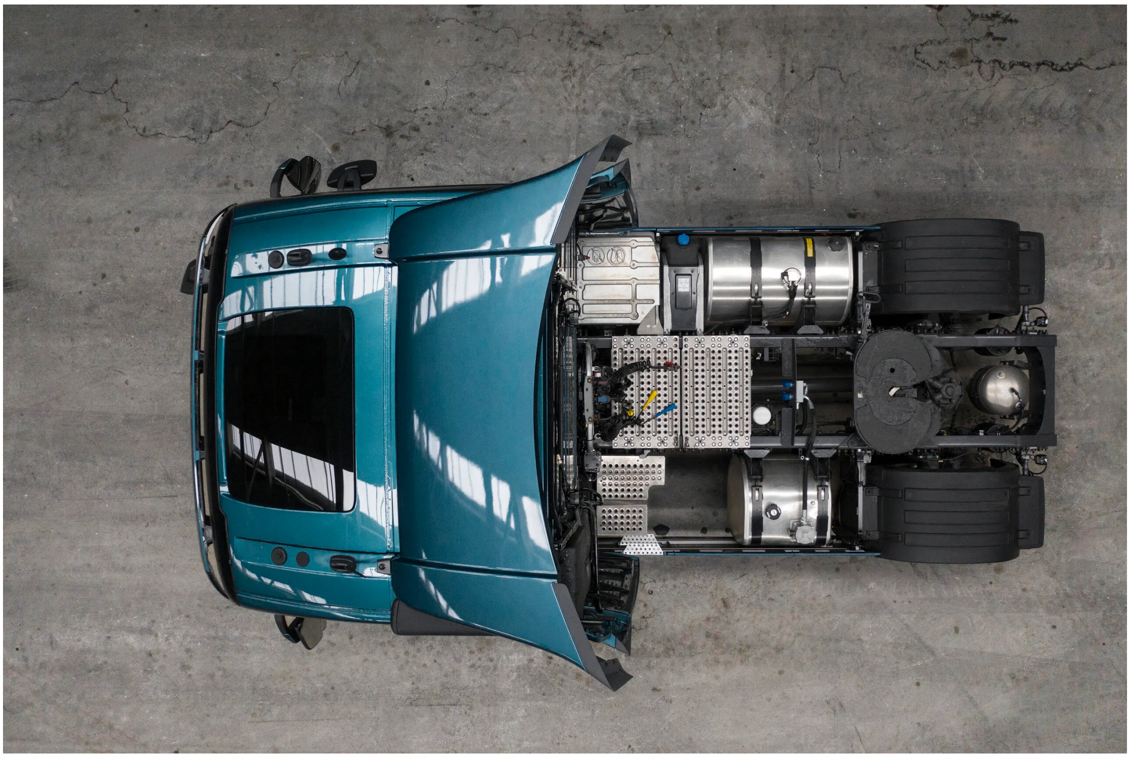

Development of a Verification Process for Truck Pneumatic Systems

A Case Study on Air-Leakage Detection and End-of-Line Quality Assurance

Master's Thesis in Production Engineering

Cornelia Falkhage

Matilda Graad

DEPARTMENT OF MECHANICAL ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026
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MASTER'S THESIS 2026

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Cover: Top-view image of a Volvo truck of model FM showing the chassis layout and driver cab.

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Abstract

This thesis investigates the development of a verification process for pneumatic systems in heavy-duty trucks, with a focus on air-leakage detection at the End-of-Line stage. The study was conducted at Volvo Group Trucks Technology & Industrial Division in Tuve, Sweden, and evaluates the feasibility of integrating digital pressure decay measurement equipment to improve quality assurance, reduce operator dependency, and enable data-driven decision-making. A combined methodology was applied, including a literature review, stakeholder interviews, benchmarking across production sites, and experimental testing utilizing PDCA methodology. Key process parameters were assessed through statistical hypothesis testing, including equivalence testing and paired one- and two-tailed t-tests. These were utilized to evaluate the effects of test duration, stabilization time, filling method, and subsystem activation on leakage detection accuracy. The results demonstrate that pressure decay testing can be significantly optimized. Equivalent detection accuracy was achieved with reduced test durations compared to the current 4-minute reference, enabling cycle time reductions of up to 2–3 minutes under controlled conditions. However, the inclusion of a stabilization phase was shown to be critical for reliable measurements due to transient pressure variations caused by thermodynamic effects. The required stabilization time was also found to vary across trucks, supporting the implementation of a dynamic threshold-based approach to balance measurement reliability and efficiency. Furthermore, subsystem activation was shown to influence measured pressure decay, indicating the need to adapt leakage thresholds depending on test conditions. Based on these findings, a standardized verification process with automated OK/NOK decision-making is proposed, integrating digital measurement equipment into the existing production environment. The process improves consistency, enables data collection, and reduces operator dependency. While the concept is technically feasible, further validation is required before full-scale implementation.

Keywords: Pneumatic systems, air leakage detection, leak testing, End-of-Line (EOL) testing, pressure decay, quality assurance, heavy-duty vehicles, statistical hypothesis testing, equivalence testing.

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Cornelia Falkhage & Matilda Graad, Gothenburg, June 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AI	Artificial Intelligence
APM	Air Production Modulator
CA	Compressed Air
CI	Confidence Interval
EBS	Electric Brake System
EOL	End-of-Line
EDPB	European Data Protection Board
FSO	Full Scale Output
GDPR	General Data Protection Regulations
IR	Infrared
NDT	Non-Destructive Testing
NOK	not OK
PDCA	Plan-Do-Check-Act
QA	Quality Assurance
QC	Quality Control
R&D	Research and Development
SPC	Statistical Process Control
TR	Technical Requirement
TQM	Total Quality Management

Nomenclature

Below is the nomenclature of parameters and variables that have been used throughout this thesis.

Parameters

ΔP	Differential pressure
t_c	Cycle time
t_t	Test time
Q	Leak rate

Variables

e	Standard error
D_U	Upper equivalence bound
D_L	Lower equivalence bound
F	Force
μ	Sample mean
P	Pressure
R	Universal gas constant
σ	Sample standard deviation
T	Temperature in Kelvin
V	Volume

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1

Introduction

This chapter introduces the master's thesis project, including background, aim, limitations, and issues to be investigated throughout this project.

1.1 Background

In the manufacturing industry, there is a clear shift towards increased automation, data-driven decision making, and the adoption of advanced technologies. As a result, traditional quality control performed by operators is being improved by the use of automated systems [1]. The shift also applies to the End-of-Line (EOL) testing, where reliable and consistent quality assurance (QA) is critical for verifying product functionality, maintaining competitive performance, and reducing the risk of costly customer complaints.

This trend is very relevant for the operations at the Volvo Trucks plant in Tuve. Founded in 1982, the plant facility spans 117 500 square meters of land and employs approximately 2 400 employees. It produces approximately 66 heavy-duty trucks per day of the models FH16, FH, FM, and FMX [2] using a mixed-model assembly line. The facility follows a fish-bone assembly principle, where a fully built truck is completed in just over six hours starting from the frame. In addition, the plant handles complete knock-down (CKD) shipments for transport to other global assembly sites. With approximately 65% of trucks involving customer-specific adaptations, production is highly variable, placing strong demands on flexible and robust QA methods.

This challenge is not unique to the Tuve plant but reflects a broader issue in modern manufacturing environments, where increasing system complexity and high product variability require more robust and scalable quality assurance methods. As highlighted by Lasi et al. [3], this variability is driven by a growing demand for product individualization, which increases the need for flexibility in production systems. At the same time, despite significant progress in Industry 4.0 technologies, a gap remains between available digital solutions and its practical implementation in industrial environments Xu et al. [4]. As a result, fully integrated and standardized end-of-line verification systems are still not widely implemented across production sites.

In this context, standardized work is important because it reduces variation and errors by establishing a clear baseline for task execution, enabling consistent performance across operators and conditions [5]. It also reduces the routine workload for operators, allowing them to focus on process improvements and waste reduction, while providing a stable reference point for evaluating process changes and differentiate real improvements from variation [5].

1.2 Problem description

Pneumatic systems play a key role in ensuring vehicle safety, performance, and reliability, especially for braking functions [6]. In order to verify that these systems work as intended, EOL testing is conducted before the vehicle leaves production. However, the current verification process at the Tuve plant remains heavily operator-dependent and lacks data logging capabilities, which limits the traceability for troubleshooting purposes and the ability to apply Statistical Process Control (SPC). Furthermore, testing practices lack standardization including variation in utilized equipment, work instructions and process sequences across different manufacturing plants, which limits the possibility to continuously evaluate and update Technical Requirements (TR) to accurately reflect the systems of the current vehicle generation. Therefore, it is necessary to evaluate alternative control setups, including a need for evaluating digital pressure drop equipment to automate the air leakage detection process and collect reliable measurement data. Investigating this solution is important for eliminating manual errors, standardizing the verification method across plants, improving working conditions for operators, and establishing a foundation for improving production efficiency.

1.3 Aim

The aim of this thesis project is to identify and assess a feasible verification process for truck pneumatic systems using a digital pressure drop measurement equipment prototype. The study focuses on evaluating requirements, constraints, and potential process designs to determine whether prototype integration can improve quality assurance while meeting standards for safety, efficiency, and operator usability. The work also assesses the potential scalability and transferability of the proposed process concept to other Volvo Trucks plants.

1.4 Specification of the issue being investigated

Based on the aim presented in section 1.3, the following research questions guided the project.

- **RQ1:** What requirements and constraints define the design space for a pneumatic leakage verification process at EOL?
- **RQ2:** What verification process plan can be created to effectively integrate digital pressure decay equipment while fulfilling the identified requirements

and staying within the project constraints?
- **RQ3:** What are the expected impacts and risks of implementing the proposed process plan?

The research questions are addressed through a combination of literature review, qualitative stakeholder analysis, experimental evaluation, and process development within a process engineering framework.

2

Theoretical Background

This section presents relevant theory related to pneumatic systems, quality assurance technology, and methods used and researched within the area of leakage detection and localization.

2.1 Pneumatic systems and braking fundamentals

Pneumatic technology has a long history of application across various vehicle types. The first trial of using pneumatic brakes, instead of mechanical ones, was in the railway industry during the 1980s [7]. This transition was mainly driven by the idea of faster response and long-distance force transmission with a fail safe behavior, which enabled trains to be used at full speed with more load due to use of air brakes.

2.1.1 Heavy vehicle pneumatic systems

Pneumatic systems transmit power and control the energy from one source to an application by utilizing compressed gas, typically air or nitrogen [8]. Atmospheric air is widely used due to its availability at no cost, compressibility for compact storage, non-flammability, and poses no risk of equipment contamination in the event of a system leak. The operation relies on a sequence of key components. Atmospheric air enters the pneumatic system through a filter, removing dirt and unwanted particles [9]. From the filter, the air is drawn into the compressor, which is driven by the truck engine. The compressed air then goes through a cooling pipe to reduce its temperature before entering the Air Production Modulator (APM). The APM contains an integrated dryer that removes excess moisture from the air and has a function of regulating pressure and determining when the compressor operates.

The pneumatic system is divided into two independent circuits, one supplying the front axle and the other supplying the rear axle [9]. This ensures that if one circuit fails, the second circuit can still stop the truck. However, air can flow between the two circuits if the relative pressure is within a set interval. If the system loses air rapidly, the truck's engine speed (RPM) increases so the compressor runs faster to compensate for the pressure drop, and the driver is alerted on the dashboard to stop the truck. Beyond braking, additional subsystems rely on this same pneumatic supply network. For example, engaging the differential (diff) lock or lowering the trailing axle to its lowest position, pressurizing specific air bellows to push the wheels against the ground, both utilize air supplied by the shared supply network [9].

2.1.2 Braking system

When force is applied to the service brake pedal in the cab, an electrical signal commands the brake valves to open, releasing pressurized air from the tanks [9]. The amount of air released is proportional to the force applied to the pedal, with maximum pressure causing the brake valves to open fully. The Electronic Brake System (EBS) distributes and modulates this air to the left and right sides of the system, preventing the wheels from locking if the driver brakes hard. Within this network, some components require a continuous supply of pressurized air to function, while others are only pressurized when the brakes are actively applied. Depending on the truck's axle configuration, the rear circuit will integrate either a single or a double EBS unit. A system mapping of the air brakes is shown in figure 2.1.

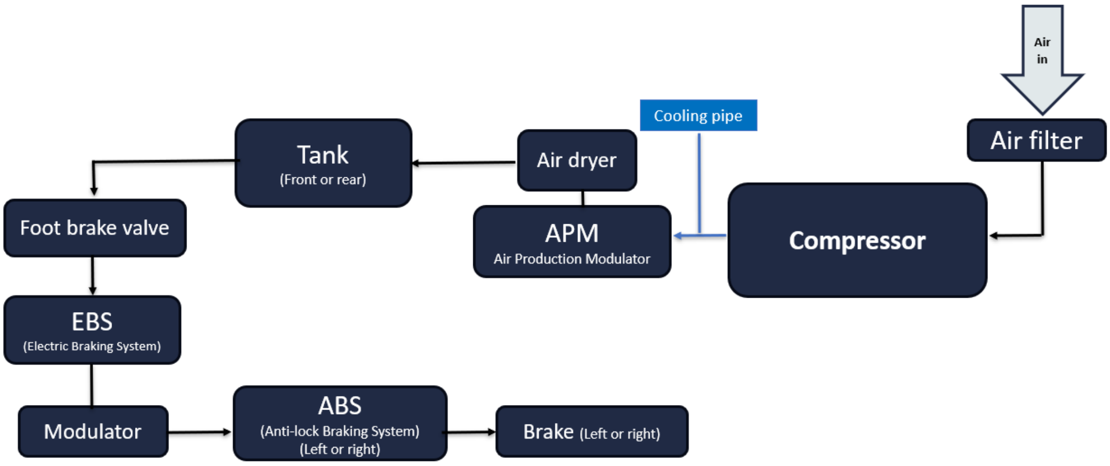


Figure 2.1: Block diagram of the braking system.

2.2 System air leakage

Because no component can be completely leak-free, for example due to natural leakage paths created by seals and connection points, it is essential to define which level of leakage is acceptable [10]. Establishing an acceptable leak rate ensures that the system performs as intended while maintaining the required safety and reliability standards. Leakage above the approved level can be due to incorrect assembly or faulty parts. The air leakage test at EOL increases the difficulty compared to visual identification of liquid leaks, such as fuel-based leakage. The testing and verification of the system should be done quickly to avoid any production line delays or cause a bottleneck. Before designing the verification process, some critical factors to consider to avoid any additional costs of change in infrastructure are testing time, physical space, and compatibility with the current setup.

An air leakage testing process commonly includes four key phases: air filling (pressurization), stabilization, testing (measurement), and evacuation, as illustrated in figure 2.2.

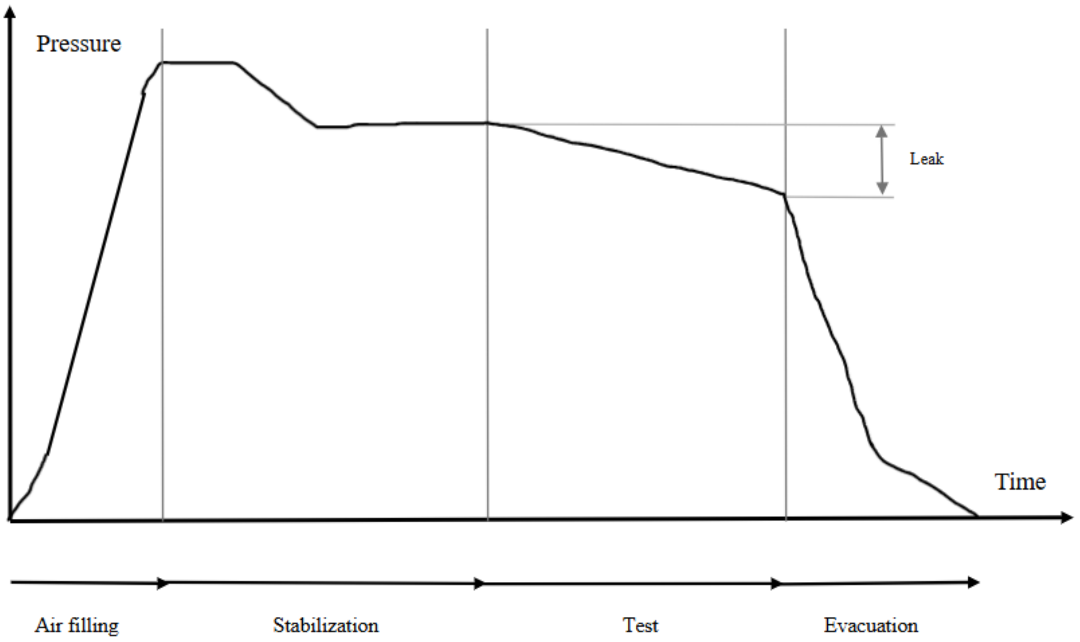


Figure 2.2: An air pressure curve with specified test phases.

There are key factors to assess and evaluate in order to determine the quality and integrity of a pneumatic system during an air leakage test. To ensure that the test conditions are realistic, the system is first pressurized to a predetermined level, typically to operating pressure [11]. However, raw pressure measurements during a pneumatic air tightness test are influenced by more than just the presence of leakage. During the stabilization phase, the temperature of the compressed gas decreases, and in alignment with the ideal gas law, see equation 2.1, the temperature drop corresponds with a decrease in pressure, even when there is no leakage in the system. The stabilization phase allows the pressure and temperature to equalize throughout the system to ensure stable conditions, preventing initial readings from reflecting thermal effects rather than true leakage behavior. Once equalized, the actual leakage test is performed during the testing phase, where any further decline in pressure indicates the presence of a leak within the tested component.

In addition, pressure measurements are dependent on the system volume [12]. Larger volumes often result in slower pressure variations, while smaller volumes respond more quickly. The complexity and geometry of a pneumatic system also affect the duration of the stabilization phase. As a result, the required stabilization time and its impact on pressure measurements can significantly vary depending on the specific characteristics of a system. Once the system reaches a stable state, a leakage test can be performed.

$$PV = nRT \tag{2.1}$$

Where
- P is the pressure
- V is the volume
- n is the moles for the gas
- R is the universal gas constant
- T is the temperature in Kelvin

2.3 Methods for leakage detection and localization

Commonly used industrial leakage detection and localization methods are described below, along with state-of-the-art studies aimed at improving reliability, accuracy, and overall quality control.

2.3.1 Pressure decay

The pressure decay method is one of the most straightforward and widely used methods for leakage detection in sealed components. In this method, the tested workpiece is filled with a gas to a predetermined pressure and after a stabilization time, pressure changes over time is monitored [13]. If there is a leak, the trapped gas escapes causing a pressure drop after a set interval. This method is operationally simple, cost-effective, and enables a relatively short detection time. However, its performance strongly depends on the precision of the pressure sensor. Lower-grade sensors lack the resolution to detect minor air losses, making this approach better suited for identifying medium to large leaks where pressure changes are clearly measurable.

2.3.2 Pressure differential

The differential pressure method is based on the ideal gas law (equation 2.1) and is similar to direct pressure detection, but introduces a reference component for better measurement sensitivity [13]. Instead of only monitoring the pressure of the test piece, the system compares with a "master" tank without leakage. Both the tested and master tank are pressurized to the same level, and a sensor measures the pressure difference between them. A leakage in the test tank will result in an internal pressure decrease while the reference part will be stable. The sensor can then detect the pressure difference with high accuracy. However, this method requires close matching between the test volume and the reference volume and consistent thermal conditions to ensure reliable measurements.

2.3.3 Vacuum decay

Vacuum decay is a non-destructive leak detection method used to assess the integrity of sealed containers [14]. The container is placed inside a sealed test chamber, a vacuum pump evacuates the air from the chamber to create a vacuum around the container, and the system monitors for any rise in pressure. A pressure increase indicates that gas is escaping from the container into the chamber, which confirms the presence of a leak. The method is clean, simple, fast, and cost-effective because it requires no consumables or immersion fluids. The tested part remains fully intact. However, its performance is limited by the maximum achievable pressure difference. If a package is designed for much higher internal pressures than the vacuum system can simulate, the test may not provide meaningful sensitivity for that application. Vacuum decay is compatible and often used for container types of glass, plastic, and metal vials, bottles, syringes, ampoules, and various rigid or flexible packages, provided they can be sealed or masked during testing. It is widely used in pharmaceutical, food, and beverage packaging due to its ability to detect both gross defects and micro-leaks when properly applied [14]. However, it can be less suitable for bigger and more complex systems.

2.3.4 Acoustic methods (ultrasonic)

Acoustic emission methods are based on the principle that pressurized gas escaping from an opening creates turbulent flow. This turbulence generates acoustic waves in both audible and non-audible (ultrasonic) frequency ranges above 20 kHz [10]. These sound signals can be captured using microphones, ultrasonic sensors, and/or accelerometers. The signals are analyzed over either the time domain through comparing arrival times of the sound between multiple sensors, or in the spatial domain to visualize leak location through intensity maps. The detection readability heavily relies on the filtering and signal processing algorithms to remove environmental noise. When properly filtered this method can provide rapid and accurate localization of leaks, even at small flow rates. An example of an acoustic imager device is presented in figure 2.3.

Figure 2.3: Acoustic imager camera of model ii900 [15], where red regions indicate detected acoustic emissions associated with a leak.

Acoustic technologies has shown potential for implementation at EOL leakage control stations [16]. Beyond conventional ultrasonic techniques, modern developments have aimed to improve performance of the handheld detection devices. For example, Liao et al. [17] employed multiple ultrasonic sensors combined with time delay estimation, achieving improved detection accuracy. In addition, recent efforts focused on improving the performance of the technology for leakage testing by integrating computer-vision-based algorithms within the manufacturing sector [16].

2.3.5 Infrared imaging

Infrared (IR) imaging uses a camera to detect differences in the thermal radiation naturally emitted by objects and surfaces [18]. When a leak occurs, the escaping gas often disturbs the local heat exchange, and IR cameras can capture and visualize the contrast. The technique offers a wide area coverage, provide real time visualization, and can be performed during the normal operations. An example of a thermal imager camera is presented in figure 2.4.

Figure 2.4: Thermal imager camera of model Thor002 [19], where areas shown in red indicate elevated temperatures associated with a leak.

A study by Xie et al. [20] concluded that the use of infrared cameras in combination with algorithms for automatic inspection in industrial applications is promising. However, when evaluating the automated system against the traditional approach of using a trained manual observer, the infrared camera failed to identify several critical leak locations. These limitations highlight that further technical development is still required before such technology can be fully implemented to reduce the reliance on manual inspection.

2.3.6 Bubble testing

Pressurized systems can be inspected for leaks by applying a soap solution on the test surface at the region of interest (ROI) and observing whether bubbles form at points where air escapes [21]. In some cases, parts are submerged in water so that escaping air creates visible bubbles, making it easier to pinpoint the leak. Although traditional bubble testing is simple and cost-effective, it is also highly time-consuming, can promote corrosion on certain materials, and does not accurately provide quantitative data on the leakage rate. In recent years, the traditional water-based methods have been complemented by computer-vision-based approaches to automate bubble detection, reducing human judgment and improving measurement reliability. Saworski and Zielinski [22] introduced an optical flow-based segmentation approach that applies the so called Horn-Schunck algorithm to detect bubbles in both laboratory and underwater deep-sea video sequences. Hessenkemper et al. [23] later investigated bubble identification and segmentation using Convolutional Neural Networks (CNNs) capable of producing pixel-to-pixel predictions.

2.3.7 Method comparison

When comparing methods for EOL quality assurance processes in production, several practical requirements need to be considered, such as minimizing cycle time, ability to provide qualitative results, robustness to environmental variations, and ability to ensure operator compliance/standardization of process.

Pressure based methods, such as pressure decay and pressure differential, are well suited for these conditions. They provide relatively fast testing, can be automated to a high extent, and it can offer direct quantitative measurements, critical to enable data-driven decision making. The pressure differential method can improve sensitivity but at the cost of increasing complexity due to needing a reference volume.

Vacuum decay is less flexible for larger and more complex systems. Acoustic and infrared methods enable fast, contactless detection that is useful for leak localization as well. However, they provide more qualitative results, and are too heavily reliant on environmental conditions for adequate performance. Bubble testing is low-cost and simple, but is time consuming, difficult to automate, and cannot record precise measurement data.

Ultimately, pressure decay is the more suitable leakage detection method in this context. It adequately balances measurement speed, cost, and ability to produce repeatable and quantitative results. Though limitations include difficulty in detecting extremely small leaks, its performance is sufficient for medium leakages and larger, making it practical for industrial production environments and truck pneumatic system leakage detection.

2.4 Industrial quality assurance methods

There are various aspects to consider when it comes to QA in a production environment. The primary methods for maintaining and enhancing quality are material testing, performance testing, SPC, and Total Quality Management (TQM), with the latter two serving as central analytical frameworks for this thesis [24]. Applying and combining these methods, help organizations identify issues, drive continuous improvement and proactively increase customer satisfaction.

SPC identifies variations that can lead to defects through analyzing statistical data collected during production [24]. It is critical for ensuring opportunities to take corrective action before defects occur, directly minimizing manufacturing waste. Finally, TQM focuses on continuous improvement and customer satisfaction across the entire organization. It integrates QA practices into all operations, encouraging employees to take own responsibility for quality.

2.4.1 Importance of assuring pneumatic tightness

Larger air leaks can often be detected by the human ear when the system is pressurized as they produce a distinct sound that often remains noticeable even in loud production environments. However, smaller leaks are more difficult to identify [25]. Although initially minor, such leaks might negatively impact the performance of the braking system. Most trucks are equipped with safety features, such as sensors that monitor the system and trigger warnings when pressure decreases rapidly. Smaller leakages that do not cause immediate damage still force the compressor to compensate for the pressure loss during operation. This often results in increased wear on components such as, along with higher energy consumption, reduced system efficiency.

Furthermore, air loss during a longer parking period can result in longer pressure build-up times when starting the truck, causing a negative impact on the customer through lost time and decreased productivity [6]. Over time, these issues can contribute to increased maintenance needs, customer complaints, and warranty claims.

2.5 Statistical analysis frameworks

To evaluate experimental hypotheses and draw conclusions about a population based on sample data, hypothesis testing can be utilized to determine whether an observed effect between two groups is significant or if it can be attributed to random variation [26]. Two examples are equivalence testing and paired t-Testing. The framework selection is based on the underlying objective of each hypothesis, whether it aimed to address a statistical difference between two states or to demonstrate that the states behave identically for all practical purposes.

2.5.1 Paired t-Test

According to Montgomery and Runger [26], the paired t-Test is utilized to determine whether a statistically significant difference exists between the means of two related groups. This framework is suitable for experimental designs where dependent observations are grouped into pairs, such as gathering data from the same vehicle evaluated under two distinct operational conditions. The paired t-Test uses dependent samples, where the test computes the individual differences between these linked observations to evaluate whether the sample mean of these differences deviates significantly from zero.

$(X_{11}, X_{21}), ..., (X_{1n}, X_{2n})$, represent the set of n paired observations [26].

- Condition 1 is represented by X_1 with the mean and variance, μ_1 and σ_1^2
- Condition 2 is represented by X_2 with the mean and variance, μ_2 and σ_2^2

The individual difference of each data pair is defined as:

$D_i = X_{1i} - X_{2i}$, where $i = 1, 2, ..., n$.

The differences D_i are assumed to be normally distributed with an expected population mean difference μ_D and population variance σ_D^2, defined as:

$\mu_D = E(X_1 - X_2) = E(X_1) - E(X_2) = \mu_1 - \mu_2$

By evaluating the mean difference μ_D using a one-sample t-Test framework, it is possible to determine whether there is a statistically significant difference between the two states. The baseline target difference is denoted as Δ_0. For a two-tailed t-Test, the null hypothesis, H_0, and the alternative hypothesis, H_1, are generally formulated as follows:

$$H_0 : \mu_D = \Delta_0$$

$$H_1 : \mu_D \neq \Delta_0$$

The alternative hypothesis can be adapted to directional, one-tailed, t-Test depending on expected system behavior. For a directional hypothesis, the equations are structured as:

$$H_0 : \mu_D = \Delta_0$$

$$H_1 : \mu_D < \Delta_0 \text{ (Left-tailed)}$$

$$H_1 : \mu_D > \Delta_0 \text{ (Right-tailed)}$$

The test statistic for the t-Test is calculated using equation 2.2

$$T_0 = \frac{\bar{D} - \Delta_0}{S_D/\sqrt{n}} \tag{2.2}$$

Where

- $\bar{D}$ is the sample mean difference
- S_D is the sample standard deviation of the observed differences

If the test results in a probability value (P-value) below 0.05, the null hypothesis can be rejected, indicating a statistically significant effect. If the P-value exceeds or is equal to 0.05, the null hypothesis cannot be rejected. However, this does not confirm the null hypothesis, but rather indicates there is insufficient evidence to support the alternative hypothesis.

2.5.2 Equivalence test

According to Lakens [27], equivalence testing is a statistical approach to provide support for the absence of a meaningful effect unlike traditional null hypothesis significance testing, aimed to reject the hypothesis of "no difference". The goal is to reject effects that are larger than a predefined smallest effect size of interest and conclude that the effect is close enough to zero. This would determine that one option is as good as another for all practical purposes. Equivalence testing requires the specification, defined by an upper and a lower equivalence bound, D_U and D_L. These bounds represent the maximum allowable deviation that can be tolerated without affecting the function or decision. It is considered best practice to specify these bounds before data collection. Furthermore, equivalence is often evaluated using a Confidence Interval (CI) of 90 %, which directly corresponds to the use of α= 0.05 for a two-sided test.

Hypotheses are formulated as:

$$H_0\text{: } D \leq D_L \text{ or } D \geq D_U.$$

The alternative hypothesis is:

$$H_1 : D_L < D < D_U$$

In conceptual terms:

H_0 : The difference is too large to accept equivalence
H_1 : The difference is small enough to accept equivalence

The observed effect D is estimated from the data and represents the measured deviation between conditions or methods. For paired or repeated study designs, this effect is defined as the difference between observations:

$$D_i = X_{1,i} - X_{2,i}$$

Following quantities are estimated:

- Sample mean according to formula 2.3.
- Standard deviation according to formula 2.4.
- Standard error according to formula 2.5.

$$\bar{D} = \frac{\sum_{i=1}^{n} D_i}{n} \tag{2.3}$$

$$S_D = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(D_i - \bar{D}\right)^2} \tag{2.4}$$

$$SE = \frac{S_D}{\sqrt{n}} \tag{2.5}$$

Where
- D is the observed effect
- $\bar{D}$ is the sample mean
- S_D is the sample standard deviation
- SE is the standard error
- n is the total number of paired observations

Consequently, a CI is calculated and compared against the predefined equivalence margins, and a decision rule is made. From an engineering perspective, the approach provides a statistically correct method to support hypotheses of method interchangeability, functional equivalence, or acceptable performance deviation. However, the validity of this approach relies heavily on boundaries that are well-justified, typically through design specifications or direct input from domain experts.

3

Methodology

This chapter describes the research methodology applied to design a new verification process for truck pneumatic systems. This project combined a literature study with qualitative field investigations and a quantitative development process. The use of a mixed methods approach is based on the principle that it provides a more comprehensive understanding of the research problem than either qualitative or quantitative approaches used in isolation [28]. Following a structured engineering approach, the development phase utilized an iterative Plan-Do-Check-Act (PDCA) cycle for experimental testing and final process design. The chapter therefore encompasses the problem context and benchmarking activities, experimental development and evaluation, and the resulting engineering conclusions and recommendations for validation and implementation.

3.1 Literature study

A literature study was conducted to create a theoretical foundation for the research. The search strategy primarily focused on four domains: pneumatic system architecture, quality assurance parameters, established and emerging leak detection methodologies, and comparable industrial technologies. Research was performed using academic databases such as *Statista*, *Science Direct*, *Google Scholar*, and *Scopus*. To ensure higher level of relevance, searches utilized Boolean operators (AND, OR) to combine thematic keywords as presented below. AI-assisted research tools, such as *Scopus AI*, were also employed to enhance the search and identify recent developments. Furthermore, internal documentation from previous projects was analyzed to evaluate historical process improvements and to address potential gaps. This literature review aligns with the framework described by Ajimotokan [28], who notes that identifying existing knowledge gaps and recommendations allows a study to fill such gaps and contribute to the field by enhancing existing methodologies, principles, or theories.

Keywords:

- **Industrial Context:** Heavy-duty vehicle maintenance, pneumatic brake systems, compressed air leakage.
- **Detection Technologies:** Infrared thermography, ultrasonic leak detection, computer vision, pressure decay, non-destructive testing (NDT).
- **Process & Quality:** Quality assurance, fault diagnosis, process verification, maintenance optimization, Industry 4.0.

3.2 Qualitative study

Qualitative studies included the identification of relevant stakeholders, interviews, and on-site analysis of the current process. As outlined by Ajimotokan [28], a qualitative research approach in engineering is essential to assess human and operational behaviors, providing insight into how operators experience and address technical challenges in their active work settings. Consequently, a Gemba walk was initially carried out at the verification station to observe the process in operation and to discuss current work methods with the relevant team leader. Grounded in The Toyota Way framework, this approach is highly beneficial because it prevents engineers from making flawed assumptions based solely on secondary reports or abstract data sheets [29]. Following this initial observation, stakeholders were identified by mapping the end-to-end life cycle of the pneumatic verification process, selecting key representatives from production operations, the engineering function, and the core project development team. Collectively, these interviews and observations collected critical technical requirements, usability insights, constraints, and requests for both the current and proposed processes. The interviews were a combination of semi-structured and unstructured. Semi-structured interviews allowed for in-depth information from the interviewee through predetermined open-ended questions, allowing modification of the questions, while maintaining the track of the study [30]. Unstructured interviews with stakeholders enabled free-flowing conversations [31]. The questions for the unstructured interview was based on the interviewees answers, focusing on their personal experience, specialized knowledge, and daily work methods.

A total of 10 interviews were conducted with identified stakeholders such as production engineers, domain experts, technical trainers, operators, and team leaders at Tuve, as well as other Volvo Group plants. Examples of interview questions with both primary and secondary stakeholders are provided in appendix A. Their input supported benchmarking activities, including current-state analysis, knowledge building regarding the pneumatic system and its technical requirements, and the evaluation of previous and ongoing improvement initiatives. Interview questions were kept open-ended to encourage further discussion and enable in-depth understanding. The scope and focus of the questions were adapted based on the level of prior knowledge obtained from internal documentation and the specific information required at each stage of the study. Specifically, interviews with domain experts, the engineering function, and technical trainers targeted the pneumatic and braking systems, alongside key technical variables to ensure all project assumptions remained robust. Interviews with production engineers, operators, and team leaders were aimed at understanding the current process and identifying specific operational pain points for improvement. Most interviews were followed by additional interview sessions throughout the project to further clarify and deepen the understanding of the findings.

Additionally, one initial interview was conducted with prototype suppliers to understand the technical constraints of the prototype. This was followed by successive interviews to discuss and explore potential improvements and future development opportunities, as well as their associated limitations.

3.3 Development process

The project development process relied on a quantitative approach. As outlined by Ajimotokan [28], quantitative engineering research focuses on testing theories objectively by exploring the interdependence of measured parameters. This data-driven methodology builds safeguards against bias, ensuring that outcomes can be replicated and generalized. Guided by these principles, the research incorporated an experimental development phase, utilizing a PDCA cycle to manage hypothesis testing and prototype evaluation. Specifically, this included testing of the digital pressure decay prototype, shown in figure 4.3, and hypothesis testing of various influencing factors, applying the statistical analysis approaches described in section 2.5. Performed alongside operators and team leaders, these tests were essential to understand critical parameters and assess the feasibility of different process designs. Based on these insights, this section concludes with the finalized process design.

3.3.1 Experimental development

PDCA is a four step iterative method which is widely used in quality management systems and process optimization for continuous improvement of products and processes [32]. The method consists of the steps Plan, Do, Check, Act, see figure 3.1. After performing each step, the next iteration starts over at the planning phase, where gained knowledge are used to perform the steps until desired results are accomplished. In this project, the PDCA method was applied in parallel to both the experimental testing of the hypotheses, detailed in section 3.3.2, and the prototype evaluation, detailed in section 3.3.3.

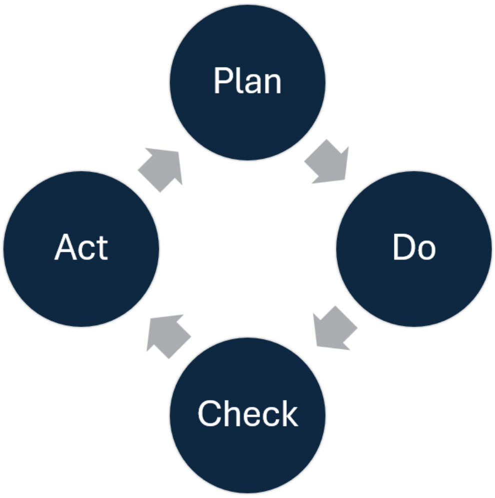


Figure 3.1: Steps of the PDCA cycle.

Plan:
This phase was used to structure experimental design with focus on defining controlled experiments capable of evaluating pressure change under varying test durations and system configurations. Additionally, tests were planned to gather data for analysis, which was used to determine the necessary input parameters for integrating the digital pressure decay equipment.

Do:
This phase included the execution of experimental work. Initially, a measurement system verification of the prototype was conducted using built-in self-tests detailed in section 3.3.3. This was followed by a series of experiments using a manometer to test the formulated hypotheses and establish baseline input values for the prototype during leakage testing. For each truck test, five experimental cases were conducted to represent different operational states of the truck. These cases were defined by varying combinations of the independent variables test duration, measurement stabilization, filling method, and subsystem activation state, as presented in table 3.1. Other parameters were kept constant throughout the experiments to ensure comparability between tests. These controlled variables are also described in table 3.1. Finally, the prototype was tested using these defined parameters to assess its actual performance.

Check:
This phase involved analyzing pressure decay curves and system behavior through data visualization and applying statistical analysis methods, specifically paired t-Tests and equivalence testing. Equivalence testing was applied to determine equivalence or interchangeability of methods. Paired t-Tests were performed for the cases of evaluating the same vehicle under two different conditions, either by specifically determining an increase or decrease (one-tailed), or determining a difference in any direction (two-tailed). Ultimately, conclusions were drawn based on hypotheses acceptance or rejection criteria. Additionally, the prototype was evaluated using experimental results to assess its performance and suitability for the intended application.

Act:
This phase included making engineering decisions based on the conclusions derived from the Check phase. Recommended procedures, conditions, limitations, and durations were established. Improvements were proposed and formed a decision about the next iteration.

3.3.2 Hypotheses testing

The first PDCA iteration for hypothesis testing was conducted to evaluate the current air leakage testing method in relation to the current technical requirements and work procedure for air leakage testing. This initial cycle enabled the development of a deeper understanding regarding key parameters, process steps, and the components of the pneumatic system. The insights gained from the testing and stakeholder interviews formed the preliminary guidelines used for the final PDCA cycle involving hypothesis testing.

Hypotheses and experimental variables:
Several hypotheses were formulated based on knowledge gaps from stakeholder interviews and the initial process analysis. These gaps reflected both explicitly recognized uncertainties and differing perspectives among stakeholders regarding key process parameters. Several existing assumptions lacked quantitative data to support them, which highlighted the need for a experimental evaluation. Consequently, these knowledge gaps motivated the design of controlled experiments.

A set of statistical hypotheses was formulated in the form of null hypotheses, $H_0(n)$, representing the absence of a statistically significant effect, and corresponding alternative hypotheses, $H_1(n)$, representing the presence of a statistically significant effect. Hypothesis testing was then applied to evaluate whether the controlled variables had a significant effect on the measured outcomes, whereby the null hypothesis could be rejected in favor of the alternative hypothesis. An overview of experimental variables and parameters is presented in table 3.1.

Table 3.1: Overview of experimental variables and parameters.

Variable type	Description	Parameters
Independent variables	Test duration Measurement stabilization Filling method Subsystem activation state	1 min - 4 min 0 min - 4 min External/internal Differential lock, trailing axle position (drive/low)
Dependent variables	Pressure change rate System stabilization time	bar/min s
Controlled variables	Initial system pressure Ambient conditions Measurement equipment Brake application Vehicle state	10,7 - 12,2 bar Indoor, constant $C°$ Prototype or manometer Hydraulic crutch (constant F) Engine Off, Ignition On, Parking brake Off, gear in neutral

The following hypotheses were evaluated, highlighting dependencies on cases 1-5:

Hypothesis 1 *Cases 1, 2, 4 and 5*

$H_0(1)$: The inclusion of a stabilization phase prior to air leakage testing has no significant effect on the measured pressure decay.

$H_1(1)$: The inclusion of a stabilization phase prior to air leakage testing has a significant effect on the measured pressure decay.

Hypothesis 2.1 *Case 1*

$H_0(2.1)$: When additional pneumatic components are deactivated, pressure decay-based leakage detection at a test duration shorter than 4 minutes does not provide equivalent detection accuracy compared to a 4-minute reference test.

$H_1(2.1)$: When additional pneumatic components are activated, pressure decay–based leakage detection at a test duration shorter than 4 minutes provides equivalent detection accuracy compared to a 4-minute reference test.

Hypothesis 2.2 *Case 4*

$H_0(2.2)$: When additional pneumatic components are activated, pressure decay–based leakage detection at a test duration shorter than 4 minutes does not provide equivalent detection accuracy compared to a 4-minute reference test.

$H_1(2.2)$: When additional pneumatic components are activated, pressure decay–based leakage detection at a test duration shorter than 4 minutes provides equivalent detection accuracy compared to a 4-minute reference test.

Hypothesis 3 *Cases 1 and 3*

$H_0(3)$: The required stabilization time is equal for internal and external air filling methods.

$H_1(3)$: The required stabilization time differs between internal and external air filling methods.

Hypothesis 4.1 *Cases 1 and 4*

$H_0(4.1)$: Activation of differential lock and pusher or trailing axle in low position does not significantly affect the required stabilization time.

$H_1(4.1)$**:** Activation of differential lock and pusher or trailing axle in low position significantly affect the required stabilization time.

Hypothesis 4.2 *Cases 1 and 4*

$H_0(4.2)$**:** Activation of differential lock and pusher or trailing axle in lowest position does not significantly increase the pressure decay measured during the quick test phase.

$H_1(4.2)$**:** Activation of differential lock and pusher or trailing axle in lowest position significantly increase the pressure decay measured during the quick test phase.

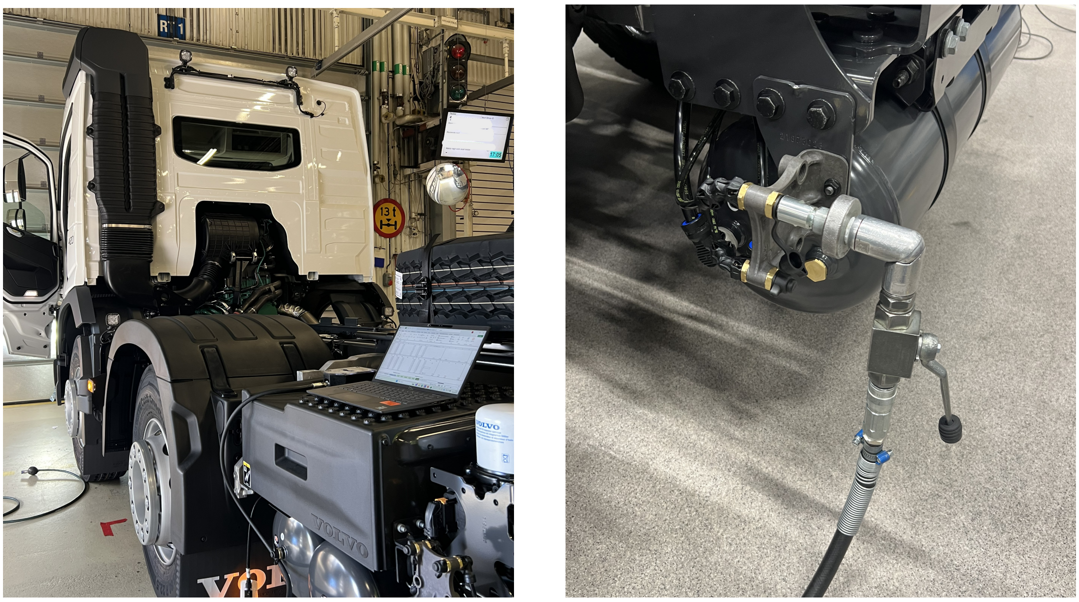
Data sampling:
Data collection in this study was conducted using a random sampling approach, to the extent permitted by practical constraints [33], in order to reduce selection bias and improve the representativeness of the collected data. However, due to limitations such as the availability of test space and operators, vehicle selection ultimately followed a convenience sampling approach. Therefore, the timing of tests and selected vehicles were influenced by production flow and logistical conditions at the plant. Although this approach cannot be considered a fully random sampling method, efforts were made to reduce systematic bias where possible. Vehicles were sampled without preselection based on axle configuration, model, or customer order. Data collection was carried out during both the day and evening shifts to capture variation related to operating conditions and production schedules.

Design of hypothesis tests:
The following experimental cases, summarized in table 3.2, were designed to be conducted on each truck. All cases included having the truck in neutral gear level, parking brake deactivated, ignition on, and engine off during the experiment. Cases were designed to have a set stabilization time, pressure drop test time, pressurization method, and additional components of the pneumatic system activated or deactivated. Pressurization of the pneumatic system up to 11.9-13.3 bars before brake application was achieved through either external air supply by connecting a hose to an air tank, or internal air supply from compressor by turning on the truck engine. The additional components, which are activated during case 4 and 5 include the differential lock and lowering the trailing axle to its lowest position. The measurement interval was chosen to balance practical constraints and data accuracy. To ensure data was reliable and not missing values due to high-frequency manual measurements, a 30-second interval was chosen.

Table 3.2: Summarized description of experiment design for cases 1 to 5.

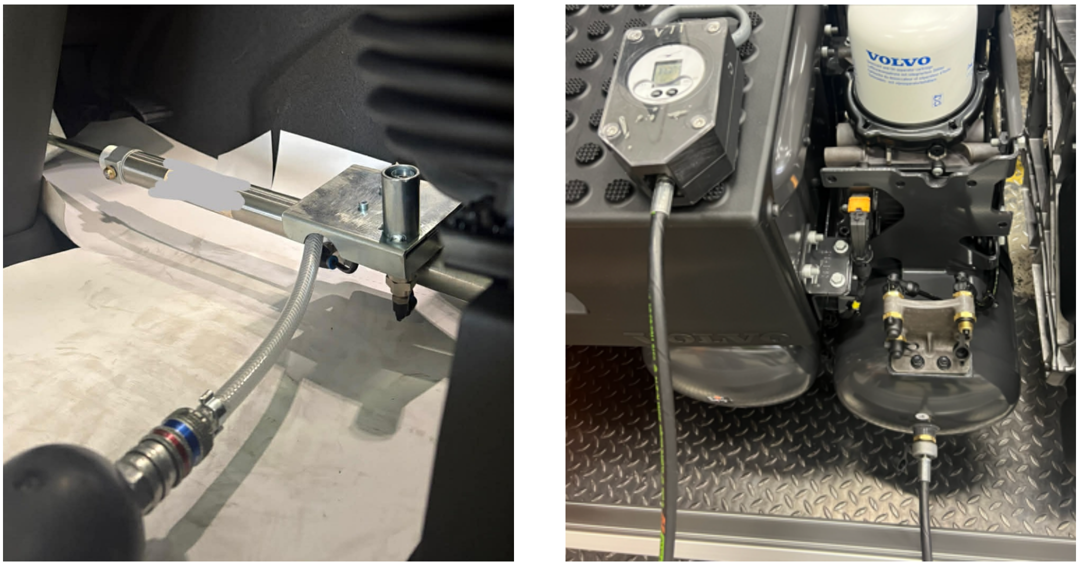
Case	Stabilization Time [min]	Pressure Drop Test [min]	Pressurization Method	Pneumatic Configuration
1	4	4	External Air Supply	Deactivated Components
2	0	4	External Air Supply	Deactivated Components
3	4	0	Internal Compressor Fill	Deactivated Components
4	4	4	External Air Supply	Activated Components
5	0	4	External Air Supply	Activated Components

Hypothesis test setup:
For the manometer tests, the test setup is shown in figure 3.2a. Cases 1 to 5 described in table 3.2 was conducted on every truck. Figure 3.2b shows the setup for how external air is supplied when connected to tank nozzle, with pressure valve in open position. A hydraulic crutch, shown in figure 3.2c, was used to apply full and constant force on brake pedal, initiating the test. Applying full force on the brake pedal allows for air to move between the tanks, and both front and rear circuit. Pressure measurements were collected at 30-second intervals during both the stabilization and pressure decay test phases using a manometer as shown in figure 3.2d wich has a detection accuracy of 0.05 % Full Scale Output (FSO), . Most trucks are equipped with air suspension, connected to the pneumatic system, making it important to follow the identical preparation procedures for each truck, and remain outside the cabin once the test has been initiated.



(a) Test setup in the experimental development phase.

(b) External air supply connection to tank.



(c) Actuated pneumatic crutch applied to brake pedal.

(d) Manometer connected to air tank during experimental testing.

Figure 3.2: Figures, a-d, showing the hypotheses testing set-up for performing cases 1-5.

Data analysis:
To test each hypothesis, collected data was analyzed using the data analysis methods described in section 2.5. The methods used to test each hypothesis are summarized in table 3.3.

Table 3.3: Analysis methods for each hypothesis.

Hypothesis	Data	Analysis method
1	Case 1, 2, 4 and 5 Test phase	Data Visualization
2.1	Case 1 Test phase	Equivalence Test
2.2	Case 4 Test phase	Equivalence Test
3	Case 1 and 3 Stabilization phase	Paired t-Test (two-tailed)
4.1	Case 1 and 4 Stabilization phase	Paired t-Test (two-tailed)
4.2	Case 1 and 4 Test phase	Paired t-Test (one-tailed)

Testing $H_0(1)$:

Data visualization was performed according to following steps.

- The pressure change data from the stabilization phases for each truck was plotted in excel with 0 bar as baseline to compare how pressure evolves over time with focus on the dynamic behavior. Consequently, hypothesis acceptance or rejection could be determined visually.
- The analysis extended beyond the specific hypothesis, utilizing plots to identify specific target values suitable for various prototype input parameters. The key factor to determine suitable input values was identifying clear time points where oscillations and vast pressure changes were no longer prevalent in relation to the previous measurement points of the same instance.

Testing $H_0(2.1)$ and $H_0(2.2)$:

An equivalence test was performed according to following steps.

- Equivalence bounds were set to $[D_L, D_U]$, derived from collaborative input from production engineers and data analysts familiar with the specific process at the station and general pressure monitoring of trucks. Additionally, following internal recommendations to avoid unnecessarily conservative tolerance settings, effects smaller than ±0.4 standard deviations were considered to be practically negligible. This threshold is also in alignment with industry standards and corresponds to a standardized effect size of Cohen's $d = 0.4$,

typically interpreted as a medium effect size [27]. The equivalence bounds in raw units were ultimately set to $[-0.006, 0.006]$ bar/min based on discussions with local domain experts in Tuve.
- The difference between pressure measurements at time intervals 1 min and 4 min was calculated for every observation, $x_{i,1} - x_{i,4}$, for the relevant case.
- The mean difference was calculated based on these values, using the excel function *AVERAGE.*
- The standard error and standard deviation was calculated based on these values, using the excel functions *STDEV/SQRT(COUNT)* and *STDEV.S.*
- The CI interval was calculated by multiplying the mean difference with 0.9 for the lower limit and 1.1 for the lower limit in the case of $\alpha = 0.05$.
- If results showed that the difference was too large to accept equivalence, the equivalence testing was performed again using interval times 2 min or 3 min against 4 min.

Testing $H_0(3)$:

A paired t-Test was performed according to the following steps.

- The pressure difference for each interval was calculated.
- The time(s) from the start of stabilization which the pressure difference first fell within allowed tolerance (±15 mbar) and remained within this tolerance for the rest of the test was identified. The tolerance setting was based on discussions with production engineers with extensive domain knowledge.
- A t-Test was performed using the "t-Test: Paired Two Sample for Means" function from the Data Analysis ToolPak in Excel, comparing case 1 and case 3 observations for each truck. The hypothesized mean difference was set to 0, and an α of 0.05 was used.
- The two-tailed P-value, P, was evaluated relative to the significance level, α. If $P < 0.05$, the null hypothesis was rejected, indicating that a statistically significant difference in stabilization time between filling methods could be established. In this case, sample means for internal and external filling was compared to determine which method has the shorter stabilization time. If $P \geq 0.05$, the null hypothesis failed to be rejected, since this indicated that no statistically significant difference could be established between the two filling methods.

Testing $H_0(4.1)$:

A paired t-Test was performed in the same way as for testing $H_0(3)$, but instead comparing cases 1 and 4.

- If the two-tailed P-value, $P < 0.05$, the null hypothesis was rejected, indicating that a statistically significant difference in stabilization time could be established when activating additional components. In this case, the sample mean values from observations of activated and deactivated components were used to indicate which method results in shorter stabilization times. If P $\geq$ 0.05, this indicated that no statistically significant difference in stabilization time could be established between the two truck conditions, and the null hypothesis failed to be rejected.

Testing $H_0(4.2)$:

A paired t-Test was performed according to following steps.

- The pressure difference for each interval was calculated.
- A one-tailed t-Test was performed using "t-Test: Paired Two Sample for Means" function from the Data Analysis ToolPak in Excel, comparing case 1 and case 4 observations for each truck during a 4-minute test. The hypothesized mean difference was set to 0, and an α of 0.05 was used.
- The one-tailed P-value, P(T$\leq$t) or P(T$\geq$t), was evaluated relative to the significance level, α. If P $<$ 0.05, the null hypothesis was rejected, indicating that a statistically significant difference in pressure change could be established between activated or deactivated additional components. If P $\geq$ 0.05, the null hypothesis failed to be rejected since this indicated that no statistically significant difference in pressure change could be established between the truck conditions.

3.3.3 Prototype testing

This section describes the three PDCA iterations conducted to evaluate the prototype and make future improvement suggestions related to the software and hardware of the prototype.

Functional prototype tests:
For the verification of the initial measurement system, each sensor and corresponding cable were connected individually to isolate potential faults. The sensor was connected to a self-test ball valve and pressurized using a manual air pump, see figure 3.3. Pressure was gradually increased to approximately 1.5 bar, and the pressure response was measured for a duration of 1 minute. Only sensors that exhibited stable and repeatable behavior during these self-tests were used in subsequent experiments.

Figure 3.3: Assembled air pump, ball valve, and sensor for self-testing sensor functionality.

Design of prototype tests:
The second PDCA iteration for prototype testing involved performing a quick test with trial values, following the same test setup as in the experimental hypotheses tests, but replacing the manometer with the prototype. This allowed for evaluation of the functionality and constraints of the prototype. The results of prototype testing, along with interviews, were discussed with the project supervisor and the prototype supplier to provide an updated software version of prototype. The last iteration of prototype testing was conducted to evaluate the new prototype updates outside the production setting to identify the adjustable parameters available to production technicians and future improvements.

3.3.4 Process design

Based on both qualitative and quantitative data, a requirement specification for the verification process design which integrates the prototype was created. The requirement specification was critical for defining the design space for the pneumatic leakage verification process. Time estimations for each activity will be based on experience from experimental testing during hypothesis and prototype testing.

4

Results

This chapter presents the results from benchmarking activities, hypothesis- and prototype testing, and proposed verification process design.

4.1 Benchmarking

This section presents results from the interviews, internal documentation, the current process, and the prototype assessment. It also highlights the knowledge gaps identified during the benchmarking.

4.1.1 Volvo Group organization and relevant stakeholders

Identified stakeholders which have been interviewed are presented in figure 4.1, along with a mapping of the organizational structure within Volvo Group.

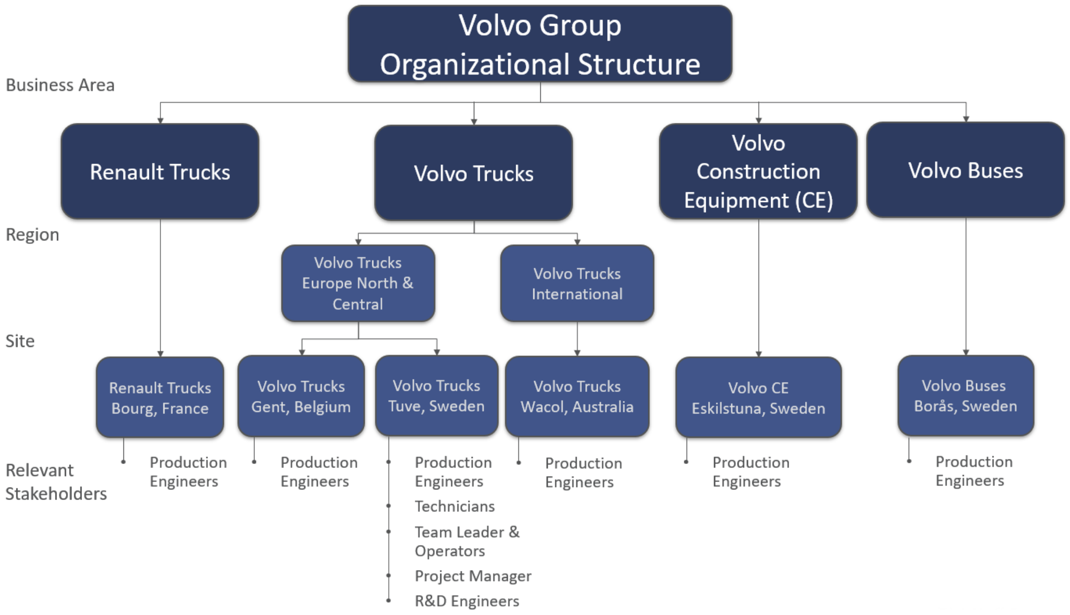


Figure 4.1: Mapping of the Volvo Group organizational structure.

Primary stakeholders were identified as production engineers, team leaders, operators within the Volvo Trucks plant in Tuve. These stakeholders are directly involved in the improvement of the verification process or performing the leakage test, making their roles critical to the study. Secondary stakeholders at the Tuve plant included technical trainers, production engineers at other Volvo Plants, R&D engineers, and the project manager. Technical trainers contributed specialized knowledge of the pneumatic brake system and its components. Specialists from the engineering department and the project manager provided insights into previous improvement projects and experiments, the current verification process, and planned future developments. In addition, input from production engineers from other global Volvo Group plants enabled a broader assessment of existing methods and technologies currently utilized within the organization.

4.1.2 Methods mapping

A mapping of the detection and localization methods used within the organization is presented in table 4.1. Currently used air leak detection and localization methods were investigated more in detail at Volvo trucks in Tuve and Gent, and Renault trucks in Bourg. There are varying degrees of documentation of the truck quality status throughout the process, but currently, no quantitative data is logged which would support improvement initiatives or future troubleshooting for any of the sites.

Table 4.1: Leakage detection methods used at different organizations and locations within Volvo Group.

Business Area	Site	Detection Method	Localization Method	Data logging capability
Volvo Trucks	Tuve, Sweden	Pressure Decay	Bubble Soap	No
Volvo Trucks	Gent, Belgium	Pressure Decay	Ultrasonic	No
Renault Trucks	Bourg, France	Ultrasonic	Ultrasonic	No
Volvo Buses	Borås, Sweden	Pressure Decay	Bubble Soap	No
Volvo CE	Eskilstuna, Sweden	Pressure Differential	Foam Spray	No
Volvo Trucks	Wacol, Australia	Pressure Decay	Ultrasonic	No

4.1.3 Current state of Tuve plant, Sweden

This section outlines the current state of the Tuve plant by analyzing the factory and station layouts, as well as the existing verification process.

Plant layout:
From beam stage to final assembly, each truck moves through the main production line, where its assembled individually according to its specification. Each assembly station on the main line operates at a takt time of 6.5 minutes. The truck then proceeds to the verification station where the truck is tested for pneumatic tightness, among other tests, to ensure that the truck meets production and safety requirements before the next step. The truck then continues to the dynamometer

test to measure vehicle performance.

A mapping of the verification station and connected processes is presented in figure 4.2.

Figure 4.2: Mapping of the verification station and connected processes.

Verification process:
The current verification process involves two operators, one in the driver's seat and one on the floor. The truck is retrieved by operator 1 from the last assembly station to the verification station. Operator 2 connects the truck by cable to the stationary computer to access a Volvo-specific tool, which manages chassis-unique embedded software and production data. The operators follow the test procedure and manually click OK/not OK (NOK) using a handheld computer.

To check the pneumatic system for any major or medium air leakage, operator 2 attaches the external air supply hose and manometer to the pneumatic system and front circuit air tank. The operator in the cap relieves the truck. The truck engine is started to pressurize the pneumatic system after using external air supply for the initial pressurization. The engine is turned off, keeping the ignition on. Operator 1 puts pressure on the brake pedal. Operator 2 monitors the pressure behavior on the manometer. If the pressure drops below 10 bar, the test is treated as NOK. If the pressure drop stops, usually around 11.4 bar, and starts to increase within the predetermined time window, the test is considered OK, and no major or medium leaks have been identified. After the test is finished, the operators disconnects the equipment.

If the test indicates a potential leakage, the operators performing the test fill in a deviation form, explaining the outcome and observations made while executing the test. However, no measurement data is logged. Further investigation and troubleshooting is done at another station along with other necessary reparations.

4.1.4 Current process in Gent plant, Belgium

The Volvo truck site in Gent currently uses pressure decay equipment. The leak detection test is performed after dynamometer testing and takes about 11 minutes to perform. The truck is connected to the pressure decay measurement equipment, the truck's engine is turned on, and the gear is in a neutral position. When the compressor has built up to the cut-in pressure, an external air filling hose is connected to one of the air tanks to pressurize the system to 12 bar. Using a crutch, the brake pedal is pressed down and the stabilization phase begins. After a set stabilization time of 5 minutes, the pressure drop test is conducted following the same technical requirements as in the Tuve plant. If leakage is detected, the truck is moved to the repair area where an ultrasonic detector is used to locate the leak.

4.1.5 Current process in Bourg-en-Bresse plant, France

The current leakage detection process of the pneumatic system at Renault Trucks in Bourg-en-Bresse, France, is performed at EOL, after the dynamometer test. To initiate the test, the differential lock and parking brake is active, while the brake pedal is pushed down using a clamp. To detect and localize leakage, the operators use an ultrasonic "pistol". Aiming the probe at the pneumatic system, any sounds from the equipment indicates that there is a leak in the direction of which the probe is pointed in. To pinpoint the location of the leak, a sensitivity dial can be mounted on the pistol. However, this means that no data is stored, the test is fully operator dependent, and it requires the operators to be trained on how to interpret the result.

4.1.6 Technical requirement

The technical requirements (TR) for pneumatic system tightness followed at both the Tuve and Gent plants includes both a short-duration "quick test" and an "overnight test" [34]. The quick test is designed to detect medium to high leakages. The procedure requires equalizing the pressure to the compressor cut-in pressure. The TR specifies a maximum allowable pressure drop within any single braking circuit air tank of 0.1 bar per 4-minute interval. The TR for the overnight test allows for a minimum retained pressure of 7.5 bar, measured on one brake circuit air tank and air suspension tanks (if equipped), measured 15 hours after truck has been pressurized to cut-in pressure. This allows for smaller leakages to be detected. Detailed truck conditions for both tests are summarized in table 4.2.

Table 4.2: Truck conditions for quick- and overnight test.

Quick Test	Overnight Test
1. Main switch on 2. Ignition on 3. Parking brake off foot pedal at full pressure 4. Power takes off (PTO) on 5. Differential lock on 6. Trailer brake on 7. Gear level in neutral position, with low range and high split 8. Pusher or trailing axle in low position	1. Indoors, minimum 10 Celcius 2. Parking brake on 3. Main switch off 4. All extra equipment off 5. Ger lever in neutral position, with low range and high split 6. Pusher or trailer axle lifted up

4.1.7 Previous improvement initiatives

Previous experimental test and data analysis had been conducted in regards to pressure decay of trucks in various conditions. One assessment was the effect of utilizing Prosit+, a production system tool for managing chassis-specific embedded software and data, to open valves instead of manually applying the service brake. This approach is technically feasible, with the requirement that the ignition is active and the vehicle is in pre-running mode. The results indicated that in this operating state, the vehicle has higher level of air consumption and internal air leakage, making smaller leakages more difficult to detect. An alternative test method for detecting small leakages has therefore been developed with the ignition turned off.

Furthermore, a parallel project is being conducted involving several stakeholders, including production engineers from different plants as well as technical experts and project manager from the engineering function at Volvo Trucks. The project aims to update the verification process for pneumatic tightness, with focus on the TR. In addition, discussions are ongoing about redistributing the testing of additional components, such as differential lock and PTO, currently included in the test to other stages of the production process.

4.1.8 Assessing the prototype

The prototype includes a touch-display with an embedded controller system, one USB-C and one USB-A port for power supply and data collection, and five ports for sensor-cable connection, see figure 4.3.

Figure 4.3: Prototype with sensor connections 1–5, power button, and USB ports.

The display must be continuously powered via a cable during testing, alternatively, be connected to a power bank. The prototype allows for five pressure sensors to be connected by a 10 meter cable to the truck's air tanks. Measurements are performed with an accuracy of ± ≤0.25% FSO. With a measurement range of 0 to 16 bar, this corresponds to an absolute error of ±0.04 bar across the entire measurement span. Measurement and vehicle data can be collected and stored through scanning the QR-code after the test is performed, or by using the USB-stick. However, due to storage availability on the USB and in QR-code, the suppliers decided to only include; start and end pressure for used sensors, if stabilization- and quick-test is OK or NOK, chassi-number, date and time, and input variables set for test.

Technical data and constraints regarding the prototype is summarized in table 4.3 and a schematic illustration of the prototype is shown in figure 4.4.

Table 4.3: Equipment constraints including technical and sensor data.

Characteristics	Value
Technical data	
Power supply	USB-C PD. PDO = 12 V/3 A
Power consumption	36 W
Environment temperature	0... +50°C / 0...95% RH
Storage temperature	-10... +60°C / 0...95% RH
Operating temperature	-10... +50°C
Weight handheld	1.66 kg
Display	Touch 10" 1024 x 600
Permissible degree of contamination	1
Dimensions	22 x 29 x 5.5 cm
Sensors	
Number of available sensors and ports	5
Measurement range	0...16 bar rel.
Accuracy	rel. ± ≤0.25% FSO
Test medium	Compressed air

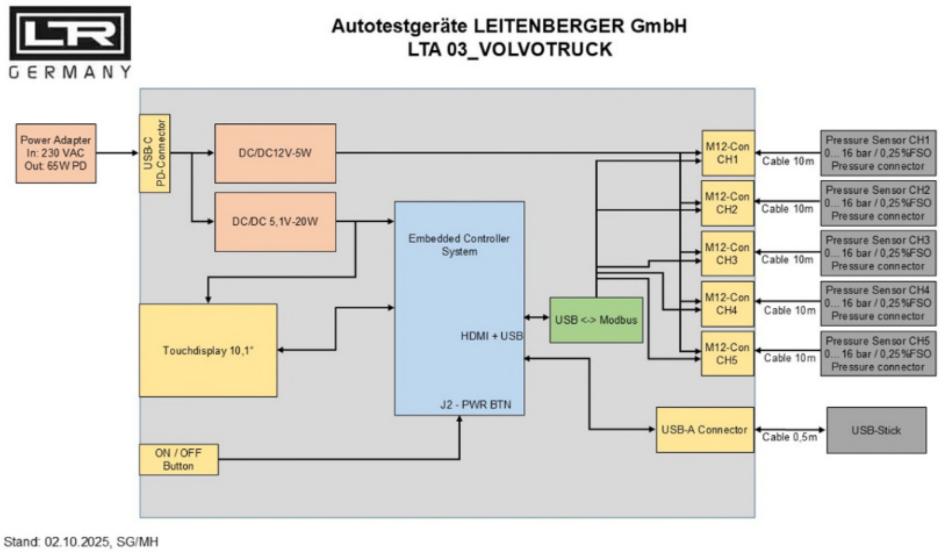


Figure 4.4: Schematic illustration of the prototype, provided by the supplier.

The first version of the prototype included certain adjustable input parameters for performing a quick test, see table 4.4.

Table 4.4: Adjustable parameters for the quick test in prototype version 1.0.

Parameter	Description	Unit
Stabilization time	Time allowed for the pressure to stabilize before the measurement phase begins	s
Test time	Duration over which pressure measurements are collected during the test	s
Minimum start pressure	Lower allowable pressure limit required to initiate the test	bar
Maximum start pressure	Upper allowable pressure limit required to initiate the test	bar
Pressure drop threshold	Maximum permitted pressure decrease during the test before triggering a fault condition	bar
Pressure rise threshold	Maximum permitted pressure increase during the test before triggering a fault condition	bar
Abort on threshold	Defines whether the test is automatically aborted when a threshold is exceeded	yes/no
Measuring point interval	Time interval between consecutive pressure measurement points	s

4.2 Identified knowledge gaps

The benchmarking and initial analysis, identified several knowledge gaps:

- Whether equivalent leakage detection accuracy can be achieved with a test duration shorter than four minutes.
- The role of measurement stabilization in achieving accurate and repeatable results.
- Whether different filling methods affect required stabilization time.
- Whether selected pneumatic subsystem activations influence pressure behavior during stabilization or quick testing.

4.3 Results from the experiments

This section presents the experimental developments carried out in the study, including hypotheses testing and prototype evaluation and improvements.

4.3.1 Hypotheses testing

The results from testing hypotheses 1-4.2, described in section 3.3.2, are presented below.

Hypothesis 1:
For the hypothesis, $H_0(1)$, "The inclusion of a stabilization phase prior to air leakage testing has no significant effect on the measured pressure decay", the visualization plot gathering all data collected during the stabilization phase is presented in figure 4.5.

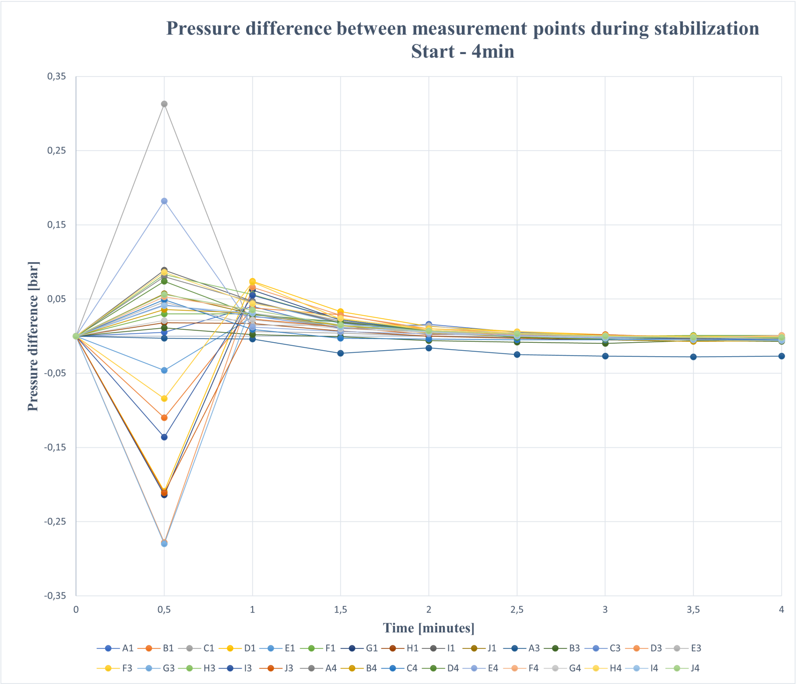


Figure 4.5: Plot of measuring points collected during stabilization phases across the trucks for cases 1, 3, and 4.

The graph clearly show a wide spread at 0.5 minutes, with values ranging from around -0.28 bar to +0.31 bar, and high instability in the beginning of the measurement duration. The curves converge slightly after 1 minute and for the remainder, the trend is a continuous decrease in variation between each measurement point. From 2.5 minutes, values clustering around ±0.02 bar, and fluctuations between consecutive points from here onward are small and consistent, indicating stable and repeatable behavior. Therefore, the null hypothesis can be rejected

However, assessing curves individually, some trucks present stable behavior earlier than others. Therefore, implementing a dynamic stabilization can be a way to reduce cycle time, since not all trucks will require the same stabilization time in order to conduct a reliable air leakage test. Following discussions with a production engineer with extensive experience with the process, a suitable approach for designing the dynamic stabilization phase is to consider the system unstable if the pressure increases under 30 seconds or if it decreases too rapidly. The dynamic test therefore requires a tolerance for maximum allowable pressure decrease between consecutive measurements, slightly below the leakage threshold defined in the current TR.

A plot showing pressure change monitoring from 2.5 minutes with narrower y-axis scale, is presented in figure 4.6. The graph highlight the much smaller variations occurring throughout the remainder of the quick test.

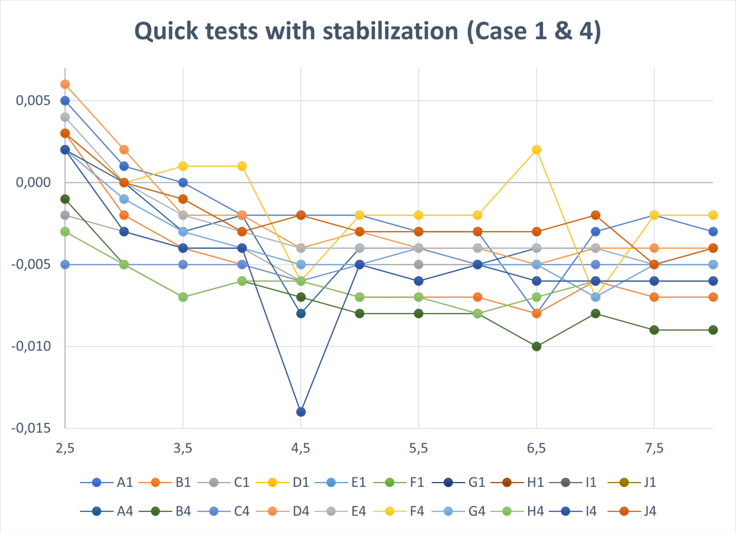


Figure 4.6: Plot of a quick test starting after a stabilization time of 2.5 minutes.

Hypothesis 2.1:
For the hypothesis, $H_0(2.1)$, "When additional pneumatic components are deactivated, pressure-decay–based leakage detection at a test duration shorter than 4 minutes does not provide equivalent detection accuracy compared to a 4-minute reference test", the result is shown in figure 4.5. Within the equivalence margin [-0.006, 0.006] and with a CI 90%, statistically equivalent detection accuracy is achieved with a 1-minute quick test compared to the 4-minute reference test. Therefore, $H_0(2.1)$ can be rejected and the alternative hypothesis, $H_1(2.1)$, can be accepted. The same

is true for the test durations 2 and 3 minutes, see appendix B.1. This result enables an action that for deactivated components during a test, the test duration can be reduced significantly, resulting in a 3-minute reduction in cycle time at the station with the defined test prerequisites. However, one notable aspect is that considering a shorter stabilization time, this result differ. For example, 2.5 minutes of stabilization no longer provides a valid assumption of equivalence between minute 1 and 4, see appendix B.2. Instead, a 2-minute drop test is required, making this input parameter dependent on this aspect of the final test design. The results of the equivalence test of a 2-minute test time following a 2.5-minute stabilization phase is presented in table 4.6.

Table 4.5: Results for equivalence testing of hypothesis 2.1 following 4 minutes of stabilization.

1-minute vs. 4-minute	
Parameter	**Value**
Equivalence margin	[-0.006, 0.006]
Mean difference	-0.00050
Standard deviation	0.00306
Standard error	0.00097
90% CI	[-0.00045, -0.00055]

Table 4.6: Results for equivalence testing of hypothesis 2.1 following 2.5 minutes of stabilization.

2-minute vs. 4-minute	
Parameter	**Value**
Equivalence margin	[-0.006, 0.006]
Mean difference	-0.00460
Standard deviation	0.00184
Standard error	0.00058
90% CI	[0.00414, 0.00506]

Hypothesis 2.2:

For the hypothesis, $H_0(2.2)$, "When additional pneumatic components are activated, pressure-decay–based leakage detection at a test duration shorter than 4 minutes does not provide equivalent detection accuracy compared to a 4-minute reference test", the result is shown in figure 4.7. Within the equivalence margin [-0.006,0.006] and with a CI 90%, equivalent detection accuracy is achieved with a 1-minute quick test compared to the 4-minute reference test. Therefore, $H_0(2.2)$ can be rejected and the alternative hypothesis, $H_1(2.2)$, can be accepted. The same is true for the test durations 2 and 3 minutes, with even narrower confidence intervals, see appendix B.3. This result enables an action that also for the condition where additional components are activated during a test, the cycle time at the station can be reduced by 3 minutes. The same conclusion as for Hypothesis 2.1 applies in this case, where 2.5 minutes of stabilization no longer provides a valid assumption of equivalence between minute 1 and minute 4, see appendix B.4. A reduction in stabilization time to 2.5 minutes requires a reduction of the test duration to 2 minutes, resulting in an overall cycle time reduction of 2 minutes. The results of the equivalence test of a 2-minute test time following a 2.5-minute stabilization phase is presented in table 4.8.

Table 4.7: Results for equivalence testing of hypothesis 2.2.

1-minute vs. 4-minute	
Parameter	**Value**
Equivalence margin	[-0.006, 0.006]
Mean difference	-0.00220
Standard deviation	0.00941
Standard error	0.00298
90% CI	[-0.00198, -0.00242]

Table 4.8: Results for equivalence testing of hypothesis 2.2 following 2.5 minutes of stabilization.

2-minute vs. 4-minute	
Parameter	**Value**
Equivalence margin	[-0.006, 0.006]
Mean difference	-0.00522
Standard deviation	0.00502
Standard error	0.00167
90% CI	[0.00470, 0.00574]

Hypothesis 3:

For the hypothesis "The required stabilization time is equal for internal and external air filling", the t-Test result is presented in table 4.9. The test resulted in a P-value of around 0.853, strongly indicating that there is no statistically significant difference in required stabilization time between external and internal air filling. Therefore, the null hypothesis cannot be rejected.

Table 4.9: Results for the t-Test of hypothesis 3.

t-Test: Paired Two Sample for Means		
	Case 1	Case 3
Mean	108	111
Variance	640	3010
Observations	10	10
Pearson Correlation	0.41788	
Hypothesized Mean Difference	0	
df	9	
t Stat	-0.19012	
P(T<=t) two-tail	0.85344	
t Critical two-tail	2.26216	

Hypothesis 4.1:
For the hypothesis "Activation of differential lock and pusher or trailing axle in low position does not significantly affect the required stabilization time", the t-Test result is presented in table 4.10. The two-tailed test resulted in a P-value of around 0.394, strongly indicating no statistically significant effect in required stabilization time when activating pneumatic subsystems. Therefore, the null hypothesis cannot be rejected.

Table 4.10: Results for the t-Test of hypothesis 4.1.

t-Test: Paired Two Sample for Means		
	Case 1	Case 4
Mean	105	96
Variance	850	560
Observations	10	10
Pearson Correlation	0.28989	
Hypothesized Mean Difference	0	
df	9	
t Stat	0.89553	
P(T<=t) two-tail	0.39382	
t Critical two-tail	2.26216	

Hypothesis 4.2:
For the hypothesis "Activation of differential lock and pusher or trailing axle in lowest position does not significantly increase the pressure decay measured during the quick test phase", the t-Test is presented table 4.11. The one-tailed test measuring sample means for a duration of 4 minutes resulted in a P-value of around 0.042, indicating a statistically significant increase in pressure decay when pneumatic subsystems are activated. Therefore, the null hypothesis is rejected and the alternative hypothesis accepted for a 4-minute test. However, results differed when shortening the test duration. A 2-minute test resulted in a P-value over 0.05, where the null hypothesis failed to be rejected.

Table 4.11: Results for the t-Test of hypothesis 4.2.

t-Test: Paired Two Sample for Means		
	Case 1	Case 2
Mean	0.0382	0.0441
Variance	0.000	
Observations	10	10
Pearson Correlation		
Hypothesized Mean Difference	0	
df	9	
t Stat	-1.94177	
P(T<=t) one-tail	0.04203	
t Critical one-tail	1.83311	

4.3.2 Prototype testing

The prototype tests along with interviews and prototype evaluation led to software updates and suggestions for further improvement of the prototype presented in table 4.12.

Table 4.12: Summarization table of improvement suggestions for the prototype.

Improvement suggestions		
Software		
1.	Live pressure data during the entire test	Implemented
2.	Increase of the upper limit for the minimum start pressure	Implemented
3.	Extension of the stability test to enable more dynamic behavior. Three new variables have been added and more are suggested for future prototype updates:	
3a.	Minimum stability test duration (in seconds)	Implemented
3b.	Maximum oscillation amplitude (in mbar)	Implemented
3c.	Checkbox to allow early termination of the stability test if the minimum duration and maximum oscillation amplitude criteria are met	Implemented
3d.	Update in terms to enable condition-based logic to allow early termination that includes both a defined time period (s) without pressure increase within a specified tolerance (mbar) and a pressure drop over one minute below a defined threshold.	Suggestion
4.	Added option to log measurement data. Behavior when enabled:	
4a.	Measurement data is logged during the test. After the test is completed, the log file can be saved to the USB drive together with the existing results	Implemented
4b.	Logging interval: 500 ms	Implemented
5.	Fail-proof user interface	Suggestion
6.	Clear displaying of result	
6a.	Green as OK and Red as NOK	Suggestion
6b.	Include start- and final pressure	Suggestion
6c.	Additional option to view more information after test	Suggestion
7.	Auditory alerts:	
7a.	When cut-in pressure is reached and test can be started	Suggestion
7b.	When test is aborted due to not stable or leak detected	Suggestion
7c.	Test is finished	Suggestion
Hardware		
8.	Reduce to only 2 sensor ports	Suggestion
9.	Cable length depending on station design	Suggestion

Live pressure data during testing, point 1 in table 4.12, allow the operators to monitor and evaluate the current pressure and act accordingly. Increase of upper limit for the minimum start pressure ensures that the leakage test cannot be initiated before cut-in pressure is reached, "fail-proofing" the test and increasing the usability of the test. To reduce the test duration, a dynamic stabilization test was implemented to automatically end the stabilization test when pressure oscillations are within allowed tolerances. To achieve this, three new variables for the stabilization test, 3a, 3b, and 3c in table 4.12, was implemented. However, the final PDCA iteration still yielded in unsatisfactory result for the dynamic stabilization test. The primary issue was due to the prototype measuring amplitude relative to the initial start pressure, which does not accurately reflect how stabilization will be determined during the test.

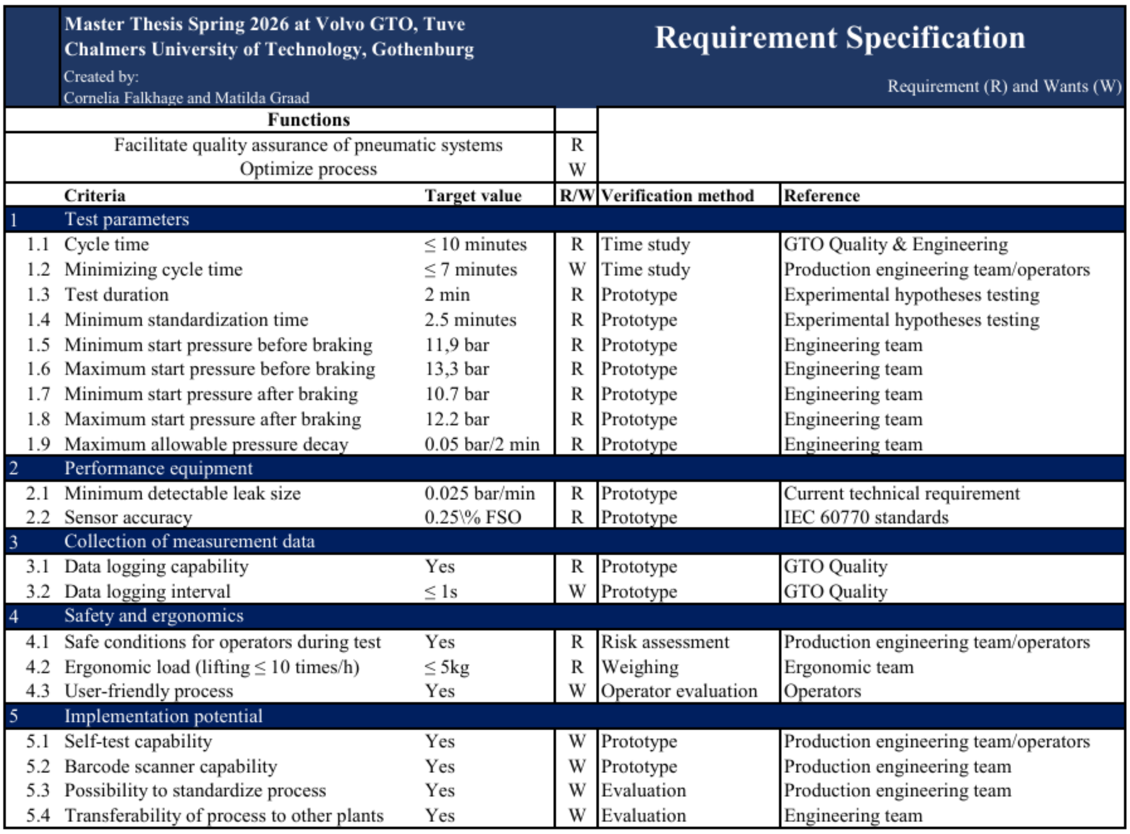
The updated software version enables pressure measurements to be recorded with 500 ms intervals and stored on the USB device, allowing the data to be used for future analysis and project investigations.

The final PDCA iteration resulted in the following key improvement suggestions, yet to be implemented or tested:

- **(5) Fail-proof interface:** Enhance usability and robustness of the interface by redesign based on input from operators and team leader to make display intuitive and initiating a test simple.
- **(6) Clear results:** Display the result OK as green and NOK as red, removing unnecessary information. Include start and final pressure as well as possibility to view more if interested.
- **(7) Auditory or visual alerts:** Alerts when cut-in pressure is reached, test is aborted due to system instability or detected leak, and when test is complete would allow operators to avoid continuously monitoring of the screen, reducing active operator time and minimizing idle time.
- **(8) Reduce to 2 sensor ports:** The current leakage testing process requires only one sensor. The current prototype version has 5 ports. The proposal is to have 2 available ports which will allow for more systems to be simultaneously tested if necessary in the future.
- **(3d) Updated dynamic stabilization logic:** The proposed solution to achieve a successful integration of a dynamic stabilization test is to set an allowed tolerance for pressure rise and drop. During 1 minute, the pressure drop allowance is 0.025 bar while the maximum allowed pressure rise during the last measured 30 second interval is 0.001 bar. If the pressure measurement fulfill these conditions, the system can be considered stabilized and the equipment can proceed to pressure decay test.

4.4 Process design

Based on the insights from benchmarking and results of the hypotheses testing, a set of criteria was defined to guide the development of the verification process. The corresponding requirement specification for process design is presented in figure 4.7.



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Chalmers University of Technology, Gothenburg
Created by:
Cornelia Falkhage and Matilda Graad

Requirement Specification

Requirement (R) and Wants (W)

	Functions				
	Facilitate quality assurance of pneumatic systems		R		
	Optimize process		W		
	Criteria	**Target value**	**R/W**	**Verification method**	**Reference**
1	Test parameters				
1.1	Cycle time	≤ 10 minutes	R	Time study	GTO Quality & Engineering
1.2	Minimizing cycle time	≤ 7 minutes	W	Time study	Production engineering team/operators
1.3	Test duration	2 min	R	Prototype	Experimental hypotheses testing
1.4	Minimum standardization time	2.5 minutes	R	Prototype	Experimental hypotheses testing
1.5	Minimum start pressure before braking	11,9 bar	R	Prototype	Engineering team
1.6	Maximum start pressure before braking	13,3 bar	R	Prototype	Engineering team
1.7	Minimum start pressure after braking	10.7 bar	R	Prototype	Engineering team
1.8	Maximum start pressure after braking	12.2 bar	R	Prototype	Engineering team
1.9	Maximum allowable pressure decay	0.05 bar/2 min	R	Prototype	Engineering team
2	Performance equipment				
2.1	Minimum detectable leak size	0.025 bar/min	R	Prototype	Current technical requirement
2.2	Sensor accuracy	0.25\% FSO	R	Prototype	IEC 60770 standards
3	Collection of measurement data				
3.1	Data logging capability	Yes	R	Prototype	GTO Quality
3.2	Data logging interval	≤ 1s	W	Prototype	GTO Quality
4	Safety and ergonomics				
4.1	Safe conditions for operators during test	Yes	R	Risk assessment	Production engineering team/operators
4.2	Ergonomic load (lifting ≤ 10 times/h)	≤ 5kg	R	Weighing	Ergonomic team
4.3	User-friendly process	Yes	W	Operator evaluation	Operators
5	Implementation potential				
5.1	Self-test capability	Yes	W	Prototype	Production engineering team/operators
5.2	Barcode scanner capability	Yes	W	Prototype	Production engineering team
5.3	Possibility to standardize process	Yes	W	Evaluation	Production engineering team
5.4	Transferability of process to other plants	Yes	W	Evaluation	Engineering team

Figure 4.7: Requirement specification for verification process design.

The hypothesis testing indicated that certain test conditions influence the appropriate tolerance setting, which should be accounted for in the process design. For instance, if additional pneumatic subsystems are included to verify a larger system, a tolerance of 0.05 bar/2 min is sufficient. However, when only the brake supply circuits are considered, a stricter tolerance may need to be set, since the two conditions have shown to significantly affect the measured pressure decay, even in leak-free systems.

4.5 Recommended work procedure for new verification process

The recommended verification process is based on the current leakage testing. The suggested station layout is shown in figure 4.8. Currently, each station is equipped with external air supply, a computer, and one hand-scanner. To minimize the risk of tripping accidents and physical interference with operators, the display is recommended to be placed mounted on a stationary mount with access to an electrical outlet within charging cable length. In both cases, the sensor should remain continuously connected to the display and safely positioned in assigned spot. The sensor cable must be adapted to accommodate the distance between the stationary display and the nipple on braking circuit air tank, which varies depending on where the air tank is placed on the truck and where the stationary display is placed. It is suggested that input variables suitable for every truck variation are pre-set based on recommendations.

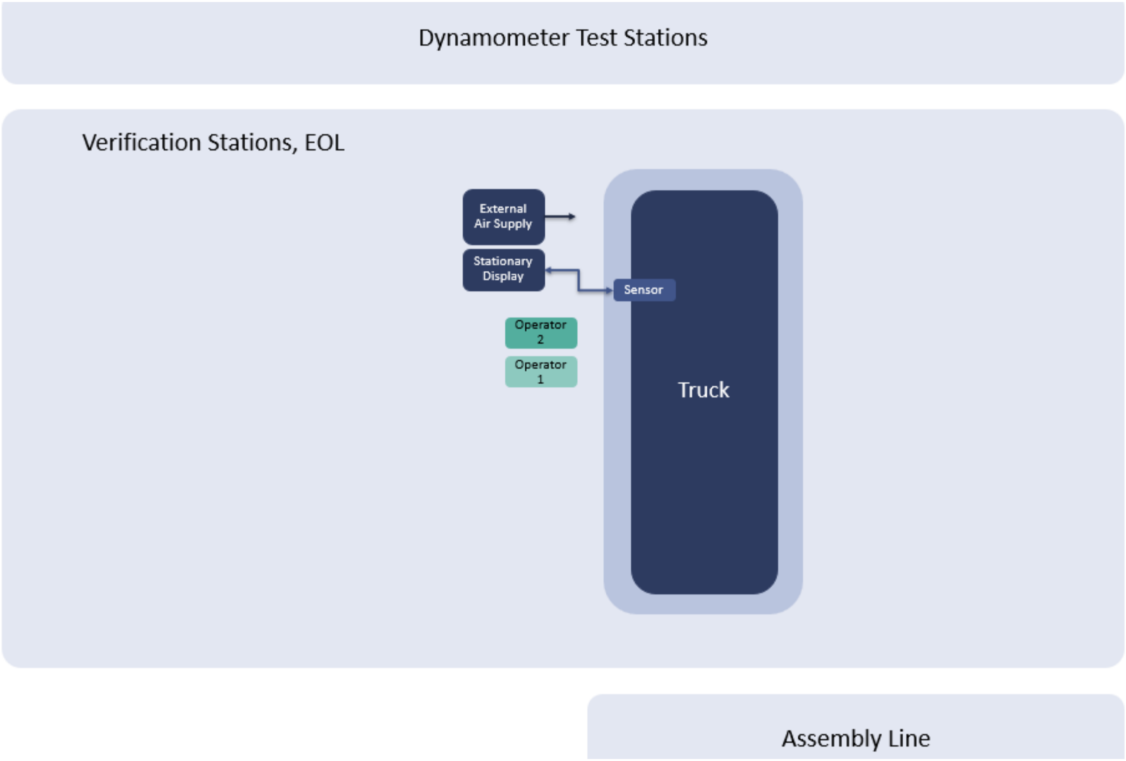

Figure 4.8: Suggestion of layout during leakage testing at EOL.

The proposed process includes 2 operators. Operator 2 scans the truck with the hand-scanner. Operator 1 sets the vehicle in neutral gear level, deactivates parking brake, engine off with ignition on, activates additional subsystems (differential lock and trailing axle in lowest position), and exits the cab. Operator 2 connects the external air supply hose to the selected air tank nipple and opens the valve to initiate system pressurization. During the filling process, operator 1 connects a pressure sensor to the tank. The operators are alerted that cut-it pressure is reached and the external air supply is detached from the nipple. Using Prosit+ to activate the braking function, opening the valves for the pneumatic system during both stabilization and pressure decay test, operator 2 can click then on "start test" to initiate the dynamic stabilization test. If stabilization is achieved within 4 minutes, the equipment automatically proceeds to the two minute pressure decay test. Operators are alerted when test is finished or terminated. The display shows if pneumatic tightness is verified or if leakage is detected by green or red box with OK or NOK.

Operator 2 scans the pop-up QR code with hand-scanner to save the results, while operator 1 detaches the sensor from the tank.

Table 4.13 presents the planned steps, estimated time per activity, responsible operator, total testing time, and active operator time. Note that the times are estimated and not based on time studies utilizing trained operators.

Table 4.13: Process steps and estimated time for each activity during suggested verification process.

Activity	Time [sec]	Responsible
1. Scan truck	20	Operator 2
2. Prepare testing conditions in truck	20	Operator 1
3. Connect external air supply and start pressurization	20	Operator 2
4. Pressurization	60	Automatic
5. Connect sensor	20	Operator 1
6. Detach air hose	20	Operator 2
7. Activate brake function using Prosit+	20	Operator 2
8. Start test	10	Operator 2
9. Stabilization	150-240	Automatic
10. Pressure decay	120	Automatic
11. Check result and scan QR-code	30	Operator 2
12. Disconnect sensor	30	Operator 1
Total testing time	450 - 540	
Total time, operator 1	70	
Total time, operator 2	120	

The total estimated testing time accounts for the simultaneous execution of steps 1 and 2, and 11 and 12 by operators 1 and 2. Step 5 is performed while the system is pressurizing (step 4). The total test duration is estimated to be between 7.5 minutes and 9 minutes. Active operator time is 2 minutes for operator 1 and 1 minute and 10 seconds for operator 2.

5

Discussion

The following chapter will discuss the results of chapter 4, as well as present the answers to all three research questions. This section also includes industrial and academic contributions along with project limitations, key takeaways and future direction for Volvo, and, finally, reflections on ethical and sustainability.

5.1 Interpretation of results

The results of the experimental development provide strong evidence that the current leakage verification process can be significantly improved in terms of efficiency and quality assurance.

The results from hypothesis 1 confirm that the stabilization phase is critical for ensuring reliable pressure decay measurements. The observed large pressure variations in the initial phase, followed by convergence after about 2.5 minutes, indicate that early measurements are strongly affected by transient effects such as temperature changes and redistribution of air within the system. This aligns well with the theoretical background presented for pneumatic systems, which explains that pressure variations can occur independently of leakage as a result of thermodynamic effects. Consequently, incorporating a stabilization phase is crucial to avoid false conclusions regarding the presence of leakage.

An implication of the variation between individual curves is that stabilization behavior is not identical across all trucks. This finding supports the implementation of a dynamic stabilization approach, where the transition to the measurement phase is based on system behavior rather than a fixed time, only including a general minimum stabilization time. This approach has the potential to further reduce cycle time while maintaining robustness and reliability, although it brings additional complexity in defining appropriate stability criteria.

The equivalence testing performed for hypotheses 2.1 and 2.2 demonstrates that shorter test durations, such as 2 minutes following at least 2.5 minutes of stabilization, are statistically equivalent compared to the current 4-minute reference test. This finding is critical from a production perspective, as it enables a 2-minute reduction in cycle time per truck, which is a significant improvement in station efficiency. However, it should be noted that the equivalence is dependent on the defined test conditions and variation in vehicles such as axle configurations. Therefore, the reduced test duration should not be interpreted as universally applicable, but can be considered valid under controlled and well-defined conditions based on the conducted sampling.

The results from hypotheses 3 and 4.1 indicate that neither the filling method nor the activation of additional pneumatic subsystems significantly affects the required stabilization time. This shows that the same stabilization strategy can be applied for varying operating conditions, which simplifies the process design. In contrast, hypothesis 4.2 shows that the activation of additional pneumatic subsystems has a statistically significant effect on the measured pressure decay during a 4-minute leakage test. From a process design perspective, this implies that leak tolerances should be adjusted depending on the scope of the test. However, this effect may differ when shorter test durations, such as 2 minutes, are applied. The prototype testing further complements these findings by identifying practical considerations for its implementation in production. The introduction of features such as live pressure data and data logging improves transparency and enables future data-driven improvements, for example through statistical process control.

The results confirm that the concept of the developed verification process is technically feasible and aligned with the identified requirements. The achieved improvements in terms of reduced test time, potential adaptive stabilization, and improved data availability represent a shift towards a more standardized, data-driven, and less operator dependent verification process. However, optimization of the proposed approach will depend on careful calibration of the parameters over time, validation under broader production conditions, and successful integration into the existing production system. The same applies for its transferability to other plants, although the potential for successful implementation is considered high based on benchmarking insights and discussions with production engineers at relevant global plants.

Finally, transferability of the developed concept to other plants is considered promising due to similarities in production layout, verification requirements, and the position of the process within the production system. The approach is based on measurable process parameters and standardized verification logic rather than operator-specific practices, meaning that implementation at other sites would mainly require assessing compatibility with local station layouts. Since the verification step is carried out at similar stages across plants, integration into existing manufacturing setups is expected to be feasible with minimal adaption. This is supported by benchmarking insights and discussions with production engineers at relevant global plants, indicating that the proposed solution has potential for broader implementation.

5.2 Answers to the research questions

This section addresses the research questions defined in section 1.4, based on the results from benchmarking activities, experimental development and process design.

5.2.1 Answering of RQ1

The results show that the design space for a pneumatic leakage verification process at EOL is defined by a combination of technical, operational, and organizational constraints.

From a technical perspective, the results indicated that stabilization of the pneumatic system before pressure decay measurements is critical to obtain reliable verification. Furthermore, since the smallest detectable leaks are limited by sensor accuracy and measurement resolution, these constraints must be factored into the threshold values and technical requirements of the verification process. In addition, the hypothesis results also demonstrated that, provided that the system is stable, the test duration can be reduced without affecting the leak detection accuracy. However, the tests show that the activation of additional pneumatic subsystem has an impact on the measured pressure decay, implying that the design of a verification process has to account for different operating conditions when determining acceptable leakage thresholds.

From the operational perspective, the verification process must be compatible with cycle time constraints determined by takt time from the production line, while also minimizing the operator dependency and ensuring ease of use. Organizational constraints, such as compatibility to current infrastructure and adherence to TR, further define the feasible design space. These factors are key to balance accuracy, efficiency, and standardization when designing a verification process.

5.2.2 Answering of RQ2

A verification process which effectively integrates digital pressure-drop equipment equipment into excising EOL was developed. The recommended process utilizes pressure decay measurement with an initial stabilization phase to ensure valid test conditions and reduce unnecessary delays.

The improved verification process includes automated stabilization and reduced measurement duration. The process also enables automated decision-making, based on predefined evaluation criteria, making it less operator dependent. Furthermore, it incorporates data logging to support future QA activities. The developed verification process is designed to be compatible with current station layout, using existing infrastructure to ensure practical feasibility. This results in a standardized process concept which supports a more efficient and consistent leakage verification.

5.2.3 Answering of RQ3

The recommended process enables a reduced cycle time and operator dependency, while improving consistency by automated evaluation of measurement. Including data logging and data-driven QA supports more advanced QA and facilitates process standardization across production sites while also enabling SPC in future improvements. However, the process is dependent on setting the correct parameters, which is influenced by sensor accuracy limitations, affecting the detection accuracy. Another risk is the need for further validation of certain functions, for e.g. Prosit+ functions, and continued development of the prototype.

Finally, the implementation of the recommended process is also dependent on alignment with currently ongoing projects and organizational approval. Further testing and validation are therefore essential before deployment.

5.3 Contributions of the thesis

This section outlines the contributions of this study to both industry and academia.

5.3.1 Industry contributions

This study contributes to industry by demonstrating that the leakage verification process for truck pneumatic systems can be made more efficient, standardized, and data-driven. The findings show that test time can be significantly reduced without compromising detection accuracy for medium to high leakages, enabling shorter cycle times at the EOL station. The proposed process improvements has the potential to improve production efficiency and reduce bottlenecks.

Furthermore, the proposed verification process reduces operator dependency by implementing a structured and more automated approach to leakage detection. It enables consistent test execution and interpretation of measurement results, contributing to a more reliable quality assurance practice.

Another key contribution is the introduction of data logging capabilities, which were not present in the current process. By storing measurement data, the proposed solution supports traceability in relation to customer claims and creates opportunities for continuous improvement through data-driven analysis, such as SPC.

The study also highlights the importance of adjusting tolerance limits based on the scope of the test, ensuring that leakage detection remains sensitive (capable of detecting relevant leakages) and robust (stable despite variations in system behavior) across different conditions. In addition, the proposed use of dynamic stabilization introduces a more flexible testing approach, allowing the process to adapt to variations between individual trucks.

Ultimately, the study provides a feasible concept for integrating digital pressure drop equipment into the verification process, along with actionable recommendations for implementation and further development within the specified production environment.

5.3.2 Academic contributions

This study contributes to the academic field by extending the application of pressure decay methods for leakage detection in complex pneumatic systems within an industrial context. Although pressure decay is a well-established method in theory, this work provides empirical evidence of how key factors such as test duration, stabilization behavior, and system configuration affect measurement reliability and interpretation. In addition, the study reviews and evaluates alternative leakage detection methods based on state-of-the-art research and industrial practices, providing an understanding of their suitability for EOL verification.

A key contribution is the use of equivalence testing to evaluate varying test durations. Unlike traditional hypothesis testing, which focuses on identifying differences, equivalence testing demonstrates that shorter test durations can perform comparably to a reference method, highlighting how statistical methods can support process optimization in engineering.

Furthermore, the study offers data-driven insights into the role of stabilization in pneumatic systems, linked to thermodynamic principles such as the relationship between temperature and pressure described by the ideal gas law. The results confirm that transient pressure variations can significantly influence measurements, emphasizing the need for a sufficiently long stabilization phase that is based on the specific system prior to leakage assessment. The concept of dynamic stabilization further contributes to the understanding of adaptive testing strategies, demonstrating how stability can be defined based on pressure behavior rather than fixed durations, and applied in a production environment.

Finally, the introduction of data logging connects practical implementation with quality assurance theories such as SPC and TQM, enabling continuous improvement and supporting a shift towards data-driven quality control in industrial practice.

5.4 Limitations

Following limitations for the project was identified.

- There are two types of air leakage tests, a short pressure drop test for identifying medium/high leakages and an overnight test for checking small leakages. The test equipment software supports both tests, however, since the second test is intended to be performed less frequently and at a different station, the short pressure drop test was prioritized in the verification process design.
- The verification design was limited to the use of predetermined measurement equipment.
- The project scope was limited to the models produced in the Tuve plant.
- Sampling method and sample size was limited by operational and logistical constraints, including production flexibility, physical floor space, and operator availability.

- For the scalability of a solution to other Volvo Group plants, the assessment was limited to the plants in Gent, Belgium and Bourg-en-Bresse, France. These sites were prioritized mainly due to their size and order quantities, arguably yielding the most benefit from an improved or automated solution to the pneumatic systems' verification process.
- Though the aim was to assess current methods for comparable verification processes outside of Volvo Group, the opportunity to study this was based on the access provided by the method users.
- The task of implementing the process, monitoring, and following up, was not feasible within the project time frame.

5.5 Key takeaways and future directions

The findings from this project provides Volvo Trucks with both the technical feasibility and practical implementation of digital pressure-drop equipment. The proposed verification process show a clear potential for improving efficiency, standardization, and data accessibility and traceability. In order for Volvo to have a successful deployment several technical, practical, and validation related aspects has to be addressed. This section highlights the key insights related to the prototype, the robustness of the results, and required future work.

5.5.1 Reflections on the prototype

The prototype evaluation showed that several areas require further development before ensuring the solution can be effectively implemented in real production settings. Firstly, a redesign of the dynamic stabilization test has to be implemented and discussed with suppliers to fully reflect the stabilization behavior of the pneumatic system as it does not currently capture the pressure variation over set intervals.

In addition, the measurement capability of the current sensors must be considered when defining verification thresholds. The sensor accuracy of 0.25% FSO limits the ability to detect small leakages and may reduce the effectiveness of the dynamic stabilization logic during testing. It should be noted that the experimental evaluation in this study was conducted using a manometer with an accuracy of 0.05% FSO, which enabled detection of smaller pressure variations and supported more precise identification of stabilization behavior. A potential improvement for future equipment implementation is upgrading to a higher-precision sensor, for example with an accuracy of 0.05-0.1% FSO. Improved sensor accuracy would enable more reliable detection measurement of small pressure changes, support more robust pressure measurements and stabilization criteria, and potentially allow for further reductions in process cycle while increasing overall result reliability.

Potential to integrate the equipment into the overnight test has been identified and justifies further investigation. While the scope of this project has focused on the quick test for detecting medium to high leakages, the prototype could also be applied in overnight testing to assess smaller leakages when the vehicle has remained stationary for an extended period of time.

Lastly, from a usability perspective, improvements of user interface to ensure intuitive and fail-proof use of equipment in a production setting. Clear visualization of results, simplified interaction, and integration of auditory alerts would reduce the operator dependency and support consistent operation during the verification process. These aspects are further discussed in section 5.5.3.

5.5.2 Data sampling

The convenience-based sampling strategy likely results in over-representation of vehicle models produced in higher volumes during the data collection period, while less frequently produced variants may be underrepresented. Despite efforts to improve representativeness, the sample reflects the short-term production mix rather than long-term variability. Therefore, the results should primarily be interpreted in the context of the dominant vehicle configurations at the Tuve plant. Transferability to other production plants may be applicable where production conditions are comparable. However, differences in local production setups or product mixes can limit direct applicability.

5.5.3 Further validation actions

The proposed verification process is technically feasible. However, several validations activities are required before a efficient and reliable deployment in a production environment can be achieved.

Technical validation after suppliers provide an updated algorithm for the dynamic stabilization test based on suggestions is essential to ensure reliable performance and accurate results. In addition, the integration of Prosit+ for brake activation requires experimental verification to confirm that is provides equivalent result compared to utilizing the hydraulic crutch used for hypothesis testing.

From the operational perspective, user interaction with prototype must be evaluated by operators. The current interface is somewhat user-friendly, but not optimal for a production setting and ease of use. Feedback and collaboration with operators and team leaders is critical to ensure that the equipment and process is intuitive with clear interface design, minimizing the risk of incorrect use, and supports the efficient use in a production environment. To establish an accurate cycle time for the verification process, time studies with trained operators should be conducted. The current time estimate presented in table 4.13 is indicative, but should be validated quantitatively before deployment.

Lastly, additional validation to ensure robustness across different truck variations, see section 5.5.2. This includes verifying that selected input parameters are suitable for all variants, making the process transferable to other Volvo Group plants.

5.6 Ethical and sustainability reflections

This project was conducted within Volvo Group Operations in Tuve, an industrial environment where ethical considerations are primarily related to data handling, operator well-being, safety, and long-term sustainability impacts.

The experimental work involved the collection of pressure measurements from production vehicles. From a data ethics perspective, no personal data related to operators was collected or stored, and no individual vehicles are identifiable in the report results. The study therefore complies with the ethical guidelines for data privacy, confidentiality, and anonymization of the EU General Data Protection Regulations (GDPR) and the European Data Protection Board (EDPB) [35]. However, the use of digital measurement equipment with data logging capabilities raises future considerations for Volvo Group regarding data ownership, access, and usage.

Another ethical aspect to consider is ergonomics and operator safety. The proposed verification process uses digital equipment for decision-making, reducing the cognitive load on the operators by eliminating the need for continuous monitoring and evaluation of pressure measurement. However, before implementing new equipment, the process must be assessed to avoid creating new risks. For example, the new process involves a longer cable from display to truck, increasing the risk of tripping hazards. Collaborating with operators and team leaders to further validate and improve the process will ensure a safer and ethically responsible implementation.

In terms of sustainability, improved detection of air leakage contributes to increased system efficiency during vehicle operation. Reduced leakage lowers the need for continuous compressor use, thereby decreasing energy consumption and emissions that are associated. In addition, improved system tightness can reduce component wear, supporting longer service life and more efficient use of resources.

Finally, the conclusion and result are presented with transparency and within the limitations of the study. Since the proposed process has not been fully validated or implemented, the results should be interpreted as indicative rather than definitive and further testing and validation is required.

6

Conclusion

This thesis has investigated the development of a verification process for pneumatic systems in heavy-duty trucks, with the objective of improving air-leakage detection at the EOL stage through the integration of digital pressure decay measurement equipment.

The results show that the current verification process can be significantly improved in terms of both efficiency and quality assurance. Experimental findings indicates that reduced test durations can achieve equivalent leakage detection accuracy compared to the current 4-minute reference test, enabling meaningful reductions in cycle time. The study also confirms that the inclusion of a stabilization phase is essential to ensure reliable and repeatable measurements, due to transient pressure variations within the pneumatic systems. The analysis also imply that the required stabilization time varies between trucks, supporting the implementation of a dynamic stabilization approach based on defined thresholds. This approach allows the process to adapt to system behavior while maintaining measurement reliability. In addition, while stabilization time was not significantly affected by filling method or subsystem activation, the measured pressure decay was influenced by pneumatic subsystem activation. This highlights the importance of defining appropriate leakage thresholds depending on test conditions.

The evaluation of the digital pressure decay prototype demonstrates that the concept is technically feasible and suitable for integration into a production environment. The proposed process enables automated decision-making, reduces operator dependency, and introduces data logging capabilities, supporting improved traceability and future data-driven quality control. Based on these findings, a verification process has been developed, integrating the equipment into the existing production setup. Although the proposed solution shows strong potential, more truck data and further validation is required to ensure robustness across different truck configurations and operating conditions. Overall, this work provides a practical and scalable basis for optimizing pneumatic leakage verification and supports the continued transition toward standardized, automated, and data-driven quality assurance in heavy-duty vehicle manufacturing.

7

Declaration for use of Artificial Intelligence

Artificial intelligence (AI) tools, including *Microsoft Copilot*, *ChatGPT*, and *Google Gemini*, were used for this report to assist with grammar refinement, improve clarity and coherence, and ensure consistency in writing style. All AI assisted contributions were critically reviewed and validated by the authors.

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A

Appendix

Examples of questions from the semi-structured interviews are provided below for each type of interviewee. These questions were used to initiate discussion with the identified stakeholders.

A.1 Questions for operators and team leader in Tuve, and production engineers in Bourg-en-bresse and Gent

- Describe in detail the current verification process for pneumatic tightness.
- What are the drawbacks and limitations of your current method?
- What requirements and expectations do you have for a future, improved verification process?

A.2 Questions for technical trainers

- What does the braking system architecture look like?
- What are the key components of the pneumatic system and how do they work in this application?
- How does the air flow within the braking system based on varying truck conditions?

A.3 Questions for domain experts with previous improvement initiative knowledge

- What have been your main focus to improve the current process?
- What challenges have you faced during your projects?
- What are your recommendations for experimental testing?
- What are suitable equivalence margins for data analysis of specified pressure monitoring experiments.

A.4 Questions for Volvo Engineering function

- What are the reasoning behind the tolerances set in the current TR?

- What are key process parameters to consider for the verification process?
- What is the required pressure interval of the system before starting a pressure decay test?
- What are associated risks you can identify with the suggested new verification process?

A.5 Questions for prototype suppliers

- What constraints does the prototype have?
- What potential improvements are possible for the prototype?

B

Appendix

B.1 Equivalence test results for hypothesis 2.1 after 4 minutes of stabilization

2-minute vs. 4-minute	
Parameter	**Value**
Equivalence margin	[-0.006, 0.006]
Mean difference	1,776E-16
Standard deviation	0.00156
Standard error	0.0.00049
90% CI	[1.599E-16, 1.954E-16]

3-minute vs. 4-minute	
Parameter	**Value**
Equivalence margin	[-0.006, 0.006]
Mean difference	-0.00050
Standard deviation	0.00255
Standard error	0.00081
90% CI	[-0.00045, -0.00055]

B.2 Equivalence test results for hypothesis 2.1 after 2.5 minutes of stabilization

1-minute vs. 4-minute	
Parameter	**Value**
Equivalence margin	[-0.006, 0.006]
Mean difference	-0.01126
Standard deviation	0.00236
Standard error	0.0075
90% CI	[0.01013, 0.01239]

B.3 Equivalence test results for hypothesis 2.2 after 4 minutes of stabilization

2-minute vs. 4-minute	
Parameter	**Value**
Equivalence margin	[-0.006, 0.006]
Mean difference	0.0000
Standard deviation	0.00240
Standard error	0.00076
90% CI	[4.796E-16, 5.861E-16]

3-minute vs. 4-minute	
Parameter	**Value**
Equivalence margin	[-0.006, 0.006]
Mean difference	0.00090
Standard deviation	0.00202
Standard error	0.00064
90% CI	[-0.00081, -0.00099]

B.4 Equivalence test results for hypothesis 2.2 after 2.5 minutes of stabilization

1-minute vs. 4-minute	
Parameter	**Value**
Equivalence margin	[-0.006, 0.006]
Mean difference	0.01310
Standard deviation	0.00917
Standard error	0.00290
90% CI	[0.01179, 0.01441]

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