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Design and Simulation of a Pneumatic Test-Bench for Locomotive Brake Valves

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Abstract

Pneumatic braking systems are critical for the safe and reliable operation of locomotives. However, conventional brake valve testing utlizing onboard locomotive brake panel can be highly time-consuming as the valve must be fully reinstalled before the leakage behaviour can be verified. To adress this challenge, this study develops a simulation-based pneumatic test-bench model to evaluate locomotive brake valve pressure retention and leakage behaviour. The model was developed using MATLAB/Simulink and Simscape Fluids incorporating components such as a compressed air reservoir, flow restriction, brake cylinder chamber, leakage orifice, atmospheric reservoir, pressure sensor, gas properties, and solver configuration. Validation of the model was based on the KTMB Class 26 independent brake cylinder leakage test protocol, which requires the system pressure to remain above 3.6 bar for 1800 seconds after being initially charged to approximately 3.90 bar. Under normal operating conditions, the simulated pressure decreased from 3.90 bar to 3.79 bar, resulting in a PASS clasification. Converseley, under simulated leakage conditions, the pressure decreased from 3.90 bar to 2.95 bar resulting in a FAIL clasification. The results show that the proposed simulation model can distinguish between acceptable and excessive leakage behaviour, thereby supporting early-stage brake valve leakage analysis prior to physical prototype development.

1. Introduction

Pneumatic braking systems are widely employed in railway vehicles because of their reliability, fail-safe characteristics, and ability to generate sufficient braking force under demanding operating conditions. The brake cylinder (BC) is one of the most important components within the pneumatic braking system because it converts compressed air pressure into mechanical braking force. Loss of pressure caused by leakage can reduce braking performance, increase maintenance requirements, and compromise operational safety. Consequently, accurate monitoring of brake cylinder pressure retention is essential to ensure the serviceability of pneumatic brake valves before they are returned to operation (Bhardawaj et al., 2025; Wang et al., 2026).

The increasing adoption of simulation techniques has enabled researchers to investigate pneumatic system behaviour without relying entirely on physical experiments. Mathematical modelling and simulation using

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MATLAB/Simulink and Simscape Fluids have been successfully applied to predict pressure propagation, airflow characteristics, and leakage behaviour in railway pneumatic systems. These simulation approaches allow engineers to analyse different operating conditions efficiently while reducing experimental cost and development time (Cantone & Ottati, 2023; Ge et al., 2023; Wu et al., 2023).

Leakage within pneumatic brake systems remains one of the most common causes of brake performance deterioration. Even relatively small leakage paths may gradually reduce brake cylinder pressure and eventually affect braking effectiveness if left undetected. Several studies have demonstrated that pressure-time response provides an effective indicator for identifying leakage severity and evaluating pneumatic component health. Pressure decay analysis has therefore become an important technique in railway condition monitoring and predictive maintenance (Hou et al., 2023; Galimberti et al., 2024; Wang et al., 2021).

At SMH Rail, repaired brake valves are currently tested using the locomotive braking system during maintenance activities. This approach requires technicians to prepare the complete pneumatic circuit before each test, making the validation process time-consuming and dependent on locomotive availability. Furthermore, leakage diagnosis is only performed after the brake cylinder fails the pressure retention test. To overcome these limitations, this study proposes a simulation-based pneumatic test-bench capable of reproducing brake cylinder pressure behaviour under both normal and leakage conditions. The simulation model provides a controlled environment for evaluating valve performance and leakage characteristics based on KTMB Class 26 maintenance practice while reducing dependence on the complete locomotive system (Li et al., 2021; Pfaff et al., 2022).

2. Methodology

This study odopts a simulation-based research design. The pneumatic test-bench configuration was initially conceptualised based on the functional requirements of standard brake cylinder leakage testing. As illustrated in Fig. 1, the proposed arrangement comprises a compressed air source, flow restriction, brake valve representation, brake cylinder chamber, leakage orifice, atmospheric outlet, pressure sensor and data output system. The primary output evaluated from this system is the brake cylinder pressure-time response.

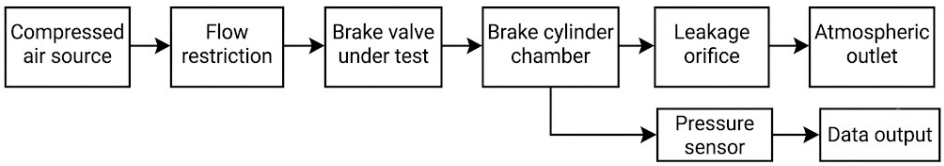


Fig. 1 *Proposed pneumatic test-bench configuration for locomotive brake valve leakage analysis*

The model was developed using MATLAB/Simulink and Simscape Fluids gas-domain components as illustrated in Fig. 2. The compressed air reservoir supplied the pressure input, while the brake cylinder chamber represented the controlled volume used for pressure retention analysis. The leakage orifice represented air loss through possible defects such as valve leakage, seal leakage, fittings or pneumatic connections. A pressure sensor measured the brake cylinder pressure and converted it into a Simulink output signal for subsequent plotting and numerical analysis.

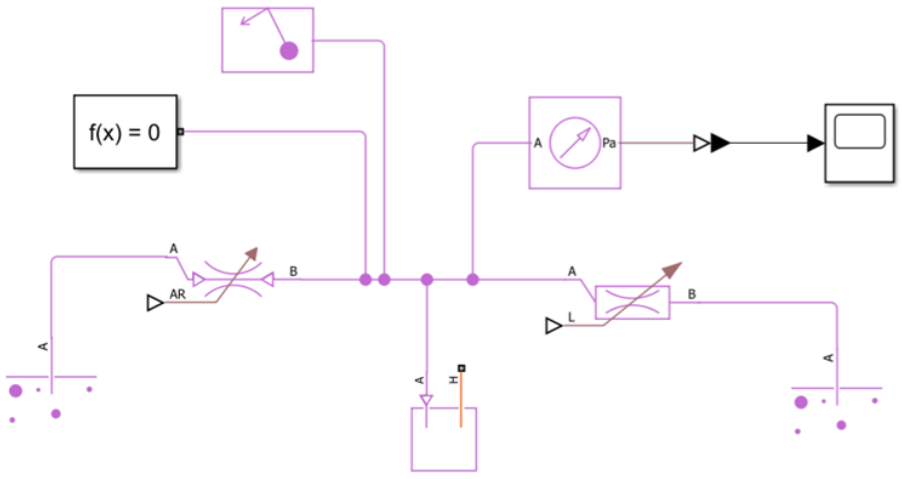


Fig. 2 *Pneumatic test-bench simulation model developed in MATLAB/Simscape Fluids*

The validation criterion adopted in this study was based on the maintenance practice currently implemented for KTMB Class 26 locomotive independent brake cylinder leakage testing during overhaul activities at SMH Rail. According to this maintenance practice, the brake cylinder is initially charged to approximately 3.90 bar before the pneumatic circuit is isolated and monitored continuously for 1800 seconds. Throughout the testing period, the brake cylinder pressure must remain above 3.60 bar to satisfy the maintenance acceptance criterion. If the pressure falls below 3.60 bar before the completion of the test, the brake valve is classified as having excessive leakage and further inspection is required to identify the leakage source before the component is returned to service. Although this maintenance procedure is routinely applied in workshop practice, no publicly available KTMB standard operating procedure currently documents this validation criterion. Therefore, the maintenance requirement adopted in this study was obtained directly from industrial maintenance practice observed during the author's industrial training at SMH Rail.

The leakage path within the simulation model was represented using an equivalent leakage orifice. The selected orifice areas were chosen based on leakage modelling approaches commonly reported in pneumatic system simulation studies, where leakage is represented using calibrated equivalent openings to reproduce different leakage severities without modelling actual physical crack geometry (Cantone & Ottati, 2023; Ge et al., 2023; Jiang et al., 2023).

2.1 Mathematical model

The pneumatic chamber pressure response is governed by the relationship between air mass, chamber volume, pressure and leakage flow. For a simplified leakage analysis, the pressure decay can be evaluated from the pressure-time output. The total pressure drop (P_{Decay}) and the average pressure decay rate ($P_{Average}$) are calculated using Eq. (1) and Eq. (2) respectively:

$$P_{Decay} = P_{Initial} - P_{Final} \tag{1}$$

$$P_{Average} = \frac{P_{Initial} - P_{Final}}{t} \tag{2}$$

where $P_{Initial}$ denotes the initial brake cylinder pressure, P_{Final} represents the final pressure at the end of the simulation and t is the test duration in seconds. These two metrics serve as quantitative indicators to differentiate between normal and faulty leakage states.

3. Results and Discussion

Two primary operational conditions were simulated: normal operating condition and leakage condition. The normal operating condition represents an acceptable leakage behaviour, whereas the leakage condition represents excessive pressure loss. The pressure-time responses were evalueted based on final pressure, total pressure drop, average pressure decay rate, threshold crossing time and pass/fail classification. A quantitative summary of these findings is consolidated in Table 1.

Table 1 Quantitative comparison between normal and leakage simulation results

Condition	Initial pressure (bar)	Final pressure at 1800 s (bar)	Pressure drop (bar)	Average decay rate (bar/s)	Result
Normal operating condition	3.90	3.79	0.11	6.11×10^{-5}	PASS
Leakage condition	3.90	2.95	0.95	5.28×10^{-4}	FAIL

The comparison demonstrates a clear difference in pressure retention behaviour between the two operating conditions. Under the normal operating condition, the brake cylinder experienced a pressure reduction of only 0.11 bar, corresponding to an average pressure decay rate of approximately 6.11×10^{-5} bar/s. The pressure remained above the acceptance threshold throughout the simulation, indicating that the pneumatic system retained sufficient compressed air despite the presence of minor leakage. Conversely, the leakage condition produced a pressure reduction of approximately 0.95 bar with an average pressure decay rate of 5.28×10^{-4} bar/s, which is approximately 8.6 times greater than that observed under the normal operating condition. Consequently,

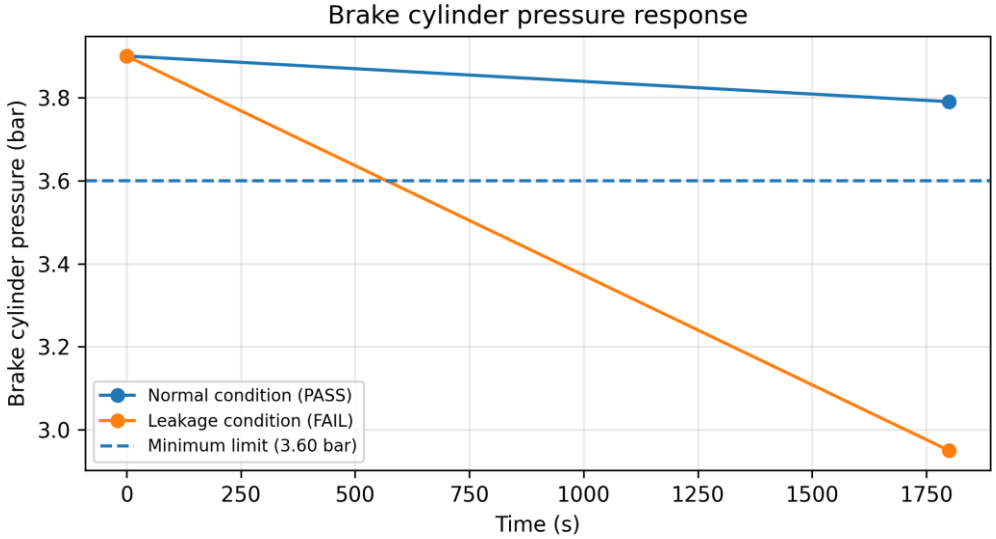
the brake cylinder pressure fell below the KTMB acceptance threshold before the end of the 1800 s test duration, indicating excessive leakage within the simulated pneumatic system.

The difference in pressure decay behaviour is attributed to the amount of compressed air escaping through the equivalent leakage path. After the brake cylinder reaches the initial charging pressure, the pneumatic chamber becomes isolated and the internal pressure gradually decreases as air escapes through leakage paths. Even under normal operating conditions, a small pressure reduction is expected because practical pneumatic systems are not perfectly airtight. Minor leakage may occur through valve seats, elastomeric seals, threaded fittings, and pneumatic connections due to manufacturing tolerances and component clearances. Since the equivalent leakage area is very small, the resulting mass flow rate remains low and the brake cylinder is able to maintain pressure above the prescribed maintenance limit throughout the validation period. Under the leakage condition, the larger equivalent leakage path provides a lower flow resistance, allowing compressed air to escape from the brake cylinder at a significantly higher mass flow rate. The continuous reduction in the mass of compressed air within the fixed chamber volume results in a faster decrease in brake cylinder pressure until the maintenance threshold is exceeded. This behaviour demonstrates that leakage severity has a direct influence on the pressure retention capability of the brake cylinder and can therefore be used as an indicator of brake valve serviceability.

The simulated pressure responses are consistent with previous studies on railway pneumatic braking systems. Ge et al. (2023) reported that pressure decay increases with leakage severity because a larger leakage path permits a greater mass flow of compressed air to escape from the pneumatic chamber. Similarly, Galimberti et al. (2024) demonstrated that pressure-time characteristics provide an effective basis for distinguishing between healthy and faulty pneumatic brake systems during condition monitoring. Hou et al. (2023) further concluded that brake cylinder pressure retention is one of the most reliable diagnostic indicators for pneumatic brake fault detection, while Cantone and Ottati (2023) showed that simplified pneumatic models are capable of accurately reproducing brake cylinder pressure behaviour during railway braking simulations. The agreement between the present simulation results and published studies indicates that the proposed model provides a realistic representation of pneumatic pressure decay and leakage behaviour under both serviceable and faulty operating conditions.

The findings demonstrate that the proposed simulation-based pneumatic test-bench is capable of reproducing the pressure retention characteristics required for KTMB Class 26 brake cylinder leakage testing and can effectively differentiate between acceptable and excessive leakage conditions. Future work should validate the simulation results experimentally using a physical pneumatic test-bench to verify the predicted pressure response under actual operating conditions. In addition, a wider range of leakage locations and equivalent leakage sizes should be investigated to improve the robustness of the model and enhance its applicability for railway maintenance planning and brake valve fault diagnosis.

Figure 3 illustrates the simulated brake cylinder pressure response under both the normal operating condition and the leakage condition throughout the 1800 s validation period. Under the normal operating condition, the brake cylinder pressure decreased gradually from an initial pressure of 3.90 bar to 3.79 bar while remaining above the KTMB maintenance acceptance threshold of 3.60 bar. In contrast, under the leakage condition, the brake cylinder pressure decreased more rapidly from 3.90 bar to 2.95 bar and crossed the minimum allowable pressure before the completion of the testing period, resulting in a FAIL classification according to the KTMB maintenance criterion.



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Fig. 3 *Brake cylinder pressure response under normal and leakage conditions*

3.1 Sensitivity analysis of leakage size

To evaluate the robustness of the model, a parametric sensitivity analysis was conducted by varying the leakage orifice size while maintaining the initial pressure, chamber volume, gas temperature and simulation duration constant. The results confirmed that larger leakage orifice sizes accelerated the pressure decay and led to lower final pressure at 1800 s. This trend verifies that leakage size has a direct influence on brake cylinder pressure retention. Furthermore, this sensitivity analysis also supports the identification of acceptable, borderline and excessive leakage conditions for future test-bench calibration.

Since no publicly available KTMB documentation specifies the equivalent leakage orifice size for brake valve leakage testing, the leakage areas adopted in this study were selected based on the leakage modelling approach commonly used in pneumatic system simulations reported in previous studies. Small equivalent leakage orifices are frequently employed to represent seal degradation and minor internal leakage in compressed air systems, while progressively larger leakage areas are used to simulate severe leakage conditions (Galimberti et al., 2024; Li et al., 2024). Therefore, the selected leakage sizes provide a practical range for evaluating the sensitivity of the proposed simulation model. **Table 2** presents the simulation results obtained for different leakage orifice areas.

Table 2: Sensitivity analysis of leakage orifice size

Leakage Orifice Area (m^2)	Final Pressure (bar)	Pressure Drop (bar)	Average Pressure Decay Rate (bar/s)	Result
1×10^{-9}	3.89	0.01	5.56×10^{-6}	PASS
1×10^{-8}	3.82	0.08	4.44×10^{-6}	PASS
1×10^{-7}	3.15	0.85	4.72×10^{-6}	FAIL

Table 2 presents the sensitivity analysis of the brake cylinder pressure response for three different leakage orifice areas, namely 1×10^{-9} m^2, 1×10^{-8} m^2, and 1×10^{-7} m^2. The comparison includes the final brake cylinder pressure, total pressure drop, average pressure decay rate, and the corresponding PASS or FAIL classification based on the KTMB brake cylinder leakage acceptance criterion.

The simulation results demonstrate that increasing the leakage orifice area significantly affects the pressure retention capability of the brake cylinder. For the smallest leakage orifice area of 1×10^{-9} m^2, the brake cylinder pressure decreased only slightly from 3.90 bar to 3.89 bar, resulting in a pressure drop of 0.01 bar, and the system satisfied the KTMB acceptance criterion. When the leakage orifice area was increased to 1×10^{-8} m^2, the final pressure decreased to 3.82 bar, corresponding to a pressure drop of 0.08 bar, although the brake cylinder pressure still remained above the minimum allowable pressure of 3.60 bar, resulting in another PASS classification. However, when the leakage orifice area reached 1×10^{-7} m^2, the brake cylinder pressure decreased substantially to 3.15 bar, producing a pressure drop of 0.85 bar. Since the final pressure fell below the KTMB acceptance threshold, the simulated brake valve was classified as FAIL. These findings indicate that the proposed simulation model is sensitive to changes in leakage severity and is capable of distinguishing between acceptable and excessive leakage conditions.

The observed pressure behaviour is governed by the principles of compressible gas flow through an orifice. As the equivalent leakage orifice area increases, the resistance to airflow decreases, allowing a greater mass of compressed air to escape from the brake cylinder chamber within the same period. Because the brake cylinder has a fixed internal volume after charging, the continuous loss of compressed air reduces the chamber pressure progressively over time. For very small leakage areas, such as 1×10^{-9} m^2, the leakage flow rate is negligible, resulting in only a slight reduction in brake cylinder pressure. Increasing the leakage area to 1×10^{-8} m^2 causes a moderate increase in airflow through the leakage path, leading to a larger pressure drop while still maintaining sufficient pressure for safe operation. When the leakage orifice reaches 1×10^{-7} m^2, the airflow escaping from the chamber becomes sufficiently large to accelerate pressure decay, causing the brake cylinder pressure to fall below the KTMB maintenance limit before the completion of the validation period. This demonstrates that leakage orifice size is a critical parameter governing pressure retention and brake valve serviceability.

The simulation results are consistent with previous studies on pneumatic leakage modelling and railway braking systems. Ge et al. (2023) reported that increasing leakage severity accelerates pressure decay because a larger leakage path permits a higher mass flow rate of compressed air leaving the pneumatic chamber. Similarly, Galimberti et al. (2024) demonstrated that pressure-time response provides an effective indicator for

distinguishing between healthy and faulty pneumatic brake systems during condition monitoring. Li et al. (2024) further showed that equivalent leakage orifice models can accurately represent leakage behaviour in pneumatic simulations and are suitable for evaluating system performance under different fault conditions. The agreement between the present findings and published studies indicates that the proposed simulation model realistically represents the influence of leakage size on brake cylinder pressure retention.

Based on these findings, the proposed simulation model can be used as a practical tool for evaluating brake valve leakage performance before physical maintenance testing. Future work should investigate additional leakage orifice sizes between 1×10^{-8} m^2 and 1×10^{-7} m^2 to determine the critical leakage threshold that causes the brake cylinder pressure to fail the KTMB acceptance criterion more precisely. In addition, experimental validation using a physical pneumatic test-bench is recommended to verify the simulation results under actual railway maintenance conditions.

4. Conclusion

This study successfully developed a simulation-based pneumatic test-bench model using MATLAB/Simulink and Simscape Fluids to characterize locomotive brake valve leakage behavior. The proposed model reproduced brake cylinder pressure behaviour under normal and leakage conditions based on the KTMB Class 26 independent brake cylinder leakage criterion. The normal operating condition maintained pressure above 3.60 bar for 1800 s and was classified as PASS, while the leakage condition dropped below the allowable threshold and was classified as FAIL. The results show that final pressure, pressure drop, average pressure decay rate and threshold crossing time can be used as practical indicators for evaluating leakage severity. The model provides a foundation for future physical pneumatic test-bench development and experimental validation.

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