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Zbigniew KAMIŃSKI
Jarosław CZABAN

DIAGNOSING OF THE AGRICULTURAL TRACTOR BRAKING SYSTEM WITHIN APPROVAL TESTS

DIAGNOSTYKA UKŁADU HAMULCOWEGO CIĄGNIKA ROLNICZEGO W RAMACH BADAŃ HOMOLOGACYJNYCH*

The paper describes the requirements for type approval testing of agricultural tractors with regard to braking, while taking into account the draft Regulation drawn up by the European Commission's Working Group on Agricultural Tractors (WGAT). A programme and methodology for testing the performance of the tractor brake system and its air brake system to supply and control the braking system of a towed vehicle are presented. Examples of diagnostic tests of a prototype tractor with hydraulically actuated brakes are given. These diagnostic tests may be wholly or partially used to develop a programme of qualification testing of tractors on production lines and a programme of periodic technical inspections of operated tractors.

Keywords: *agricultural tractor, approval tests, diagnostics, brakes, air brake system.*

W pracy opisano wymagania dotyczące badań homologacyjnych ciągników rolniczych w zakresie hamowania, uwzględniające propozycje przepisów opracowywanych przez grupę roboczą Komisji Europejskiej ds. ciągników rolniczych (Working Group on Agricultural Tractors - WGAT). Przedstawiono program i metodykę badań skuteczności układu hamulcowego ciągnika oraz jego instalacji powietrznej do zasilania i sterowania hamulcami pojazdu ciągniętego. Zamieszczono przykłady testów diagnostycznych prototypowego ciągnika z hamulcami uruchamianymi hydraulicznie. Opisane testy diagnostyczne mogą być w całości lub częściowo wykorzystane do opracowania programu badań kwalifikacyjnych ciągników na liniach produkcyjnych oraz programu okresowych badań technicznych ciągników eksploatowanych.

Słowa kluczowe: *ciągnik rolniczy, badania homologacyjne, diagnostyka, hamulce, instalacja pneumatyczna hamulcowa.*

1. Introduction

Type approval tests are an integral part of the official procedure that determines a vehicle being approved to be allowed to move on public roads. Type approval tests are only conducted by authorized testing establishments following the testing methods specified in relevant regulations. The aim of the diagnostic tests of both newly manufactured or operated vehicles is to verify and assess the technical conditions of subassemblies that have a significant impact on the technical performance of the vehicle in the light of the requirements imposed on them.

In view of the road safety, the braking systems of agricultural vehicles must meet a number of requirements for, among other things, braking efficiency, the follow-up action during slow braking, and a high speed of action during sudden braking (a response time less than or equal to 0.6 s). Tests carried out in the UK on tractor units with trailers equipped with hydraulic braking systems [14] showed that as many as 90% of the operated trailers did not attain the required value of the braking rate (z=0.25); after making the necessary adjustment, the fraction of trailers failing to meet the braking rate fell to 40%. Particularly hazardous is the operation of assemblies of incompatible vehicles due to the different efficiency of action of their respective braking systems (braking asynchrony) [12]. The operation of a high-speed modern agricultural tractor with high-efficiency brakes coupled with a low braking-efficiency trailer will, on the one hand, lead to the accelerated wear and premature damage of the trailer's braking system and, on the other hand, cause overloading, rapid wear and possible damage of the tractor's braking system [14]. The incompatibility of the braking systems of vehicles in tractor units, resulting in jack-knifing or skidding during braking, was the cause of about 9.7% fatal road accidents involving agricultural vehicles in the UK in the years 1999-2004 [4].

In Poland, air braking systems are commonly used in agricultural trailers. Therefore, agricultural tractors used for transport, regardless of the design of their own brakes (hydraulic – Fig. 1, mechanical, or pneumatic), are furnished with pneumatic systems intended for braking the towed trailers. Older tractors are equipped with single-line air braking systems, while in newer ones, there are usually combined systems that allow the use of both older trailers furnished with single-line air braking systems and new trailers that have dual-line air braking systems. The recommendation to use dual-line systems and increase the braking rate of tractors to 0.45 was introduced in 2004 within the amendment of the regulations on the approval of agricultural tractors for braking [6], [13], because of increasing the maximum permissible driving speed to 40 km/h for tractors of categories T1–T4 and above 40 km/h for tractors of category T5. In practice it happens that T5 category tractors move at a speed of around 60–70 km/h. The unsatisfactory state of implementation of the new regulations, the consent on continuing the manufacture of trailers with obsolete single-line braking systems and the operation of agricultural vehicles with inoperative or incompatible braking systems or even with no

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** braking system, as is the case for forestry trailers [11], all constitute a threat to the safety of road traffic involving those vehicles. Each year in Poland, of about 900 accidents involving agricultural vehicles, 90-100 have tragic consequences [5]. Therefore some [2] even call for the enforcement of upgrading the air braking systems of agricultural vehicles and trailers and introducing the inspection of braking systems to be carried out by Vehicle Inspection Stations.

For several years now, work has been continued in the European Union on the comprehensive proposal for the unification of technical regulations regarding the braking of agricultural and forestry vehicles modelled on Regulation 13 of the European Economic Commission for motor vehicles [8]. The recent proposals by the Working Group on Agricultural Tractors (WGAT) [7] assume, among other things, increasing the braking rate $z \geq 0.5$ for agricultural tractors moving at a speed of above 30 km/h and trailers and towed agricultural machinery with a Total Technically Permissible Mass (TTPM) of over 1.5 tons (trailers of categories R2, R3, R4; and towed agricultural machines of category S2). It is also proposed, similarly as for an assembly of road vehicles, to introduce compatibility corridors, that is the permissible variations in the braking rate value as a function of pressure at the coupling head connecting the tractor's and the trailer's control line for tractors moving at a speed of above 30 km/h and trailers with an TTPM of above 3.5 tons (categories R3 and R4) and towed agricultural machines of category S2.

A key issue for the improvement of the quality and safety of transport means for the agricultural and forestry sectors, in the light of the above-mentioned technical and legal status of their braking systems, seems to be to improve the methods and tools for diagnosing the braking systems of agricultural vehicles within the framework of approval and qualification tests and periodical technical inspections. The present paper describes the methodology for diagnosing agricultural tractor braking systems within approval tests following the programme [9] taking into account the requirements of the Regulation for agricultural and forestry vehicles as developed by the WGAT [7] and the Regulation 13 of the European Economic Commission [8] for motor vehicles. Example results of tests on a tractor with hydraulically actuated brakes are provided.

2. Requirements of braking systems

The current requirements of tractor braking systems contained in applicable [6], [8], [10], [13] and proposed [7] regulations can be grouped as shown in the schematic in Fig. 1, similarly as for motor vehicles [1].

Groups I and II of requirements apply to the supply unit (compressor, pressure regulator, compressed air reservoirs), whereas group IV applies to the air brake system control unit. The requirements of group III are applicable to the tractor's service and parking braking systems.

2.1. The energy source

The criterion for the performance assessment of the compressor (**I** – in Fig. 1) in the supply unit is assumed as the time of filling the tractor's reservoir and the substitute reservoir connected to the supply coupling head to a pressure value *p*, as specified by the manufacturer, at which the vehicle attains the braking efficiency prescribed for the service brakes. The capacity of the substitute reservoir imitating the

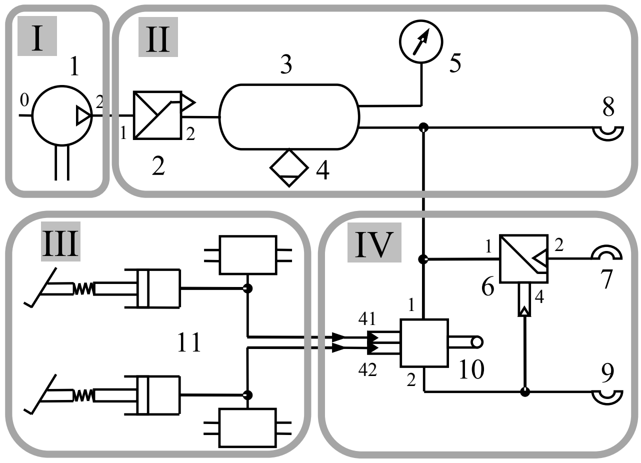

Fig. 1. Schematic diagram illustrating the division of a tractor braking system according to the requirements: I – energy source, II – distribution of energy and assurance of its required level, III – tractor braking system, IV – trailer brake control system (a combination of the tractor and trailer pneumatic systems), 1 – compressor, 2 – unloader valve (pressure regulator), 3 – air reservoir, 4 – drain valve, 5 – manometer, 6 – inversion trailer control brake valve, 7 – "single-line" coupling head (black), 8 – supply coupling head (red), 9 – control coupling head (yellow), 10 – trailer brake control valve, 11 – tractor hydraulic brake system

capacity of the trailer supply system is calculated from the relationship:

$$V = 20 \cdot R / p_{\max} \quad (1)$$

where: p_{max} – maximum value of pressure controlled in the system [bar], *R* – permissible maximum load on the all trailer axles [t].

The times t_1 and t_2 of filling the reservoirs to 65% and 100% of the *p* pressure value, respectively, as given in Table 1, should be measured during the compressor operating at the maximum power or the maximum rotational speed of the combustion engine. The value of pressure *p* is normally equal to the value of minimum controlled pressure $p_{\min}$. If additional reservoirs intended for accumulating energy needed for actuating devices not belonging to the brake system are installed in the tractor, and their capacity does not exceed the 20% of the total capacity of the braking system reservoirs, then, in accordance with the new regulations [7], the time t_3 needed for filling the reservoir most unfavourably situated relative to the compressor must also be determined.

2.2. Distribution of energy and assuring its required level

Maintaining the necessary energy level in the supply unit (**II** – in Fig. 1) of the tractor's pneumatic system depends on the capacity of the compressed air reservoir, pressure control parameters (i.e. the values of minimum and maximum controlled pressure, p_{min} and p_{max}) and, in high-pressure systems, also on the unloader valve.

With the compressor not operating and at the initial reservoir pressure equal to *p*, after eight full actuations of the service brake the value of reservoir pressure should not be lower than the value necessary for achieving the efficiency of the emergency brake. The location of control pressure measurement is the 0.5 dm³ capacity compressed air reservoir connected to the control line and vented prior to each

Table 1. Time of filling the supply unit during testing of the compressor [7], [8], [10]

Pneumatic supply system option	Filling time [min]		
	t_1 at 65% *p*	t_2 at *p*	t_3 at *p*
The system of a vehicle designed for towing a trailer	6	9	11
The system of a vehicle not designed for towing a trailer	3	6	8

successive braking; the supply line should be blanked off. In tractors designed for towing trailers, the pressure in the control line after 8 consecutive braking events should have a value not lower than half the value obtained after the first brake aplication.

For single-line systems, the reservoir capacity should be selected such that after the complete one-off braking and releasing cycle a pressure reduction from the minimum value be not greater than 0.5 bar [10]. The pressure is measured at the end of the 2.5 m-long 13 mm-internal diameter line connected to the tractor's supply and control coupling head (a line simulating the capacity of the trailer's supply & control line).

2.3. The tractor brake system

Brakes (**III** – in Fig.1) have a decisive effect on the safety of driving under normal operation conditions, therefore special requirements are laid on them. These relate to the braking performance of both cold and hot brakes, acting speed, the compatibility of the braking systems of vehicles making up a road unit, and the design of the system.

The efficiency prescribed for a braking system should be determined based on the stopping distance s_z or the mean value of fully developed deceleration d_m:

$$s_z = \frac{v}{3.6}\left(t_o + \frac{1}{2}t_n\right) + \frac{1}{2}\frac{\left(v/3.6\right)^2}{d_m} \quad [m] \tag{2}$$

where: v – initial speed [km/h]; t_o – brake actuation time referred to as the braking system delay time [s]; t_n – braking deceleration increase time [s], d_m – fully developed braking deceleration [m/s²].

The requirements for cold tractor brakes (test of type 0) are summarized in Table 2. The required decelerations for the emergency brakes are given in parentheses.

Table 2. Requirements for the efficiency of tractor service and emergency brakes in tests with cold brakes – (the 0 type test); the recommended method of checking is highlighted with the grey background

Vehicle category	s_z [m]	d_m [m/s²]	$z= d_m/g$	Conditions
Applicable requirements [10], [13]				
T1÷T5	≤0.15 v + v²/116	≥4.5	≥0.45	
Proposed by the WGAT [7]				
T1÷T4	≤0.15 v + v²/116	≥4.5 (1.5)	≥0.45	vmax ≤ 30 km/h
T1÷T4, T5	≤ 0.15 v + v²/130	≥ 5.0 (2.2)	≥0.50	vmax > 30 km/h

The initial velocity v may not be lower than 98% of the velocity prescribed for given tests (the maximum velocity). The mean fully developed deceleration dm should be calculated as the average deceleration related to the distance in the range from v_b to v_e according to the following formula:

$$d_m = \frac{v_b^2 - v_e^2}{25,92(s_e - s_b)}[m/s^2] \tag{3}$$

where: v_b – vehicle velocity corresponding to 0.8 v [km/h]; v_e – vehicle velocity corresponding to 0.1 v [km/h], s_b – distance covered between v and v_b [m]; s_e – distance covered between v and v_e [m].

Next, the efficiency of vehicle braking with hot brakes is checked. This is the so called fade test (type I). After the type I fade test with hot brakes, the efficiency of the service brakes should not be less than 75% of the prescribed efficiency and not less than 60% of the value measured in the 0 type test (for cold brakes). The basic differences between the regulations being currently in force and the proposed regulations result from the brake heating mode and conditions. In accordance with the applicable requirements [13], heating of brakes should be carried out in such a manner that the energy lost in the brakes corresponds to the energy needed for maintaining the vehicle velocity at a level of 80%±5% of the maximum velocity per 1 km of a 10% slope road stretch.

In the proposed regulations [7], the fade test of hot tractor brakes should be performed with repeated braking through consecutive applications and releases of the brakes. The number of braking and releasing cycles n and the testing conditions are given in Table 3. The force applied to the control should be selected so that the mean fully developed deceleration value equal to 3 m/s² could be achieved with the first braking. This force should be maintained in all subsequent brakings.

Table 3. Conditions of service brake efficiency testing (the I type test with hot brakes)

Vehicle category	Conditions			
	v_1 [km/h]	v_2 [km/h]	Δt [s]	n
T	80% v_{max}	½ v_1	60	20

The respective quantities in Table 3 are denoted as follows: v_1 – velocity at the start of braking; v_2 – velocity at the end of braking; n – number of brakings; Δ_t – duration of the braking cycle between the start of a braking and the start of the next braking.

The tractor parking brake system should assure the tractor to be immobilized on both a declivity and an acclivity with an 18% slope (for category T4.3 the acclivity slope value is 40%). In the case of a vehicle unit with an unbraked trailer, the tractor should hold the vehicle unit immovable on both a declivity and an acclivity with a 12% slope. As per the applicable regulations, the mass of an unbraked vehicle may not be greater that the mass of the tractor and may not in any case exceed 3 tons. In the proposed regulations, the maximum mass of a drawing vehicle-towed unbraked vehicle unit should not exceed the maximum permissible mass of the loaded tractor multiplied by the quotient of the prescribed maximum stopping distance by the stopping distance as determined in the 0 type test [7]:

$$P_C \le P_M \frac{s_p}{s_a} \tag{4}$$

where: P_C – maximum mass of the combination of the tractor and the un-braked towed vehicle, as declared by the tractor manufacturer, P_M – maximum mass of the laden tractor, s_p – prescribed stopping distance, s_a – achieved stopping distance measured during type 0 test (the tractor laden to its maximum mass P_M). In any case, the total load on all axes of the towed unbraked vehicle should not exceed 3.5 tons.

The emergency brake system of a tractor should reduce the speed of the vehicle until its stop with deceleration equal to at least 1.5 m/s² when v_{max}≤30 km/h, and 2.2 m/s² when v_{max}>30 km/h. The efficiency tests of emergency brakes should be done by simulating a failure of the service brake system.

Braking systems are required to show a follow-up action in slow breaking and a high-speed action in sudden braking. The notion of follow-up action is understood as the braking system ability to maintain the proportional relationship between the input signal change and the output signal change under steady state conditions. This means that the pressure in the actuator chambers should change proportionally to the displacement of the brake pedal.

During sudden braking, the action speed of the braking system of the tractor and the trailer should be such that the prescribed service brake efficiency be achieved in a time not longer than 0.6 s. In hydraulic braking systems, this condition is considered satisfied, if the braking deceleration or the brake fluid pressure in the most remote actuator attains a value corresponding to the prescribed braking efficiency. In sudden braking, a pedal force increase time of 0.2 s is assumed.

2.4. Trailer brake control

In dual-line systems, the connection between the tractor pneumatic system and the trailer braking system is done using two lines, of which one is intended for supplying and the other for controlling the trailer braking system. To assure the exchangeability of tractors and trailers, the values of pressure in the both lines have been unified. With the full application of the service brake, the pressure values should lie in the range from 6.5 to 8.5 bar. In single-line systems, the pressure at the coupling head should range from 5.8 to 6.3 bar.

The control of the trailer brakes (**IV** – in Fig. 1) should be effected exclusively with the simultaneous application of the drawing vehicle's brakes, therefore the required times of pressure variations in the couplig head of the drawing vehicle's control line are specified. In a single-line system, the time elapsing from the start of pressing the brake pedal until the moment when the pressure in the control line (2.5 m long and 13 mm in internal diameter) connected to the tractor's coupling head decreases to 90% of the minimum value should not exceed 0.2 s, and when the pressure decreases to 25% of this value, it should not exceed 0.4 s with a full pedal application time of 0.2 s [10]. In the proposed new regulations [7], there is no requirement for testing for the response time of the control unit for dual-line systems. To evaluate the action speed of this unit, the provisions of EEC Regulation 13 [8] can be used. In dual-line systems, the time of pressure build-up in the control line up to 10% of the asymptotic pressure should not exceed 0.2 s, and up to 75%, 0.4 s. The requirements for the response time of the tractor control unit are illustrated in Fig. 2.

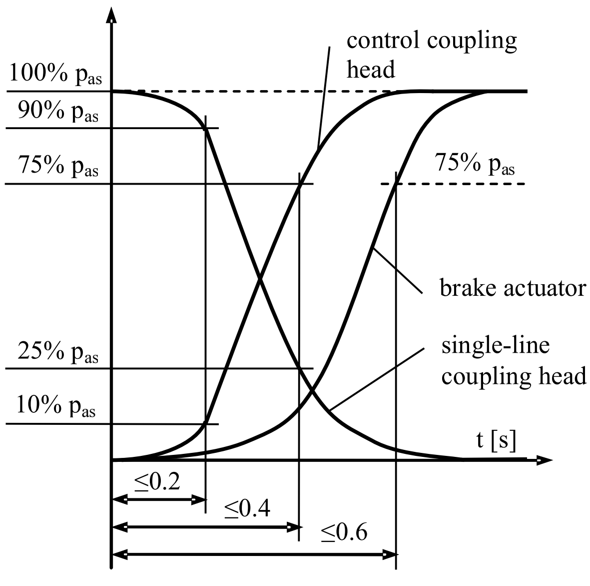

Fig.2. Variation in pressure as a function of time and the required response times of the tractor control unit

In addition to the requirements for action speed, there are also requirements for the compatibility of the braking systems of a tractor unit's vehicles [7]. Braking of the trailer only in an assembly of vehicles is not permissible. The proper synchrony of action of the both vehicles' brakes should prevent the loss of running stability that would lead to a folding of the unit. The condition for the proper braking synchronism is the selection of trailer braking intensity as a function of control line pressure such that a slight tensile force arises in the towing attachment in the first braking phase, which will maintain the alignment of the tractor and the trailer.

2.5. General technical requirements

Aside from the requirements that determine the roadworthiness of a vehicle, there are specific requirements for the tightness of the system and the reliability and durability of assemblies and parts under varying conditions of operation of pneumatic braking systems.

The leakage of the system is checked by measuring the pressure drop in the system after a specified time. According to [10], the reservoir pressure drop from the minimum controlled pressure value should not exceed 2% for 10 minutes. Much less strict requirements are used by the Wabco company, which assume as permissible a 5% pressure drop after 3 minutes in brake actuators pressurized initially up to half the maximum controlled pressure value [1].

3. Testing methodology

The primary goal of the undertaken diagnostic tests was to try out the methods and procedures of the developed testing programme [9] including the efficiency testing of the brakes of a tractor and testing of its air braking system. The air braking system testing programme included the verification of:

- air system leakage,
- unloader valve operating range,
- coupling head pressure values,
- compressed air reservoir capacity,
- air compressor capacity,
- control unit response time.

The tests were carried out for a Pronar 81.6 KM prototype tractor equipped with hydraulically actuated brakes. The tests of the tractor's pneumatic braking system included the recording of the time variations of the brake pedal force and air pressure at selected points in the system. The measuring method, testing conditions and the requirements of the subassembly tested are described in detail in reference [9]. The measuring system consisted of:

- a Pentium III PC,
- an input-output adapter,
- an MC1212 measuring card by Senga with a resolution of 12 bits and a processing accuracy of 0.02% FSR ±1 LSB,
- a CL 23 force strain gauge by ZEPWN complete with a converter, with a measuring range of 0÷1 kN and accuracy class 0.1,
- MBS 32 pressure transducers by Danfos, with a measuring range of 0÷10 bar, accuracy class 0.3, DMT-21 digital revolution counter (for measuring the engine rotational speed) with a measuring range of 0÷9999, accuracy class 0.2, and
- the „MC1212" the program for the recording and acquisition of measurements.

The efficiency tests of the tractor's main brakes included the recording of the distance, deceleration and the brake pedal force during the braking process. For recording, a measuring system (Fig. 3) described in detail in reference [3] was used, which was made up of:

- a portable computer,
- an LTC1286 measuring module,
- a CL 23 force strain gauge by ZEPWN complete with a converter, with a measuring range of 0÷1kN, accuracy class 0.1,
- a fifth wheel with a rotary-pulse converter,
- an electronic decelometer with a measuring range of ±2g,
- Holux GPSlim 236 GPS receiver,
- the „POMIAR1286" program for recording data during braking.

The use of the LTC1286 measuring module including a 12-bit LTC1286 A/C converter and an HCF4051 multiplexer enabled the frequency of measurements from the analog outputs to be increased to 10 kHz. In addition, the module had 8 digital inputs and 8 digital outputs relying on HCF4051 and MC4094circuits. Communication with

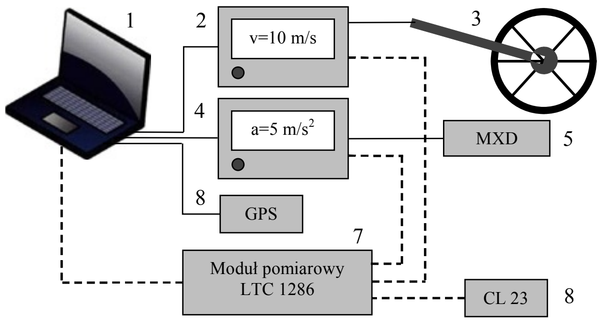

Fig. 3. Schematic of the measuring system for testing the vehicle braking process: 1 – portable computer, 2 – "fifth wheel" controller, 3 - fifth wheel, 4 - electronic decelometer, 5 - MXD7202 acceleration sensor, 6 – Holux GPSlim 236 GPS receiver, 7 – LTC1286 measuring module, 8 – CL23 brake pedal pressure sensor

the portable computer was effected through the LPT port or the USB connection using the SPI synchronous data transmission interface.

For recording the braking distance, the fifth wheel was used, in which the pulses generated by the disc were recorded by a TCST1103 optical sensor (Fig. 4-a) and then counted by a microcontroller relying on the ATMega 8 circuit and programmed in the Bascom language. Based on the counted pulses, the distance covered by the vehicle and the vehicle instantaneous velocity and acceleration were determined. The microcontroller system was equipped with an RS232 interface for its calibration (storing of the wheel rolling radius value and the number of disc pulses in the EEPROM memory) and the transmission of measurement data to the portable computer.

The braking deceleration was determined by an indirect method through the differentiation of the signal received from the fifth wheel and by a direct method using accelerometric sensors as shown in Fig. 4-b. For their construction, MXD7202 acceleration sensors manufactured by MEMSIC were used, which were connected via a signal amplifier to the microcontroller furnished with an RS232 interface for communication with the portable computer. Circuit diagrams for the measuring module and the fifth wheel and decelometer microcontrollers are provided in reference [3]. The „Pomiar1286" program written in the environment was used for handling the measuring system.

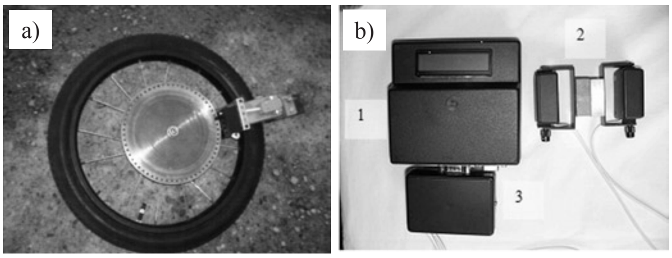

Fig. 4. Devices for measuring the braking distance and braking deceleration: a – fifth wheel pulse disc with an optical sensor, b – decelometer components: 1 – microcontroller, 2 – measuring sensors, 3 – signal amplifier

4. Examples of diagnostic tests

4.1. The air system leakage test

The leakage test involved recording of the 10 minute drop in pressure $p_z(t)$ at the supply coupling head of a dual-line system from the initial value equal to the minimum controlled pressure value p_{min}. Should a leak be detected (Fig. 5), it would be necessary to locate and remove the leakage before proceeding with subsequent tests.

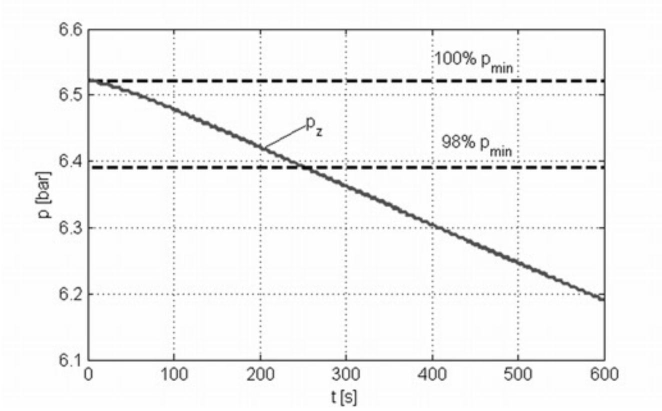

Fig. 5. Testing the air system leakage based on the variation of pressure p_z at the supply coupling head

4.2. The unloader valve operation test

The unloader valve operation test was performed with the operating engine by recording changes in pressure in the tractor's compressed air reservoir which was vented through the drain valve. A 385±5 cm³ capacity reservoir was connected to the control coupling head of the dual-line system, which was an equivalent for the capacity of the 2.5 m-long 13 mm-diameter trailer supply line. Based the recorded variation of pressure p_{zb} (Fig.6), the values of the unloader valve switch-on pressure p_{min}=6.40÷6.47 (6.5÷6.8 bar acc. to the specification) and switch-off pressure p_{max}=7.85÷7.88 bar (8±0.2 bar acc. to the specification) were determined, at a confidence level of 95%. The tests demonstrated the need for controlling the switch-on pressure. From the tests, incorrect Visteon 51 10 018 inloader valve switch-on pressure values, not conforming to the specification, were found. However, no irregularities in the cyclic operation of the unloader valve were identified.

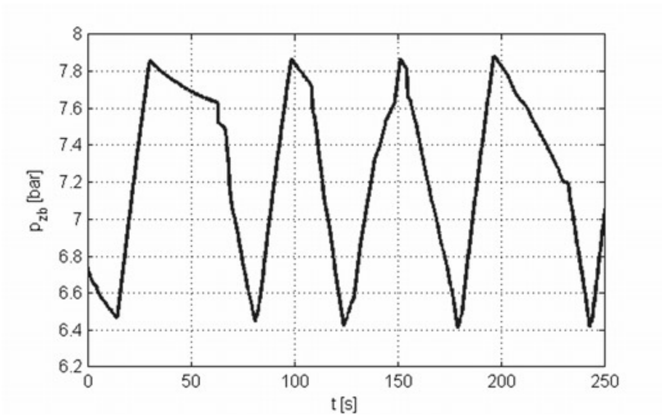

Fig. 6. Example variation of pneumatic system reservoir pressure p_{zb} during testing of the Visteon 51 10 018 unloader valve

4.3. The coupling head pressure test

Testing of the value of pressure p_s at the control coupling head and pressure p_z at the supply coupling head of the dual-line system and pressure p_v at the single-line coupling head involved cyclic braking and releasing with the engine operating. A fragment of the example time variation of the brake pedal force F_p, the hydraulic braking system pressure p_h, the reservoir pressure p_{zb} and the coupling heads pressures, as recorded during the testing of tractor, is shown in Fig. 7.

As determined from the measurements, the pressure variations in the dual-line system were contained in the range of 6.43÷7.87 bar, while in the single-line system, in the range of 6.08÷6.41 bar. The reduction of the minimum controlled pressure value in the dual-line

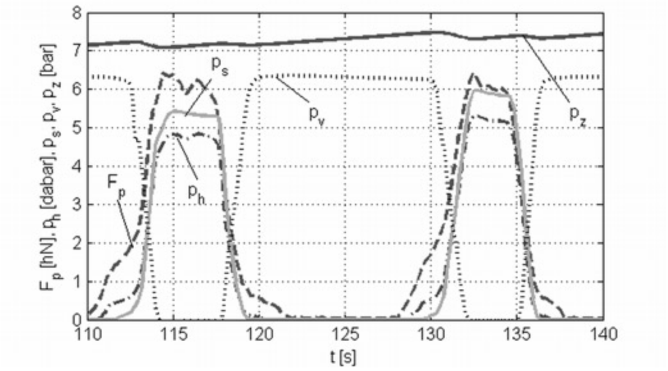

Fig. 7. Example variations of measured quantities during testing the air system coupling head pressure: F_p – brake pedal force; p_s, p_z, p_v – control, supply and single-line coupling head pressure, respectively; p_h – service brake system hydraulic pressure

system (below the required 6.5 bar) results from the too low unloader valve switch-on value, not conforming to the specification.

4.4. The compressor capacity test

The test involved the recording of changes in the pressure of compressed air filling the reservoir connected to the supply coupling head of the tractor's air system (Fig. 8).

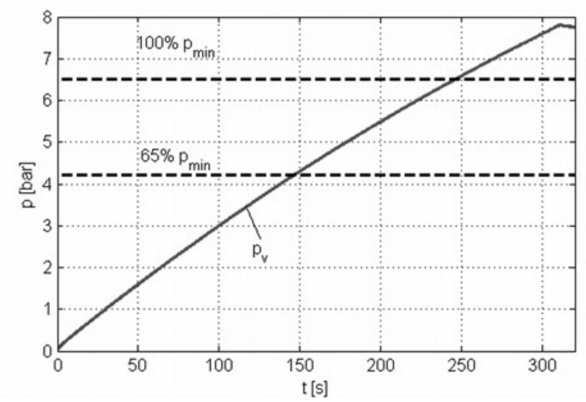

Fig. 8. Example variation of the increase in pressure p_V in the V=60.38 dm³ substitute reservoir during the compressor capacity test.

The time of filling the substitute reservoir with the volume V=60.38 dm³ calculated form relationship (1) was measured from the moment of starting up the heated-up engine up to the point of attaining the required pressures at the maximum engine rotational speed of n_s=2450 rpm. Then, based on 3 measurements, the average time t1 =147.18 s of pressure increasing from zero to 65% of the minimum controlled pressure value and the time t_2=246.23 s needed for attaining 100% of this pressure were determined. The obtained values are less that the maximum values – 360 s and 540 s, respectively – permissible for tractors designed for towing trailers.

4.5. The air reservoir capacity test

The verification of the correctness of selection of the compressed air reservoir in the dual-line system involved carrying out 8 consecutive full brakings with the compressor not operating, and measuring the pressure in the 0.5 dm³ control reservoir connected to the control coupling head (Fig. 9).

From 3 recorded control reservoir pressure measurements, the average pressure values of p_1=6.08 bar after the first braking and p_8=3.81 bar after the eighth braking were determined. The test results indicate the correct selection of the compressed air reservoir pressure.

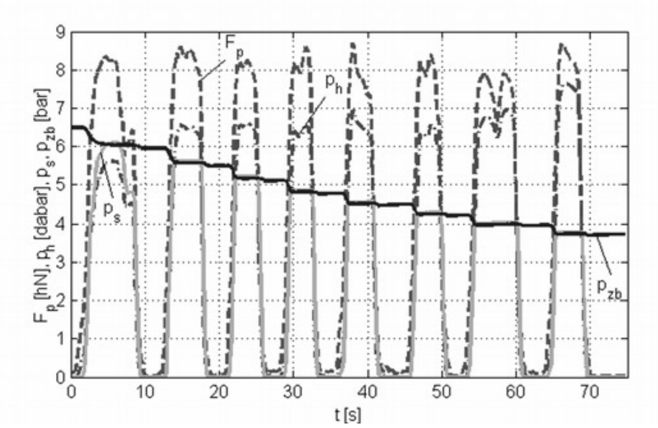

Fig. 9. Example variation of quantities recorded during testing the capacity of the compressed air reservoir in the dual-line system; F_p – brake pedal force, p_h – hydraulic system pressure, p_s – control coupling head pressure, p_{zb} – reservoir pressure

4.6. The test of the control unit response time

The response time of the tractor's braking system control unit was determined from the recorded variations in the brake pedal force and the pressure at the end of the 2.5 m-long 13 mm-diameter line (simulating the trailer control line) connected to the control coupling head when testing the dual-line system or to the supply & control coupling head when testing the single-line system. Example variations of the measured quantities are shown in Fig. 10.

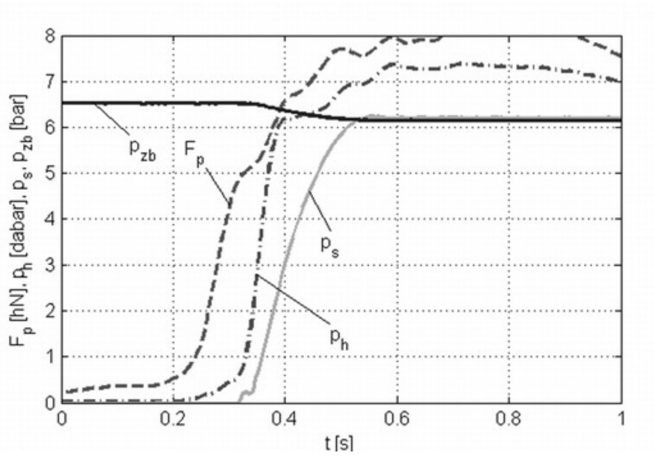

Fig. 10. Example variation of the quantities recorded during testing the tractor response time in the dual-line system: F_p – brake pedal force, p_h – hydraulic system pressure, p_s – control coupling head pressure, p_{zb} – reservoir pressure

Next, based on the recorded variations, the response time t_{10} and t_{75}, i.e. the time of attaining 10% and 75% of the asymptotic pressure value, respectively, was determined as a function of brake pedal application time, starting from the shortest possible applications and then gradually increased up to about 0.4 s. After determining the linear regression equations of the response time t_r as a function of the brake pedal force change time t_f by the least squares method (Fig. 11), the response time corresponding to the time of actuation under sudden braking conditions, i.e. at t_f=0.2 s, was calculated.

The determined response time values t_{10}=0.17 s and t_{75}=0.27 s are lower than the permissible values, which evidences the correct selection of the elements determining the dynamic characteristics of the dual-line braking system of the tractor tested.

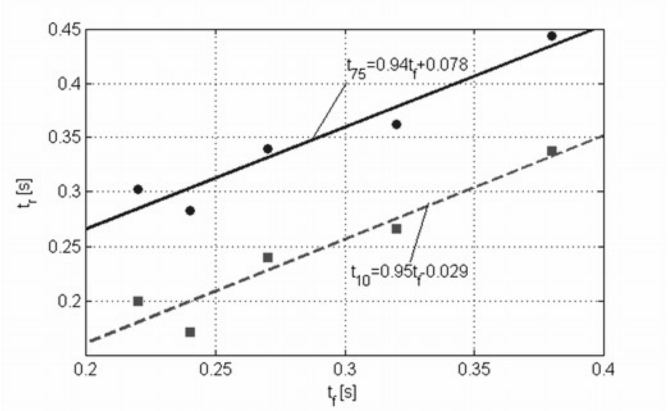

Fig. 11. The effect of the brake pedal force increase time tf on the response time t_{75} (R^2=0.9275) and t_{10} (R^2=0.9122) of the dual-line braking system

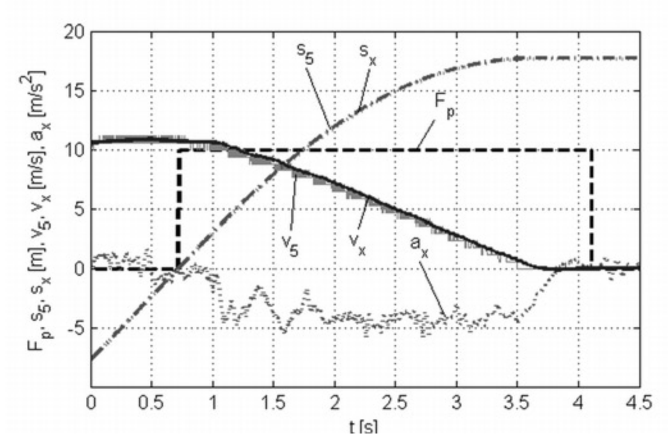

Fig. 13. Example measurement result obtained in the service braking system efficiency test: F_p – brake pedal force indicator; s_5, v_5 – distance and velocity as determined from the fifth wheel measurements; a_x, v_x, s_x – acceleration, velocity and distance, as determined from the electronic decelerator measurements

4.7. The test of the service braking system efficiency

Example variations of voltage from the fifth wheel pulse sensor, the electronic decelerator and the brake pedal pressure sensor, as recorded during braking of an agricultural tractor using the described measuring system, are shown in Fig. 12.

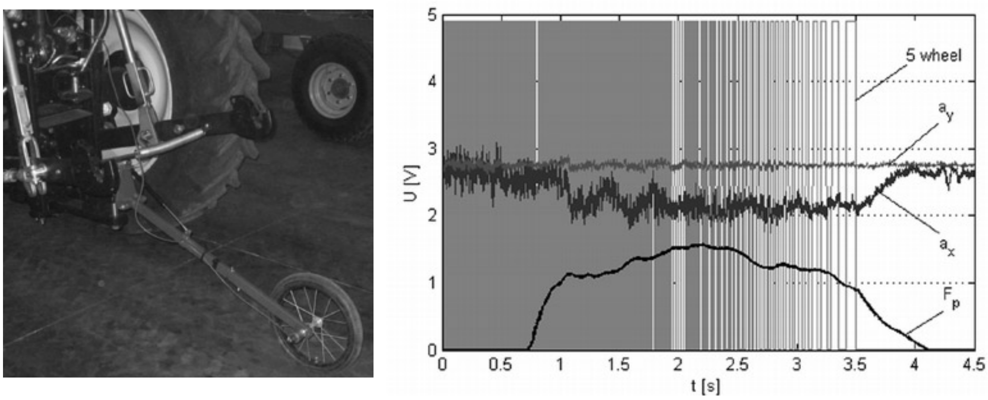

Fig. 12. An example of using the measuring system in braking efficiency tests

Next, based on the recorded quantities, the braking distance, velocity and deceleration were determined as a function of time (Fig. 13) and main braking system efficiency evaluation indicators, such as the stopping distance and the mean fully developed braking deceleration, were calculated. In the performed tests, accelerations of up to 5.22 m/s^2 (as measured with a decelometer), so greater than the minimum value of 4.5 m/s^2 required after the revision of the regulations, were achieved.

5. Summary

The agricultural tractor braking system approval testing programme described in the paper covers the most important aspects of diagnosing the brakes of a tractor and its air system for supplying and controlling the brakes of the towed vehicle. The conditions and requirements assumed in individual diagnostic tests are consistent with the proposals of the new Regulation for testing agricultural vehicle brakes [7]. In the authors' view, the proposed provisions should consider the testing of the response time of an agricultural tractor's air system control circuit similarly as is the case in utility vehicles designed for towing trailers.

The presented braking system diagnosing methodology may be either wholly or partially used for developing a programme of diagnostic testing of both newly manufactured agricultural tractors (by qualification testing on production lines) and operated ones (within periodical technical testing on the Vehicle Inspection Stations). This would enable any vehicles with inoperative brakes and air braking systems to be removed from the road traffic, which could improve the safety of road traffic involving tractors coupled with trailers and agricultural machinery.

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Zbigniew KAMIŃSKI, Ph.D., Eng.
Jarosław CZABAN, Ph.D., Eng.
Faculty of Mechanical Engineering
Bialystok University of Technology
ul. Wiejska 45C, 15-351 Białystok, Poland
E-mail: z.kaminski@pb.edu.pl, j.czaban@pb.edu.pl