apply to vehicles classified in the corresponding category. According to the classification set out in Directive 2003/37/EC of the European Parliament and of the Council [27], the following categories of agricultural vehicles are distinguished:

- Category T and C: wheeled and track-laying tractors. Qualification for categories T1 to T5 and C1 to C5 shall be determined by technical characteristics such as unladen mass, track width, ground clearance, height of gravity centre and maximum design speed;
- Category R: trailers of different gross weights, which are divided into subcategories R1, R2, R3 and R4;
- Category S: interchangeable towed machinery for use in agriculture and forestry, including subcategories S1 and S2 according to technically permissible mass.

In addition, R and S category vehicles are identified by the letter “a” if their maximum design speed is 40 km/h or less, and with the letter “b” if this speed is greater.

A general classification of road tests for agricultural vehicles according to the EU’s Delegated Regulation 2015/68 is shown in Figure 2.

Typically, the tests are performed in the order of the block numbers. Examining the service brakes of agricultural vehicles involves four tests. The most important of these is the cold brake performance test, which marks the beginning of the braking approval process. Other tests on service brakes for a given category of vehicle are carried out in the same way, but the preparation for the tests (warm-up) and the requirements placed on the brakes are different.

Type-0 test

Normal cold performance test for vehicles in categories T, C, R and S. Brakes are considered ‘cold’ if the temperature measured at the disc or outside the drum is below 100 °C, or if the housing temperature of fully enclosed brakes is below 50 °C. The required stopping distance and MFDD for tractors, as well as the braking rates

for towed vehicles, for the Type-0 basic test are outlined in Table 1.

The expressions used in Delegated Regulation (EU) 2015/68 to define the maximum permitted stopping distance (Table 1) are based on a simplified two-phase braking model. In this model, the quasi-linear phase of braking deceleration build-up is split equally between the constant speed (zero deceleration) phase and the fully developed deceleration phase. The stopping distance is then described by the relation [28]:

$$s = \frac{v_o}{3.6} \cdot (t_o + 0.5t_n) + \frac{1}{2} \frac{v_o^2/3.6^2}{d_m} \quad (7)$$

where: t_o – braking system response time (brake application time), t_n – braking deceleration rise time.

The brake application time is calculated from the moment force is exerted on the brake pedal until deceleration occurs. This time depends on the design features and condition of the braking

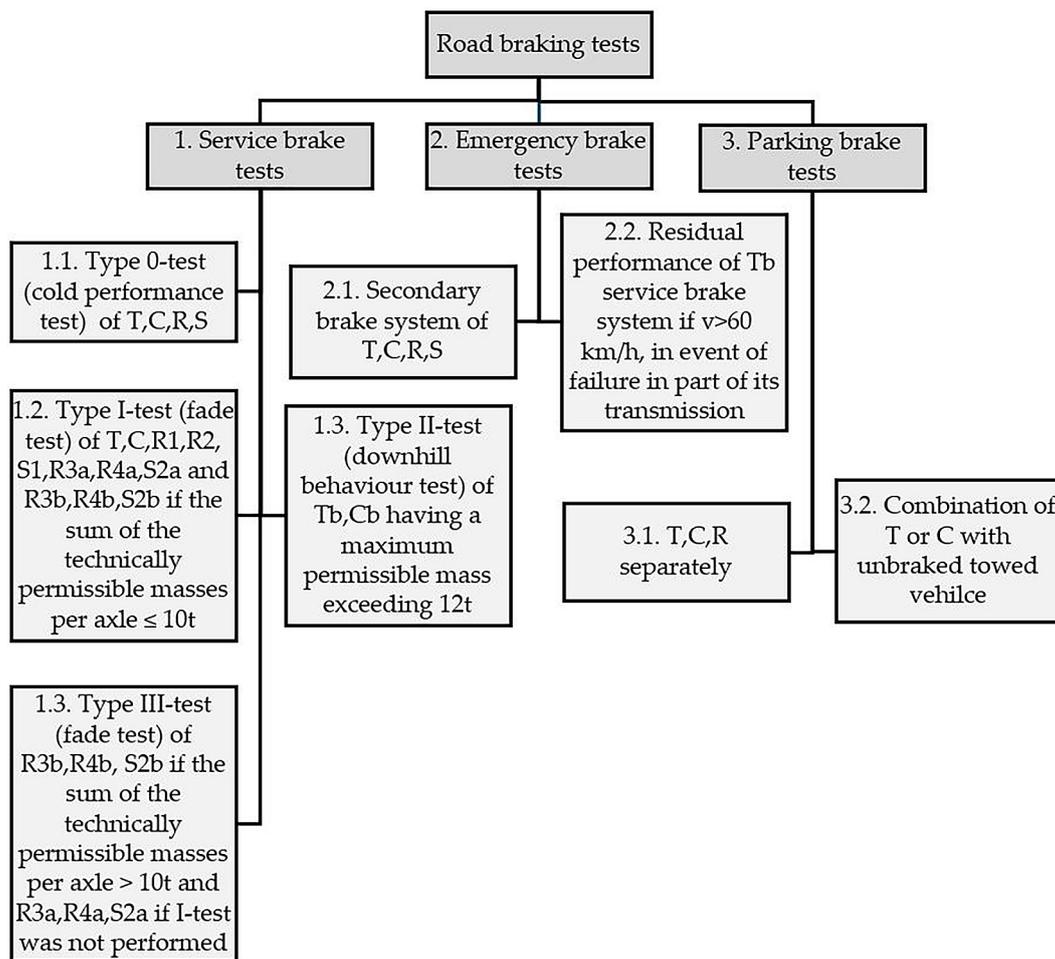


Figure 2. General classification of road tests for agricultural vehicles

system. Adding more components to the braking system or increasing the length of lines in pneumatic and hydraulic systems increases the brake application time. The deceleration rise time is calculated from the moment the friction elements make contact until intentional braking deceleration is reached. This time depends on the intensity with which the driver presses the pedal and the transition processes in the braking system.

Type-I test

Performance test (under the same conditions as the Type-0 tests) after the brakes have warmed up (fade test). The brakes of vehicles in categories T and C shall be warmed up by repeated application and release. Vehicles in categories R and S undergo brake warming through continuous braking.

For motor vehicles, the hot performance shall be at least 80% of the level specified for the relevant category, or at least 60% of the level recorded in the Type-0 test with the engine unconnected. For towed vehicles, the braking performance at the wheel periphery when tested at 40 km/h shall not be less than 36% of the force corresponding to the maximum static wheel load with a maximum speed >30 km/h, or 26% for towed vehicles with a maximum speed ≤30 km/h. It shall also not be less than 60% of the value recorded in the Type-0 test at the same speed.

Type-II test

Test of the downhill behaviour of the Tb and Cb vehicles with a maximum permissible mass of more than 12 tonnes. The performance of the service braking system is examined (under the same conditions as for the Type 0 test) once the brakes have warmed up.

Table 1. Required braking performance indices for type-0 test of agricultural vehicles (F_p – pedal control force) [12]

T- and C-category vehicles		
Parameter	$v_{max} \leq 30$ km/h	$v_{max} > 30$ km/h
v_0 [km/h]	$\geq 0.98 v_{max}$	$\geq 0.98 v_{max}$
s [m]	$\leq 0.15v_0 + v_0^2/92$	$\leq 0.15v_0 + v_0^2/130$
d_m [m/s ²]	≥ 3.55	≥ 5
F_p [N]	≤ 600	≤ 600
R- and S-category vehicles		
Parameter	$v_{max} \leq 30$ km/h	$v_{max} > 30$ km/h
z [%]	≥ 35	≥ 50

Type-III test

Fade test for high-speed trailers and agricultural tractors in categories R3b, R4b and S2b where the sum of the technically permissible masses per axle exceeds 10000 kg; or in categories R3a, R4a and S2a, provided these vehicles have not been subjected to Type I testing. As in the Type-0 test, the performance of the service braking system is checked, but under different temperature conditions and from an initial speed of 60 km/h. With the brakes heated, the braking force at the wheel periphery shall not be less than 40% of the maximum static wheel load, nor less than 60% of the value recorded in the Type-0 test at the same speed.

Emergency brake test

The secondary braking system of vehicles in categories T and C must provide the required stopping distance and MFDD, even if the control that operates it is also used for other braking functions. Additionally, for category Tb tractors with a maximum design speed exceeding 60 km/h, the residual performance of the service braking system must be verified by simulating the failure of part of its transmission.

In the event of simulated damage (e.g. rupture) to one of the pneumatic pipes connecting the tractor with the loaded towed vehicle, the braking efficiency of the automatic system of vehicles of categories R and S at an initial speed of 40 km/h or $0.8 v_{max}$ (whichever is lower) must not be less than 13.5% of the maximum static wheel load. It is permissible to engage the wheel locking mechanism at an efficiency level that exceeds 13.5%.

Parking brake test

The braking system of agricultural vehicles, even when combined with an alternative braking system, must demonstrate the capability to immobilise the loaded vehicle on an 18% upward or downward gradient with both the brakes cold and hot (towed vehicle uncoupled from the tractor). For the tractors designed to tow vehicles, the tractor parking brake must be capable of holding the vehicle combination at its maximum permissible mass on gradients of 12%, as specified by the manufacturer.

DEVICE FOR TESTING THE BRAKING INTENSITY OF FARM VEHICLES, ESPECIALLY TRAILERS

As it was mentioned in the introduction, there are two acceptable methods for determining the braking rate of a towed vehicle. In the first method, the braking rate and coupling force of the tractor-trailer combination are measured. The braking rate z_R of the towed vehicle is then calculated using the following formula:

$$z_R = z_{R+M} \pm \frac{D}{F_R} \quad (8)$$

where: z_{R+M} – braking rate of the tractor plus the towed vehicle, D – thrust on the coupling ('+' when D is tractive, '-' when D is compressive), F_R – total normal static reaction on all wheels of a towed vehicle.

In the second method, the tractor rolls freely and only the towed vehicle is braked. The braking rate z_R of the towed vehicle is obtained using the following expression:

$$z_R = (z_{R+M} - R) \frac{F_M + F_R}{F_R} + R \quad (9)$$

where: z_{R+M} – braking rate of the tractor plus the towed vehicle, R – rolling resistance value: $R = 0.02$ when $v_{max} \leq 40$ km/h, $R = 0.01$ when $v_{max} > 40$ km/h, F_M – total normal static reaction on the wheels of the tractor, F_R – total normal static reaction on all wheels of the towed vehicle.

The main merit of this method is that it can be used for towed vehicles with different chassis designs (trailers, semi-trailers). The initial speed should be equal to the maximum design speed of the towed vehicle, but not more than 60 km/h. During braking, the pressure in the supply line must not surpass 7 bar, and the pressure in the control line must not surpass 6.5 bar. Since the service braking system of the tractor is inactive, the air braking system of the trailer can be controlled using either a handbrake valve or a device that simulates the air braking system of the tractor.

A special measuring and diagnostic device have been developed to check the braking performance of tractors and agricultural trailers with air braking systems in a road test. The device consists of:

- A tractor braking system simulator, which enables the trailer to brake independently of the towing vehicle;
- A control unit with a data acquisition card featuring analogue inputs for connecting transducers and digital outputs for controlling the pneumatic valves of the simulator;
- An input/output adapter, which is designed to supply the measurement equipment and the pneumatic valves of the simulator, collect voltage signals from the measurement transducers, and transmit them to the control unit;
- A device for measuring the following time courses: deceleration; speed or distance travelled during braking of an agricultural tractor; force on the brake pedal; pressure at selected points of the pneumatic braking system of the trailer; and piston rod travel of the brake actuator;
- A laptop computer with a program for controlling the diagnostic session, recording measurements, calculating deceleration and braking rates, assessing pneumatic braking system performance, graphing results and printing test reports.

A schematic diagram of such a device in the version for stationary and road testing of agricultural vehicles [22] is shown in Figure 3. The simulator is connected to the SH and CH coupling heads of the tractor CSDT combined single and dual line braking system. The desired pressure in the 30-litre air reservoir R, as measured by the pressure gauge M and the pressure transducer PT1, is set by opening the reservoir inlet or outlet via a three-way, three-position solenoid valve SV1 (3/3).

Solenoid valve SV2 (3/3) supplies compressed air to the trailer braking system under test when voltage is applied to the left coil of the valve (right override). When voltage is applied to the right coil of this valve (left overdrive), the supply line is vented, and the automatic trailer brake is applied. During the road tests, the trailer service brakes are applied using a monostable OS switch, which is operated from the tractor cab and overrides a direct-acting SV3 three-way two-position solenoid valve (normally closed, or NC). Compressed air with an initially set pressure of 6.5 bar flows from the R reservoir of the simulator's to the trailer control line, causing the trailer to brake. The velocity of the pressure signal from the simulator controlling the trailer brakes is

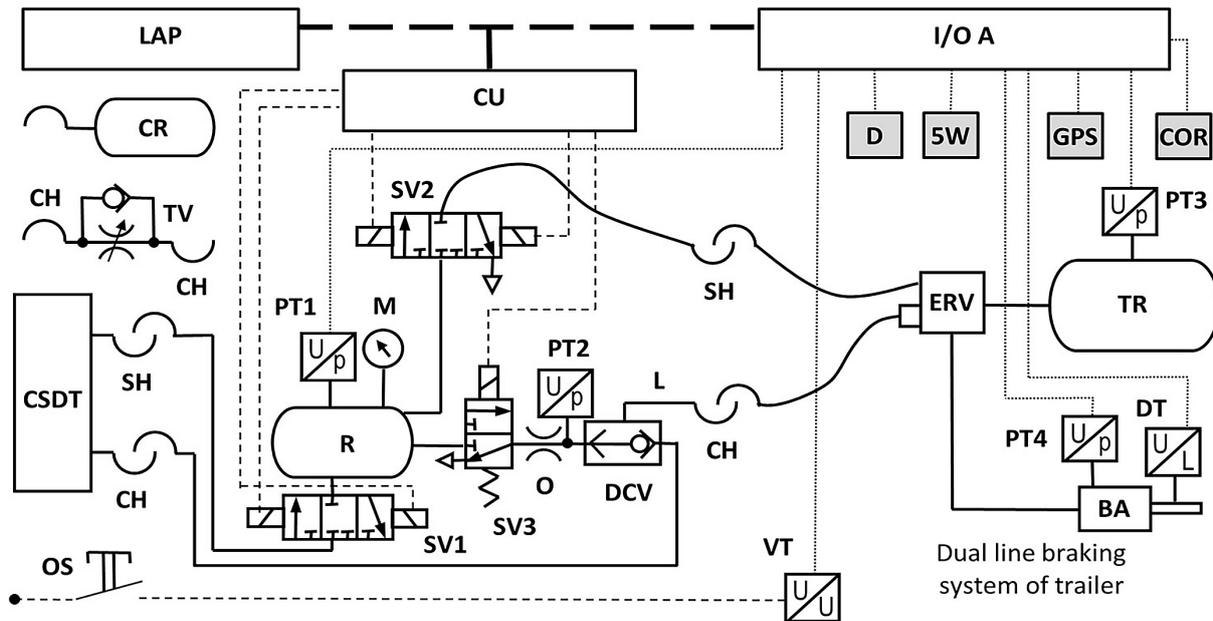


Figure 3. Schematic diagram of a device for diagnosing dual-line air brake systems of trailers and towed agricultural machinery in road and stationary tests: BA – brake actuator, CH – control coupling head, COR – Correvit optical sensor, CSDT – combined single and dual line system of tractor brakes, CR – calibration reservoirs with volumes of $385 \pm 5 \text{ cm}^3$ and $1155 \pm 15 \text{ cm}^3$ respectively with CH head, CU – control unit, D – decelerometer, DCV – double check valve, DT – displacement transducer (line encoder), ERV – emergency relay valve, GPS – GPS converter, I/O A – input/output adapter, L – line from orifice O to CH coupling head, with an internal volume of $385 \pm 5 \text{ cm}^3$ at 6.5 bar, LAP – laptop, M – pressure gauge, O – calibrated orifice, OS – on/off switch or BP tractor brake pedal in the case of tractor-only braking test, PT_i – i-th pressure transducer, R – air reservoir of 30 litres capacity, SH – supply coupling head, SV1, SV2 – solenoid valve 3/3, SV3 – solenoid valve 3/2 (NC) with direct action, TR – trailer air reservoir, VT – voltage transducer or force transducer on brake pedal FT in case of tractor-only braking, 5W – fifth wheel

determined by the orifice passage O. This shall be selected experimentally in a calibration procedure using a PT2 pressure transducer and calibration reservoirs CR of $385 \pm 5 \text{ cm}^3$ and $1155 \pm 15 \text{ cm}^3$, respectively, which are connected to the control line. This calibration tests the braking system response time under steady-state conditions to obtain the required reproducible rate of rise of the pressure control signal. The length of the control line L is determined by the test requirements of the simulator reaction time. If the trailer brakes too hard during the road test, a TV throttle/return valve should be fitted between the simulator and the control line of the trailer braking system.

For safety reasons, a DCV double check valve is fitted immediately after orifice O and pressure transducer PT2, allowing the driver to brake the tractor-trailer combination at any time. Pressure transducers PT3 and PT4, and displacement transducer DT were fitted for stationary tests to check the leakage, response time and capacity of the TR trailer air reservoir. The methodology for

carrying out such tests is described in [23]. During these tests, the CU control unit activates the solenoid valves (including the SV3 valve) based on signals generated by the digital outputs of the DAQ board, which have been amplified by the I/O A adapter. A study carried out in [23] showed that the difference in mean trailer response time obtained from 15 measurements taken using two different simulators was just 0.0004 seconds. Both simulators were built on the same concept and with the same critical components (valves). The results of the Welch's t-test and Mann-Whitney-Wilcoxon test confirmed that the observed difference between the two means is not statistically significant at a 0.01 level of confidence. This demonstrates the ability of the simulator to generate highly repeatable pressure waveforms for trailer braking control.

The reservoir supply and control pressure of the simulator can be determined before the test, and the rate of pressure rise in the control line can be established. This reduces the influence

of random factors on the trailer braking performance, including the driver’s behaviour and the variability of pressure in the trailer braking system. Compared to a method in which both the tractor and trailer are braked, this improves the repeatability and accuracy of trailer braking measurements. Additionally, there is no need for extra equipment to measure the force in the coupling. Controlling the course of measurement with a computer programme facilitates the operation of the developed device.

Developed according to [21], Figure 4 shows a schematic of a simplified version of the simulator designed for braking towed vehicles in a road test only.

The trailer braking system is connected to a simulator supplied with compressed air from the tractor via the coupling heads SH and CH. To apply the trailer brakes, the driver presses the OS switch in the cab, which closes the electrical circuit of the coil of the three-way, two-position solenoid valve SV. Opening this valve allows air to flow into the trailer control line via the throttle valve TV and the CH coupling head.

An increase in pressure on the trailer control line overrides the ERV emergency relay valve and activates the trailer brakes. Compressed air then flows from the TR reservoir to the BA brake actuator on the trailer, causing it to brake when the tractor brakes are not applied. When pressure

is removed from the SO switch, the SV solenoid valve is reset to its initial position. This vents the control line and releases the trailer brakes. The TV throttle valve is used to regulate the braking rate and allows the trailer control line to be freely vented when the trailer brakes are released. A CR reservoir is used to calibrate this valve. With the DCV double check valve connected to the tractor control bus (CH head), the driver can brake all the vehicles in the combination in an emergency. The main inconvenience of using the simulator in the simplified version is that the desired supply pressure (7 bar) and control pressure (6.5 bar) cannot be accurately set before braking, which affects the repeatability of the measurements.

Several devices (highlighted in grey in the diagram) may be used to measure the braking parameters of agricultural vehicles. These include a D electronic decelerometer, a 5 W fifth wheel with a rotating pulse sensor, a GPS converter and a Correvit COR optical sensor. Testing the braking performance of agricultural tractors does not require connection of the simulator or the pressure transducers PT3 and PT4, or the displacement transducer DT, greatly simplifying test preparation. The force transducer on the brake pedal FT is connected instead of the voltage transducer VT. In the diagrams (Figures 3 and 4) the OS switch then indicates the tractor brake pedal BP.

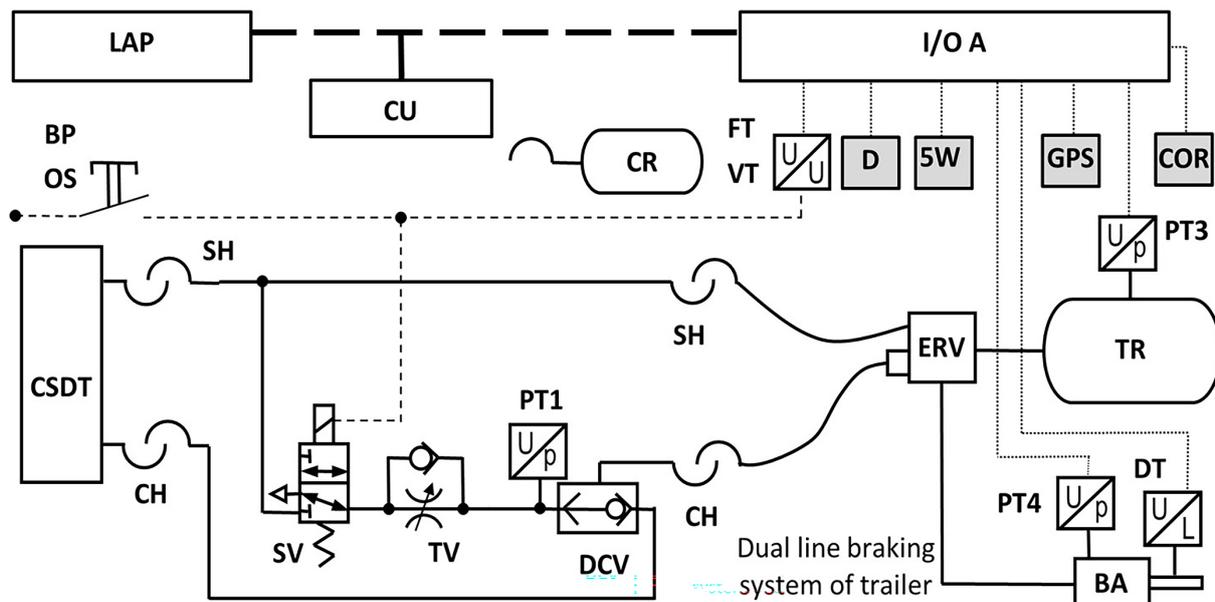


Figure 4. Schematic diagram of the simplified simulator according to [21]: BP – brake pedal, FT – brake pedal force transducer, SV – solenoid valve 3/2 (NC) for trailer brake actuation, TV – throttle and check valve (other markings as in Figure 3)

ROAD TEST EXAMPLES

The road tests of braking performance were carried out on prototype agricultural vehicles, including a 12-tonne trailer and a 26-kN tractor. The tests were carried out on a straight section of asphalt road in compliance with the general test conditions described in the Polish standard PN-76/S-47000 [26]. The road tests on the trailer were conducted to determine the stroke length and effective area of the actuators, as well as the length of the slack adjusters. A prototype simulator based on the concept shown in Figure 4 was used to brake the trailer connected to the tractor. This simulator enables the control of the trailer braking system without activating the tractor's service brakes. The tests involved measuring the stopping distance and deceleration of the tractor-trailer combination, as well as measuring the pressure at the control coupling head, the pressure in the trailer air reservoir and brake chamber of one axle, and the displacement of the brake chamber rod.

A portable Advantech USB-4716-AE data acquisition module mounted in the control unit (CU in Figure 4) was used to record the measurements. WIKAA-10 pressure transducers with a measurement range of 0÷10 bar and an output voltage of 0÷10 V were used to measure air pressure at selected points on the simulator and trailer (PT1, PT3, PT4 transducers in Figure 4). The stroke of the chamber piston rod was measured using a miniature D5.3501 cable encoder with a voltage output of 0÷10 V (transducer DT in Figure 4).

A '5-wheel' transducer (5W in Figure 4) based on the 2159 tachograph pulse transmitter was used to measure distance and speed. To increase the accuracy of the distance measurement, the rising and falling edges of the sensor pulse were used, giving 16 pulses per revolution. This resulted in an accuracy of distance measurements of approximately ±0.08 m. Braking deceleration was measured using an electronic decelerometer of authors' design (D in Figure 4), using the 3-axis accelerometer module MMA7361 with a measuring range of ±1.5 g/6 g, configurable via a DIP switch. The apparatus used to measure distance, speed, and deceleration are shown in Figure 5.

A performance test of the trailer braking system was carried out on cold brakes (Type 0 test), with a simulator attached to the drawbar (see Figure 6).

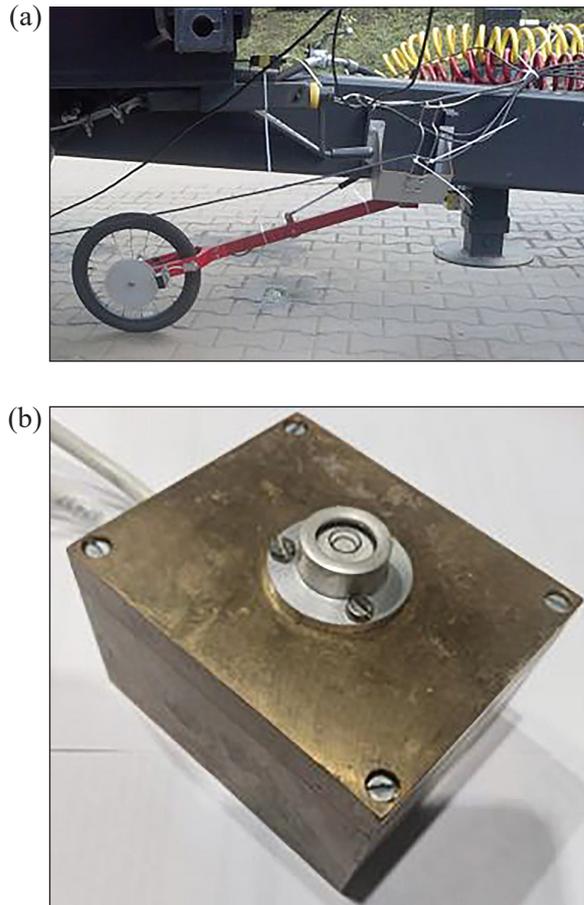


Figure 5. Measurement devices used in trailer road test: a) fifth wheel transmitter for measuring distance and speed; b) decelerometer for measuring brake deceleration

During the test, the tractor-trailer combination was accelerated to the maximum possible speed and then the trailer alone was braked at maximum intensity to a standstill, with signals recorded from the impulse-turn transducer (fifth wheel), decelerometer (longitudinal and vertical axis deceleration), pressure transducers, line encoder and voltage across the solenoid valve coil of the trailer air braking system control device.

Figure 7 shows an example of a trailer braking test result, including the time courses of deceleration d_f (measured by the decelerometer), speed v , distance s and voltage U controlling the solenoid valve. Figure 8 shows the measured voltage U (scaled to 5 V), which controls the solenoid valve, as well as the waveforms of the pressure p_c at the trailer control coupling, the pressure p_t in the trailer reservoir, the pressure p_b in the brake chamber and the stroke (L) of the brake chamber rod. These are shown over a 2-second period. The measurements were taken using voltage, pressure

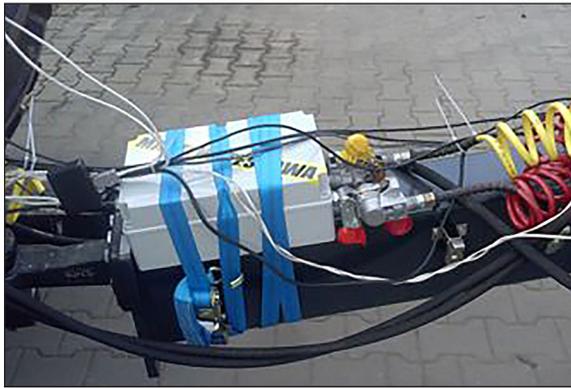


Figure 6. Mounting the tractor simulator on the trailer drawbar

and displacement measuring transducers installed in the simulator (Figure 4).

Five braking tests were completed at an initial speed v_0 of around 42 km/h. After two integrations of the decelerometer measurements, the time courses of speed and braking distance were obtained. From the time courses of distance $s(t)$ and speed $v(t)$, the mean fully developed deceleration from the fifth wheel d_{m5} and the decelerometer measurements d_{mf} were determined according to Equation 2, and then the braking rate of the vehicle combination z_{R+M} as well as the trailer braking rate z_R were calculated. The results of the trailer braking tests are summarised in Table 2.

The relative differences in deceleration measurement results obtained using the five-wheel method (d_{m5}) and the decelerometer method (d_{mf}) are insignificant and do not exceed the permissible measurement error of $\pm 3\%$. However, the braking rate values indicate that the test trailer does not achieve the assigned braking performance. It is therefore advisable to increase either the size of the brake chamber or the length of the slack adjuster arm span.

The GPS converter and electronic decelerometer described above were used to measure the braking parameters of an agricultural tractor. The converter (Figure 9a) is based on the UBX-G7020-KT GPS module and has a 56-channel receiver operating from 3.3 V to 5 V. The refresh rate of the GPS converter for speed measurement is 10 Hz, and the accuracy of the speed measurement is less than 0.1 m/s. At speeds below 36 km/h, the margin of error in the speed measurement is greater than the permitted 1%. A CL23 sensor from ZEPWN [29] with a measuring range of up to 1 kN was used to measure the brake pedal force, together with a signal amplifier with a voltage output of 0–10 V (Figure 9b).

Braking tests were conducted on cold brakes (Test-0) after the tractor had been accelerated to around 30 km/h. During the tests, the force applied to the brake pedal was recorded in order to determine the beginning of the

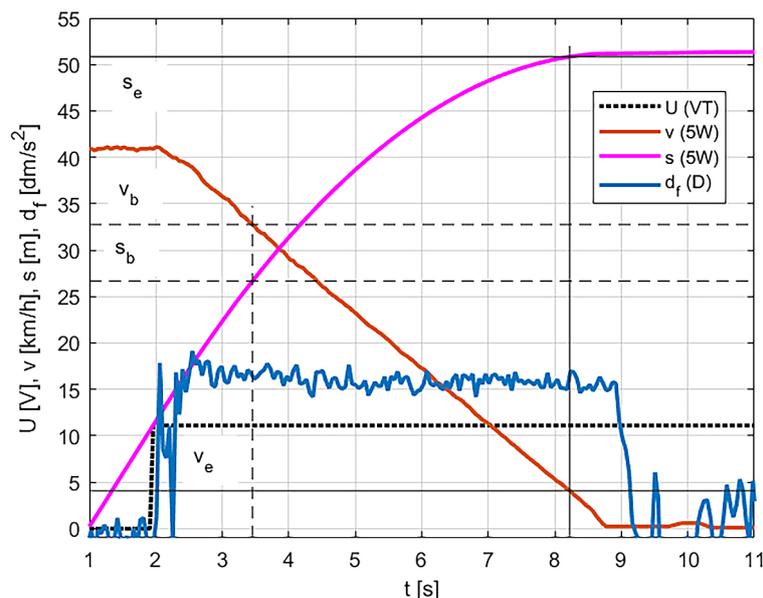


Figure 7. Trailer braking measurement: U – voltage on the solenoid coil, v , s – braking speed and distance measured with the fifth wheel, d_f – braking deceleration measured with the decelerometer (VT, 5W, D – measuring devices shown in Figure 4)

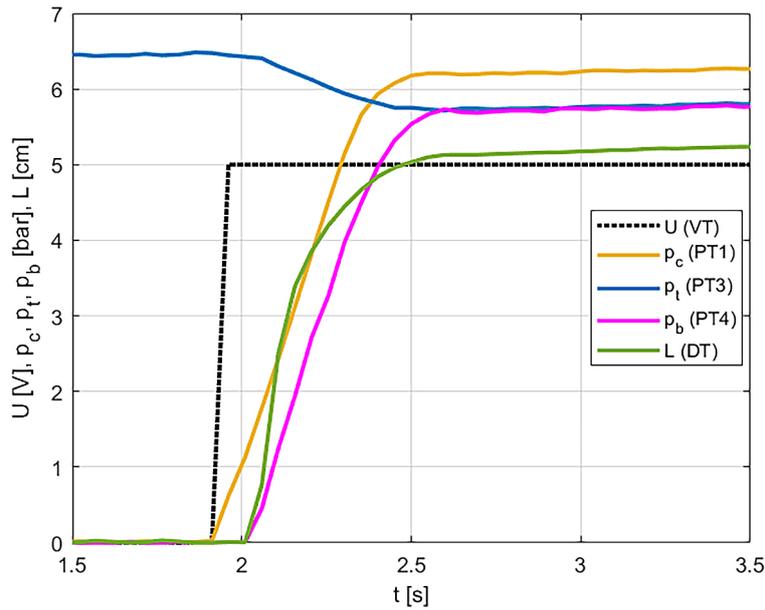


Figure 8. Variations in voltage U , pressure p_c at the trailer control coupling, pressure p_t in the trailer reservoir, pressure p_b in the brake chamber and stroke L of the brake chamber rod (VT, PT1, PT3, PT4 and DT – the measuring devices shown in Figure 4)

Table 2. Braking rates z_R of agricultural trailer in road tests (z_s – braking rate based on measurement from 5th wheel, z_f – braking rate based on measurement with decelerometer)

v_o [km/h]	d_{m5} [m/s ²]	d_{mf} [m/s ²]	z_s [%]	z_f [%]
41.9	1.74	1.77	30.6	31.0
41.3	1.70	1.73	29.7	30.4
41.7	1.75	1.73	30.6	30.4
42.0	1.72	1.76	30.1	30.9
42.2	1.71	1.69	29.9	29.6
Mean	1.72	1.74	29.9	29.6

stopping distance, as well as the driving speed and the deceleration. After integrating the measurements from the GPS transducer once and the measurements from the decelerometer twice, the time courses of speed and braking distance from both measuring instruments were obtained (Figure 10).

Roadside measurements were used to determine the stopping distance s_f and s_{GPS} calculated from the moment the brake pedal was depressed. From the time courses of the distances $s(t)$ as well as speeds $v(t)$, the mean fully developed deceleration d_{mf} and d_{mGPS} were determined according to Equation 2. In addition, the deceleration d_{mISO} was calculated by numerically integrating the deceleration time curve from the decelerometer. The values of the deceleration rates obtained from the three measurements are summarised in Table 3.

The resulting braking indices for the tractor are not conclusive. The average fully developed braking deceleration of d_{mf} and d_{mGPS} does not reach the value of 3.55 m/s² required for a slow-moving tractor according to (EU) 2015/68, while the deceleration of d_{mISO} calculated according to ISO/TR 13487 is higher than required. Nevertheless, the braking deceleration values determined using different methods vary only slightly, with their relative differences falling within the recommended deceleration measurement accuracy of $\pm 3\%$. The s_{GPS} and s_f stopping distances are also less than the maximum permitted 14.28 m, which proves that the braking requirements for cold brakes are met. As the initial driving speed achieved is higher than that declared for a slow-moving tractor, it would be appropriate to limit the maximum driving speed of the tractor to 30 km/h.



Figure 9. Measurement devices used in tractor road test: a) GPS converter built based on the UBX-G7020-KT GPS module; b) brake pedal force sensor CL23 from ZEPWN [29] together with a signal amplifier with a voltage output of 0–10 V

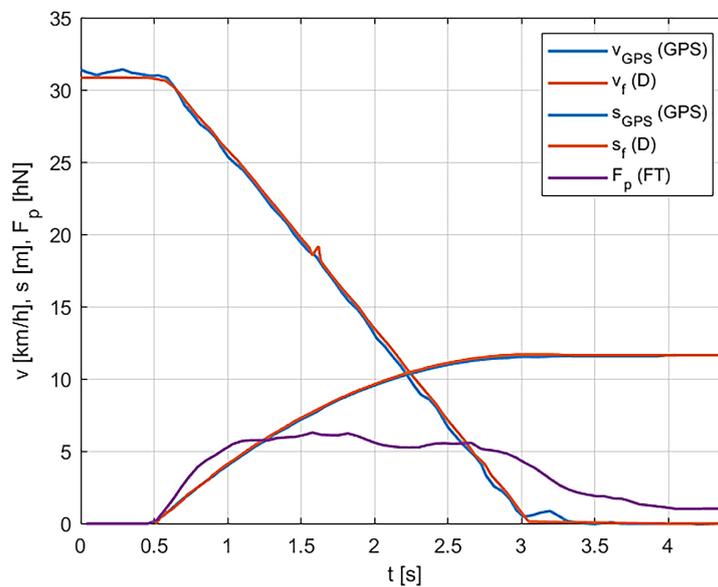


Figure 10. Courses of the brake pedal force F_p and the speed and the stopping distance, as determined by the decelerometer and the GPS converter (v_f and s_f or v_{GPS} and s_{GPS} , respectively); GPS, D, FT – measuring devices shown in Figure 4

Table 3. Braking performance indices for agricultural tractor

v_{or} [km/h]	d_{mISO} [m/s ²]	d_{mr} [m/s ²]	s_f [m]	v_{oGPS} [km/h]	d_{mGPS} [m/s ²]	s_{GPS} [m]
30.53	3.55	3.52	11.48	30.90	3.56	11.62
31.14	3.60	3.54	11.39	30.87	3.31	11.47
31.13	3.52	3.50	11.71	31.31	3.51	11.64
Mean	3.56	3.52	11.53	mean	3.46	11.58

CONCLUSIONS

The results of the road tests show that the developed measuring and diagnostic device is suitable for testing the braking efficiency of agricultural

vehicles in accordance with the requirements of Delegated Regulation (EU) 2015/68. The advantage of this device is its ability to implement various instruments for measuring the parameters of the braking process, including the Correvit optical

sensor, GPS converter, fifth wheel, and electronic decelerometer. The use of a simulator of the tractor pneumatic system control unit allows for assessing the effectiveness of braking the towed vehicle without relying on the tractor service brakes, enabling the driver to brake all vehicles in the set during an emergency on the road. Using an enhanced version of the simulator reduces the impact of stochastic factors on trailer braking, such as driver behaviour or transient processes within the tractor-trailer braking system, ensuring repeatability and measurement accuracy. The advanced simulator also facilitates stationary tests to measure leakage, check response times, and assess the trailer air reservoir capacity. Additionally, simulators can be used to verify the permissible relationship between the trailer braking rate and the pressure at the control coupling head during road or stationary tests. The findings of this work may prove useful to type approval authorities, as well as manufacturers of agricultural vehicles and towed machinery equipped with air braking systems.

Example road tests of a high-speed agricultural trailer, for which the braking rate should not be less than 50%, showed that it did not meet the required braking performance for cold brakes. Braking rates of around 30%, as determined by 5-wheel and decelerometer measurements (Table 2), indicate that the type of brake chamber or the length of the slack adjuster arm span on each axle should be increased.

Road tests on a slow-moving tractor showed that the average stopping distance, as measured by the GPS converter and decelerometer (11.58 m and 11.53 m, respectively; see Table 3), is less than the permitted calculated value of 14.28 m. However, the mean fully developed deceleration values of 3.46 m/s^2 and 3.52 m/s^2 are slightly below the required value of 3.55 m/s^2 . Therefore, it can be concluded that the tested tractor prototype also does not meet the type-approval requirements for braking, and modifications to the braking system are necessary. It should be noted that in the tractor tests conducted at approximately 30 km/h, the accuracy of speed measurement using a GPS converter was $\pm 1.2\%$, which slightly exceeds the allowable limit. This highlights the need for GPS converters with greater precision when measuring the speed of slow-moving vehicles.

Future work is planned to present a measurement system and computer programme for acquiring measurement data and controlling the simulator during road tests of agricultural vehicles.

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