Development of an Automated System for Enhanced Repeatability and Efficiency in Brake Pedal Feel Evaluation

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ABSTRACT

Customer confidence in vehicle braking performance is heavily influenced by perceived pedal feel. This paper presents a method for automating the Brake Pedal Feel test, which traditionally relies on subjective evaluation and objective measurements performed by highly trained personnel. The automated system, utilizing brake pedal applicator, acquires objective measurements of confident braking characteristics on vehicles with vacuum or hydraulic boosters. Key parameters, including pedal force and travel, are captured via a data acquisition system, accelerometers, and specialized transducers. The automated approach addresses the challenge of achieving consistent and linear pedal application rates across varying vehicle speeds, leading to improved test repeatability, reduced execution time, and enhanced efficiency compared to manual methods.

INTRODUCTION

The landscape of automotive engineering is being fundamentally reshaped by accelerating technological innovation. As vehicles become more complex, incorporating advanced powertrain technologies, sophisticated electronic systems, and evolving safety features, the demands placed on validation and testing processes intensify. Alongside the development of these new vehicle systems, significant advancements in testing technologies themselves are enabling engineers to collect objective data with greater efficiency and accuracy than ever before. This capability is vital for ensuring performance, reliability, and compliance with stringent safety and environmental standards.

Despite the wealth of objective data available, a core challenge persists in predicting and engineering for the subjective perception of vehicle attributes by the end customer. While metrics like force, displacement, and timing can be measured precisely, the integrated sensory experience – the "feel" – is inherently subjective. This gap between objective measurement and subjective experience is particularly critical for driver interfaces that directly impact confidence and control. Among these, brake pedal feel stands out as a paramount attribute. It communicates vital information to the driver about the vehicle's deceleration capability and influences their sense of security and command [1]. The transition towards electrified vehicle architectures introduces additional layers of complexity, often decoupling the braking system's assist from the traditional engine vacuum source and presenting new challenges in consistently delivering desired pedal feel characteristics.

This paper explores the pursuit of efficiency and accuracy in objective measurement through test automation, the crucial task of interpreting the data, and engineering for the subjective customer experience, using brake pedal feel as a central case study. We will discuss the specific technical challenges presented in the analysis of this attribute and explore an objective execution method.

BRAKE ASSIST TECHNOLOGIES

This chapter provides an overview of the systems designed to supplement or amplify the driver's manual input to the braking system, primarily to reduce the physical effort required to achieve desired deceleration levels. These technologies are crucial for driver comfort, safety, and enabling advanced vehicle features. Although, the vehicle behavior during braking is a result of the characteristics of the brake system as a whole; specifically, it stems from the interaction among the system's various components.

The Conventional Hydraulic Braking Systems, the foundational technology relying solely on hydraulic pressure generated by driver pedal effort to apply friction brakes. While simple and cost-effective, these systems require significant pedal force for effective deceleration. This technology has been discontinued as it is unsuitable for the higher power and speed levels characteristic of contemporary vehicles.

Next, Vacuum-Assisted Hydraulic Braking Systems (incorporating a brake booster or servo) are predominantly used in Internal Combustion Engine (ICE) vehicles, these systems utilize engine intake vacuum to amplify pedal force, significantly reducing driver effort and enhancing comfort. Benefits include proven reliability and a well-understood pedal feel characteristic [2].

The chapter then transitions to braking systems in Electric Vehicles (EVs). While EVs retain a hydraulic friction braking system for safety and high deceleration requirements, the absence of a traditional engine vacuum source necessitates alternative power assistance.

Electric Vacuum Pump (EVP) Systems are explored as a common solution for providing vacuum assist in EVs and certain ICE vehicles with insufficient manifold vacuum, such as engines equipped with turbo compressor. These systems use an electrically driven pump to generate vacuum independently of the engine. Benefits include flexibility in packaging and consistent vacuum supply. However, they introduce additional component cost, power consumption (though typically low), and complexity compared to passive vacuum sources. Managing pedal feel to mimic conventional systems can also be a challenge.

Finally, Electro-Hydraulic Braking (EHB) Systems are discussed. These systems, often enabling Brake-by-Wire functionality, replace the direct mechanical link with electronic control, using electric pumps and valves to generate and distribute hydraulic pressure. A key benefit is the precise control over individual wheel braking, which facilitates optimal blending of friction braking with Regenerative Braking (the process of using the electric motor to decelerate and recharge the battery). EHB systems offer enhanced performance for advanced safety features (like Autonomous Emergency Braking - AEB), potential for faster response, and packaging flexibility. The cost implications are significantly higher due to the complexity of electronics, hydraulics, and control software, requiring robust redundancy for safety-critical functions. The chapter also touches upon the benefits of Regenerative Braking itself, primarily improved energy efficiency/range and reduced friction brake wear, noting its integration within the overall braking strategy enabled by EHB or sophisticated control systems.

TEST METHOD

The purpose of the procedure is to characterize brake pedal feel using Conventional Hydraulic Braking or Electric Vacuum Pump (EVP) Systems by objective measurements related to confident braking characteristics.

The existing testing methodology translates subjective pedal feel into objective data by measuring relevant parameters under various operational conditions. These conditions typically include static measurements, specified vehicle speeds and deceleration rates, brake system response time delay, and hysteresis characteristics. In 1970, Mortimer et al, published a study identifying, under various conditions and based on pedal force gain (defined as the ratio of pedal force to deceleration), an optimal range of pedal comfort that facilitates achieving maximal vehicle braking performance [3].

The test vehicle utilized shall be representative of the appropriate design level, encompassing all relevant subsystems and components. Prior to testing, the vehicle is inspected to confirm its mechanical integrity and suitability for test operations.

The decelerometer is affixed to a flat mounting surface located at the vehicle centerline, positioned as close as practical to the vehicle's center of gravity. Calibration and zeroing of the decelerometer are performed prior to testing. Zeroing is conducted at the specific test location to account for local grade influences.

The pedal force transducer is mounted on the brake pedal at the nominal driver foot contact point. Precise vertical and horizontal placement is critical, as off-center positioning can introduce measurement errors. The transducer is calibrated and zeroed before testing commences. The required alignment of the pedal force transducer is illustrated in Figure 1.

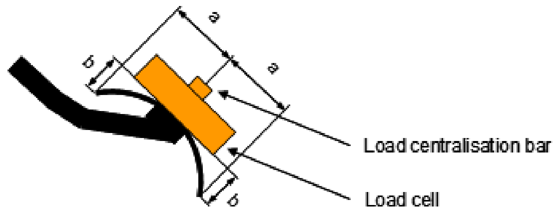

Figure 1 – Pedal force sensor on brake pedal

Pedal application shall be performed with a controlled profile, specifically either a defined force ramp or constant pedal travel. This application may be executed by the driver or by an automated brake applier, proposal in this study. Use of an automated applier is permissible provided its performance satisfies the specified quality criteria for achieving the defined ramp and maintaining constant travel.

Pedal Feel Curves are a series of the following graphs, based on vehicle deceleration, brake pedal travel, brake pedal force, work, time delay, hysteresis and static brake pedal force, as illustrated in Figure 2 and 3.

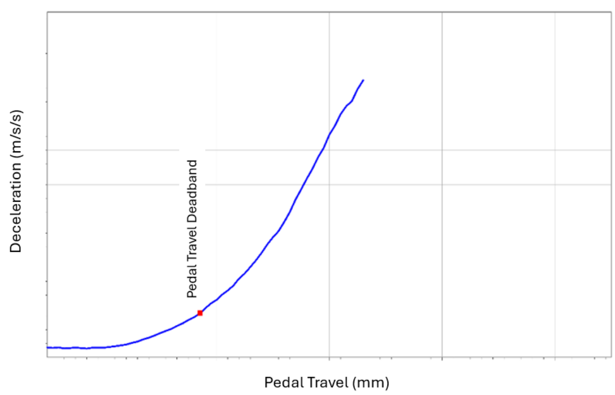

Figure 2 – Deceleration vs Pedal Travel

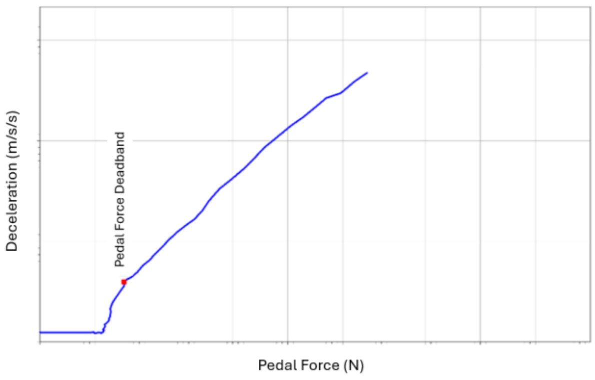

Figure 3 – Deceleration vs Pedal Force

The results are analyzed by the excel tool developed by Ford Motor Company, following the pedal travel criteria in mm/sec (with variation less than 19%) or pedal force in N, as illustrated in the Figure 4.

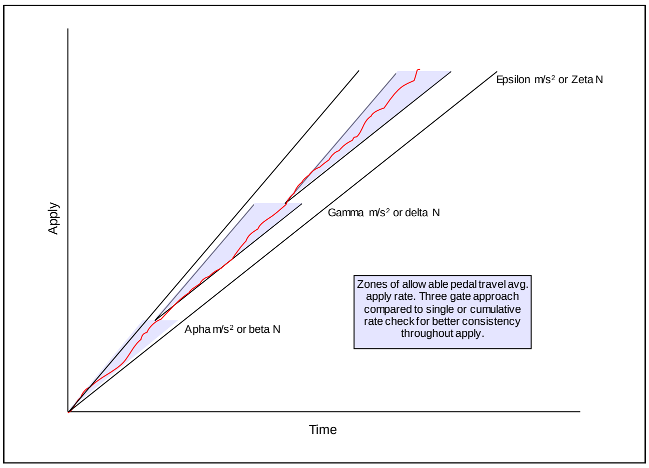

Figure 4 – Pedal Apply Rate Verification

OPTIMIZATION PROPOSAL AND TEST RESULTS

The manual execution of this test requires the driver to maintain a consistent pedal travel rate as pedal force increases – a task presenting inherent challenges for human control. The Figure 5 below quantifies the accuracy achieved when these tests are performed by a skilled driver, illustrating the variability associated with manual input.

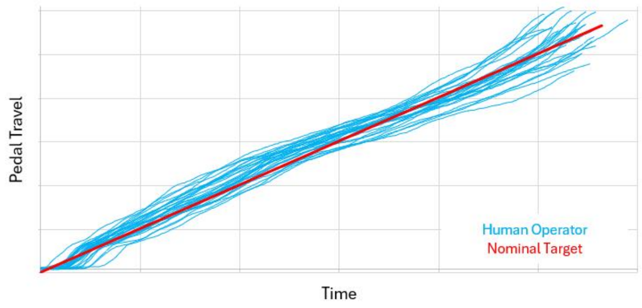

Figure 5 – Manual Pedal Apply Rate Results

In this case, a series of 30 consecutive vehicle deceleration tests were conducted under consistent conditions, including parameters such as initial braking speed and initial front brake temperature. The results demonstrated significant variability in test execution, with only 7 tests meeting the validation criteria. This yielded a success rate of merely 23%.

Aiming to optimize testing time and improve both accuracy and repeatability, a review of the existing literature and relevant publications revealed no studies specifically focused on the automation of brake pedal feel testing. Therefore, a system for automated test execution was developed. This system utilizes an available electric actuator, which was previously employed for clutch pedal actuation on chassis rolls tests. A travel transducer fitted between the pedal pad and a point below the steering column calculated to align the transducer tangentially to the line of action of the pedal at half stroke, as illustrated in Figure [6]. To adapt this actuator for brake pedal application, it was necessary to fabricate a custom adapter in our internal tooling shop, Figure 7.

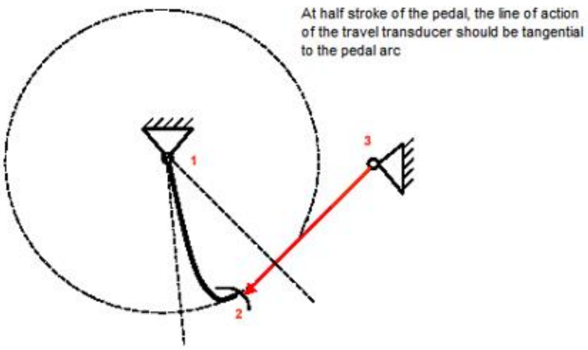

Figure 6 – Brake Pedal Actuator and Adapter

Figure 7 – Brake Pedal Actuator and Adapter

The results obtained using the automated system were highly satisfactory. We conducted 30 consecutive measurements under the same test conditions that were previously employed during the manual trials by the driver. The results demonstrated a high degree of consistency, with all 30 braking events meeting the predefined validity criteria, resulting in a 100% validation rate, as shown in Figure 8.

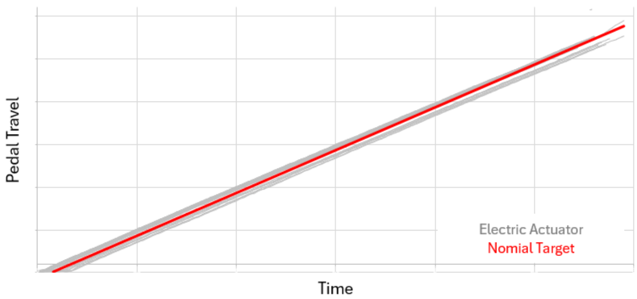

Figure 8 – Actuator Pedal Apply Rate Results

Although the proposed automated system demonstrated significant promise, a limitation was identified concerning the capacity of the available electric actuator. This actuator did not possess the capability to generate the maximum pedal force required for the chosen test vehicle. As illustrated in Figure 9, the actuator is shown increasing force (gray lines), however, this applied force is insufficient to complete the vehicle deceleration.

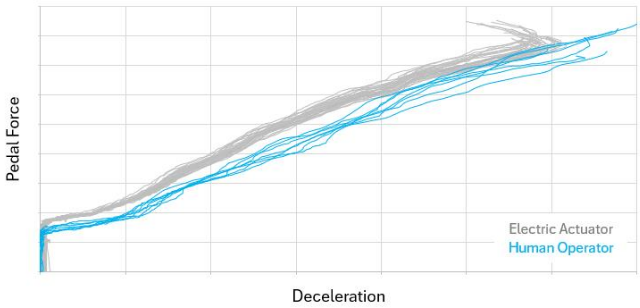

Figure 9 – Actuator versus Manual Deceleration Results

Another area for improvement identified concerns the support interface between the actuator and the load cell. For the initial evaluation, an L-shaped adapter was fabricated (Figure 10). During subsequent testing, it was observed that the recorded pedal force exhibited step-like variations. This phenomenon is hypothesized to be caused by slippage occurring between the L-shaped adapter and the load cell interface, as depicted in Figure 11.

Figure 10 – Actuator-load cell adapter

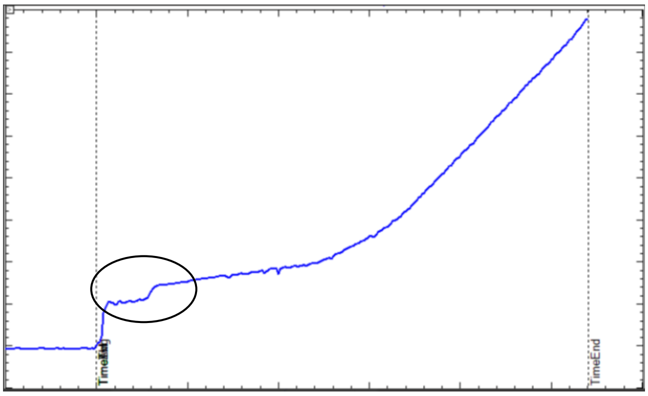

Figure 11 – Actuator Pedal Force

CONCLUSION

The proposed automated system proved effective in several key aspects, particularly in meeting the initial objectives established regarding repeatability and efficiency in test execution.

Considering that the test was executed under only one operational condition, at a single vehicle speed, the average time required for an experienced driver to perform 30 events was approximately 60 minutes. As presented in the previous chapter, the success rate for this manual execution was 20%. A minimum of 5 valid events, meeting the pedal travel criteria, are required for analysis.

With the implementation of automation, the validation rate for these events was 100%, although vehicle instrumentation requires more time initially. For the complete test, encompassing all operational conditions, an estimated reduction in execution time of up to 83% is projected.

As remaining challenges, it is still necessary to identify and procure a higher-capacity actuator capable of meeting the required application forces. Furthermore, development of an improved adapter is needed to prevent slippage between the actuator and the load cell interface.

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DEFINITIONS / ABBREVIATIONS

ICE - Internal Combustion Engine

EV - Electric Vehicles

EVP - Electric Vacuum Pump

EHB - Electro-Hydraulic Braking

AEB - Autonomous Emergency Braking