



University of Wales Trinity Saint David
School of Engineering



ACMA 6013 - Independent Project
Feasibility of Objective NVH Detection
Bachelor of Engineering: Manufacturing Systems Engineering
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Declaration of Authenticity

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

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Abstract

Noise, Vibration and Harshness (NVH) quality is a critical factor influencing customer-perception within premium automotive manufacturing. At Aston Martin, overall vehicle NVH assessment is currently conducted using a technician-led proving-ground evaluation process based primarily on subjective judgment. Although effective at identifying obvious concerns, the process lacks objective measurement capability, repeatability, and traceability.

This project investigates how the current end-of-line (EOL) NVH detection process could be improved through the introduction of a more objective and repeatable measurement system. The study applies the DMAIC (Define, Measure, Analyse, Improve, Control) methodology to evaluate the existing process, identify sources of variation and assess suitable objective measurement technologies for production implementation.

The current proving-ground process, associated cycle times, measurement limitations, warranty exposure, and operational inefficiencies were analysed using process mapping, timing studies, stakeholder analysis, PFMEA and Gage R&R principles. Several potential improvement solutions were evaluated, including acoustic camera systems, rig-based excitation testing, and binaural measurement systems.

The findings identified that the primary limitation of the current process is the absence of measurable acoustic data and dependence on technician interpretation. A proving-ground overlay system using binaural measurement equipment and objective pass/fail thresholds was identified as the most practical short-term solution due to its balance between repeatability, production integration, and customer relevance.

The project concludes that objective acoustic measurement can significantly improve traceability, repeatability and process control while maintaining compatibility with existing manufacturing operations. The proposed system also creates opportunities for future digital manufacturing integration, predictive quality analytics, and automated anomaly detection.

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1 Introduction

1.1 Company Background

Established in 1913 by Lionel Martin and Robert Bamford, Aston Martin has evolved into an internationally recognised automotive brand synonymous with elegance, precision craftsmanship, high-performance engineering, and exclusivity. The company combines cutting-edge automotive innovation with meticulous hand-built production methods and sophisticated design language to deliver a range of celebrated luxury vehicles, including the Vantage, DB12, Vanquish, and DBX707 and the Valhalla shown in Figure 1. Aston Martin's strategic ambition is to establish itself as the most desirable ultra-luxury British automotive brand globally, delivering highly distinctive and emotionally engaging high-performance vehicles (Aston Martin Lagonda, 2026).



Figure 1: Aston Martin Valhalla (Aston Martin Lagonda, 2026)

Headquartered in Gaydon, England, Aston Martin Lagonda designs, engineers, manufactures, and exports vehicles to over fifty international markets. Core sports car production is based in Gaydon, while the DBX luxury SUV is manufactured in its St Athan facility in South Wales, Figure 2. Lagonda, originally founded in 1899, merged with Aston Martin in 1947 following the acquisition by Sir David Brown. The company is currently listed on the London Stock Exchange under the name Aston Martin Lagonda Global Holdings plc.



Figure 2-Aston Martin's Production Facility in South Wales (Aston Martin Lagonda, 2026)

Within this market segment, customer expectations extend beyond styling and performance alone. Increasing emphasis is placed on perceived quality, comfort refinement, and consistency between vehicles. As a result, manufacturing systems must ensure that each vehicle meets both engineering specification and customer expectation before release to the market (Juran & De Feo, 2010)

1.2 Background and Motivation.

Noise, Vibration and Harshness (NVH) is a critical aspect of vehicle quality within the automotive industry and has a direct influence on customer perception of refinement, comfort, and overall product value. In premium automotive manufacturing, NVH performance is critical because customers expect elevated levels of cabin refinement, acoustic consistency, and ride comfort (Heisler, 2002).

Modern NVH concerns are no longer limited to major powertrain or drivetrain noise. As vehicle refinement improves, secondary noises including squeaks, rattles, wind noise, and transient disturbances become more noticeable to customers. As overall vehicle refinement improves, secondary noises become increasingly significant during EOL inspection (Masri, et al., 2024) (Panza, 2015).

From an engineering perspective, NVH can be understood through the relationship between excitation sources, transfer paths, and the receiver where noise and vibration generated by the vehicle systems are transmitted through the structure and air before being perceived by the occupant. Common excitation sources include powertrain, road-tyre interaction, aerodynamic effects, suspension inputs, and interior trim components (Rao, 2017).

Although NVH is often associated with vehicle development and validation, it is also highly relevant at the manufacturing stage. Small variations in build quality, trim fit, assembly condition, fastener retention, or component tolerance can introduce abnormal noise events. If issues are not identified before vehicle release, they can negatively affect customer satisfaction, damage brand perception, and increased warranty and rectification costs (Pyzdek, 2018). As a result, effective EOL NVH inspection is an important part of manufacturing quality assurance.

1.3 Current Process and Problem Statement

At present, overall vehicle NVH detection is conducted using a technician-led proving-ground evaluation at the end of the production process. A trained technician drives the vehicle as part of the road test process. The vehicle is driven across a predefined route shown in Figure 3, containing multiple road surfaces intended to excite the vehicle structure to reveal abnormal noise.

During the route, the technician listens for unacceptable sound and determines whether the vehicle should pass or be referred for further investigation.

This process provides several practical advantages. It exposes the vehicle to realistic dynamic inputs and allows experienced technicians to use professional judgment developed through repeated exposure to product standards. However, the method also presents significant limitations.

The process relies on subjective operator judgment, introducing variation between inspections. In addition, no recording or measurement equipment is currently used, meaning there is:

- No permanent acoustic record
- No measurable pass/fail threshold
- Limited traceability
- Reduced opportunity for data analysis
- High dependence on specialist skill

These factors reduce repeatability and make it difficult to operate the process as a robust manufacturing quality control system (Montgomery, 2009).



Figure 3- Current process document for the NVH detection process (Aston Martin, 2026)

1.4 Potential Future Approaches

1.4.1 Enhancing Proving-Ground Test

Retain the current proving-ground route while introducing objective measurement technology. This approach would incorporate binaural microphones, automated data acquisition software, and pass/fail thresholds based on reference vehicle data.

1.4.2 Rig-Based Excitation Testing

Replace or supplement the proving-ground route with a dedicated vehicle excitation rig capable of simulating road induced vehicle inputs under control conditions.

Such a system could use hydraulic actuators, shaker tables, or wheel excitation platforms to reproduce road surfaces and suspension inputs while acoustic and vibration measurements are recorded. Compared with proving-ground testing, a rig-based solution may offer:

- Improved repeatability
- Reduced dependency on weather conditions
- Controlled cycle time
- Easier automation and data integration
- Safe indoor testing environment

However, Rig based systems may involve high capital investment, facility space requirements, additional maintenance, and challenges in fully replicating real-world customer operating conditions.

As a result, this project considers both enhancement of the current proving-ground method and the longer-term feasibility of rig-based alternatives.

1.5 Why the Project Matters

The central issue is not whether skilled technicians can detect some vehicle noise concerns. It is whether the existing process is sufficiently objective, repeatable, and scalable to protect quality consistently across all vehicles.

Process variation therefore creates risk to both customer satisfaction and brand perception. A premium customer expects every vehicle to deliver consistent refinement, not only vehicles assessed by the most experienced technician. Variability in NVH quality therefore creates a direct risk to customer satisfaction and brand perception (Kotle, et al., 2016).

From an operational perspective, the current subjective process may also create inefficiencies, including:

- Ambiguous borderline decisions
- Repeated proving-ground tests
- Delayed fault escalation
- Weak trend data for continuous improvement
- Over-reliance on a limited number of experienced operators

For these reasons improving the current NVH detection process offers both quality and manufacturing benefits.

1.6 Aim of the Project

The aim of this project is to investigate an objective and repeatable NVH detection process for overall vehicle noise within automotive manufacturing, while assessing the suitability of proving-ground enhancement and rig-based excitation testing as future solutions.

1.7 Objectives

1. To review the principles of automotive NVH and their relationship to perceived vehicle quality
2. To evaluate the current subjective proving-ground NVH detection process
3. To identify causes of variation and limitations within the existing system
4. To review objective NVH measurement technologies suitable for production use
5. To assess the feasibility of rig-based excitation testing as an alternative or supplementary solution

6. To apply DMAIC methodology to improve the current process
7. To propose a practical implementation strategy with minimal disruption to production
8. To define the control required to sustain long-term process performance.

1.8 Scope of the Project

The study focuses on overall vehicle noise detection during EOL manufacturing inspection. It does not seek to redesign the vehicle or fully resolve detailed engineering root causes of every NVH concern. Instead, the emphasis is placed on improving the manufacturing detection process so that abnormal vehicle noise can be identified more consistently and efficiently before release.

The project considers technology selection, process integration, measurement system capability, standards, health and safety, stakeholder management, and long-term control requirements.

1.9 Report Structure

The dissertation is structured around the DMAIC improvement methodology, commonly used within Six Sigma projects. Following the introduction and literature review, the project progresses through the Define, Measure, Improve, and Control phases shown in Figure 4 to investigate the current process and develop an improved, objective NVH detection system (Bhargava & Gaur, 2021).

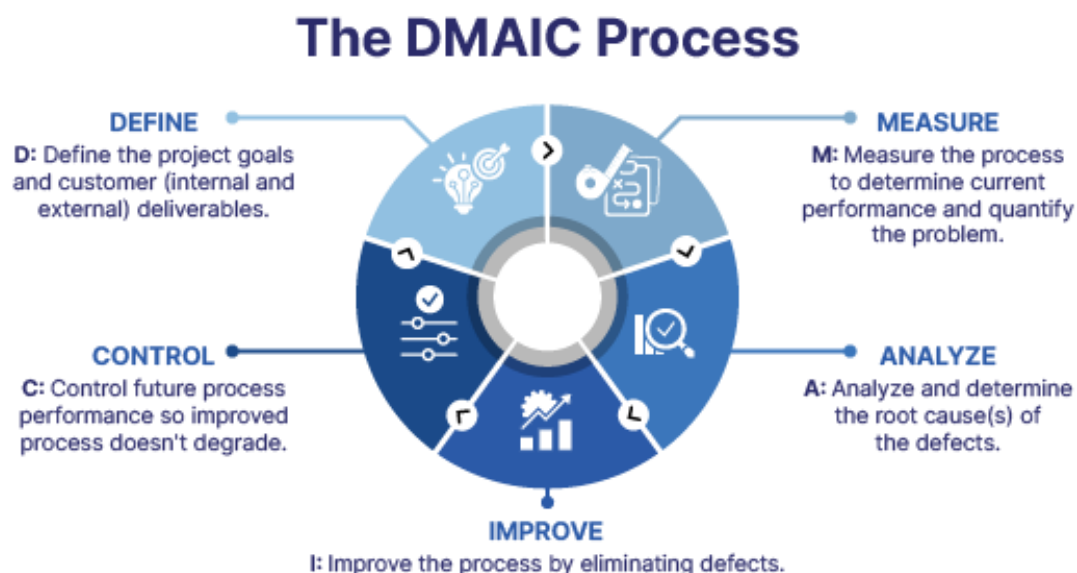


Figure 4- The DMAIC process (Six Sigma Online, 2025)

2 Literature Review

Noise, Vibration and Harshness is a fundamental area of automotive engineering concerned with the generation, transmission and perception of unwanted sound and vibration within a vehicle. Although NVH is commonly associated with product development, it is also highly relevant during vehicle manufacturing, where small variations in build quality or component fitment can create unwanted noise issues (Heisler, 2002).

2.1 Fundamentals of Automotive NVH

NVH behaviour is commonly explained using the source-transfer-path-receiver model. In this framework, noise or vibration originates from one or more excitation sources, travels through structural or airborne paths before being perceived by the vehicle occupant. This is important for manufacturing inspection because NVH problems may arise from small build variations rather than design faults. Therefore, the production quality system must be capable of identifying abnormal acoustic behaviour caused by assembly variation, trim fit, fastener condition, or component tolerance, see Figure 5 (Masri, et al., 2024) (Panza, 2015).

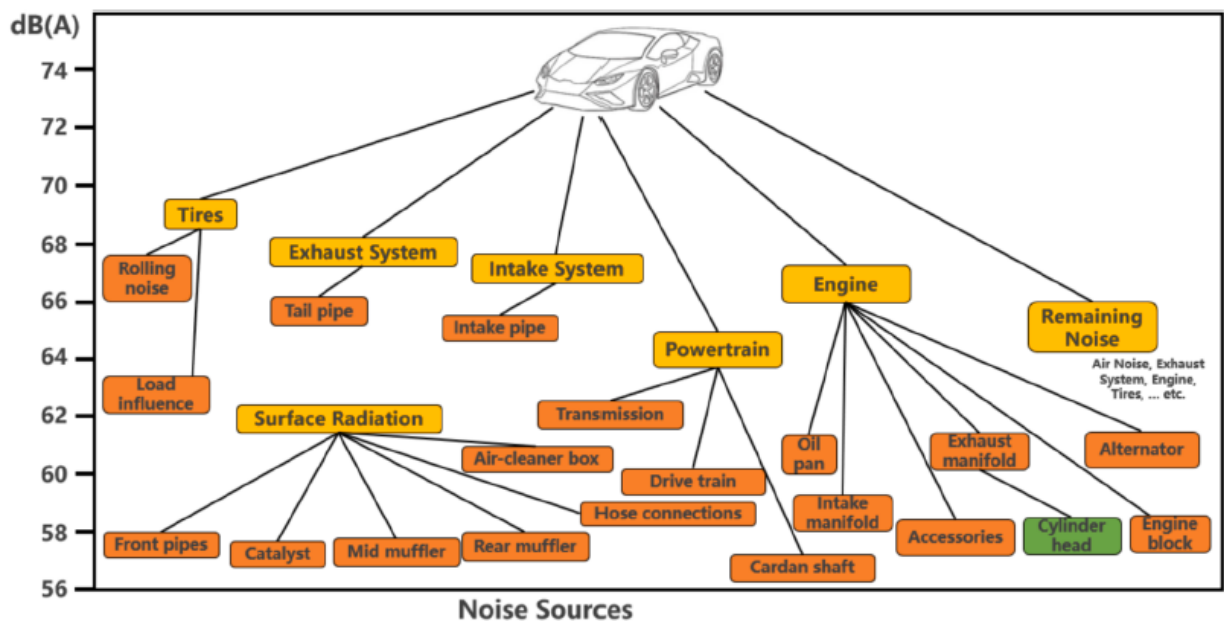


Figure 5-Vehicle noise source ranking during a pass-by noise test (Masri, et al., 2024)

2.1.1 Noise Sources

In modern premium vehicles, improvements in engine and powertrain refinement have reduced traditional dominant noise sources, increasing the relative significance of secondary noises including road noise, trim squeaks, and rattles. Panza (2015) notes that as powertrain noise has been reduced over time, other sources including road noise have become more prominent, while squeaks and rattles arise from dynamic movement of dashboard and

interior trim interfaces. This has increased the importance of interior NVH quality for manufacturers.

2.1.2 Structure-Borne and Airborne Noise

Vehicle NVH issues are often categorised into two main transmission mechanisms:

Structure-borne noise- Occurs when mechanical vibration is transmitted through the chassis, body, or components before radiating as sound into the passenger cabin. Typical examples include suspension excitation from road inputs, engine vibrations, and movement of loose or insufficiently secured components. (Mohanty, et al., 2000) note that in automotive applications, structure borne noise is predominant at lower frequencies, particularly below approximately 250 Hz.

Airborne Noise- Airborne noise, in contrast, is transmitted through the air and is typically associated with aerodynamic effects, airflow around the vehicle body, and acoustic radiation from vibrating surfaces. Interior trim components and cabin air cavities can contribute to airborne noise through resonance effects. Airborne noise becomes more dominant at higher frequencies (Panza, 2015).

At lower frequencies, structure-borne noise tends to dominate, while higher frequency behaviour is more strongly influenced by airborne transmission.

2.1.3 Customer Perception

The importance of NVH extends beyond engineering measurement. Customers interpret sound quality as an indicator of craftsmanship, comfort, and product maturity. Research indicates that occupants often assess perceived quality through NVH performance, more so within premium market segments (Masri, et al., 2024). Consequently, a vehicle that exhibits rattle, squeaks or inconsistent refinement may be judged negatively even when all functional mechanical systems operate correctly (Dowsett, et al., 2016).

2.2 Subjective NVH Detection Methods

2.2.1 Advantages of Subjective Methods

Subjective NVH assessment remains valuable as technicians evaluate vehicles under realistic operating conditions and can identify transient noises that may not be captured through instrumentation alone. These approaches also align closely with customer-perceived sound quality and typically require minimal specialist equipment and can be deployed quickly within production road test environments. Experienced technicians are often able to identify subtle squeaks, rattles, tonal disturbances, or intermittent noises that may be difficult to capture through conventional instrumentation alone. Technician-based assessment remains

a crucial element of NVH evaluation despite advances in objective measurement systems (Masri, et al., 2024) (Thompson, 2011).

2.2.2 Limitations of Subjective Methods

While technician-based NVH evaluation can be effective for detecting obvious vehicle noise issues, subjective inspection methods introduce several limitations within manufacturing environments.

Firstly, human perception of sound varies between individuals. Operator-dependent assessment introduces measurement variation between inspections. Variability can lead to inconsistent inspection outcomes between vehicles. Research into variability suggests that vehicle acoustic response and measurement outcomes can vary even when vehicles are nominally similar. This supports the concern that a technician-led process may introduce additional variation because the measurement system depends on hearing sensitivity, judgment, and interpretation. In a production environment, this creates risk because pass/fail decisions must be repeatable across operators, shifts and vehicle variants (Dowsett, et al., 2016) (Hills, et al., 2009).

Secondly, environmental factors such as background noise, weather conditions, and external disturbances may influence the technician's ability to accurately detect abnormal sound during testing.

Additionally, subjective NVH inspection provides limited quantitative data that can be used for analysis or comparison across multiple vehicles. Without measurable data, it is difficult to establish repeatable acceptance criteria for vehicle noise performance.

Montgomery (2009) states that processes lacking measurable outputs are more difficult to control statistically and improve systematically.

2.3 Objective NVH Measurement Technologies

Objective systems use sensors and signal processing methods to quantify vehicle noise and vibration. These systems provide measurable outputs that can be stored, compared, and used for pass/fail logic.

2.3.1 Acoustic Cameras

Acoustic cameras are advanced measurement systems that use arrays of microphones to visualise sound sources in real-time. These systems can provide spatial mapping of noise sources, making them useful for identifying the locations of NVH issues.

Two types of acoustic cameras were considered: 2D and 3D systems.

2D cameras are limited in their ability to distinguish between front and rear noise sources, which reduces their effectiveness in complex vehicle environments, the approximate cost for 2D camera is £30,000. A 3D acoustic camera system offers improved spatial resolution and can provide more accurate localisation of noise source. The approximate cost of 3D camera is £120,000 plus cost of software development.

Modern systems provide high resolution acoustic imaging capabilities and can operate over a wide frequency range. For example, microphone array systems can map acoustic source frequencies from approximately 200 Hz to 20 kHz depending on configuration.

However, several limitations have been identified.

Research has shown that acoustic camera systems have limitations related to spatial resolution and signal processing. The use of beamforming techniques introduces artefacts. Side lobes, which can affect the accuracy of sound source localisation (Kudriashov, et al., 2016). Although acoustic cameras provide strong diagnostic value, their suitability for routine EOL inspection is limited. Vehicle cabins contain reflective surfaces, complex geometries, and multiple potential sound paths, which can reduce localisation accuracy. Therefore, acoustic cameras are better suited to detailed engineering investigation than high-throughput production screening (Chiariotti, et al., 2018)

Acoustic camera systems are typically used in research and development environments rather than production. They are relatively expensive, with high-end systems costing in the region of £100,000, these systems require substantial development and integration effort to be used effectively within a production environment.

Miljko(2011) analytically evaluates acoustic cameras as array signal processing systems, showing that performance depends on wave modelling, array design, and processing methods. It highlights that near-field beamforming enables accurate source localisation and true sound level estimation, while far-field beamforming only provides direction information. It also identifies key trade-offs between resolution, ambiguity, and side-lobe interference, demonstrating that techniques like NAH and beamforming are complementary but limited by practical factors such as microphone spacing, array geometry, and frequency range.



Figure 6--Acoustic Camera Array Sphere120 AC Pro (GFAI tech, 2026)

Modern acoustic camera systems provide high-resolution sound-source localisation using multi-channel microphone arrays, example shown in Figure 6 and 8 (GFAI tech, 2026), enabling detailed three- dimensional acoustic mapping. The system operates in conjunction with specialist software with noise imaging, Figure 7 which enables a sound source to be isolated and analysed in both the time and frequency domains.



Figure 7-Noise Image Analysis Software for Acoustic Imaging Beamforming 3D (GFAI tech, 2026)



Figure 8-Acoustic camera used in a vehicle for interior testing (GFAI tech, 2026)

Another limitation is their performance within vehicle interiors. Reflective surfaces within the cabin can interfere with acoustic measurements, making it difficult to accurately identify noise sources. Furthermore, acoustic camera can only detect surface noise and cannot identify internal source of components located behind trim panels.

Although acoustic camera systems provide excellent diagnostic resolution, their suitability for Aston Martin's manufacturing environment is limited by throughput constraints, setup complexity, and cost. Within a low-volume production environment, rapid deployment and minimal operator disruption are critical requirements. Therefore, despite their strong engineering capability, acoustic cameras are more suitable as secondary diagnostic tools rather than primary EOL inspection systems.

2.3.2 Particle Velocity and Microflown Technology

Particle velocity represents the oscillatory motion of air particles in a sound field and, when combined with sound pressure, enables calculation of sound intensity (energy flow).

Microflown technology provides a direct measurement of this quantity using micromachined heated sensors, overcoming limitations of traditional pressure-based techniques and enabling more accurate near-field acoustic analysis and source localisation (De Bree, 2003).

Unlike traditional acoustic cameras, Microflown sensors measure both sound pressure and tri-axle particle velocity, allowing direct calculation of sound intensity.

This enables:

- Accurate localisation of sound sources
- Measurement across a broad frequency range (20 Hz- 10 kHz)
- High speed spatial resolution (down to three millimetres)

A key advantage of this technology is the ability to operate effectively in a non-anechoic environment. Vehicle interiors for example, where traditional acoustic methods struggle due to reflections.

Microflown sensors are particularly effective for identifying specific noise sources and can be considered as a “sniffer” tool for detailed NVH diagnostics.

However, like acoustic cameras, these sensors are more suited to diagnostic applications rather than full vehicle testing. Their use within a production environment would likely be limited to targeted investigations of identified issues rather than continuous NVH monitoring. Approximate cost £15,000-£20,000.

2.3.3 Binaural Measurements System

Binaural measurement systems are designed to replicate human hearing by using microphones positioned at the ears of a dummy head or worn by a test operator. These systems are widely used in NVH research and development to capture realistic acoustic data from the driver’s perspective.

In this application, a binaural dummy head including two microphones illustrated in Figure 9 or headset worn by the driver during the proving-ground test can capture acoustic data that

closely represents human perception. The system can record sound pressure levels, frequency content, and buzz, squeak, and rattle (BSR) characteristics.



Figure 9-Binaural microphone (Audiocube, 2026)

This approach provides a balance between objectivity and practicality, making it well suited to supplement the current process. This makes binaural systems highly suitable for production environments, where customer-perceived cabin sound quality is important (Genuit & Poggenburg, 1999).

Binaural measurement is more suitable for this project than a fixed microphone or acoustic camera alone because it captures sound at the approximate ear position of the driver. This improves alignment between objective measurement and customer-perceived cabin sound quality. However, it does not fully remove subjectivity because threshold setting requires expert judgment and validation against acceptable reference vehicles (Fajersson & Wikner, 2008). The approximate cost £15,000 plus a microphone mount development is required. This could be 3D printed internally.

2.3.4 Data Acquisition and Analysis System

Data acquisition systems are essential for capturing and processing NVH signals. These systems can record data from multiple sensors and perform real-time analysis.

Modern systems can perform frequency analysis, calculate sound pressure levels, and identify vibration characteristics. The integration of such systems with user-friendly software allow operators to perform tests with minimal training.

Additionally, these systems can be integrated with production databases, enabling long-term tracking of NVH performance across multiple vehicles.

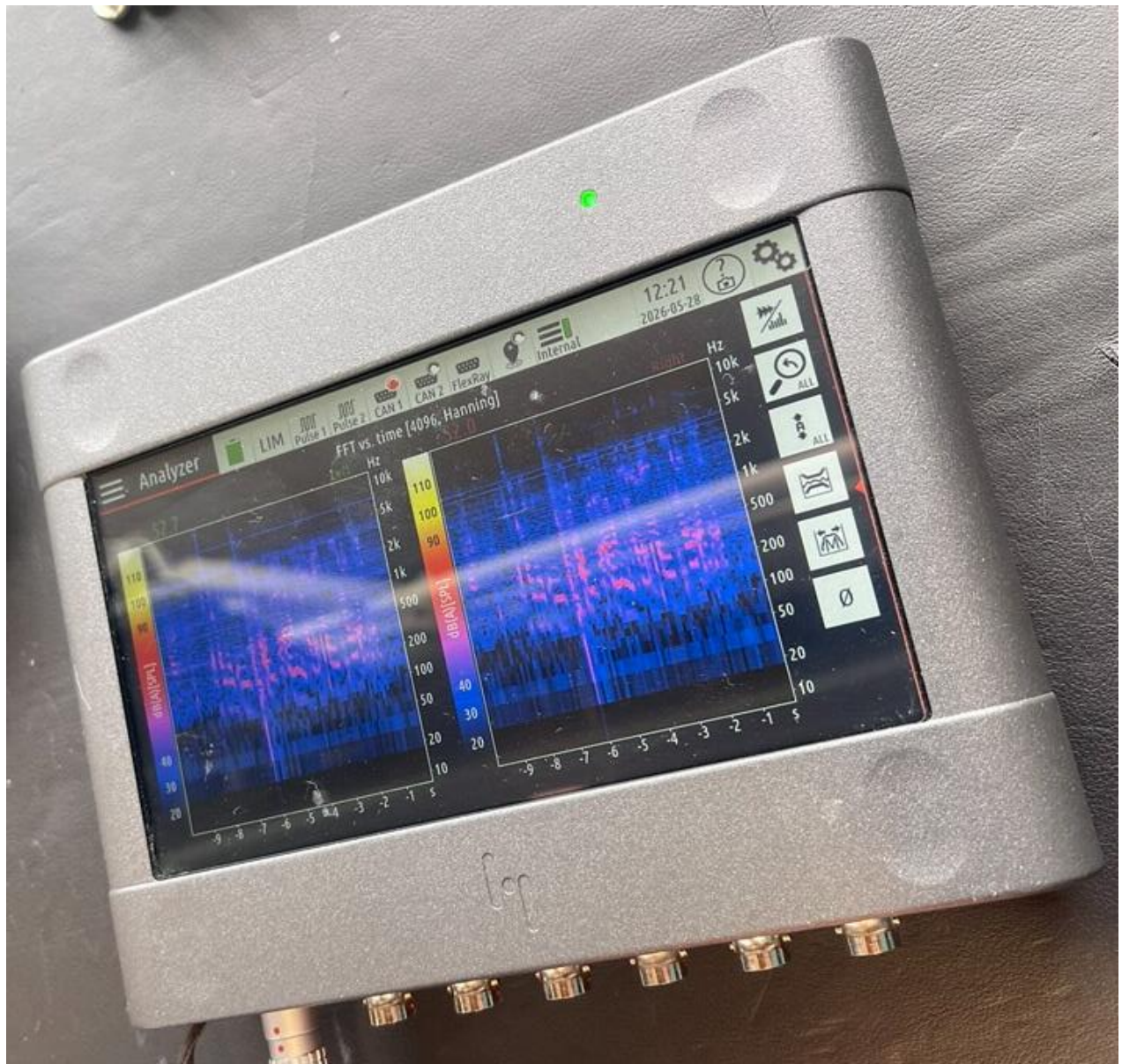


Figure 10-Head acoustic demonstration of binaural equipment.

A demonstration was carried out during an organised visit by HEAD acoustic of the binaural measuring device, Figure 10. The system scales and filters various sound frequencies to recording. Using this feature enables the development of a pass/fail criterion when thresholds are set. A feature that is key to the implementation of the objective test required at Aston Martin.

2.4 Rig-Based Excitation testing.

Rig-based excitation is widely used within automotive research and development to reproduce road-induced vehicle inputs under controlled laboratory conditions. Unlike proving-ground road testing, excitation rigs apply repeatable forces directly to the vehicle through hydraulic actuators, shaker tables, or wheel-mounted input systems. This allows suspension movements, body response, and cabin acoustic behaviour to be analysed with greater repeatability and control than on-road testing, where environmental and surface variability can influence results (Cvok, et al., 2021).

Rig-based systems present significant implementation challenges, the capital cost of purchasing and installing a vehicle excitation rig is significant. Additional costs may include:

- Building modifications
- Hydraulic and electrical infrastructure
- Maintenance contracts
- Calibration requirements
- Operator training
- Disruption to production during install.

Secondly, while rigs can reproduce many suspension and wheel inputs in a repeatable environment, they may not fully represent all customer driving conditions. Complex transient events, steering inputs, tyre-road surface interactions, and environmental influences, where wind and changing temperatures can be difficult to reproduce with complete accuracy, meaning correlation with road validation remains important (Masri, et al., 2024).

Thirdly, Production throughput must be considered. If rig loading, unloading, setup, or test duration exceeds the current routine, the system may create a manufacturing bottleneck or add the requirement for additional resource. A time study of the proposed new process should also be carried out and costed.

Rig-based excitation offers a stronger controlled measurement environment than outdoor proving-ground testing because inputs can be repeated under laboratory conditions, However, the main limitation is correlation with real customer driving conditions. Road inputs include tyre-road interaction, steering behaviour, transient events, and environmental effects that may not be fully reproduced on a rig. This creates a trade-off between repeatability and real-world representativeness (Cvok, et al., 2021).

Should the rig-based solution meet the business throughput requirements, it is more suitable for a future long-term strategy, validation tool for production issues, a secondary

confirmation process or a quality audit station in Aston Martin, the customer perception audit (CPA) where a more thorough inspection and validation process is carried out.

Within this project, rig-based excitation testing is therefore considered a strategically valuable alternative, but one that requires greater investment and feasibility assessment than an enhanced proving-ground objective measurement solution.

Figure 11 illustrates an example of available shaker rig with the following specification:

- Two shakers to fully represent drive conditions: twist, dual axis etc.
- Near silent shakers (1 sone) for Road Load Data.
- Able to replicate all durability tests up to 15m/s^2 .
- Shakers on moveable air caster base, easily configurable.
- Total cost: € 298,410 (plus delivery)



Ziegler / MB dynamics

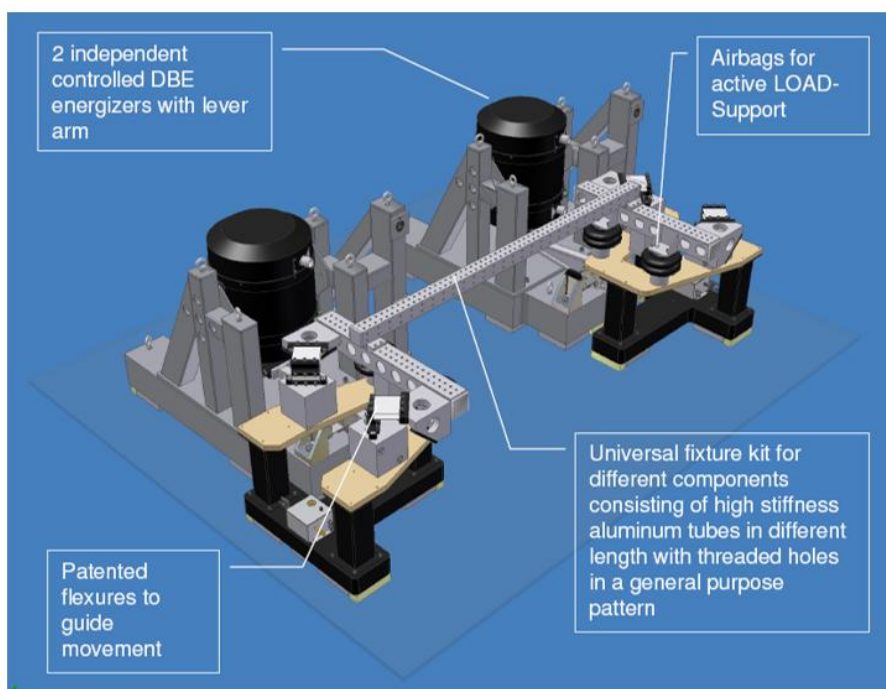


Figure 11-Ziegler/MB dynamics Shaker Rig (Aston Martin, 2026)

2.5 Technology Review

Although laboratory-based NVH testing systems such as shaker rigs and chassis dynamometers offer high levels of repeatability and environmental control, their ability to accurately reproduce complex real-world aerodynamic and transient acoustic conditions remains limited. This creates a trade-off between measurement consistency and operational

representativeness. Highly controlled laboratory environments reduce external variability and improve data repeatability; however, they may not fully capture the interaction between airflow, vehicle body geometry, trim components, and road-induced excitation experienced during actual driving conditions.

Conversely, subjective road testing provides high levels of real-world realism but introduces substantial variability due to environmental conditions, technician judgment, and inconsistent operating parameters. Within the Aston Martin manufacturing environment, the proposed acoustic camera approach offers a more balanced solution by combining objective measurement capability with relatively high deployment flexibility and shorter testing duration compared with large-scale laboratory systems. This improves suitability for end-of-line manufacturing integration while still maintaining sufficient diagnostic capability for rapid fault localisation.

A technology comparison Table 1 was created to highlight advantages, limitations, and manufacturing suitability.

Table 1-Technology comparison (Purnell-Whitehead, 2026)

Technology	Advantages	Limitations	Manufacturing Suitability
Subjective technician assessment	Fast, flexible, low cost	Inconsistent, non-repeatable	Moderate
Chassis dynamometer	Controlled conditions	Expensive, low throughput	Low
Shaker rig testing	High repeatability	Poor real-world representation	Low
Acoustic camera	Fast localisation, visual output	Sensitive to environment	High
Traditional microphones	Simple and cheap	Poor localisation	Moderate

2.6 DMAIC Methodology

Several improvement technologies were considered, including PDCA, Kaizen and lean problem-solving models, however, DMAIC was selected because it is specifically designed for improving existing processes where variation, inconsistency and poor measurement systems are key concerns (Sharma, et al., 2018).

The current NVH inspection process contains all three of these characteristics. DMAIC provides a structured framework to address these issues through sequential phases, Figure 12.

DMAIC is appropriate for this project because the problem is not the absence of test, but variation within the existing inspection process. The current NVH process already detects some concerns, but it lacks measurable outputs, repeatability, and traceability. DMAIC therefore supports the transition from a judgment- based inspection method to a controlled measurement system (Monday, 2022).

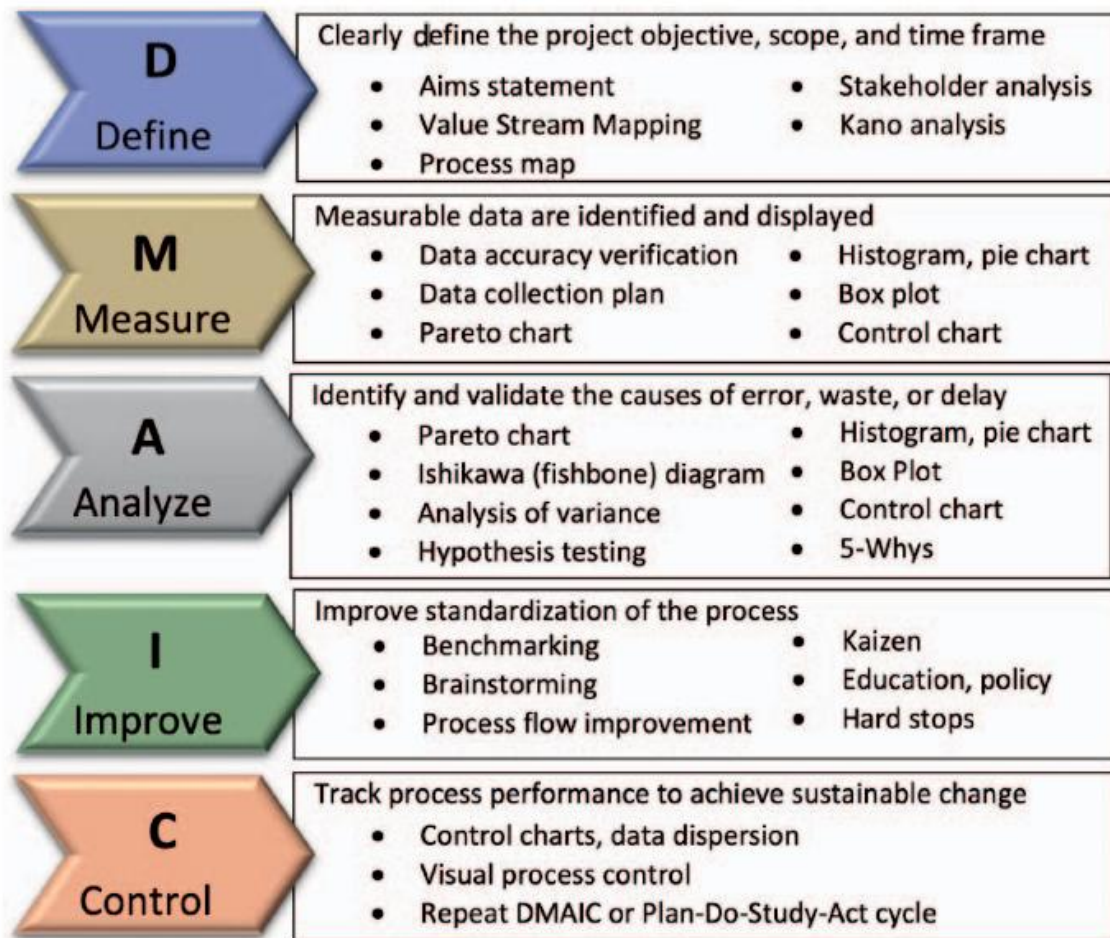


Figure 12-DMAIC methodology and process tools (Monday, 2022)

3 Define

3.1 Problem Statement

During the current process, a trained operator drives the vehicle over a predefined route containing multiple road surfaces intended to excite potential cabin noise concerns. The technician then determines whether the vehicle is acceptable or whether further investigation is required.

Several limitations were identified:

- Pass/fail decisions are based largely on subjective perception.
- No acoustic or vibration data is formally recorded.
- No standard measurable threshold is used.
- Results may vary between technicians or shifts.
- Borderline vehicles may require repeated evaluation.
- Limited traceability exists for quality decisions.

3.2 Voice of the Customer (VOC)

Voice of the customer (VOC) is used within Six Sigma projects to translate customer expectations into measurable process requirements. For this project, VOC was interpreted from customer perceptions through surveys, Figure 13, aftersales concerns, and brand expectations for the quality delivery of the vehicle. The vehicle confirmation department's requirements are also considered as the owner of the current and new proposed process (George, et al., 2005).

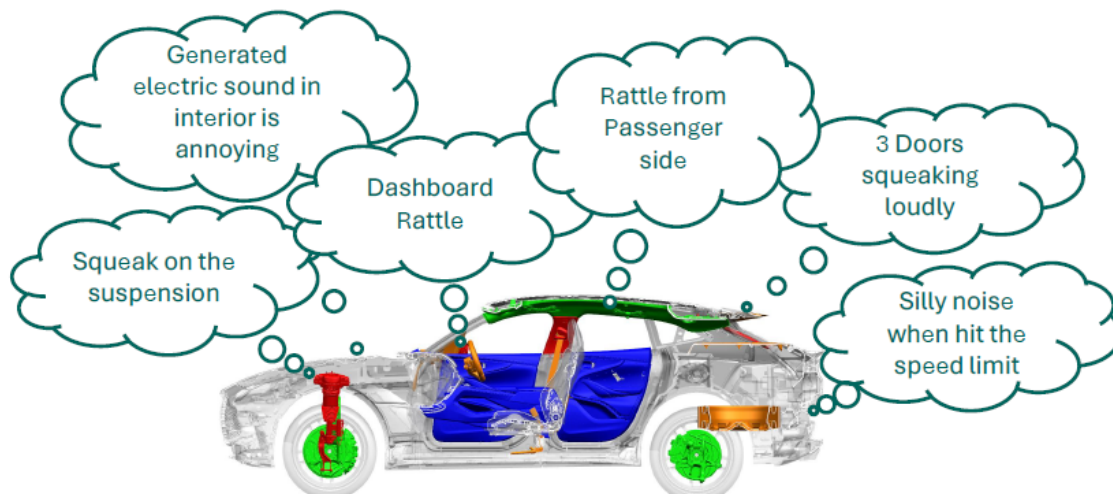


Figure 13- Aston Martin Customer Survey (Yasuda, 2026)

Field data gives an example of issues affecting customers shown in Figure 14.


Warranty Claim
WCN-2439273


Summary


Customer reported a rattle from the dash. The issue was traced to the right corner of the instrument cluster. The panel was re-glued and rebuilt. After road testing, the rattle was resolved. Technical PDR-030220 confirms the correction.


Extended Summary


The causal part identified was the SY83-045F56-CB, with the failure mode classified as Loose / Not Fully Connected.

The customer reported a rattle coming from the dashboard area. The technician investigated and confirmed the rattle was coming from the right-hand corner of the instrument cluster (IC). Upon removing the IC, the technician discovered that the hot glue securing the component had failed. The technician re-glued the IC panel, rebuilt the assembly, and performed a road test to ensure the issue was resolved. The rattle did not recur, and the repair was deemed successful.

No parts have been claimed yet for this warranty claim.

Figure 14-Example Warranty claim (Aftersales, 2026)

3.3 Critical to Quality (CTQ) Requirements

Critical to quality analysis converts vague customer comments into clear, measurable requirements that can be acted upon. Customers often express their needs in broad or imprecise terms, making direct implementation difficult. This process helps translate those general statements into specific functional requirements, improving the organisation's ability to deliver products or services that consistently meet or exceed expectations (George, et al., 2005).

The VOC requirements gathered from the CSI survey were converted into the following Critical to Quality (CTQ) characteristics shown in Table 2:

Table 2-Critical to quality gathered from VOC and internal questionnaire (Purnell-Whitehead, 2026)

Customer Need	CTQ Requirements
Quiet Cabin	Acceptable sound pressure level
Premium refinement	Stable acoustic quality
No rattles	No abnormal transient events
Consistency	Standard pass/fail criteria
Reliability	Low NVH-related warranty return rate
Seamless integration with current system	Minimal change to current test
User friendly interface	Minimal training required for end user
Minimal disruption to production	Protect volume loss
Health and safety compliance	Safe working process
Improved test efficiency	Minimise if any additional process time
Accurate and repeatable test	High quality standards

These CTQs help define what the improved process must achieve.

3.4 Stakeholder Analysis

A detailed stakeholder analysis is critical to successful delivery of the NVH project. Successful implementation depends on coordination between manufacturing, quality, NVH engineering, maintenance, and IT functions. This process also strengthens change management, supports efficient resource allocation, and helps achieve the wider strategic objectives of the project. The following identifies the key stakeholders involved and outlines their roles and contributions (Aaltonen, 2011).

Project Lead-Responsible for coordinating the project and ensuring all stakeholders are aligned to ensure the successful delivery of the project.

NVH Engineers- Responsible for the measurement quality, diagnostic value and defining the required measurement parameters.

Quality Team- Ensuring traceability and repeatability are met.

Maintenance- Responsible for safe installation and continued control of the assets.

Health and Safety- Ensures the new process is compliant with health and safety regulations and a safe working environment during installation.

IT Department- Installation of the required network connectivity is available and the integration of test results to the current quality reporting software.

Technicians- As the end users, their feedback on the new process is critical to the testing functionality and usability of the new process.

3.5 SIPOC Analysis

A SIPOC model was used to define the current process at a high level, Table 3.

Table 3-SIPOC analysis (Purnell-Whitehead, 2026)

Suppliers	Inputs	Process	Outputs	Customers
Production Line	Completed vehicle	Proving-ground route	Pass / Fail decision	Customer
Quality Team	Test route standard	Technician evaluation	Rework request	Quality
NVH Team	Quality criteria	Final release decision	Released vehicle	Dealer

3.6 Risk of Not Improving the Process

If no improvements are made, several risks remain:

- Continued dependence on specialist operator skill
- Inconsistent quality decisions
- Higher likelihood of escaped NVH issues
- Reduced learning from production data
- Increased warranty costs
- Limited scalability as production demands change
- Reputation damage
- Increased risk of buy-back.

This further strengthens the justification for process improvement.

3.7 Project Charter

The project charter Table 4 outlines the project. Detailing who, what, and why the project is taking place and outlines the targets set out, risks involved, and what support is required.

Table 4-Project Charter

Project Name	<i>NVH detection automation</i>	Business / Location	St Athan
Engineer	<i>Shea Purnell-Whitehead</i>	Telephone Number	<i>07386687717</i>
Start Date:	<i>12/12/2025</i>	Target End Date:	<i>12/07/2026</i>
Project Details			
Project Description	Investigate objective testing methods or NVH.		
Business Case	To help reduce warranty cost in field, reduce internal rework costs and improve vehicle quality.		
Process/Part and Owner	Road test		
Expected Business Results	Reduction in warranty and internal rework costs. More objective, repeatable and measurable testing		
Expected Customer Benefits	Vehicle quality improvement, Enhanced data capture		
Team members	Phill Moreton, Luke Evans, Shea Purnell-Whitehead, Adrian Payne, Lloyd Pemberton		
Support Required	CME dept, NVH engineering team, Production dept		
Risks or Constraints	Production disruption, cost of improvements		

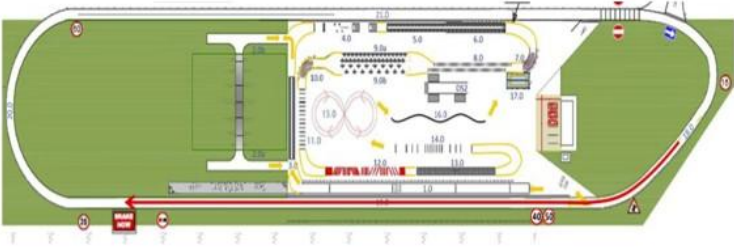
4 Measure

For this project, the measure phase focuses on the present EOL NVH detection process. The chapter evaluates the current process cycle time, decision methods, repeatability concerns, data limitations, and potential measurement system weaknesses.

The objective of this phase is to convert an experienced based inspection process into a measurable baseline against which future improvements can be assessed.

4.1 Current Process Description

The current NVH detection is included as part of the road test process carried out in the vehicle confirmation department. The vehicle is driven by a trained technician at the proving-ground over a predefined route designed to excite potential noise sources including trim movement, suspension input, tyre interaction, and body response. Route shown in Figure

ASTON MARTIN		Desc	PSS AM800 29328	Released	George Griffiths	ID	22629
		Rev#	1				
		Status	Released, 11/1/2024				
							
Step:	Key point loop	Key point / why:					
Road Test – Road Circuit Technician is to start to accelerate to 40mph at the junction. Technician to brake from 40mph to 25mph at the "Brake now" sign before entering PL corner.		Technician to listen for high frequency squeaks and rattles whilst driving on the ISO noise generating surface. Technician to check the DIM for sign recognition. Technicians to take care in adverse weather conditions, whilst maintaining at least 20m (4 car lengths) behind other cars on the outer circuit.					
 Safety		 Quality	 Critical	 Knock	 Environment	 Sequence	3

15. TEMPLATE Issue 8 - 10/11/2018

Figure 15-EASE-Process instruction (Griffiths, 2024)

The route contains multiple surface conditions intended to excite potential NVH concerns. At the end of the route, the technician makes one of three practical decisions. To accept/pass, concern identified that will require rework or unclear which could result in retest or second opinion. There is no formal acoustic recording system currently used during the test.

ViewEASE

EASEworks version 7

VAC

PREVIOUS

SEARCH

NEXT

STATION SUMMARY

LINE SUMMARY

PREVIOUS STATION

NEXT STATION

ORDER PARTS

REPORTS

ABOUT

HELP

BACK

CLOSE

Welcome! [Log out](#)

Operation Header

Area Number

Station Number

Status

Released Date

Crew Size

PF/D% Run

PF/D % Set Up

Number of Analysis Lines

ZZZZ2023 - VC : AMS V2

5100-1

Released REV# 2

0

1

0

0

Description

Engineer

Work Center

Planned Run

Planned Set Up

Road Test Re-Work

George Griffiths

Off Tracks

0

1

Build Number

Body

Drive

Gear Box

Filter

Vin Number

Model

Territory

Vehicle Colour

⌚ Time

Set Up - Mins

0.00000

Run - Hours

0.01417

Sub header	Ref#	Options	Run Hrs	Setup Hrs	
Station Tooling			0.00000	0.00000	Process Document
EASE login	122801		0.00833	0.00000	Elements
Connect Deutronic battery support	475		0.00583	0.00000	Ref Docs
Suspension/Steering Wheel - Safety Check	21568		0.00000	0.00000	Graphics
Under Bonnet Inspection Process	27246		0.00000	0.00000	Video
Underbody Checks - Wheel Fixings	21270		0.00000	0.00000	Tooling
Prep For Road Test	21287		0.00000	0.00000	Parts
Wheel Damage Check	21563		0.00000	0.00000	Notes
Road Test	21288		0.00000	0.00000	Change History
Road Test - Brake Straight	29312		0.00000	0.00000	Station Docs
Road Test - Hill Climb	29313		0.00000	0.00000	RFC
Road Test - Washboard	29314		0.00000	0.00000	StationS SUMMARY
Road Test - Speed Bumps	29315		0.00000	0.00000	Search
Road Test - Belgium Blocks	29316		0.00000	0.00000	
Road Test - RHS Twist and Turn	29317		0.00000	0.00000	
Road Test - Out of Phase Sine Wave	29318		0.00000	0.00000	
Road Test - LWB Pyramids	23919		0.00000	0.00000	
Road Test - LHS Twist and Turn	29320		0.00000	0.00000	
Road Test - Angle Irons	29321		0.00000	0.00000	
Road Test - Ropes	29322		0.00000	0.00000	

Figure 16-Ease-Road test process steps (Griffiths, 2024)

The NVH detection forms only part of the road test process. Recently, due to restructuring and workforce reduction. The road test technicians are now responsible to guide the vehicle through all attribute test in the confirmation process. The process includes WAHA (Wheel Alignment Headlight Aim), Rolling Road, Camera set, Wind noise, Road test, and Water test Figure 16.

4.2 Baseline Cycle Time Measurement

The Manufacturing business office are responsible for the carrying out time studies of all processes throughout production. Figure 17 & Table 5 is a detail study to each process step. Highlighted are the NVH detection aspects of the test.

Work Analysis Sheet												
Area:		Derivative:								Date of Study:		
Workstation:		Op Number: Various										
Op Description:			Video Time Non-Decimal		Decimal Time			Frequency			Observed	
Element No	Op No	Element Details	Sta	Fin	Cod	Rati	Time	Multi	Divi	V	ENV	NVA
1	36273	Raise car on the ramp	0.00	0.22	n	85	0.37	1	1	0.00	0.00	0.37
2	21568	Inspect RHS front alloy/wheel	0.22	0.54	n	100	0.53	1	1	0.00	0.00	0.53
3	21568	Spin RHS front wheel	0.54	0.57	n	100	0.05	1	1	0.00	0.00	0.05
4		Inspect RHS front wheel arch	0.57	1.13	w		0.27	1	1	0.00	0.00	
5	21568	Inspect/Touch RHS front wheel structure/connections	1.13	1.32	n	100	0.32	1	1	0.00	0.00	0.32
6	21568	Move to LHS rear	1.32	1.35	n	80	0.05	1	1	0.00	0.00	0.05
7	21568	Inspect RHS rear alloy/wheel	1.35	2.13	n	80	0.63	1	1	0.00	0.00	0.63
8	21568	Spin RHS rear wheel	2.13	2.16	n	100	0.05	1	1	0.00	0.00	0.05
9		Inspect RHS rear wheel arch	2.16	2.33	w		0.28	1	1	0.00	0.00	
10		Bang/tap all areas of rear bumper with hand	2.33	2.50	w		0.28	1	1	0.00	0.00	
11	21568	Inspect LHS rear alloy/wheel	2.50	3.20	n	100	0.50	1	1	0.00	0.00	0.50
12	21568	Spin LHS rear wheel	3.20	3.24	n	100	0.07	1	1	0.00	0.00	0.07
13		re inspect wheel	3.24	3.31	w		0.12	1	1	0.00	0.00	
14		Inspect LHS rear wheel arch	3.31	3.45	w		0.23	1	1	0.00	0.00	
15	21568	Walk to LHS front	3.45	3.48	n	80	0.05	1	1	0.00	0.00	0.05
16	21568	Inspect LHS front alloy/wheel	3.48	4.24	n	80	0.60	1	1	0.00	0.00	0.60
17		Inspect LHS front wheel arch	4.24	4.45	w		0.35	1	1	0.00	0.00	
18	21568	Split LHS front wheel	4.45	4.48	n	100	0.05	1	1	0.00	0.00	0.05
19		re inspect wheel	4.48	4.59	w		0.18	1	1	0.00	0.00	
20	21568	Inspect/Touch LHS front wheel structure/connections	4.59	5.17	n	100	0.30	1	1	0.00	0.00	0.30
21		Bang/tap all areas of front bumper and inspect with torch	5.17	5.40	w	100	0.38	1	1	0.00	0.00	

Figure 17-Work Analysis Sheet (Seldon, 2026)

Table 5-Road test Time Study

Op	St Athan T&F Description	VA	ENVA	NVA	Total	Combined	Average
36273	Drive car onto ramp and raise	0.00	0.00	0.61	0.61		0.61
21568	Suspension/Steering Wheel - Safety Check	0.00	0.00	2.93	2.93		2.93
21270	Underbody Checks - Wheel Fixings	0.00	0.00	5.33	5.33		5.33
36279	Paperwork	0.00	0.00	0.96	0.96		0.96
No op 2	Lower ramp	0.00	0.00	0.93	0.93		0.93
No op 3	Remove Deuteronic	0.00	0.00	0.26	0.26		0.26
27246	Under Bonnet Inspection Process	0.00	0.00	2.13	2.13		2.13
No op 4	Fit tailgate slave template	0.00	0.00	0.37	0.37		0.37
21288	Road Test	0.00	0.00	2.77	2.77		2.77
29312	Road Test - Brake Straight	0.00	0.00	1.02	1.02		1.02
29313	Road Test - Hill Climb	0.00	0.00	0.92	0.92		0.92
29314	Road Test - Washboard	0.00	0.00	0.30	0.30		0.30
29315	Road Test - Speed Bumps	0.00	0.00	0.25	0.25		0.25
29316	Road Test - Belgium Blocks	0.00	0.00	0.23	0.23		0.23
29317	Road Test - RHS Twist and Turn	0.00	0.00	0.10	0.10		0.10
29318	Road Test - Out of Phase Sine Wave	0.00	0.00	0.18	0.18		0.18
29319	Road test-LWB Pyramids	0.00	0.00	0.35	0.35		0.35
29320	Road Test - LHS Twist and Turn	0.00	0.00	0.12	0.12		0.12
29321	Road Test - Angle Irons	0.00	0.00	0.13	0.13		0.13
29322	Road Test - Ropes	0.00	0.00	0.20	0.20		0.20
29323	Road Test - Cobblestone	0.00	0.00	0.25	0.25		0.25
29324	Road Test - Painted Lines	0.00	0.00	0.17	0.17		0.17
29325	Road Test - Figure of 8	0.00	0.00	0.48	0.48		0.48
29326	Road Test - Slalom	0.00	0.00	0.10	0.10		0.10
29327	Road Test - Morris Shelter	0.00	0.00	0.73	0.73		0.73
29328	Road Test - Road Circuit	0.00	0.00	1.93	1.93		1.93
36471	Drive to car wash	0.00	0.00	1.47	1.47		1.47
21567	Activate Car Wash Process	0.00	0.00	6.07	6.07		6.07
No op 5	Drive car back to road test	0.00	0.00	1.25	1.25		1.25
No op 6	Remove tailgate slave template	0.00	0.00	0.61	0.61		0.61
21237	Car Wash - QC Checks	0.00	0.00	0.70	0.70		0.70
34529	Scan Vehicle into Station LN Procedure	0.00	0.00	0.91	0.91		0.91
36466	Flags	0.00	0.00	1.41	1.41		1.41
No op 7	Drive to MPR	0.00	0.00	2.57	2.57		2.57
No op 8	Replace protection on steering wheel	0.00	0.00	0.50	0.50		0.50
No op 9	Walk back to road test	0.00	0.00	0.92	0.92		0.92
		0.00	0.00	40.16	40.16		

Baseline time study of complete road test procedure (On average)

Table 6-Road Test Process Time Study (Purnell-Whitehead, 2026)

Activity	Estimated Time
Vehicle underbody inspection and setup	13.52
Proving ground test	11.71
Return to Car Wash and QC checks	9.54
Decision feedback and admin	5.40
Total process time	40.17

The above timings in Table 6 do not account for any rework/repeat testing due to process failure.

4.3 Measurement Capability

A critical observation from the current process is that the output is primarily a technician judgment rather than a measurable engineering data set.

The present system does not routinely capture:

- Sound pressure level (dB)
- Dominant frequency content
- Transient noise event timing
- Route location of noise occurrence
- Audio replay evidence
- Trend data across vehicles

The process provides a quality decision but limited quality intelligence. The lack of measured outputs means the current process cannot separate vehicle variation from measurement variation. Previous NVH variability research highlights that acoustic response can be affected by test conditions and measurement methods. Therefore, without recorded data, it is difficult to determine whether inconsistent outcomes are caused by the vehicle, the environment or the operator (Dowsett, et al., 2016) (Hills, et al., 2009).

As a result:

- Repeated issues are harder to trend.
- Borderline cases are difficult to compare.
- Improvement actions are slower to validate.
- Engineering escalation on technician description rather than evidence

4.4 Measurement System Baseline Assessment

Within Six Sigma, any inspection method should itself be treated as a measurement system. In the current state, the effective “Gage” is the technicians’ hearing, experience, and interpretation. This is a key weakness because a measurement system should produce consistent results when the same condition is assessed repeatedly. In the current process, repeatability and reproducibility are not fully proven. The technician's hearing and classification judgment form part of the measurement system, which increases the risk of inconsistent defect detection (Deshpande, et al., 2020)

This introduces several sources of variance:

Operator variation:

Different technicians may interpret the same sound differently depending on experience, hearing sensitivity, and tolerance thresholds. Evidence of this is shown in Figures 18 and 19, the Flags reporting system used but technicians to record any issues found with the vehicle. Over a four-year period as the top five issues reported at road test between two technicians alone only include one of the same reported defects. There are a further four road test technicians that further add to the variation.

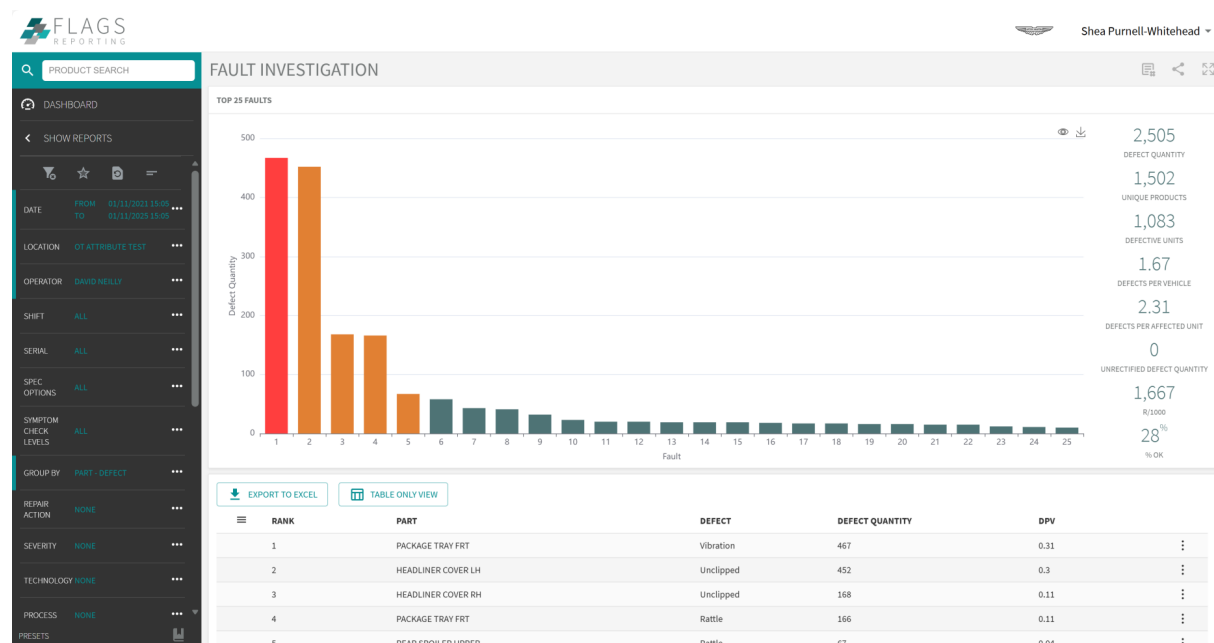


Figure 18-Flags Investigation

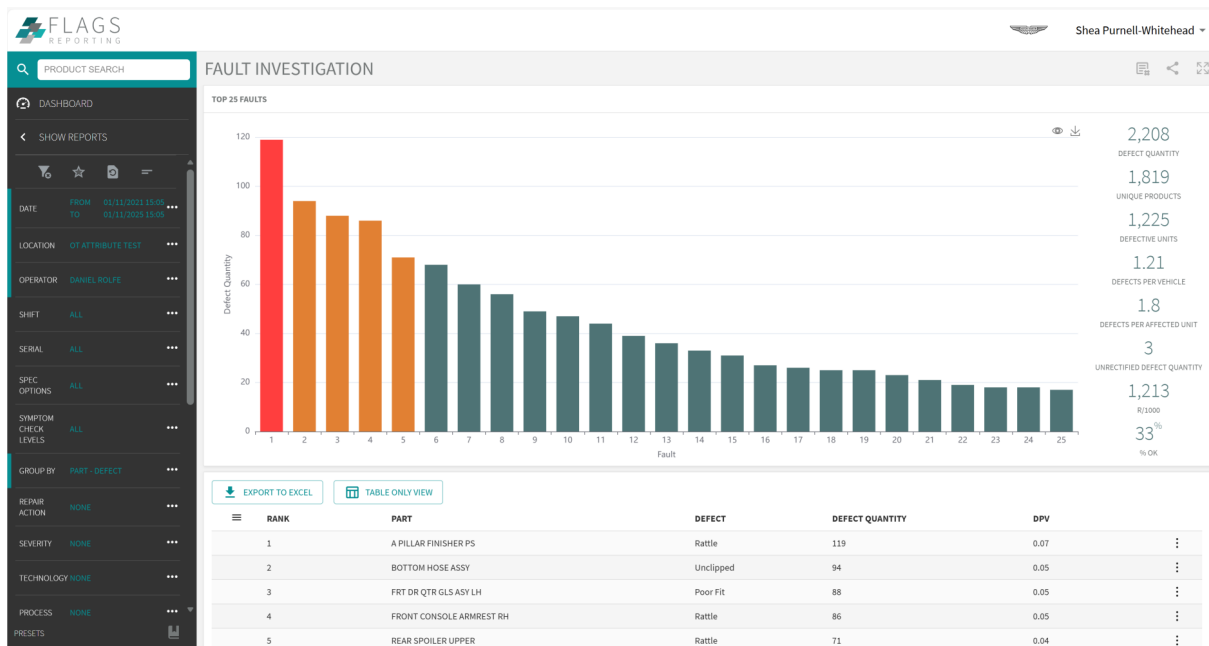


Figure 19-Flags Investigation

Within-Operator Variation

The same technician may make different decisions on different days due to fatigue, concentration, other human factors, and/or environmental condition.

Environmental Variation

Road surface condition, weather, temperature, and background noise levels. The proving-ground is situated next to an operational airport runway.

Decision Threshold Variation

Since no fixed measurable threshold exist, borderline vehicles may receive inconsistent outcomes. This indicates that the current measurement system has limited reproducibility.

4.4.1 Flags Reporting Software

Flags reporting software is the system Aston Martin uses to record any build issues. It is this system that all data is collected. Each process has a station number attributed, and it is here where the road test technicians manually enter issues found during the NVH detection process. Examples shown in Figure 14 and 15.

4.5 Indicative Gage R&R Consideration

A formal Gage R&R study is difficult under the current subjective process because the output is not continuous measured data. However, an attribute agreement study could be used.

For example:

- 10 Vehicles (mix of known good/borderline/known concern)
- Three technicians
- Repeated blind assessment

Outputs to compare:

- Pass
- Fail
- Uncertain

Expected risks may include:

- Disagreement between technicians
- Inconsistent reclassification of borderline vehicles
- over reliance on most experienced operator judgment

This supports the case for introducing an objective system with stronger repeatability.

4.6 Process Performance Risks

Several measurable inefficiencies exist in the current state.

Repeat Testing

Where a concern is uncertain or intermittent, the vehicle may require additional route testing.

Escalation Delay

Without recorded evidence, engineering team may need to reproduce this issue before diagnosis can begin.

Resource Dependency

The process relies heavily on a limited number of experienced technicians.

Limited Trend Visibility

Although Aston Martin uses the flags reporting to for any build concerns, this is a manual input from the technician so no consistent data set from repeatable means are stored to identify whether certain models, build shifts or component batches show higher NVH concerns.

4.7 Voice of Process (VOP)

The voice of the process represents what the current system is telling the business.

Current process outputs suggest:

- Route test can detect clear fault effectively.
- Systems rely heavily on technician skill/judgment.
- Process speed is acceptable but labour intensive.
- Data maturity is low.
- Repeatability is uncertain.

From the above it can be said that the process is functional but not optimised.

4.8 Rework Cost

Between January 2025 and January 2026 using the top 25 NVH related items detected requiring detected at road test shown in table 7.

Table 7-Top 25 Rework Items at Road Test (Purnell-Whitehead, 2025)

DATE: FROM 01/01/2025 05:58 TO 31/12/2025 06:58										
Defect Quantity: 1962, Unique Products: 1497, Defective Units: 1098, Defects Per Vehicle: 1.31, Defects Per Affected Unit: 1.79, Unrectified Defect Quantity: 3,R/1000: 1310,% OK: 27										
Rank	Part	Defect	Defect Quantity	DPV	Defective Units	Mean Time To Repair(Minute)	Sample Size	Total Rework Time (Minutes)	Total Rework Time (Hours)	Total Rework Time (Days)
1	FRONT CONSOLE ARMREST RH	Rattle	265	0.18	265	15	265	3975	66.25	2.76
2	FRONT CUPHOLDER LID	Rattle	92	0.06	92	44	92	4048	67.47	2.81
3	HEADLINER COVER RH	Rattle	86	0.06	86	10	86	860	14.33	0.60
4	TAILGATE STRIKER	Rattle	67	0.04	67	12	67	804	13.40	0.56
5	REAR SPOILER UPPER	Rattle	63	0.04	63	20	63	1260	21.00	0.88
6	HEADLINER COVER LH	Rattle	48	0.03	48	9	48	432	7.20	0.30
7	FRONT CONSOLE ARMREST LH	Rattle	46	0.03	46	26	46	1196	19.93	0.83
8	RAIN SENSOR COVER	Rattle	33	0.02	33	14	33	462	7.70	0.32
9	PACKAGE TRAY FRT	Rattle	30	0.02	30	8	30	240	4.00	0.17
10	A PILLAR FINISHER PS	Rattle	29	0.02	29	16	29	464	7.73	0.32
11	DOOR POCKET FRONT LH	Rattle	27	0.02	27	14	27	378	6.30	0.26
12	FRONT DIV BAR SEAL LH	Wind Noise	27	0.02	27	12	27	324	5.40	0.23
13	FRT DR QTR GLS ASY LH	Wind Noise	25	0.02	25	12	25	300	5.00	0.21
14	LOADSPACE FLOOR CARPET	Rattle	25	0.02	25	11	25	275	4.58	0.19
15	TAILGATE INNER ASSY	Rattle	24	0.02	24	14	24	336	5.60	0.23
16	A PILLAR FINISHER DS	Rattle	23	0.02	23	19	23	437	7.28	0.30
17	DOOR POCKET FRONT RH	Rattle	21	0.01	21	13	21	273	4.55	0.19
18	RR MAP LIGHT BZL LH	Rattle	18	0.01	18	8	18	144	2.40	0.10
19	HEADLINER COVER RH	Unclipped	17	0.01	17	7	17	119	1.98	0.08
20	DOOR POCKET ASY RR LH	Rattle	16	0.01	16	13	16	208	3.47	0.14
21	FRT DR QTR GLS ASY RH	Wind Noise	16	0.01	16	15	16	240	4.00	0.17
22	CONSOLE SWITCH VENEER	Rattle	15	0.01	15	37	15	555	9.25	0.39
23	FRONT DIV BAR SEAL RH	Wind Noise	15	0.01	15	11	15	165	2.75	0.11
24	HEADLINER COVER LH	Unclipped	15	0.01	15	10	15	150	2.50	0.10
25	SPARE WHEEL ASSY	Rattle	14	0.01	14	13	14	182	3.03	0.13
			1057	0.71	1057	383	1057	17827	297.12	12.38

For the top twenty-five issues alone a total rework time of 17827 minutes was recorded.

Using the cost per area calculator in figure 20 the following cost can be assigned to the total rework items, Equation 1.

$$17827mins \times £1.23 = £21,864.82$$

Equation 1-Rework cost equation

2026 Hourly Costs Per Area Calculator										
Area	Direct Labour Rate	Overhead Rate	Fully Loaded Rate	Fully Loaded/ Min	Fully Loaded/ Second	Enter Mins/ Area	Mins Cost	Enter Seconds/ Area	Sees Cost	Total Cost
BodyShop	£31.56	£79.83	£111.39	£1.86	£0.0309		£0.00		£0.00	£0.00
Paint	£33.08	£39.39	£72.47	£1.21	£0.0201		£0.00		£0.00	£0.00
T&F	£31.29	£51.49	£82.78	£1.38	£0.0230		£0.00		£0.00	£0.00
VC	£32.27	£41.32	£73.59	£1.23	£0.0204	17827.00	£21,864.82		£0.00	£21,864.82

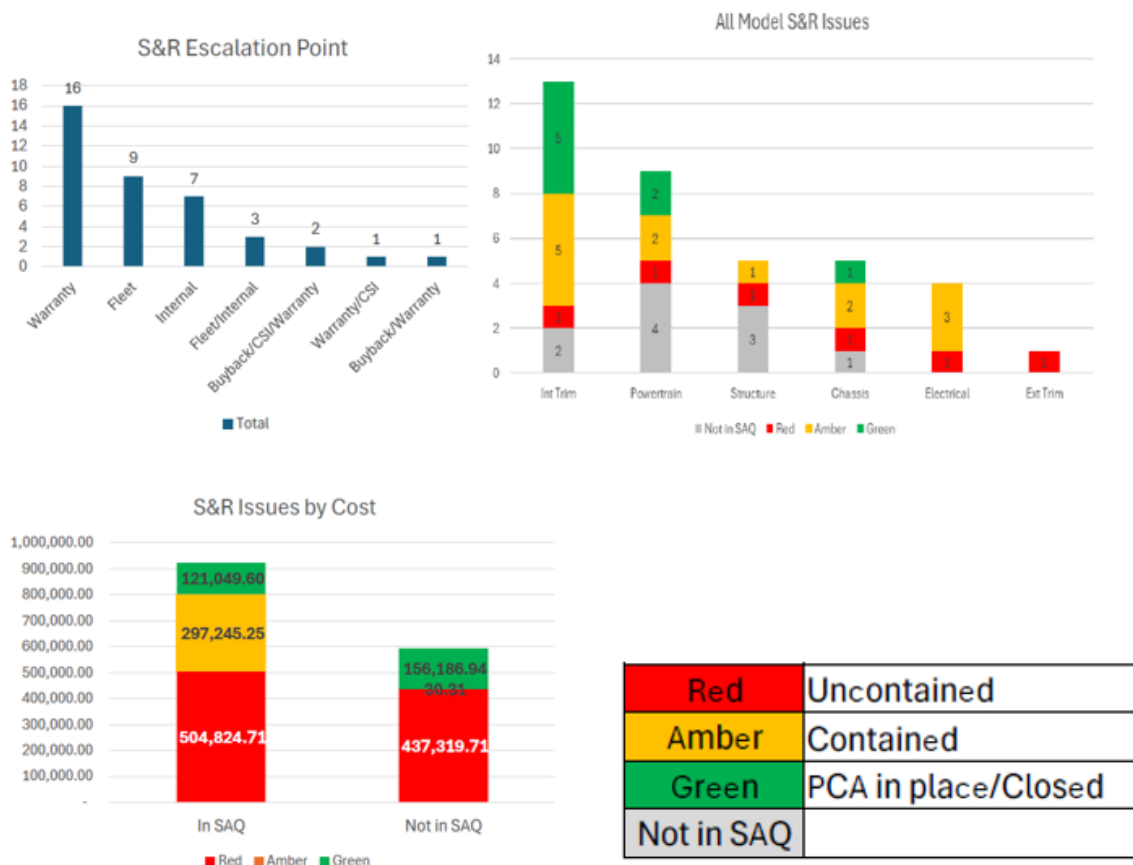
Figure 20- 2026 hourly cost per area calculator (Aston Martin, 2026)

4.9 Warranty Cost

4.9.1 Previous 12 Months

Issues have been identified and categorised from various escalation points, Table 8, including development, launch phase, production, and the field. The total cost spent for the attribute issue identified from the last 12-month period is £1.5 million. £574k (36%) of the total spent is currently contained. There are £942k (58%) of total spend uncontained.

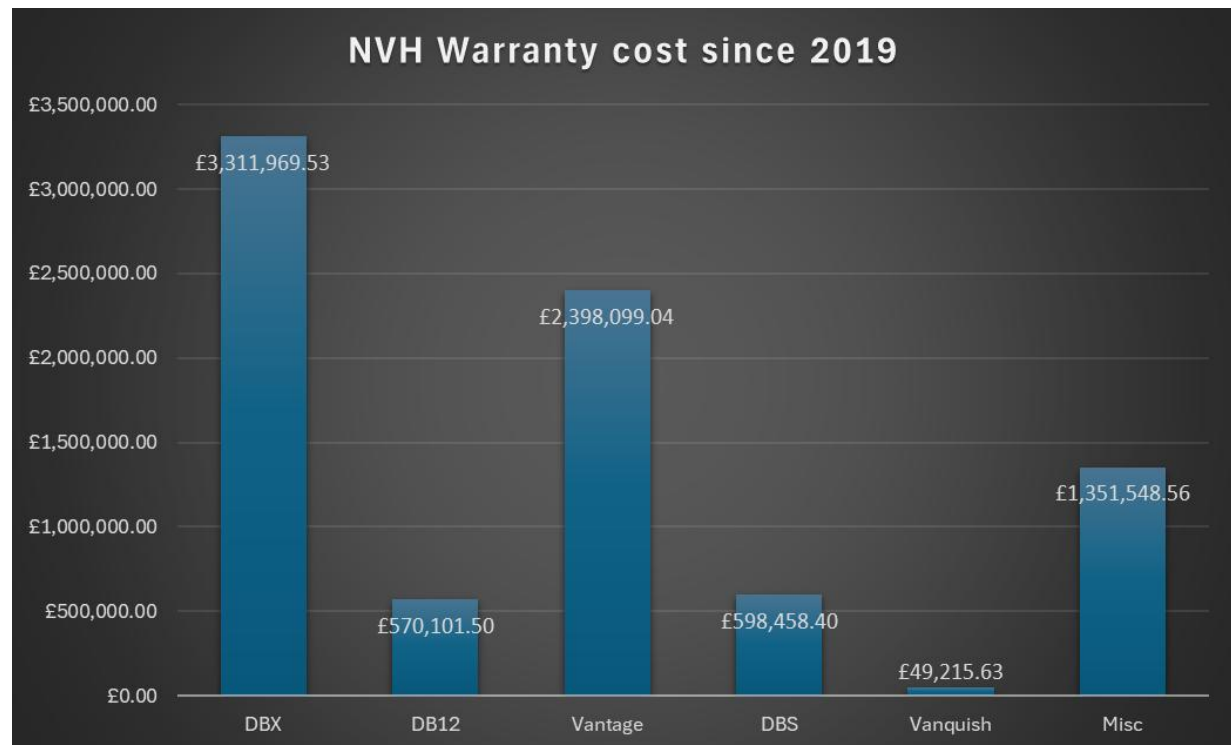
Table 8-In Field Cost Investigation



4.9.2 Breakdown Since 2019

Warranty cost since 2019 has also been analysed, Table 9. With a total warranty cost of £8,279,392.66 across all car lines of Aston Martin. Broken down across all car line (Table 8). Of the total amount the DBX model makes up 40% of the total amount.

Table 9-NVH warranty cost since 2019



Not all the warranty data gathered, and costs involved can be rectified at production where the purpose improved NVH detection process will be situated. There are other failure modes to be considered are part failure, fatigue, rework or even damage. The findings suggest that with the added objective recorded data that will be recorded. Results can be compared with what is reported in the field. With this information available (Table 10). Information can be feedback to the relevant stake holders where alteration to the verification test can be made to help detect issue before leaving factory and reaching customers.

Table 10- Top issues reported since 2019.

Row Labels	2020	2021	2022	2023	2024	2025	2026 (blank)	Grand Total
abnormal noise	9	83	111	411	529	697	42	1883
Front Door Trim			5	17	47	55	5	129
Front Quarter Glass		3	6	30	44	26	2	111
Front Corner Unit	1	2	4	36	35	32	1	111
loose / not fully connected	4	29	98	368	295	360	18	1172
Front Door Trim			10	18	26	48	1	103
Outer Handles and Actuation		2	14	70	3	6		95
(blank)			3	25	17	28	3	76
Front Door Dynamic Weatherstrips		1	8	23	16	25	1	74
Front Window Regulator			7	25	19	11		62
additional part	4	7	15	37	49	3	3	118
(blank)		1		1	11	19	3	35
Owner's Manuals					16	17		33
Engine Modules (as shipped)					2	7		9
Front Corner Unit				6	1			7
External Oil Distribution				2			3	5
vibration	5	9	15	35	47	3		114
Exterior Mirrors					7	13		20
Front Door Trim		1		1	7	2	2	13
Centre Console Mounted Switches					1	7	1	9
(blank)			1		4	1		6
Front Corner Unit				2	1	2		5
Grand Total	13	121	225	809	896	1153	66	3287

4.10 Operational Cost

The following study was carried out with the Manufacturing business office who are responsible for process efficiency and time studies.

In the Vehicle confirmation department, the technicians that carry out the road test process which includes the NVH detection are also responsible for several other processes.

Currently there are four technicians that cover WAHA (wheel alignment, headlight adjustment), Rolling Road, Inner cladding fit, Camera set, Wind noise, and Road test.

The current weighted average loading for the whole department is 78% (Table 11).

Table 11-Current Cost and Average Weighted Loading

Push 100%		VC Tests					
OPR 95.00%		5020-1 WAHA	5050-1 Rolling Road	5060-1 Inner Cladding	5070-1 Camera Set	5080-1 Wind Noise	5090-5110 Road Test
Takt Time	60.91 Minutes	4					
No. of Heads		4					
Average volume	% of Build	BMs	BMs	BMs	BMs	BMs	BMs
Takt Time		243.65					
Process time	34	29.96	20.56	7.01	3.21	14.55	39.69
Rework Time		0	0	0	0	20	35
Process time with Rework/Rerun		29.96	20.56	7.01	3.21	34.55	74.69
FTT %		82.00%	78.00%	100.00%	44.00%	47.00%	41.00%
Volume FTT		27.88	26.52	34.00	14.96	15.98	13.94
Volume Reworked		6.12	7.48	0.00	19.04	18.02	20.06
Total Volume of Machine		40.12	41.48	34.00	53.04	52.02	54.06
Avg Total Run		1202.00	852.83	238.34	170.26	1117.29	2847.74
Per Car		35.35	25.08	7.01	5.01	32.86	83.76
Total avg time to run cars		189.07					
FTT Total Timing		114.98					
Rework Worst Case		284.96					
Weighted Avg Loading		78%					
Total / Average Load	34 100%						

It was found by removing 11.71 minutes from the Road test process would reduce the overall weighted loading of the department to 70%. With the reduced average loading a rebalance could be possible. A labour reduction cost of £1.38 per minute, equalling £16.15 per minute can be achieved (Table 12).

Table 12-Reduction of 11.71mins Process Time

Push 100%								
OPR 95.00%		VC Tests						
Takt Time	60.91	Minutes	5020-1 WAHA	5050-1 Rolling Road	5060-1 Inner Cladding	5070-1 Camera Set	5080-1 Wind Noise	5090-5110 Road Test
		No. of Heads	4					
		Average volume	BM's	BM's	BM's	BM's	BM's	BM's
		% of Build						
Takt Time			243.65					
Process time	34	100%	29.96	20.56	7.01	3.21	14.55	27.98
Rework Time			0	0	0	0	20	35
Process time with Rework/Rerun			29.96	20.56	7.01	3.21	34.55	62.98
FTT %			82.00%	78.00%	100.00%	44.00%	47.00%	41.00%
Volume FTT			27.88	26.52	34.00	14.96	15.98	13.94
Volume Reworked			6.12	7.48	0.00	19.04	18.02	20.06
Total Volume of Machine			40.12	41.48	34.00	53.04	52.02	54.06
Avg Total Run			1202.00	852.83	238.34	170.26	1117.29	2214.70
Per Car			35.35	25.08	7.01	5.01	32.86	65.14
Total avg time to run cars			170.45					
FTT Total Timing			103.27					
Rework Worst Case			261.54					
Weighted Avg Loading			70%					
Total / Average Load	34	100%						

With the reduction of a technician only the overall weighted average loading becomes 103%. Meaning over utilisation and would result in Takt time not being able to be achieved. Max loading set by the business is 95% loading (Table 13).

Table 13-Reduction of Technician Only

Push 100%								
OPR 95.00%		VC Tests						
Takt Time	60.91	Minutes	5020-1 WAHA	5050-1 Rolling Road	5060-1 Inner Cladding	5070-1 Camera Set	5080-1 Wind Noise	5090-5110 Road Test
		No. of Heads	3					
		Average volume	BM's	BM's	BM's	BM's	BM's	BM's
		% of Build						
Takt Time			182.74					
Process time	34	100%	29.96	20.56	7.01	3.21	14.55	39.69
Rework Time			0	0	0	0	20	35
Process time with Rework/Rerun			29.96	20.56	7.01	3.21	34.55	74.69
FTT %			82.00%	78.00%	100.00%	44.00%	47.00%	41.00%
Volume FTT			27.88	26.52	34.00	14.96	15.98	13.94
Volume Reworked			6.12	7.48	0.00	19.04	18.02	20.06
Total Volume of Machine			40.12	41.48	34.00	53.04	52.02	54.06
Avg Total Run			1202.00	852.83	238.34	170.26	1117.29	2847.74
Per Car			35.35	25.08	7.01	5.01	32.86	83.76
Total avg time to run cars			189.07					
FTT Total Timing			114.98					
Rework Worst Case			284.96					
Weighted Avg Loading			103%					
Total / Average Load	34	100%						

(Table 14) With the reduction of a technician and 11.71 mins process time. A total weighted average of 93% is achieved, lower than the maximum load.

With this reduction a total process time saving of 11.71minutes is achieved.

The reduction of manning would achieve a monthly saving of £5256.70 and £63,080.44 per year according to information given by the MBO department.

It must be noted that the time reduction is for the total removal of the NVH detection process. A time study will need to be carried out on the improved process to then calculate the new cost.

Table 14-Time Study with Reduction of Technician and Reduction of 11.71 Process Time.

	Push	100%						
	OPR	95.00%	VC Tests					
Takt Time	60.91	Minutes	5020-1 WAHA	5050-1 Rolling Road	5060-1 Inner Cladding	5070-1 Camera Set	5080-1 Wind Noise	5090-5110 Road Test
	No. of Heads		3					
	Average volume	% of Build	BM's	BM's	BM's	BM's	BM's	BM's
Takt Time			182.74					
Process time	34	100%	29.96	20.56	7.01	3.21	14.55	27.98
Rework Time			0	0	0	0	20	35
Process time with Rework/Rerun			29.96	20.56	7.01	3.21	34.55	62.98
FTT %			82.00%	78.00%	100.00%	44.00%	47.00%	41.00%
Volume FTT			27.88	26.52	34.00	14.96	15.98	13.94
Volume Reworked			6.12	7.48	0.00	19.04	18.02	20.06
Total Volume of Machine			40.12	41.48	34.00	53.04	52.02	54.06
Avg Total Run			1202.00	852.83	238.34	170.26	1117.29	2214.70
Per Car			35.35	25.08	7.01	5.01	32.86	65.14
Total avg time to run cars			170.45					
FTT Total Timing			103.27					
Rework Worst Case			261.54					
Weighted Avg Loading			93%					
Total / Average Load	34	100%						

5 Analyse Phase

The analyse phase of DMAIC methodology focuses on identifying and validating root cause of process variation and inefficiency during the measure phase. The objective is to move beyond symptoms and determine the underlying factors that limit process performance.

For this project, the Analyse phase investigates why the current NVH detection process lacks repeatability, traceability, and efficiency. Using structured problem solving tools, the cause of variation within the proving-ground test are examined.

5.1 Root Cause Analysis Approach

To systematically identify the cause of process variation, the following tools were applied:

- Fishbone Ishikawa diagram
- 5 Why analysis
- Process reasoning based on engineering principles

5.2 Fishbone Ishikawa (Cause and Effect) Analysis

To help establish root cause, the Ishikawa Fishbone analysis diagram was used, Figure 21. This model improves diagnosis by separately analysing various aspects of potential causes while still integrating them into one overall quality analysis system (Liliana, 2016). The Ishikawa model has been since the 1960s and is a tool often used in quality-control to make sure as many contributing factors are considered (Ishikawa, 1987).

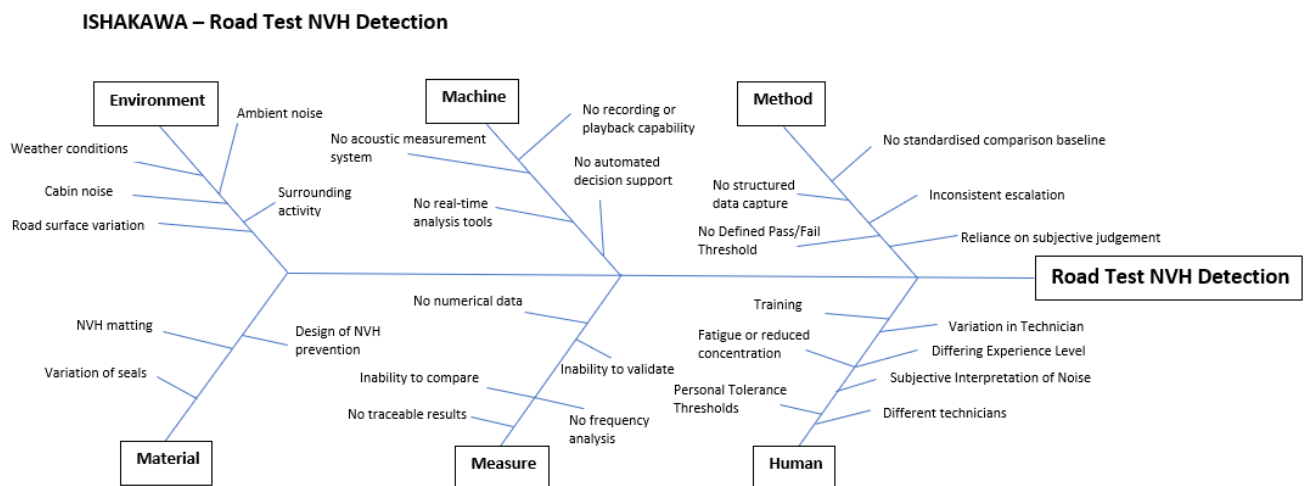


Figure 21-Road Test NVH Detection Ishikawa

5.3 5 Why Analysis

A 5 Why analysis was conducted to identify the fundamental cause of the problem.

Problem: Inconsistent NVH Pass/Fail decisions

Why 1: Because decisions are based on technician judgment.

Why 2: Because no objective measurements system is used.

Why 3: Because the process relies on auditory detection only.

Why 4: Because no data acquisition or analysis system has been introduced.

Why 5: Because the process was designed around human perception rather than a measurable output.

The root cause identified:

The NVH detection process lacks an objective measurement system and is fundamentally designed around subjective human perception.

5.4 Analysis of Process Inefficiency

Using the timing data provided by MBO during the measure phase, further inefficiencies can be identified see 4.10.

5.4.1 Disproportionate Process Time

Total process time is 40.16 minutes, 11.71 minutes makes up 29% of the total process time. This indicates that a sizeable portion of the time supports a decision system that produces no measurable data.

5.4.2 Limited Value Extraction

The proving-ground route creates useful excitation conditions, but the current process does not retain the acoustic response generated during the test. This limits process learning because repeated patterns cannot be analysed quantitatively across vehicles, build periods or defect categories. As a result, the process functions as a pass/fail gate rather than a continuous improvement data source (Monday, 2022) (Montgomery, 2009).

5.4.3 Rework and Repeat Testing

Where noise concerns are unclear. Vehicles will require repeat testing adding to cost. Additional technician time is required which adds risk throughput volume.

5.4.4 Escalation Inefficiency

Without recorded evidence, engineering teams must reproduce issues manually leading to increased diagnosis time and root cause analysis delays.

6 Improve

The improve phase of the DMAIC methodology focuses on developing and evaluation solutions capable of addressing the root cause identified during the Analyse phase. The objective is not only to improve technical performance, but also to ensure that the proposed solution is practical, sustainable, and compatible with the current operational requirements.

Within Aston Martin's manufacturing environment, the preferred solution must balance measurement capability with operational practicality. Unlike high-volume automotive production environments, the St Athan facility operates with lower production volume but significantly higher customer expectation for perceived quality and refinement. As a result, maintaining customer-relevant testing conditions while improving repeatability is more valuable than implementing a highly automated but less representative laboratory-based system.

6.1 Improvement Objectives

Based on the Define, Measure and Analyse phase, the improvement strategy required to achieve the following objectives:

- Improve repeatability of NVH decisions.
- Reduce operator to operator variation.
- Introduce measurable process outputs.
- Improve traceability of inspection decisions.
- Maintain capability with current production flow.
- Minimise disruption throughput.
- Support faster fault escalation and diagnosis.
- Maintain alignment with customer perception of refinement.

6.2 Improvement Options Considered

Several potential options were reviewed and considered, Table 15.

Table 15-Improvement Option Comparison Matrix (Purnell-Whitehead, 2026)

Criteria	Current Subjective	Acoustic Camera	Rig-Based	Binaural Overlay
Repeatability	Low	Medium	High	Medium-High
Production Integration	High	Low	Low	High
Capital Cost	Low	High	Very High	Medium
Traceability	Low	High	High	High
Throughput Impact	Low	Medium	High	Low
Customer Relevance	High	Medium	Medium	High
Ease of Implementation	High	Low	Low	High
Scalability	Low	Medium	Medium	High
Overall Suitability	Low	Medium	Medium	High

The comparison matrix demonstrates that although rig-based and acoustic camera systems provide strong technical capability, the proving-ground binaural overlay system offers the strongest overall balance between repeatability, manufacturing integration, implementation complexity, and customer relevance. This supports its selection as the preferred improvement strategy for short-to-medium-term deployment.

Within Aston Martin's manufacturing environment, the preferred solution must balance measurement capability with operational practicality. Unlike high-volume automotive production environments, the St Athan facility operates with lower production volume but significantly higher customer expectation for perceived quality and refinement. As a result, maintaining customer-relevant testing conditions while improving repeatability is more valuable than implementing a highly automated but less representative laboratory-based system.

6.2.1 Option 1-Continue Current Subjective Testing Process

Option one has its advantages. No additional investment, no process disruption and the existing operator familiarity is maintained. Disadvantages are continued lack of repeatability, no measured outputs, ongoing dependence on technician judgment and no improvement in traceability.

This option does not address the root cause identified during the analyse phase.

6.2.2 Option 2- Full Acoustic Camera implementation.

Acoustic camera systems use microphone arrays and beamforming algorithms to identify and visualise sound sources. Advantages include strong diagnostic capability, visual localisation of noise sources and advance frequency analysis capability. However, option two would have a high capital cost, complex setup requirements, reflective cabin surface reduce effectiveness, Limited suitability for routine production testing and would require a substantial amount of development and integration effort. Although acoustic cameras provide excellent engineering diagnostic capability, they are considered more suitable for R&D or secondary investigation rather than primary EOL inspection and verification.

The main trade-off with acoustic cameras is diagnostic resolution versus production practicality. They may be valuable for locating specific noise sources once a concern is known, but their cost, setup time and sensitivity to cabin reflections reduce their suitability as a primary EOL screening method (Chiariotti, et al., 2018).

6.2.3 Option 3-Rig Based Excitation Testing

Rig-based testing would replace or supplement the proving-ground NVH test; however, separate vehicle safety verification would still be required following production. Advantages

to note include highly repeatable excitation input, controlled environment, reduced weather influence, and strong automation potential. Disadvantages range from a high infrastructure cost, major production integration challenges, potential throughput limitations and may not fully replicate real-world customer conditions. Additionally having a rig-based solution would mean only one vehicle being tested at a time. While technically attractive, this option was considered impractical as a short-term implementation strategy but would be the ideal long-term solution.

The main trade-off with rig testing is repeatability versus representativeness. A rig would reduce environmental variation and improve control of excitation inputs but may not fully reproduce customer driving conditions. This makes it more suitable as a long-term validation or audit solution than an immediate replacement for proving-ground testing (Cvok, et al., 2021).

From a manufacturing perspective, the challenge is not simply achieving repeatable excitation but achieving repeatable excitation while maintaining acceptable production throughput and customer relevance. A highly controlled laboratory system may improve measurement consistency but simultaneously reduce correlation with real customer operating conditions. This creates a significant engineering trade-off between process control and real-world validity.

6.2.4 Proving-Ground Overlay System

The selected proving-ground overlay provides the strongest short-term balance because it retains real driving excitation while adding objective acoustic evidence (Dowsett, et al., 2016). It does not eliminate all environmental variation, but it improves traceability and reduces dependence on unsupported technician judgment (Møller, 1992).

The system consists of Binaural measurement headset or microphones, portable data acquisition system, software-based analysis platform, golden vehicle comparison thresholds, and an automated pass/fail result decision.

Advantages include the existing proving-ground route is retained, minimal production disruption, objective acoustic measurement, improved repeatability and trackability, lower implementation cost than the full rig option and scalable across production. The proving-ground allows for more than one vehicle to be tested simultaneously.

Disadvantages include the continued influence of environmental variation, calibration and maintenance requirements and operator training would be required. Despite these limitations, this option provided the best balance between practicality and technical capability.

6.3 Binaural Measurement System.

Binaural measurement was selected because it provides the strongest balance between objective measurement, human relevance, practicality, and production integration. Unlike fixed microphones positioned elsewhere in the cabin, binaural systems measure sound at the driver's ear position, closely representing actual occupant experience. The proposed system will allow replay of recorded events, frequency analysis, analysis of transient noise events and comparisons against golden vehicle reference data. This creates a measurable and traceable inspection process.

6.4 Golden Vehicle Benchmarking

To establish objective thresholds, the proposed system would use "Golden vehicle" benchmarking. A golden vehicle is defined as a vehicle confirmed to meet acceptable NVH quality standards under controlled conditions. The specialist NVH team at the Gaydon headquarters would determine the golden vehicle to confirm set thresholds to the newly integrated system.

Measured outputs from the golden vehicle would be used to define acceptable sound pressure ranges, frequency response limits, and transient event tolerances. This approach allows comparison between production vehicles and a known acceptable reference.

6.4.1 Proposed Threshold Strategy

Objective pass/fail thresholds should be established using statistical comparison against confirmed acceptable "Golden vehicles." Multiple reference vehicles should be tested under controlled environmental conditions to establish baseline ranges for:

- Sound pressure level,
- Frequency response,
- Transient event behaviour,
- Route-specific acoustic characteristics.

Thresholds should initially be set conservatively to minimise false failure risk before refinement through production correlation studies. Long-term threshold optimisation should incorporate warranty feedback and engineering escalation data.

6.5 Integration Into Existing Process

A key objective of the project is to minimise the disruption to production. The addition of the measuring equipment, software interface and the automated data handling will need to minimise risk and reduce implementation complexity.

The selected measurement equipment will require minimal setup time to prevent impact on cycle time.

The automated data handling is required to populate results to the current reporting system Flags. With the automated detection being directly inputted to Flags, analysis would be significantly improved with access to issue trends with quantifiable data that can be used to escalate to engineering teams with the focus on product improvement. Automation will drastically reduce time spent manually inputting each issue identified.

6.6 Proposed NVH Detection Architecture

The proposed future system architecture would operate through a sequential acoustic data acquisition and processing workflow integrated within the end-of-line inspection process. During testing, the proposed binaural measurement system would capture acoustic data from the driver ear position while the vehicle operates under controlled proving-ground conditions. The recorded signals would then be processed using FFT-based frequency analysis to identify tonal and broadband acoustic characteristics associated with potential NVH concerns.

Processed acoustic data would subsequently be compared against predefined reference thresholds and baseline frequency signatures developed during system validation stages. Where abnormal acoustic behaviour is detected, the system would generate a visual localisation map identifying probable noise source locations for technician investigation. Measurement results, defect classifications, and repair outcomes could additionally be stored within a centralised database to support long-term quality tracking, repeatability analysis, and future machine-learning-based defect classification development. Figure 22 illustrates the proposed NVH detection architecture flow.

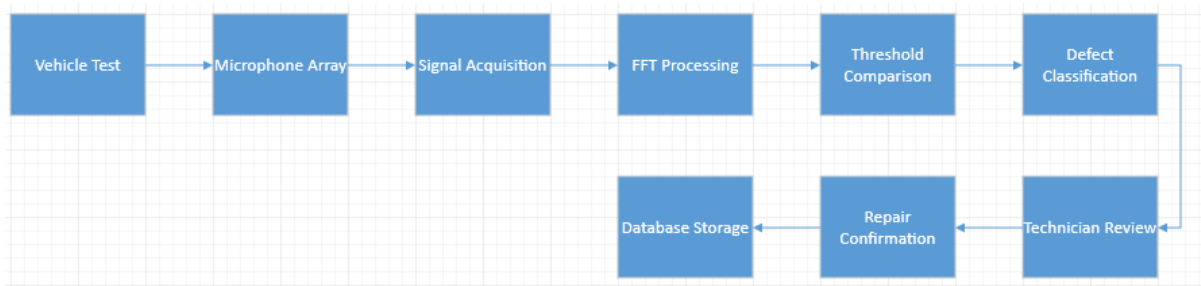


Figure 22-Proposed NVH Detection Architecture

6.7 Impact on Cycle Time.

A current process time of 40.16 minutes was identified. This includes preparation, road testing, and post-test activities. The proposed system will introduce additional cycle time. Equipment fitment and setup time are to be considered.

6.7.1 Rig Based Option

Should a rig- based option be used, a considerable time saving can be achieved. Table 16 are the NVH detection operations that could potentially be removed as they would be replaced by the automated process.

Table 16-Road Test NVH detection operations

21288	Road Test	0.00	0.00	2.77	2.77		2.77
29312	Road Test - Brake Straight	0.00	0.00	1.02	1.02		1.02
29313	Road Test - Hill Climb	0.00	0.00	0.92	0.92		0.92
29314	Road Test - Washboard	0.00	0.00	0.30	0.30		0.30
29315	Road Test - Speed Bumps	0.00	0.00	0.25	0.25		0.25
29316	Road Test - Belgium Blocks	0.00	0.00	0.23	0.23		0.23
29317	Road Test - RHS Twist and Turn	0.00	0.00	0.10	0.10		0.10
29318	Road Test - Out of Phase Sine Wave	0.00	0.00	0.18	0.18		0.18
29319	Road test-LWB Pyramids	0.00	0.00	0.35	0.35		0.35
29320	Road Test - LHS Twist and Turn	0.00	0.00	0.12	0.12		0.12
29321	Road Test - Angle Irons	0.00	0.00	0.13	0.13		0.13
29322	Road Test - Ropes	0.00	0.00	0.20	0.20		0.20
29323	Road Test - Cobblestone	0.00	0.00	0.25	0.25		0.25
29324	Road Test - Painted Lines	0.00	0.00	0.17	0.17		0.17
29325	Road Test - Figure of 8	0.00	0.00	0.48	0.48		0.48
29326	Road Test - Slalom	0.00	0.00	0.10	0.10		0.10
29327	Road Test - Morris Shelter	0.00	0.00	0.73	0.73		0.73
29328	Road Test - Road Circuit	0.00	0.00	1.93	1.93		1.93

A total of 25 mins of process time can be removed and using the hourly cost calculator in Figure 23 a saving of £25.93 per car, £881.56 per week at current run rate with a total cost per year of £40,551.72.

2026 Hourly Costs Per Area Calculator										
Area	Direct Labour Rate	Overhead Rate	Fully Loaded Rate	Fully Loaded/ Min	Fully Loaded/ Second	Enter Mins/ Area	Mins Cost	Enter Seconds/ Area	Secs Cost	Total Cost
BodyShop	£31.56	£79.83	£111.39	£1.86	£0.0309		£0.00		£0.00	£0.00
Paint	£33.08	£39.39	£72.47	£1.21	£0.0201		£0.00		£0.00	£0.00
T&F	£31.29	£51.49	£82.78	£1.38	£0.0230		£0.00		£0.00	£0.00
VC	£32.27	£41.32	£73.59	£1.23	£0.0204	21.14	£25.93		£0.00	£25.93

Enter Mins/Area	Per Car	Per Week	Per Year
25	£25.93	£881.56	£40,551.72

Figure 23-Hourly Cost Per Area (Aston Martin, 2026)

The analysis indicates that the full twenty five-minute reduction would not realistically be achieved as there would be time required for the running of the new test.

6.8 Cost Benefit Analysis

The proposed NVH detection system provides both operational savings and wider quality benefits. The current proving-ground process is labour intensive, dependent on technician

judgment, and generates limited measurable quality data. Analysis showed the current process requires approximately 40.16 minutes per vehicle, with 11.71 minutes linked to proving-ground NVH detection activities.

Manufacturing analysis demonstrated that removing or automating these activities reduces departmental loading from approximately 78% to 70%, creating opportunities for labour rebalance while maintaining operational stability. Further analysis showed that removing one technician alongside the reduced process time results in a departmental loading of approximately 93%, remaining below the business target of 95%.

Based on current labour and process costs, estimated savings are approximately £5,256.70 per month (£63,080 annually). Additional process-efficiency savings from reducing proving-ground activity were estimated at £25.93 per vehicle, equating to approximately £40,551 annually at current production volumes.

The financial case is strengthened by NVH warranty exposure. Warranty analysis identified approximately £8.28 million of NVH-related costs since 2019, with the DBX line accounting for approximately 40% of total spend. Within the previous 12 months, approximately £1.5 million of attribute-related warranty costs were identified, with £942k remaining uncontained. Although manufacturing inspection cannot prevent all warranty concerns, objective acoustic measurement and traceable NVH data would improve engineering feedback, escalation, trend analysis, and earlier detection of repeat concerns.

Additional non-financial benefits include improved inspection repeatability, reduced reliance on specialist judgment, improved traceability, faster engineering escalation, enhanced customer protection, improved manufacturing data maturity, and protection of premium brand reputation.

Compared with alternative technologies, the proposed proving-ground overlay system offers a significantly lower implementation cost. Alternative solutions, including acoustic cameras and rig-based excitation testing, require substantially greater investment and infrastructure changes. The rig-based system reviewed during the project was estimated at approximately €298,410 excluding installation and facility modification costs. In comparison, the proposed binaural overlay system requires lower investment while remaining compatible with the current production environment.

Overall, the proposed solution demonstrates a strong cost-benefit position by improving objective measurement capability while minimising production disruption and capital expenditure.

6.8.1 Implementation Cost Considerations

Although the proposed objective NVH system introduces additional implementation cost, the investment is significantly lower than full rig-based or acoustic camera alternatives.

Estimated implementation costs may include:

- Binaural headset equipment
- Portable acquisition hardware
- Software licensing
- Calibration equipment
- Operator training
- IT integration support

However, these costs should be evaluated against the potential operational and quality benefits identified during the project, including:

- Reduction in repeat testing
- Reduced technician investigation time
- Improved engineering escalation efficiency
- Reduced warranty exposure
- Improved traceability
- Enhanced customer satisfaction

Based on the current operational analysis, even small reductions in warranty concerns or repeat testing frequency could provide long-term financial benefit due to the high cost associated with premium vehicle warranty repair and customer dissatisfaction.

6.9 Return on Investment (ROI)

Although a fully detailed financial return-on-investment analysis was outside the scope of this project due to commercial confidentiality and supplier quotation limitations, an indicative ROI assessment can still be estimated using the operational savings identified during the Measure and Improve phases.

Estimated implementation costs for the proposed proving-ground overlay system may include:

- Binaural measurement hardware
- portable data acquisition equipment
- software licensing
- calibration equipment
- operator training
- IT integration support
- and development of mounting fixtures and reporting integration

Based on current industry pricing and supplier discussions, the estimated initial implementation cost for a pilot production system is expected to be within the region of

approximately £25,000–£40,000 depending on software configuration and integration complexity.

The projected annual operational saving identified through departmental loading reduction is approximately £63,080.44 per year, excluding additional benefits associated with:

- reduced repeat testing,
- reduced engineering investigation time,
- lower warranty exposure,
- improved escalation efficiency,
- reduced manual data entry,
- and improved process traceability.

Using the analytical estimation according to the study by (Botchkarev, 2015) and applying only the direct operational saving identified, the estimated simple payback period would therefore be approximately:

$$ROI = \frac{\text{Annual Savings} - \text{Initial Investment}}{\text{Initial Investment}} \times 100$$

Equation 2-ROI Equation

Assuming:

- Annual savings = £63,080,
- Implementation cost = £40,000,

$$ROI = \frac{63,080 - 40,000}{40,000} \times 100$$

$$ROI = 57.7\%$$

Equation 3-ROI Equation

This suggests that the proposed system could potentially achieve payback within the first year of implementation under favourable operating conditions.

When wider quality benefits and potential reductions in warranty exposure are considered, the long-term financial value of the proposed system could be significantly greater. Even a modest reduction in NVH-related warranty concerns could generate substantial additional savings due to the high cost associated with vehicle rectification, customer dissatisfaction, and reputational damage.

The proposed system therefore demonstrates not only technical feasibility, but also strong commercial justification for future implementation.

6.10 Proposed Implementation Strategy

Implementation of the proposed objective NVH system would ideally follow a phased deployment strategy to minimise operational disruption and reduce implementation risk.

Phase 1 – Pilot Evaluation

A limited pilot study would be conducted using selected production vehicles and experienced technicians to validate:

- Equipment functionality
- Route compatibility
- Repeatability
- Environmental sensitivity
- Operator usability

Phase 2 – Parallel Running

The objective system would operate alongside the current subjective process. This would allow:

- Comparison of pass/fail outcomes.
- Threshold refinement
- Operator familiarisation
- Confidence building

Phase 3 – Full Integration

Following successful validation, the objective system would become integrated into routine production operation with:

- Formal SOPs
- Automated reporting integration
- Calibration management
- KPI monitoring

This phased approach reduces implementation risk while supporting stakeholder acceptance and process stability.

7 Control

7.1 Standard Operating Procedures (SOPs)

One of the most essential elements of process control is standardisation. The proposed system would require formal Standard Operating Procedures (SOPs) for the process. The process would need to be built into Aston Martin's EASE system where all processes throughout production are stored for technicians to follow for each process.

SOPs would cover the following process steps:

- Headset or microphone installation
- Software startup procedure
- Proving-ground route sequence
- Vehicle preparation requirements
- Operator responsibilities
- Pass/fail escalation procedure.
- Equipment shutdown and storage

7.2 Measurement System Validation (Gage R&R)

The proposed system introduces objective measurement equipment; the measurement system itself must be validated. A Gage Repeatability and Reproducibility (Gage R&R) study would be required to evaluate the process. Gage R&R is a tool used to determine how much variation is caused by the measurement system rather than differences between parts it breaks total variation into three components:

Repeatability (Equipment variation)

Repeatability testing would need to ensure that the same technician can reproduce the same results using the same vehicle. This reflects the consistency of the measuring device.

Reproducibility (Operator variation)

There are several technicians in the confirmation department that will be carrying out the testing. To confirm reproducibility, the study would need to ensure that different operators would get the same results using the same vehicle. This is a key driver for the improvement and will help eradicate variation as mentioned in 6.4 Measurement System Baseline Assessment.

Part to Part Variation (Process variation)

Variation due to actual differences between parts. In a good system, this should be the largest portion of total variation.

According to a study by (Parashare, 2024) the overall performance of the measurement system is assessed using % Gage R&R (repeatability + reproducibility as a percentage of total variation)

- $\leq 10\%$ Acceptable (Excellent system)
- 10-30% Marginal (may be acceptable depending on use)
- $> 30\%$ Unacceptable (Unreliable system)

Additional important metrics include:

- % Study Variation: Compares measurement variations to tolerance range
- Number of Distinct Categories (NDC): Indicates system resolution (Should be ≥ 5)

The importance of Gage R&R varies across industries, for example highly regulated sectors including semiconductors and aerospace demand extremely low measurement variation, whereas less critical automotive application may tolerate higher values depending on the safety requirements.

7.2.1 Proposed Gage R&R

A proposed Gage R&R study after the installation of the new process would be:

- Ten representative vehicles
- Three operators
- Repeated measurements under controlled conditions

Outputs to be assessed would include:

- Sound pressure level.
- Transient event detection
- Pass/Fail classification consistency.

This would confirm whether the new system provide a measurable improvement over the subjective method.

Gage R&R is important because the proposed system must prove that measured differences are caused by vehicle NVH behaviour rather than equipment, operator, or environmental variation. Without this validation, the new system could create numerical data without improving measurement confidence (Deshpande, et al., 2020).

7.3 Process Failure Mode and Effect Analysis (PFMEA)

The application of Process Failure Mode and Effect Analysis (PFMEA) principles to NVH measurement highlights the importance of identifying and mitigating potential failures within the data acquisition process. (Johnson & Kahn, 2003) note that PFMEA is often undermined by poor understanding of failure modes and over-reliance on risk prioritisation, leading to unresolved lower-level issues. In context of vehicle testing, similar risks arise where environmental factors such as wind, temperature, and background noise can introduce

variability and reduce data reliability. Although these factors may not always rank highly in traditional risk assessments, their cumulative impact affect measurement repeatability and accuracy. Therefore, a more robust and holistic approach incorporating environmental control, calibration, and cross functional expertise is required to ensure objective and consistent NVH data.

Figure 24 demonstrates the PFMEA that was carried out on the current road test process to outline specific failure modes in the NVH detection section of the process. The results show a high detection ranking across all potential causes. This highlights the current method lacks a reliable method of NVH testing methods and adds further justification to improve the process. The score was then re-calculated with the recommended improvements, where a significant reduction in the overall RPN was seen. See appendix F, G and H for detailed severity, detection and occurrence scoring criteria.

 PROCESS FAILURE MODE AND EFFECTS ANALYSIS																
Process		Road Test			Responsibility:		Shea Purnell-Whitehead				Sign off					
Vehicle Program		AM8			Date:		18/01/2026				Supplier		Aston Martin			
Model:		DBX			Prepared by:		Shea Purnell-Whitehead									
Department		Vehicle Confirmation			FMEA number:		1817									
Core Team:		Engineer:		Shea Purnell-Whitehead			Page :		1			Signature		Signature		
		Quality Engineer:		Dan Marshall			FMEA Date (Orig):		18/01/2026		Revision:		1			
		CME Engineer:		Luke Huzzy-Evans			Page :		1							
		FMEA number:		1817			FMEA Date (Orig):		18/01/2026			Name:		Name:		
Process Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity Class	Potential Cause(s)/ Mechanism(s) of Failure	Occurrence	Current Process Controls Prevention	Detection	Current Process Controls Detection	RPN	Recommend ed Action(s)	Responsible Person(s)	Action Results				
												Actions Taken	Severity	Occurrence	RPN	
Road test	Abnormal noise levels	Customer dissatisfaction and sub standard performance	6	Incorrect component assembly	8	Ease process documents	6	Subjective	288	Introduces Objective testing and automated Pass/Fail	Shea Purnell-Whitehead		6	8	2	96
			6	Borderline pass/fail	5	Subjective	6	Subjective	180	Introduces Objective testing and automated Pass/Fail	Shea Purnell-Whitehead		6	2	2	24
			6	Enviromental conditions	8	No control	6	No control	288	Rig based test in controlled cell	Shea Purnell-Whitehead		6	2	2	24
			6	Technician Variability	6	Subjective	6	Subjective	216	Introduces Objective testing and automated Pass/Fail	Shea Purnell-Whitehead		6	2	2	24
			6	Undetected failures	7	Subjective	6	Subjective	252	Introduces Objective testing and automated Pass/Fail	Shea Purnell-Whitehead		6	2	2	24

Figure 24-Road test PFMEA (Purnell-Whitehead, 2026)

PFMEA is useful for identifying potential process failure modes, but literature also warns that PFMEA can be weakened if teams focus only on high RPN scores and overlook lower-ranked but recurring sources of variation. In this project, environmental effects, calibration drift, and incorrect headset positioning may appear manageable individually, but together they could significantly affect measurement repeatability (Johnson & Kahn, 2003).

7.4 Threshold Development Strategy

During future implementation, acceptable NVH thresholds would require development through a structured validation process using baseline measurements from known-good vehicles. Multiple vehicles representing acceptable production quality would be tested under controlled environmental conditions to establish statistical reference datasets for normal acoustic behaviour. Frequency-domain analysis using FFT processing would then be used to identify dominant tonal and broadband characteristics associated with acceptable vehicle operation (Rao, et al., 2015).

Threshold limits could subsequently be generated using statistical tolerance bands across critical frequency ranges. This approach would allow abnormal acoustic events to be identified objectively through deviation from validated baseline signatures rather than relying solely on operator perception. In addition, different defect categories may require individual threshold strategies, as transient impulsive noises and continuous tonal noises exhibit different acoustic characteristics and detection sensitivities.

To minimise false reject and false accept conditions, threshold validation would require iterative refinement during pilot deployment phases using comparison between technician assessments and measured acoustic data. Over time, the system could be further enhanced through the development of classified acoustic signature libraries for known defect conditions (Pedroche & Dowie, 2026).

7.5 Calibration Strategy

Future deployment of the acoustic camera system would also require a defined calibration strategy to ensure long-term measurement consistency and repeatability. Microphone array calibration would need to be performed at scheduled intervals using certified acoustic reference sources to verify channel sensitivity and phase consistency across the array. In addition, fixed positioning fixtures and standardised vehicle placement procedures would be required to minimise measurement variation caused by changes in orientation or distance between the acoustic camera and test vehicle.

Environmental control would represent another important consideration during deployment, as background factory noise, reflective surfaces, and airflow variation may influence acoustic measurements.

To maintain measurement reliability, the proposed system would require routine calibration verification. Calibration activities should include:

- Microphone sensitivity verification,
- Acquisition system validation,
- Software integrity checks,
- Environmental baseline confirmation.

Calibration intervals should align with manufacturer recommendations and internal quality standards. Any equipment found outside acceptable calibration tolerance should trigger temporary reversion to the subjective fallback process.

Aston Martins already objective wind noise test has a calibration procedure that is carried out daily by the technician as part of first line maintenance see Figure 25.

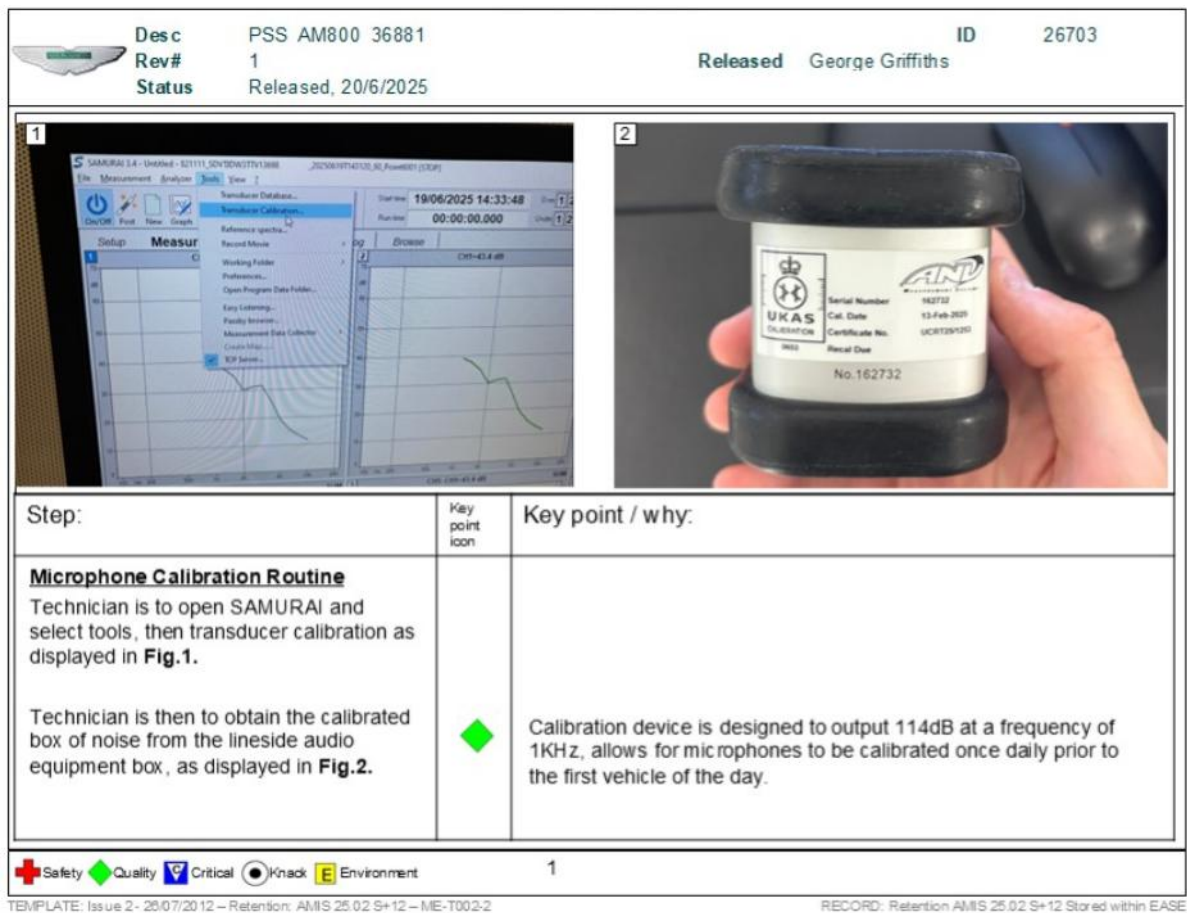


Figure 25-Windnoise calibration process document (Griffiths, 2025)

7.6 Environmental Control

One of the main limitations of the proving-ground-based measurement is the environmental variability. Potential influences are rainfall, wind noise, and surface condition changes. These conditions may impact the measured noise levels and could cause false failures. These factors cannot be eliminated entirely without a controlled environment.

Proposed environmental control include:

- Approved weather operating window.
- Predefined route and speeds
- Route maintenance and inspection

- Controlled vehicle setup

Where environmental conditions fall outside of acceptable limits, the process may require retest scheduling, engineering review, or a temporary fallback to the subjective test.

Given the UK climate and weather conditions, operating in approved weather windows is an unrealistic option as this would cause disruption to the throughput of production.

Further improvements and/or development into the recording equipment to be able to use in all conditions without causing variability which links to the Gage R&R. Environmental conditions introduce variability in outdoor acoustic measurements, affecting both sound propagation and recorded noise levels. This variability directly impacts the repeatability and reliability of NVH data, increasing measurement system error.

Environmental control is one of the most significant limitations of the proposed proving-ground overlay. Acoustic response can be influenced by wind, rain, temperature, surface condition, and background noise. Therefore, any pass/fail threshold must be validated under realistic operating conditions rather than assumed from a single reference test (Hills, et al., 2009).

7.7 Fallback Process Plan

Should the recording equipment fail, there would be no overall effect on the process should the need to revert to the original subjective method.

7.8 Process Monitoring and KPIs

Long term control requires ongoing monitoring of process performance.

Suggested Key Performance Indicators (KPIs) include:

1. NVH fail rate- Allows tracking of process quality trend. These recorded results will provide objective data of trends for escalation to the responsible engineering department and in turn drive quality to help prevent future failures, help identify supplier variation for an individual part issue and help process inconsistency between assembly operators.
2. Repeat test frequency- The proposed test aims to reduce ambiguity by introducing measurable output, limiting borderline or unclear decisions. Therefore, repeat test frequency becomes an important indicator of process clarity.
3. Equipment downtime monitoring- Important because excessive system unavailability would reduce operator confidence and increase fallback reliance on the subjective process.

4. Warranty Monitoring- Gathering trend data can then be directly correlated to warranty issue seen in the field. Test parameters can be altered to help focus on repeat issues seen in field allowing tailored detection of issues.

7.9 Compliance and Standards

To comply with relevant automotive quality standards, the process should align with the following:

- ISO 9001:2015 - Quality Management Systems (QMS)- An internationally recognised standard for quality management that help organisations consistently deliver products and services that meet customer requirements. It provides a framework for improving process, ensuring quality, and promoting continual improvement, while also building customer confidence and supporting long-term business performance (ISO, 2005)
- ISO 5128 – Acoustics: Measurement of Noise Inside Vehicles-Specifically focused on interior vehicle noise. Covering microphone placement, operating conditions, and measurement repeatability (ISO, 2023).
- ISO 45001- Occupational health and safety management systems- International standard for occupational health and safety management that helps organisations identify hazards, manage risks, and improve workplace safety. It provides a structured framework to reduce injuries and incidents, ensure legal compliance and support continual improvement, demonstrating a strong commitment to employee health and wellbeing.
- HSE Act 1974: Health and Safety at Work Act 1974-Health and safety law ensures that all workers are protected from harm at work. Employers are responsible for identifying risks, providing training, equipment, and safe working conditions, while employees must follow safety procedures, take care of themselves and others. Overall, it promotes a safe working environment through shared responsibility (HSE, 1974).

7.10 Long-Term Sustainability

The proposed is not intended as a short-term improvement, but as a foundation for future digital quality-control capability within automotive manufacturing. by introducing objective acoustic data capture and traceable measurement outputs, the system creates opportunities for further technological development and integration with wider smart manufacturing strategies. Long-term opportunities may include automated anomaly detection, machine learning-based noise classification, production trend predication, integration with manufacturing databases, and provide predictive quality analytics. These future

developments could enable earlier identification of emerging quality concerns, improved process learning and enhanced decision-making capability across production operations. This demonstrates that the proposed system is scalable beyond the initial implementation phase and has the potential to support future Industry 4.0 manufacturing initiatives.

The long-term value of objective NVH data is that it creates the foundation for automated anomaly detection and predictive quality monitoring. Recent work on AI-enabled NVH testing indicates that production acoustic data can support anomaly classification where repeatable measurement systems and sufficient data history are available (Blickensdorff, et al., 2023).

8 Results and Discussions

This chapter evaluates the outcomes of the DMAIC investigation and discusses the effectiveness of the proposed objective NVH detection process in relation to the original project objectives. The discussion combines process analysis, engineering evaluation, and manufacturing considerations to determine whether the proposed system provides a realistic improvement over the current inspection process.

Unlike purely experimental NVH studies, this project focuses on process improvement and implementation feasibility within a live automotive manufacturing environment. As a result, the discussion considers not only technical measurement capability, but also operational practicality, production integration, repeatability, cost, and long-term sustainability.

8.1 Current State Findings

Table 17-Current State Findings

Current-State Finding	Evidence from Project	Impact
NVH detection is subjective	Technician-led proving ground judgment	Operator-dependent pass/fail decisions
No objective acoustic data is recorded	No dB, frequency or audio evidence captured	Limited traceability and poor trend analysis
Current route excites NVH concerns effectively	Multiple road surfaces used during road test	Route is valuable but data is not captured
Process is labour intensive	Total road test process time is 40.16 minutes	High operator dependency
Repeat testing may be required	Borderline or intermittent concerns need confirmation	Increased cycle time and delayed escalation
Warranty exposure is significant	NVH-related warranty cost since 2019 is £8.28 million	Business case for improved detection

The project identified that the challenge of improving EOL NVH inspection is not solely a measurement problem, but a balance between repeatability, practicality, customer relevance and manufacturing feasibility, Table 17.

One of the largest engineering trade-offs identified was the balance between repeatability and real-world representativeness. Rig-based excitation systems provide highly controlled and repeatable testing conditions; however, they may not fully reproduce real customer operating environments, particularly transient road inputs, tyre interaction, and environmental influences. Conversely, proving-ground testing exposes the vehicle to realistic dynamic excitation conditions but introduces environmental variability that can influence measurement consistency.

This trade-off was a major factor influencing the selection of the proving-ground overlay system as the preferred short-term solution.

A second key trade-off exists between diagnostic capability and production practicality. Acoustic camera systems provide advanced sound source localisation and detailed acoustic analysis; however, their high cost, setup complexity and sensitivity to reflective cabin environments reduce their suitability for high-throughput production inspection. Although technically capable, their implementation within routine manufacturing operations would require substantial investment and process development.

The proposed binaural overlay system was therefore selected because it provides a practical compromise between objective measurement capability and operational feasibility.

Another important consideration identified during the project is that fully objective NVH assessment remains difficult because customer perception of sound quality is inherently subjective. Although measurable acoustic thresholds can improve repeatability and traceability, human perception still influences how customers judge refinement and perceived quality. As a result, objective measurement systems should be viewed as decision-support tools rather than complete replacements for engineering judgment.

This demonstrates that successful NVH quality-control requires both engineering measurement capability and alignment with human perception.

8.2 Operator Variation Findings.

The current measurement system is primarily based on technician hearing, experience, and interpretation. From a Six Sigma perspective, this suggests the operator effectively becomes the measurement system. This introduces both repeatability and reproducibility risk.

Repeatability may be affected if the same technician assesses the same type of noise differently on different days due to fatigue, concentration, or environmental condition.

Reproducibility may be affected because different technicians may classify or escalate the same acoustic concern differently.

The Flags reporting data supports this concern. The comparison of the road test defect categories between technicians showed limited consistency in the top reported issues, with only one common defect category appearing across the two technician datasets reviewed. This suggests that the current process is influenced by individual judgment and classification behaviour, rather than being controlled by a standard measurable threshold.

8.3 Project Limitations

Several limitations should be acknowledged within the scope of this project.

9 Conclusion and Recommendations

9.1 Conclusion

This project investigated how the current subjective EOL NVH detection process in automotive manufacturing could be improved through a more objective and repeatable measurement system using the DMAIC methodology. The study found that while the existing technician-led proving-ground process provides valuable real-world assessment, it lacks repeatability, traceability, and measurable acoustic data, making results highly dependent on operator judgment.

Analysis showed that the process is labour intensive and limited in its ability to support long-term trend analysis or continuous improvement. The main source of variation was identified as the absence of objective measurement, alongside environmental variation, and inconsistent pass/fail interpretation.

Several improvement technologies were evaluated, with the proposed binaural measurement proving-ground overlay identified as the most practical solution due to its balance of repeatability, customer relevance, and ease of production integration. The system would improve process control and traceability while maintaining existing manufacturing operations.

Overall, the project demonstrates that objective acoustic measurement can significantly improve consistency, repeatability, and data-driven quality-control within premium automotive manufacturing.

9.2 Recommendations

Based on the findings of this project, the following recommendations are proposed:

1. Conduct a pilot implementation trial using the proving-ground overlay system to validate repeatability and operational compatibility.
2. Develop a “golden vehicle” acoustic database to establish objective pass/fail thresholds.
3. Complete a formal Gage R&R study to validate measurement repeatability and reproducibility.
4. Integrate automated data reporting into the existing Flags quality system to improve trend analysis and escalation efficiency.
5. Continue investigating rig-based excitation testing as a potential future long-term strategy for automated NVH validation.
6. Investigate future machine learning and predictive analytics capability using objective NVH data collected from production vehicles.
7. Continue developing environmental compensation strategies to minimise outdoor proving-ground variability.

These recommendations provide a structured pathway toward a more objective, repeatable, and scalable NVH quality-control process.

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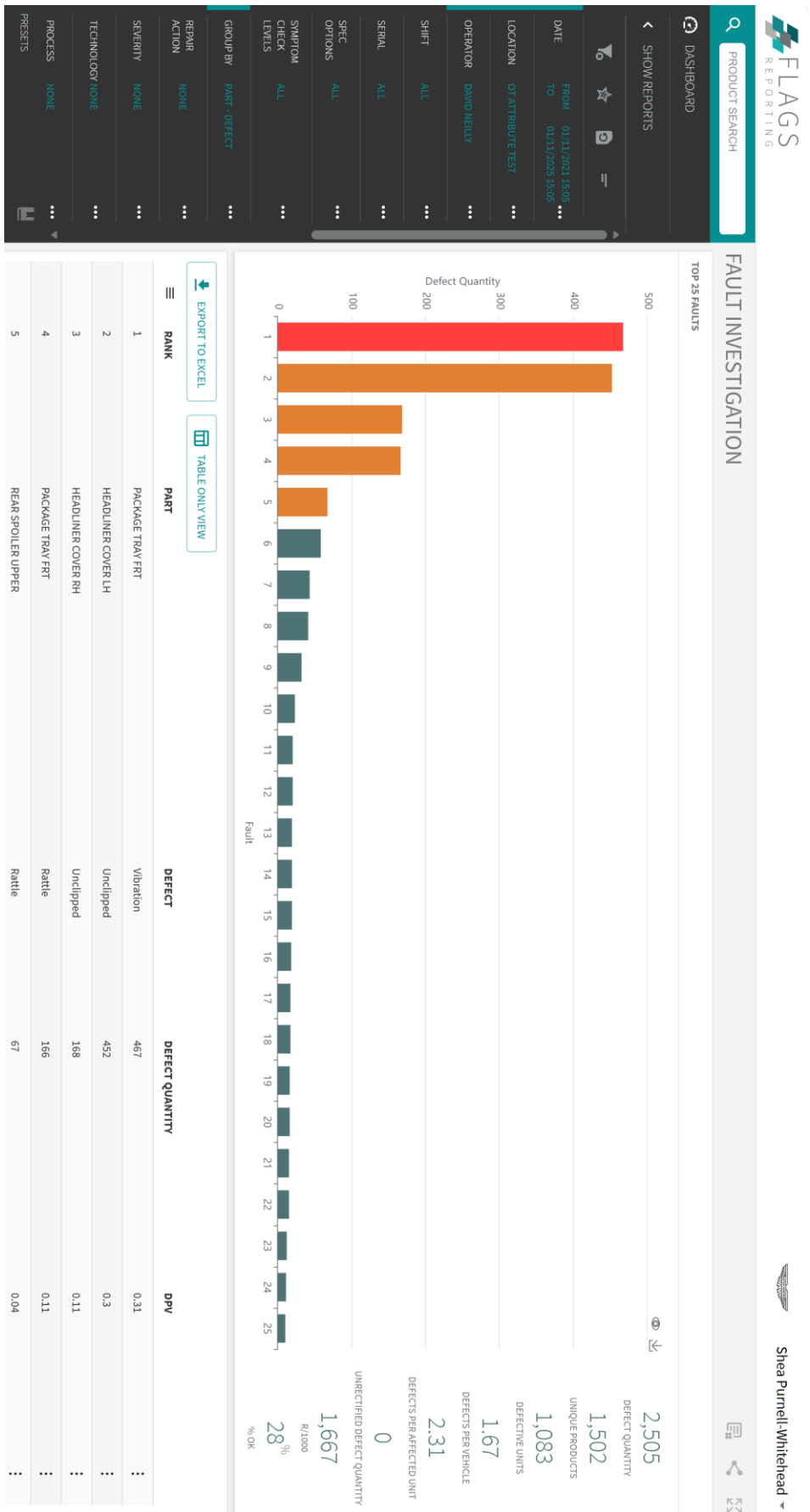
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11 Appendix

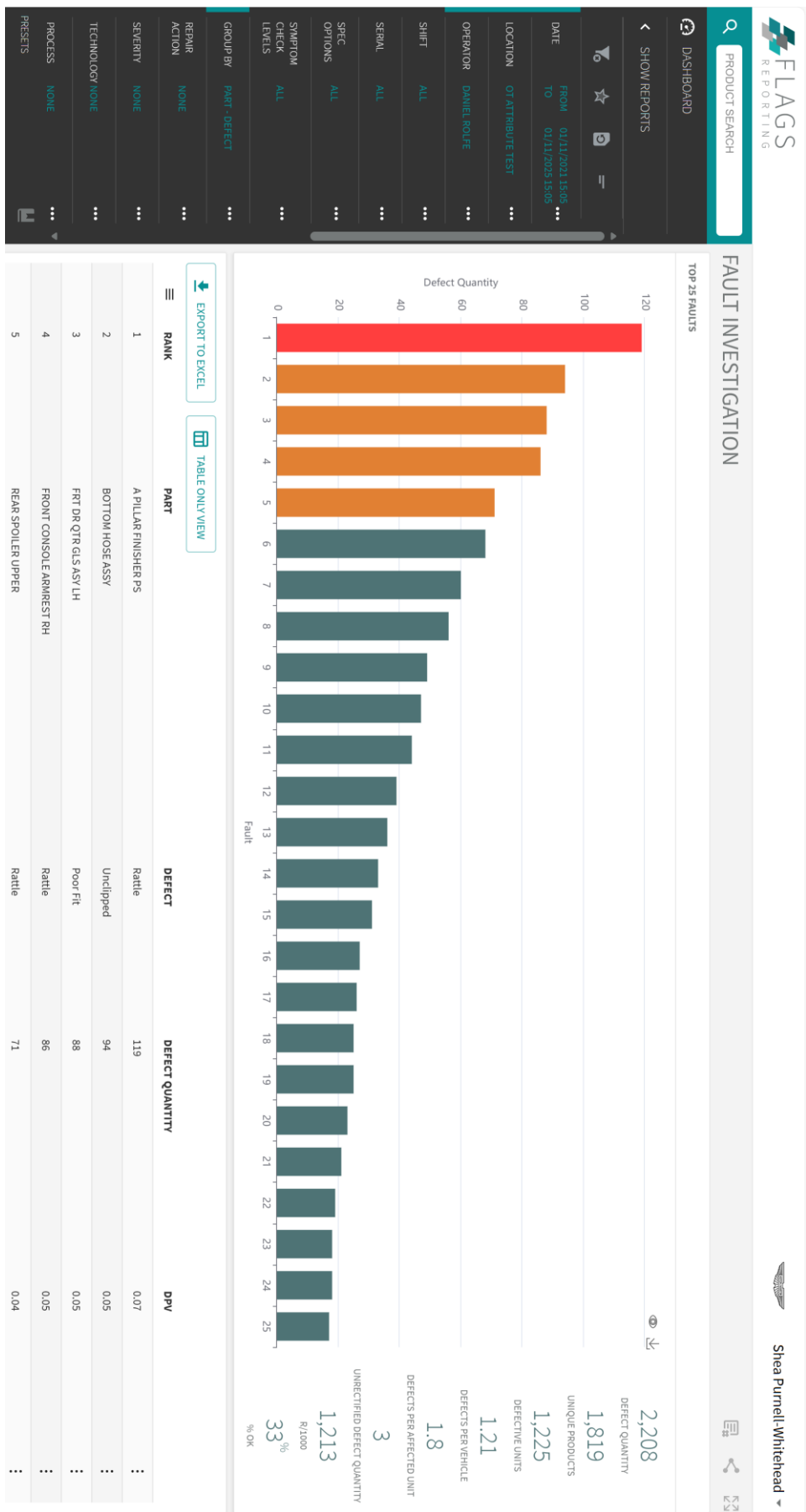
11.1 Appendix A

Op	St Athan T&E Description	VA	ENVA	NVA	Total	Combined	Average	Ease	Diff	Comment
1	36273 Drive car onto ramp and raise	0.00	0.00	0.61	0.61		0.61			Add comment explaining the difference
2	21568 Suspension/Steering Wheel - Safety Check	0.00	0.00	2.93	2.93		2.93	0	2.93	Add comment explaining the difference
3	21270 Underbody Checks - Wheel Fixings	0.00	0.00	5.33	5.33		5.33	0	5.33	Add comment explaining the difference
4	36279 Paperwork	0.00	0.00	0.96	0.96		0.96			Add comment explaining the difference
5	No op 2 Lower ramp	0.00	0.00	0.93	0.93		0.93			Add comment explaining the difference
6	No op 3 Remove deuterions	0.00	0.00	0.26	0.26		0.26			Add comment explaining the difference
7	27246 Under Bonnet Inspection Process	0.00	0.00	2.13	2.13		2.13	0	2.13	Add comment explaining the difference
8	No op 4 Fit tailgate slave template	0.00	0.00	0.37	0.37		0.37			Add comment explaining the difference
9	21288 Road Test	0.00	0.00	2.77	2.77		2.77	0	2.77	Add comment explaining the difference
10	28312 Road Test - Brake Straight	0.00	0.00	1.02	1.02		1.02	0	1.02	Add comment explaining the difference
11	29313 Road Test - Hill Climb	0.00	0.00	0.92	0.92		0.92	0	0.92	Add comment explaining the difference
12	29314 Road Test - Washboard	0.00	0.00	0.30	0.30		0.30	0	0.30	Add comment explaining the difference
13	29315 Road Test - Speed Bumps	0.00	0.00	0.25	0.25		0.25	0	0.25	Add comment explaining the difference
14	29316 Road Test - Belgium Blocks	0.00	0.00	0.23	0.23		0.23	0	0.23	Add comment explaining the difference
15	29317 Road Test - RHS Twist and Turn	0.00	0.00	0.10	0.10		0.10	0	0.10	Add comment explaining the difference
16	29318 Road Test - Out of Phase Sine Wave	0.00	0.00	0.18	0.18		0.18	0	0.18	Add comment explaining the difference
17	29319	0.00	0.00	0.35	0.35		0.35			Add comment explaining the difference
18	29320 Road Test - LHS Twist and Turn	0.00	0.00	0.12	0.12		0.12	0	0.12	Add comment explaining the difference
19	29321 Road Test - Angle Irons	0.00	0.00	0.13	0.13		0.13	0	0.13	Add comment explaining the difference
20	29322 Road Test - Ropes	0.00	0.00	0.20	0.20		0.20	0	0.20	Add comment explaining the difference
21	29323 Road Test - Cobblestone	0.00	0.00	0.25	0.25		0.25	0	0.25	Add comment explaining the difference
22	29324 Road Test - Painted Lines	0.00	0.00	0.17	0.17		0.17	0	0.17	Add comment explaining the difference
23	29325 Road Test - Figure of 8	0.00	0.00	0.48	0.48		0.48	0	0.48	Add comment explaining the difference
24	29326 Road Test - Slalom	0.00	0.00	0.10	0.10		0.10	0	0.10	Add comment explaining the difference
25	29327 Road Test - Morris Shelter	0.00	0.00	0.73	0.73		0.73	0	0.73	Add comment explaining the difference
26	29328 Road Test - Road Circuit	0.00	0.00	1.93	1.93		1.93	0	1.93	Add comment explaining the difference
27	36471 Drive to car wash	0.00	0.00	1.47	1.47		1.47			Add comment explaining the difference
28	21567 Activate Car Wash Process	0.00	0.00	6.07	6.07		6.07	0	6.07	Add comment explaining the difference
29	No op 5 Drive car back to road test	0.00	0.00	1.25	1.25		1.25			Add comment explaining the difference
30	No op 6 Remove tailgate slave template	0.00	0.00	0.61	0.61		0.61			Add comment explaining the difference
31	21237 Car Wash - QC Checks	0.00	0.00	0.70	0.70		0.70	0	0.70	Add comment explaining the difference
32	34529 Scan Vehicle into Station LN Procedure	0.00	0.00	0.91	0.91		0.91	0	0.91	Add comment explaining the difference
33	36496 Flags	0.00	0.00	1.41	1.41		1.41			Add comment explaining the difference
34	No op 7 Drive to MPR	0.00	0.00	2.57	2.57		2.57			Add comment explaining the difference
35	No op 8 Replace protection on steering wheel	0.00	0.00	0.50	0.50		0.50			Add comment explaining the difference
36	No op 9 Walk back to road test	0.00	0.00	0.92	0.92		0.92			Add comment explaining the difference
		0.00	0.00	40.16	40.16			0.00	27.96	

11.2 Appendix B



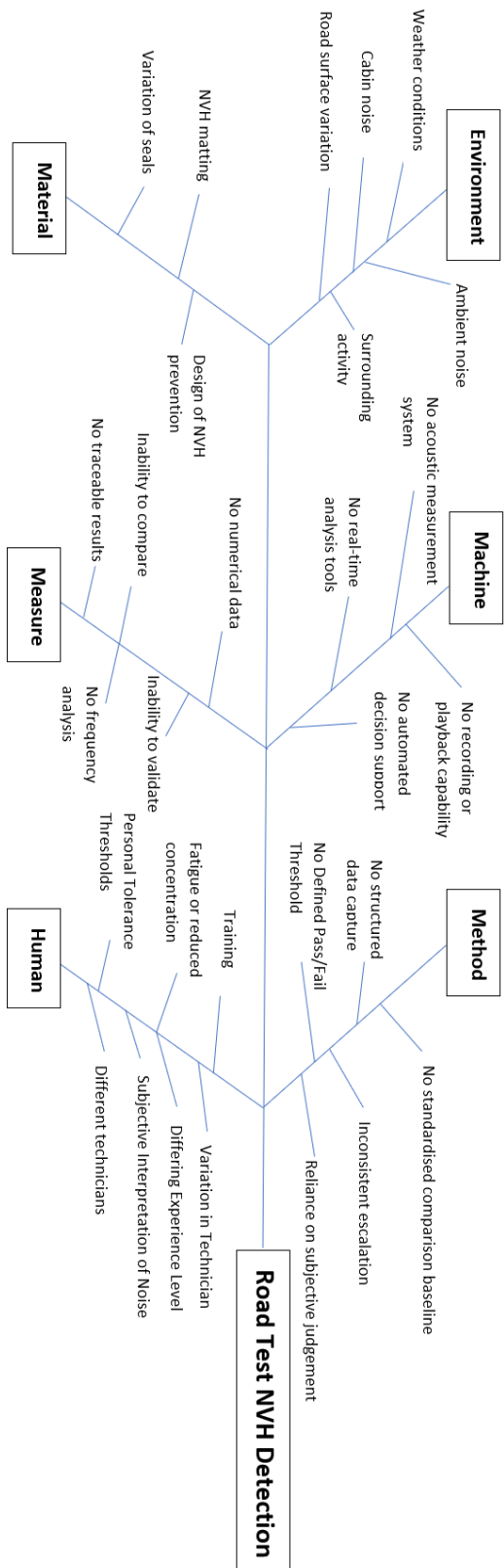
11.3 Appendix C



11.4 Appendix D

2025 Hourly Costs Per Area Calculator										
Area	Direct Labour Rate	Overhead Rate	Fully Loaded Rate	Fully Loaded/ Min	Fully Loaded/ Second	Enter Mins/ Area	Mins Cost	Enter Seconds/ Area	Secs Cost	Total Cost
BodyShop	£42.50	£95.82	£138.32	£2.31	£0.0384		£0.00		£0.00	£0.00
Paint	£43.46	£82.12	£125.58	£2.09	£0.0349		£0.00		£0.00	£0.00
T&F	£39.26	£84.32	£123.58	£2.06	£0.0343		£0.00		£0.00	£0.00
VC	£39.64	£102.96	£142.60	£2.38	£0.0396	20.00	£47.53		£0.00	£47.53

ISHAKAWA – Road Test NVH Detection



T&F PFMEA - SEVERITY RANKING

Effect on Product/Customer	Rank	Effect on Process/Manufacturing	AML Statement
SAFETY and/or REGULATORY REQ not met - NO Warning [CPA 300' Safety no Warning]	10	May ENDANGER OPERATOR (machine or assembly) - NO Warning	Extremely severe failure that affects the safe vehicle operation of the vehicle / non-compliance with legal requirements. May endanger machine / operator. High risk to company's production capability/long term, which will affect financial stability. CPA 300 call due to VIS spec or performance failure
SAFETY and/or REGULATORY REQ not met - WITH Warning [CPA 300' Safety With Warning]	9	May ENDANGER OPERATOR (machine or assembly) - WITH Warning	Without warning. With warning.
LOSS of PRIMARY Function - vehicle inoperable, does not affect safe vehicle operation [CPA 70' Walk Home no Warning]	8	MAJOR DISRUPTION - scrap 100% of product, line shut down, or stop shipping. - Yard Hold/Ship Hold - 4 hours or more - Scrap Vehicle - Mainline / Shop Hold - Excessive down time greater than 4 hours	Vehicle is inoperable, loss of primary function. Unscheduled dealer visit. Major disruption to the production line / extended line stop / stop vehicle shipment. 100% of the process related product made in station to be scrapped. CPA 70: Customer extremely dissatisfied. Damaged, incorrect or missing part. Complaint expected by >70% of customers due to VIS spec or performance failure. Tool wear / damage is high.
DEGRADATION of PRIMARY Function - vehicle operable, but at reduced level of performance [CPA 70' Walk Home with Warning]	7	SIGNIFICANT DISRUPTION - scrap some product, deviation from primary process, (decreased line speed or added manpower) -Added manpower Outside Station/Group Team Lead: example 100% Contain, Mark, etc for a shift - Loss of Trace - Scrap Major Component/Assembly - Example:Frame, Engine, Trans, etc - Mainline stopped for (3) Hours - Repair likely to cause collateral damage to nearby KCSS/PQC/Electrical parts.	Vehicle is operable, but at a reduced level of performance. Degraded primary function or loss of secondary function. Unscheduled dealer visit. Deviation from primary process with significant disruption to the production line. Delayed delivery or Tool wear. Decreased line speed or added manpower. Product may have to be sorted and a portion scrapped (<100%). CPA 70: Customer extremely dissatisfied. Damaged, incorrect or missing part. Complaint expected by >70% of customers due to VIS spec or performance failure.
LOSS of SECONDARY Function - vehicle operable, but comfort / convenience functions inoperable	6	MODERATE DISRUPTION - 100% of product reworked off-line -Standard / Procedure is offline repair -Mainline Stopped for (60) Minutes or More - Repair likely to cause collateral damage to nearby parts - Primary process followed.	Vehicle is operable, but comfort / convenience features are inoperable. Degraded secondary function. Constant squeaks & rattles. Unscheduled dealer visit. Moderate disruption to the production line which delays delivery. A portion (<100%) may have to be scrapped. CPA 70: Customer extremely dissatisfied. Damaged, incorrect or missing part. Complaint expected by >70% of customers due to VIS spec or performance failure.
DEGRADATION of Secondary Function - vehicle operable, but comfort / convenience functions at reduced level of performance	5	MODERATE DISRUPTION - some product reworked off-line -Standard Repair done online and downstream -Mainline Stopped for more than (30) Minutes	Vehicle is operable, but comfort / convenience features operate at a reduced level of performance. Intermittent squeaks & rattles. Repaired at scheduled dealer visit. Moderate disruption to the production line whereby 100% of the product may have to be re-worked off line. CPA 30: Defect noticed by average customer. Major cosmetic item / Poor appearance. Complaint expected by >50% of customers / VIS spec, performance or cosmetic defect.
ANNNOYANCE (vehicle is still operable) - appearance or audible noise - noticed by >75% of customers	4	MODERATE DISRUPTION - 100% of product reworked In-station - Line Stop Repair (in Station) - Andon Pull ; less than "two cycles" (30) Minutes	Minor disruption to the production line. The product may have to be sorted and a portion (<100%) and re-worked on-line after the station / operation. CPA 30: Defect noticed by average customer. Major cosmetic item / Poor appearance. Repaired at scheduled dealer visit. Complaint expected by >30% of customers / VIS cosmetic defect.
ANNNOYANCE (vehicle is still operable) - appearance or audible noise - noticed by 50% of customers	3	MODERATE DISRUPTION - some product reworked In-station - Line Stop Repair (in Station) - Andon Pull ; less than "one cycle" / (15) Minutes	Minor disruption to the production line. The product may have to be sorted and a portion (<100%) has to be re-worked prior to station / operation.
ANNNOYANCE (vehicle is still operable) - appearance or audible noise - noticed by <25% of customers	2	MINOR DISRUPTION - slight inconvenience to process, operation, or operator -Repair (in station) - No Line Stop	Very minor disruption to the production line. The product may have to be sorted and a portion (<100%) can be reworked within station / operation TACT. Slight inconvenience to process or operator. CPA 30: Defect noticed by discriminating customer / VIS cosmetic defect
NO EFFECT	1	NO EFFECT	No discernable effect

11.7 Appendix G

PFMEA - OCCURRENCE RANKING							
Volume per week		34	UPW				
Probability of Failure	Rank	Failure Rate	Production per week	Production per month	Production per year	AML Statement	
VERY HIGH	10	≥ 100 per thousand > 1 in 10	10%	≥4	≥16	≥208	Very High New process / technology without any existing preventive controls. Approximately 100% NOK. Process failure is inevitable.
	9	50 per thousand 1 in 20	5%	2	8	104	
	8	20 per thousand 1 in 50	2%	1	4	52	
HIGH	7	10 per thousand 1 in 100	1%	0.3	1.4	18	High Current process / technology applied to new commodity with uncertainty about effectiveness of preventive controls. Approximately 15% NOK. Generally associated with similar processes that have often failed.
	6	2 per thousand 1 in 500	0.2%	0.07	0.27	4	
	5	.5 per thousand 1 in 2,000	0.05%	0.02	0.07	0.88	
MODERATE	4	.1 per thousand 1 in 10,000	0.01%	0.003	0.01	0.18	Moderate New process / technology using proven preventive controls. Approximately 5% NOK. Generally associated with similar processes that have experienced occasional failures, but not in major proportions.
	3	.01 per thousand 1 in 100,000	0.001%	0.0003	0.001	0.02	
	2	≤ 0.001 per thousand 1 in 1,000,000	0.0001%	0.00003	0.00014	0.00177	
LOW							Low Minor changes to current processes with positive production experience under comparable conditions. Isolated failures associated with almost identical processes.
	1						
VERY LOW	1	Failure is eliminated through preventive control.					Remote No failures associated with identical processes. Failure is eliminated through preventive controls i.e. Poke yoke process / assembly.

T&F PFMEA - DETECTION RANKING

Opportunity for Detection	Rank	Detection Control	Line Stop	In Station	Subsequent Operation	100%	Sampling	AML Statement
NO DETECTION OPPORTUNITY	10	NO DETECTION - There is no detection method or the defect cannot be detected in the assembly plant.						Absolute Uncertainty Control of will not and/or cannot discover the potential failure cause or subsequent failures (in-house). No current detection method in place.
NOT LIKELY TO DETECT AT ANY STAGE	9	SINGLE SENSORY CHECK - PERIODIC <i>Examples:</i> visual check OR touch RANDOM AUDIT <i>Examples:</i> CPA, drive audits, random audits, random torque checks, random visual inspection	MANUAL		X		X	Very Remote Very remote likelihood the detection control will detect the potential failure cause or subsequent failures (in-house). Very low detection potential (e.g. Random audits).
PROBLEM DETECTION POST PROCESSING	8	ATTRIBUTE GAUGING - PERIODIC <i>Examples:</i> Squeak & rattle track, CPA water test inspection SINGLE SENSORY CHECK - 100% SUBSEQUENT OPERATION <i>Examples:</i> visual check OR touch, CAVE line, functional test (without gauge, not automatic), verification station	MANUAL		X		X	Remote Discovery Remote likelihood the detection control will detect the potential failure cause or subsequent failures (in-house). Unproven detection method.
PROBLEM DETECTION AT SOURCE	7	ATTRIBUTE GAUGING - PERIODIC <i>Examples:</i> torque audit - concalift, body leak tester (BLT) SINGLE SENSORY CHECK - 100% IN-STATION <i>Examples:</i> visual check OR touch MULTIPLE VISUAL INSPECTIONS - first check is in station DOUBLE SENSORY CHECK - 100% SUBSEQUENT OPERATION <i>Examples:</i> (visual AND tactile) visual with paint mark or visual with pull test DATA RECORDING that notifies the operator of a discrepant part (pass/fail) without line lock-out ATTRIBUTE GAUGING - IN-STATION <i>Examples:</i> go/no go, manual torque check, length of socket, click wrench VARIABLE GAUGING - SUBSEQUENT OPERATION <i>Examples:</i> auto functional test (such as door closing tool) DOUBLE SENSORY CHECK - 100% IN-STATION <i>Examples:</i> (visual AND tactile) visual with part mark or visual with pull test Kitting or Sequencing using positional pick, and marking each line on the run sheet	MANUAL	X		X	X	Very Low Uncertain in the ability of the detection measures. No previous experience with the proof procedures. Detection of the failure cause post process, failure detection in-station using visual/tactile/audible means post process (go/no go, manual torque checker)
PROBLEM DETECTION POST PROCESSING	6	CANNOT COMPLETE SUBSEQUENT OPERATION <i>Examples:</i> go/no go, manual torque check, length of socket, click wrench VARIABLE GAUGING - SUBSEQUENT OPERATION <i>Examples:</i> auto functional test (such as door closing tool) DOUBLE SENSORY CHECK - 100% IN-STATION <i>Examples:</i> (visual AND tactile) visual with part mark or visual with pull test Kitting or Sequencing using positional pick, and marking each line on the run sheet	MANUAL	X		X	X	Low Detection of the failure cause post process or failure detection at next station (go/no go, manual torque checker). Reliable inspection procedure from comparable processes under new conditions (machines, materials)
PROBLEM DETECTION AT SOURCE	5	NOTIFICATION ONLY - IN-STATION <i>Examples:</i> pick lights (part picks without line lock-out), flouting or tooling, host scaling, bar code reader, torque controlled tools with lights, break away tools, any test that notifies the operator of a discrepant part without line lock-out. Kitting or Sequencing using Operator Assisted Technology, with Self Assisted Support <i>Examples:</i> Voice Pick, Projector Pick, etc. VARIABLE GAUGING - IN-STATION <i>Examples:</i> hand held laser gap and flush gauge	MANUAL	X		X	X	Moderate Reliable test procedures from comparable processes under new conditions (machines, materials). Possible detection of the failure cause in-station by operator using automated controls that will detect discrepant part and notify the operator (light, buzzer, J). Gauging performed on set-up or checks made on first in-first-out.
PROBLEM DETECTION POST PROCESSING	4	AUTO LINE STOP - SUBSEQUENT OPERATION <i>Examples:</i> scanning (bar code readers), vision system, error proofing tied to the vehicles (not pick bins) such as pressure mats, limit switches, flouting or tooling, counter, PLC controls. VECTS, DVT, or VAST (when shipping holds are in place) PART PICK feedback - IN-STATION , or in kitting/sequencing (with notification and line lock-out)	AUTO		X		X	Moderately high Moderately high likelihood the detection measure(s) will detect the failure cause. Detection of the failure cause at next station using automated controls, which will prevent part from being processed further. Low detection of the failure cause in-station. Reliable test procedures from comparable processes under new conditions (machines, materials)
PROBLEM DETECTION AT SOURCE	3	CANNOT COMPLETE CURRENT OPERATION AUTO LINE STOP - IN-STATION <i>Examples:</i> scanning (bar code readers), vision system, error proofing tied to the vehicles (not pick bins) such as pressure mats, limit switches, flouting or tooling, counter, PLC controls or torque tools (low torque, high torque, no torque; angle monitoring for cross-threading), garage doors	MANUAL	X			X	High High likelihood tried & tested detection measure(s) will detect the failure cause. High detection of the failure cause in-station using automated controls that will detect the discrepant part and prevent it from being processed further. The required measuring equipment has been confirmed.
ERROR DETECTION AND/OR PROBLEM PREVENTION	2	DEFECT PREVENTION - IN-STATION (cannot assemble with defect) <i>Examples:</i> scanning with part lock prior to assembly (cannot continue to assembly), vision system with part lock prior to assembly	AUTO	X			X	Very High Very high likelihood that tried & tested detection measure(s) will detect the failure cause. Detection of the failure cause in-station using automated controls that will detect the discrepant part from being made. The required measuring equipment has been confirmed.
ERROR DETECTION NOT APPLICABLE; ERROR PREVENTION	1	ERROR PROOFED - the defect cannot happen	AUTO	X			X	Almost Certain Failure cause will almost certainly be detected using reliable controls. Discrepant parts cannot be made due to error prevention by process design, machine Jig, fixture design. Failure cause has been eliminated through preventive measures, thus no detection action is required.

11.9 Appendix I

