Analysis of physical and technical methods for controlling the density of the brake line of a train and ways to increase their efficiency

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Abstract. The article deals with the problem of monitoring the brake line of a train as a means of detecting dangerous failures of braking equipment and preventing emergencies. The existing methods and methods for controlling the density of the brake line are analysed, with the determination of their effectiveness. An assessment is given of the prospects for the development of brake line control devices, based on the conditions for ensuring traffic safety, and ways of improving the most effective methods are proposed.

1. Introduction

One of the most important tasks of railway transport is to ensure reliable and trouble-free operation of train brakes, as the primary means of ensuring traffic safety. When a threat to traffic safety is detected (including from the side of the running gear), the actuation of effective braking means allows you to prevent serious consequences in the form of a collision, accident or crash. In addition to the safety function, the braking devices of the train directly affect the technical and economic performance of the transport - increasing their efficiency allows increasing the permissible speed of movement and shortens the duration of transportation.

At the same time, it should be noted that the control of train brakes is functionally limited by the technical features of the rolling stock. If we consider the multi-unit and passenger rolling stock, then the control capabilities of its braking system are somewhat higher than that of the freight one. This is due to the presence of an electro-pneumatic brake in addition to the standard pneumatic brake. Considering that at present almost all railways in the world operate freight cars equipped exclusively with pneumatic brakes, control issues are especially acute. Modern locomotives are equipped with various systems for diagnostics and monitoring of traction rolling stock, but the locomotive crew practically does not have information about the technical condition of the cars, and, in particular, their braking facilities. The driver and assistant (if any) can only hope that the employees of the carriage facilities have performed a high-quality test of the brakes at the station, before the train departs. At the same time, most of the failures of the braking equipment of a particular carriage remain unnoticed by the locomotive crew. If the brakes of one carriage in the train fail to work (or if it spontaneously releases), the overall braking efficiency of the train changes insignificantly. On the part of the locomotive crew, only failures are detected, leading to a significant decrease in braking efficiency, or in the case of spontaneous operation of the brakes, or their failure to release.
But if we consider such a failure as blocking the brake line of the train (due to freezing or blocking of the end valves), then in this case we are talking about a complete loss of control, which is fraught with the most serious consequences. Indeed, when traffic safety is threatened, the safety systems are triggered on the locomotive, but these highly reliable multi-level systems use the same brake line to reduce the speed and stop the train. This means that when it is blocked, despite all the technical means available on the locomotive, the train actually loses control.

Unfortunately, these conclusions are confirmed by sad statistics - the most serious disasters on the railway transport occurred precisely because of the reasons for refusal brakes due to blockage of the brake line [1], [2], [3], [4]. Therefore, in the overall braking system of the train, the integrity of the brake line must be monitored as closely as possible.

2. Materials and methods

Several different methods of monitoring the integrity of the brake line of a train (hereinafter BL) can be distinguished. Despite the fact that these methods solve the same problem, they are based on different principles and have their own characteristics.

First of all, it is necessary to consider a method for controlling BL through the development of a brake diagnostics system based on an electro-pneumatic brake (hereinafter EPB). The presence of power supply on all cars of the train allows, by means of pressure sensors installed on each unit of the rolling stock, to monitor not only the state of the brake line, but also the brake system of each car. True, it is worth noting that in this case we are not talking about the classic EPB, intended exclusively for the implementation of the braking function, but about the electronic-pneumatic system, which is the next evolutionary link in the development of braking technology. The numerous advantages of such a system were discussed in more detail in the article [5]. But even the presence of a simple EPB, without the functions of a diagnostic brake monitoring system, allows you to avoid the loss of control of the train brakes in the event of a BL overlap. When current is applied to the EPB circuit, the brakes will operate without discharging the BL which will allow to stop the train in a timely manner and take measures to eliminate the failure. Thus, the method of monitoring the brake system of a train by means of a full-fledged diagnostic system for each car seems to be the most effective from the point of view of ensuring traffic safety. At the same time, due to the technical equipment of the rolling stock, in the short and medium term, this method can be implemented only on passenger and motor-car rolling stock, since the introduction of EPB in freight traffic requires huge financial costs and a large amount of technical and technological changes.

For freight trains, the optimal solution is the method of controlling the brake line of the train directly, as the only communication channel (albeit pneumatic) of rolling units of the train as a whole along its entire length.

When part of the train is disconnected from the BL due to overlapping or freezing, the braking efficiency decreases [6], [7], [8]. When the BL ruptures, the pressure drop between the head and tail of the train increases abruptly, which leads to the appearance of a braking effect in the tail of the cars, significant heating and damage to the wheels during braking [9], and may not be noticed by the driver. Moreover, in the event of a train rupture or the opening of a stop valve when the driver's crane is in the train position, the pneumatic brakes may lose their automatic action [10], [11].

Devices that are triggered by a decrease in pressure in the event of a line rupture are not sensitive enough, and with a driver's crane with a powerful power supply, they are generally inapplicable.

Therefore, on the railways of the Russian Federation (and before that on the roads of the USSR), devices for monitoring the integrity of the mainline by the level of compressed air consumption are used.

Air consumption from the pneumatic network of the train is the most common diagnostic feature used in various means of monitoring the BL condition. In accordance with the normative documents [12], the density of the brake system is checked just by the compressed air consumption. In a simplified form, the time of pressure reduction is measured as an indicator of consumption.

The following methods of BL control by compressed air consumption can be distinguished:
• using a flow meter installed on the locomotive;
• by changes in pressure in the main tanks (hereinafter referred to as MT) of the locomotive, in the mode of off-line compressors.

Considering the method of controlling the density of BL by means of a compressed air flow meter, it is necessary to note a number of restrictions imposed on the technical implementation of this method. Despite the significant variety of compressed air flow meters (according to the principle of operation, tachometric, vortex, thermal, ultrasonic, electromagnetic, Coriolis meters are distinguished), most of them have operating features that do not allow operation on railway rolling stock. One of the main requirements for any diagnostic device of this kind is the absence of narrowing in the BL, differences in heights and sections, the exclusion of the effect of BL throttling (even temporary). Also, we must not forget about the requirements for the stability of work under temperature influences, vibrations and other factors that characterize the operation of devices on traction rolling stock. As a result of a comparative analysis, it can be concluded that ultrasonic compressed air flow meters are applicable to locomotives. At the same time, for a high-quality control of the density of the brake line, an ultrasonic flow meter should be integrated into the on-board diagnostics system of the locomotive, in order to take into account information about the state of the brake system of the locomotive as a whole, register and record information from BL and PM pressure sensors, as well as ambient temperature and temperature sensors air in BL. This condition makes the diagnostic system very complex and expensive.

Thus, most of the devices used are based on the method of controlling the density of BL by changing the pressure in the MT of the locomotive.

In 1990, PKB TsT developed a device for monitoring the density of the brake line, type L187. Based on the operating experience of this device, VNIIZhT has developed a device for monitoring the density of the brake line of a train (UKPTM). When in the process of train movement, the density of BL increases above the limit, the device issues a special signal (flashing triangle).

But the UKPTM only automates the operation of counting the time of the pressure drop by 0.05 MPa in the MT, which is provided for by the Rules [12], in general, according to its purpose, the UKPTM deviates from the requirements of this regulatory document:

• density check is performed not “in the process of movement”, but in the parking lot;
• the density during the check should not differ from the density indicated in the VU-45 certificate by more than 20% in the direction of decreasing or increasing, and not only decreasing.

Also, PKB TsT together with JSC "Electromechanics" in Penza developed a system for indicating the density of the brake line SIPTM-395 [13]. The system is designed to prevent the departure of a train with violations in the brake line and to minimize the human factor when checking and controlling the brakes. SIPTM-395 allows detecting the brake line overlap, and also provides control over the correctness of some operations of full or reduced brake testing. The principle of operation of SIPTM-395 is based on the use of the so-called "measuring tank" installed on the locomotive feed line in front of the driver's crane. With the help of an electro-pneumatic (or electromagnetic) valve installed at the inlet to the tank from the PM side, the measuring tank itself, together with the driver's crane and the brake line of the entire train, is periodically disconnected from the supply with compressed air. At this time, the density of BL is measured by the time of pressure reduction in this reservoir. With some indisputable advantages of this technical solution, SIPTM-395 has a number of fundamental disadvantages:
• restriction on use. SIPTM-395 can be installed only on locomotives where the driver's crane KM No. 395 is installed (this can be seen even from the name of the system). It should be noted that the majority of modern locomotives are equipped with the UKTOL complex.

• SIPTM-395 is an expensive and technically complex system that requires a change in the design of the locomotive during installation.

• the main drawback of SIPTM-395 arising from the principle of its operation is the potential danger and risk of violation of traffic safety. In the event of a failure of the system (the whole or only the valve of the measuring tank), the train actually remains without brake control, which is fraught with the most serious consequences. It turns out that the diagnostic system, aimed at detecting brake failures associated with loss of control, itself, in case of failure, creates a dangerous situation associated with the loss of brake control!

It is also necessary to consider methods based on knowledge of braking processes and devices [6 ], [7 ], [8]. These include:

• control of the time of air release from the train mainline through the atmospheric opening of the driver's crane when braking with a step of 0.1 MPa;

• control of the duration of air release from the train mainline through the atmospheric opening of the driver's crane during release position I.

The listed control methods are approximate, since the result is largely distorted by the state of the controlled object - BL.

When testing the brakes, the density of the brake network in passenger trains is checked according to the rate of pressure drop in the line after 20 seconds after the power is turned off; at the same time, the rate of pressure decrease should not exceed 0.02 MPa / min regardless of the length of the train, the same rate of density at the rate was set earlier for freight trains.

The rate of pressure drop in the line when checking the density does not require information about the length composition and does not characterize the consumption of compressed air; that is why it cannot serve as a means of controlling the brake network, since the values of the rate of pressure drop in the BL of one car and a train of any length may slightly differ. In addition, the rate of pressure drop in the BL can exceed the softness of individual air distributors, which will cause them to operate on the train. In principle, this method cannot be used for freight trains, since the test result depends on the degree of density of the air distributor check valves. With a reliable density of check valves, the rate will exceed the established general standard; at the same time, situations are possible when with leaky valves the rate may be within the standard.

In accordance with the Rules [11], the density of the brake network is checked by the compressed air flow rate, which is determined by the time the compressed air pressure in the main tanks drops to 0.05 MPa after fully charging the braking network and turning off the compressors (MT volume).

The accepted control of the density of the braking network of freight trains by the air flow from the main tanks does not provide sufficient accuracy, since the norms are given with a large difference in the length of the train (interval of 50 axes), requires a number of sequential operations and taking into account the length of the train, which introduces certain difficulties in operation brakes.

In addition, the consumption of compressed air when feeding a charged braking system cannot serve as a sufficient characteristic of density. In operation, there may be cases when, in the presence of a large transit flow rate and disconnection of a part of the train, the value of the total compressed air consumption will correspond to the upper limit of the established norm for the entire train.

Therefore, for a quality control of the density of the brake line, it is not enough to simply measure the pressure drop by 0.05 MPa in accordance with the Rules. As shown by numerous experiments and theoretical studies, the density of the pneumatic networks of the locomotive itself introduces a significant error in determining the density of BL by reducing the pressure in the PM. With a relatively low density of the locomotive, situations are possible when the overlap of the end cranes in the train
will cause an increase in density by an amount not exceeding 20% of the set value. In another case, with a high density of wagons and a locomotive (as is often the case on new locomotives of the 2ES6, 2ES10, etc. series), the process of determining the density can take a long time (1000, 1500 seconds or more). Simultaneously with the process of density registration in the control systems of modern locomotives, the function of automatic purging of the main tanks is implemented. This function is implemented in time and often the pressure in the main tanks of the locomotive between two automatic blowdowns does not have time to decrease by 0.05 MPa, which makes it difficult to determine the density of the train using the technology prescribed in the Rules.

3. Results and discussion
As a result of the analysis, it can be concluded that it is necessary to improve the technology for controlling the density of the brake line, taking into account all the listed features of this process, namely:

- For quality control of the density of the BL of the train at a low density of the pneumatic system of the locomotive, the function of separate determination of the density of the locomotive and the composition of the wagons should be implemented, which will allow detecting a 20% density deviation, taking into account the leaks of the locomotive itself.
- Simultaneously with this, the function of accelerated determination of density in the case of its high values should be implemented, which will allow to quickly obtain the actual value and reduce the time for this operation.

Considering the capabilities of modern safety and control systems currently used on new modern locomotives that control the operation of all its systems and already include all the necessary instruments and measuring instruments (including pressure sensors PM, BL, TC, etc.), the most optimal a variant of the train braking network control is the development and implementation of an improved density control algorithm based on a microprocessor control and diagnostics system (MCS & D):

1. Obtaining primary data on a single locomotive.
   When the motor-compressor is turned on, the rise time is measured pressure in PM by 0.05 MPa. To calculate the compressor capacity, the result obtained is multiplied by 2. The result obtained is displayed at the driver’s request on the MPS & D monitor.
   After the compressor is turned off and the pressure in the PM is reduced by 0.05 MPa, the BL density is measured by the time the pressure in the PM is reduced. The measurement is carried out simultaneously in three ways:

   1. The time of the pressure decrease in the PM is measured for every 0.005 MPa, with subsequent multiplication by 10.
   2. The time of pressure decrease in the PM is measured for every 0.01 MPa, with subsequent multiplication by 5.
   3. The time of pressure decrease in the PM is measured for every 0.02 MPa, with subsequent multiplication by 2.5.

   The results obtained are compared with each other. Next, a method for determining the density is selected: if the density indicator exceeds 600 seconds, then the density is determined according to the first method; if the density indicator is in the range from 300 to 600 seconds, then the density is determined according to the second method; if the density indicator is equal to or less than 300 seconds, then the further determination of the density is carried out according to the third method.

   In the case of high density, until the results are obtained by the second and third methods, the density values determined by the first method should be displayed on the monitor. At the same time, before displaying the density value on the monitor, it is necessary within 2-3 seconds to make sure that
there are no signals from the MPS & D system about turning on sources of increased compressed air consumption (whistle, typhon, sand, turning on anti-unloading devices, blowing out the main tanks, braking, creating a "supercharging" pressure in the UR, etc.). In the case of maximum density (after the start of measurements, within 4 minutes the pressure in the PM did not decrease), the density indicator of the PM of the locomotive is taken for 2400 seconds.

Density measurement results, obtained after the first measurements from the start of the measurement, after lowering the pressure in the PM by 0.05 MPa, are recorded as the minimum density. Measurements continue continuously until the next activation of the motor-compressor. Density measurements taken the last time the compressor was switched on are recorded as maximum density.

At the command from the monitor keyboard, the system fixes the value of the density parameter of a single locomotive. At the same time, the memory stores the maximum and minimum density of the locomotive ПЛmax and ПЛmin.

2. Obtaining data on the density of TM of the train

When carrying out a full or reduced testing of brakes, after charging the brake network of the train and stabilizing the density of BL, measured by a decrease in pressure in the PM, a signal is generated in the MPS & D that the BL is charged and that the system is ready to fix this level of density (leaks). The decision that the BL is charged is formed after 3-fold determination of the same minimum train density ППmin (±4 sec.). After confirming the BL charging and the readiness of the system for fixing the density by the driver through the keyboard of the MPS & D monitor, the system registers the BL density of the train and calculates the difference in the time of the pressure drop in the PM by 0.05 MPa for a single locomotive and a similar decrease in pressure with the train. In this case, the value of pressure in the PM of the locomotive is taken into account at the time of determining and registering the density of the train and the maximum and minimum density of the train is determined.

\[
P_{P_{\text{max}}} = \frac{P_{\text{Pfact}}} {1 + \frac{P_{\text{FLfact}} - P_{\text{FLmin}}} {P_{\text{FLmax}} - P_{\text{FLmin}}} \left(\frac{P_{\text{Lmin}}} {P_{\text{Lmax}}} - 1\right)}
\]

\[
P_{P_{\text{min}}} = \frac{P_{P_{\text{max}}} \cdot P_{\text{Lmin}}} {P_{\text{Lmax}}}
\]

where \(P_{P_{\text{max}}} \) and \(P_{P_{\text{min}}} \) are the maximum and minimum train density;
\(P_{\text{Lmax}} \) and \(P_{\text{Lmin}} \) are the maximum and minimum locomotive density;
\(P_{\text{FLmax}} \) – is the maximum pressure in the PM, at which the density is determined, \(P_{\text{FLmax}}=0,85 \) MPa;
\(P_{\text{FLmin}} \) is the minimum pressure in the PM, at which the density is determined, before the compressor is turned on;

\(P_{\text{Pfact}} \) is the actual measured density of the train.

That is, when registering the density of the train, the maximum and minimum train density. These are the values with which then, in real time, the current density indicators will be compared in real time, also determined by the formula, the maximum current train density and the minimum current train density in order to compare them with the registered ones (and issue a warning if 20% is exceeded).

In addition, after determining the maximum and minimum train density, based on the ratio of the density of the locomotive and the train, the maximum conditional density of the wagon train is determined and recorded.

\[
P_{C_{\text{max}}} = \frac{P_{P_{\text{max}}} \cdot P_{\text{Lmax}}} {P_{\text{Lmax}} - P_{P_{\text{max}}}}
\]
In the future, this parameter is also used to control changes in leaks in the train, by comparing the current maximum conditional density of the train with the registered one.

After calculating and registering density parameters, a short-term signal is sent through the UKTOL system to activate the brakes (turning on the braking mode duration 1 sec.). At the same time, the change in the density of the train is calculated in order to determine the number of cars in the train that have been braked.

After the automatic brakes are applied, the \( t \) time starts to count. Upon reaching the pressure drop \( \Delta p \) (0.05 MPa with a non-operating MC), the time of pressure drop \( t \) is recorded and the length of the BL is calculated in conventional units (the number of cars with a volume of BL of one car of 14 litters):

\[
N_B = 14(1 - t / P_{\text{fact}}),
\]

where \( P_{\text{fact}} \) is the actual measured density of the train.

This value is also logged. Full coincidence of the obtained result with the actual number of cars is not required.

3. Control of the density of the BL of the train during the trip.

After registering the density of the train, it is continuously monitored. The current readings of the train density are compared with the registered readings of the train density and the composition of the wagons. In this case, each time the actual density of the train and the composition of the wagons is determined and the maximum and minimum density of the train and the composition of the wagons is calculated.

To quickly detect the deviation of the train density from the registered one upwards (an increase of 20% from the registered density), it is necessary to control the pressure drop in the PM during the registered time, without waiting for the actual train density and the composition of the wagons to be determined. Control should be carried out as follows:

Each time, from the moment of the beginning of the determination of the actual density, the pressure in the PM should be recorded and the time \( t_c = 0.12P_{\text{max}} \) should start counting. After this time has elapsed, the pressure in the PM is again recorded and the change in pressure is determined. If the pressure change is equal to 0 (zero), the monitor displays warning information about the possible overlapping of end valves in the train or freezing of the BL.

In the event of a decrease in train density by 20% of the minimum registered train density (but not less than 6 seconds), the monitor displays warning information about violation of the density of the train.

In the event of an increase in the density of the train by 20% of the maximum registered density of the train, the monitor displays warning information about the possible overlapping of the end cranes in the train or freezing of the BL.

To exclude false warnings, the possible error in determining the density of the train (with a value of 6 seconds) is taken into account in the formula, which is used to calculate the current maximum conditional density of the train.

\[
P_{\text{cmax}} = \frac{(P_{\text{Pmax}} - 6) \cdot P_{\text{Lmax}}}{P_{\text{Lmax}} - (P_{\text{Pmax}} - 6)}
\]

When the rupture indicator is triggered and the warning lamp comes on about spontaneous operation of the brakes, the cycle for determining the volume of BL starts immediately.

Time \( t \) starts again. Upon reaching the pressure drop \( \Delta p \) (0.05 MPa with the inoperative MC), we register the pressure drop time \( t \) and calculate the BL length in conventional units (the number of cars with a BL volume of one carriage of 14 liters):

\[
N_B = 14(1 - t / P_{\text{fact}}).
\]

Next, compares the calculated indicator \( N_B \) with the registered one. In the event of a discrepancy between the registered \( N_B \) and the actually measured (more than 10% in the direction of decrease), the display shows information about the fact of closing the end valves in the train. To determine the
location of the end cranes, overlap, the ratio between the control (registered) and actual (measured) indicator is used in the form of the number of conventional wagons.

The following features of the proposed method of density control should be noted:
- When sources of increased compressed air consumption (whistle, typhon, sand, the inclusion of anti-unloading devices, blowing the main tanks, braking, creating a "supercharged" pressure in the UR, etc.) density measurement is not performed. The density measurement algorithm is resumed 60 seconds after the sources of increased compressed air consumption are turned off. With an increased consumption of compressed air and an intensive decrease in the PM density for 10 seconds or more, the monitor displays warning information about a possible rupture of the BL.
- The system must provide a function to "reset" the fixed leakage value at the command of the driver.
- The obtained values of the compressor capacity, the fixed and current density of the BL should be registered.
- When the pressure in the UR differs from the charging pressure by 0.02 MPa or more, the density measurement is not performed.
- The density of a single locomotive and the compressor capacity can be maintained when the system is turned off.
- If the leakage value more than the value of the density of the BL of the train, then the change in density by 20% is controlled according to the last parameter.

4. Conclusions
As a result of the comparative analysis, the main directions for improving the methods of brake line monitoring can be identified:
- Control using a full-fledged diagnostic system of train brakes based on an intelligent EPB system installed on each mobile unit. The most functional, promising option, but also the most difficult and expensive, which implements the transition of rolling stock to a qualitatively new level.
- Control using a compressed air flow meter. An expensive but promising option requiring further additional study and carrying out train and operational tests.
- Density control to reduce the pressure in the main tanks on the basis of modern locomotive MPS & D. The implementation of this control method does not require significant costs, since it is carried out by improving the on-board diagnostics system, through the development and installation of additional software. Separately, it is worth noting that this control method was patented (intellectual property rights belong to NPO SAUT Ltd.) and has already proven its effectiveness during bench and acceptance tests of the latest locomotive control systems.
- Considering the simplicity and ease of implementation, as well as the possibility of functional expansion, the proposed method seems to be the most optimal option for monitoring the brake network of a train.

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