MEASUREMENT AND CONTROL OF BRAKE PEDAL FEEL QUALITY IN AUTOMOBILE MANUFACTURING

by

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Submitted to the Department of Materials Science and Engineering and the MIT Sloan School of Management in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Materials Science and Engineering
and
Master of Business Administration

In Conjunction with the Leaders for Manufacturing Program
at the Massachusetts Institute of Technology

June 2005

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ABSTRACT

Customer perception of brake pedal feel quality, as related to the perception of the brake pedal feeling soft or mushy, depends on both the customer's subjective judgment of quality and the actual build quality of the brake system. This project analyzed the different factors contributing to the soft brake condition using a fishbone diagram. A low cost tool to objectively measure brake pedal feel was developed and tested. Using this tool we found a negative linear correlation between residual air in the brake system and brake pedal feel. Even in the worst-case, a residual air level of 0.9 mL or greater is required before the brake pedal force drops 10%. The air evacuation step in the brake fluid filling process was investigated by the addition of a vacuum accumulator tank, and we found the air evacuation to depend on the brake system cross-sectional area (i.e. tube diameter) and not on the vacuum pressure. Organizational process issues were analyzed, and we found that greater cross-functional communication and collaboration are needed between manufacturing and external groups such as design and marketing.

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ACKNOWLEDGEMENTS

This project was sponsored by Toyota Motor Manufacturing North America. I would like to thank all colleagues, supervisors, and project champions who contributed to this study. The project outcome and my professional learning were greatly enhanced through my interaction with them.

I am very grateful for the advice and encouragement provided by my thesis advisors, Professor Thomas Eagar and Professor Charlie Fine. They were invaluable in refining the goals and approaches to what was initially a vague project description.

I would like to acknowledge the Leaders for Manufacturing Program (LFM) at MIT for its support of this work, and for all the opportunities it has made available to me. I enjoyed meeting, forming friendships, and collaborating with all the wonderful people. It was truly a valuable and memorable experience.

Finally, I would like to thank my parents for teaching me the value of a broad education and for their continuing support in all my endeavors.

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1 Introduction

1.1 Project Overview

This project investigated the soft brake quality problem with the Toyota Camry at the Toyota Motor Manufacturing Kentucky (TMMK) automobile assembly plant in Georgetown, Kentucky. The soft brake condition in automobiles can be described as the driver perceiving the brake pedal to feel "soft" or "mushy" when braking. Since braking feel contributes greatly to a customer's perception of an automobile's quality, Toyota considered solving the soft brake problem as important in its continuing efforts to retain its quality lead over its competitors.

The trend in vehicle initial quality, as measured by the J.D. Power Initial Quality Survey (IQS), continues to show widespread improvements, with initial quality problems dropping 11% between 2003 and 2004. Furthermore, the gap between automobile manufacturers continues to narrow (see Figure 1). Joe Ivers, partner and executive director of quality/customer satisfaction at J.D. Power and Associates, explains the significance of initial quality as follows:

> When we started tracking initial quality more than a dozen years ago, the industry said this level of quality wasn't possible and that it would cost too much. Yet, automakers could not ignore the warranty savings due to quality, as well as the impact quality has on consumer buying decisions. Even at this historically low level of initial quality problems, the ongoing quality improvements of new vehicles will continue to have a significant impact on the industry—affecting as many as one-third of new-vehicle purchases.

Toyota has been a perennial leader in quality and strives for continuous improvement as a fundamental part of its company culture. Consequently, a concerted plant-wide effort at TMMK was launched in the beginning of 2004 to improve customer satisfaction with the quality of vehicles manufactured at TMMK. The soft brake problem was quickly identified as one of several key improvement items, and a team was formed to tackle the problem.

The goal of this project was to find solutions to the soft brake problem that could be implemented in manufacturing. Since the soft brake problem had been an issue for the last several years and a lot of previous work had been done on the problem, this project sought to integrate the existing, dispersed knowledge with a new analysis of the root causes, to create a system view of the problem. Specifically, this project considered:

- The root causes of the soft brake problem
- An objective measurement tool and method to characterize the soft brake condition
- Potential manufacturing process improvements to lessen the probability of occurrence of the soft brake condition
- Organizational process issues that contributed to the problem occurring and hampered the implementation of improvement efforts

The root causes of the soft brake problem were analyzed using a fishbone diagram to get a complete and detailed picture of all the different factors contributing to the soft brake problem. We then quickly determined the need for a simple engineering tool that could quantify the soft brake condition. Due to a lack of coordination mechanisms with external design and marketing groups, we were limited to testing improvements that could be made in manufacturing. However, those organizational process issues were analyzed to determine the reasons for the lack of coordination and communication between different functional groups within the plant and various Toyota organizations outside the plant.

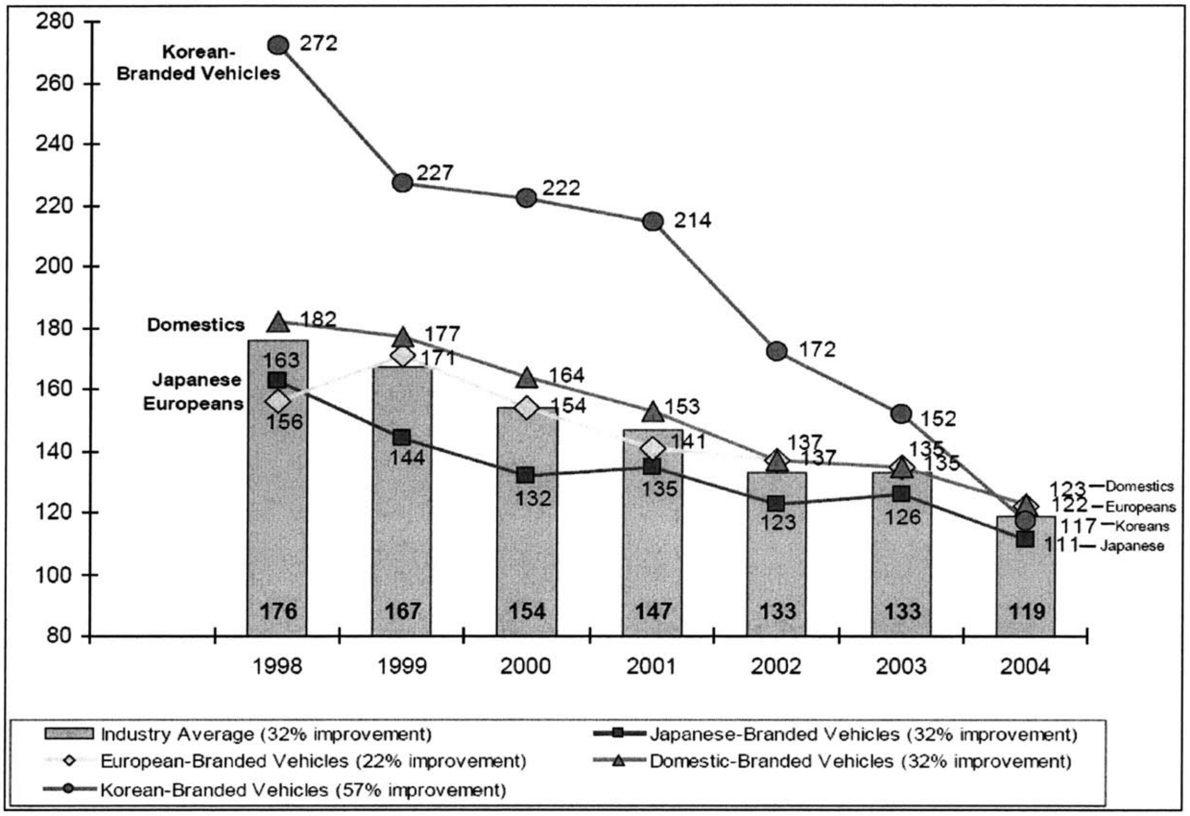

Figure 1. Initial Quality of Domestic- and Import-Branded Vehicles, 1998-2004. Source: J.D. Power and Associates 2004 Initial Quality Study, published by J.D. Power and Associates.

The scope of the project was limited to groups and processes within Toyota's North American manufacturing organization, and the majority of the work was conducted in the latter half of 2004 during the author's 6.5-month Leaders for Manufacturing internship at the TMMK assembly plant. The author worked on this project together with the production engineers, maintenance specialists, and quality engineers on the soft brake improvement team at TMMK. The author also tapped into the large body of accumulated knowledge held by the people of Toyota's North American manufacturing headquarters, Toyota Motor Manufacturing North America (TMMNA), in Erlanger, Kentucky, Toyota Motor Manufacturing Canada (TMMC), and various assembly manufacturing equipment vendors.

1.2 Thesis Structure

This thesis consists of a description of the soft brake problem (Chapter 2), results from the brake pedal feel and process improvement testing (Chapter 3), analysis of the organizational process issues (Chapter 4), and the project conclusions and recommendations (Chapter 5). The description of the soft brake problem includes analysis of customer surveys, warranty claims and a fishbone diagram of potential factors contributing to the soft brake condition. The potential solutions tested include: the development of a diagnostic tool and method to objectively measure brake pedal feel, and the use of a vacuum tank to potentially improve the brake fluid evacuation and fill process. The result of these tests were the characterization of the brake pedal feel for different vehicle types, the characterization of residual air in the brake system of production vehicles, a correlation between brake pedal feel and residual air, and a quality control plan for mitigating the soft brake problem.

2 Description of the Soft Brake Problem

2.1 What is the Soft Brake Problem?

2.1.1 The soft brake problem as "perceived quality"

Automobile drivers acquire important feedback of their automobile's braking dynamics from the feel of the brake pedal. The brake pedal should almost be an extension of a driver's leg, and a brake pedal that feels different from the driver's expectations results in a disconcerting driving experience. Consequently, drivers consider brake pedal feel to be a significant aspect of an automobile's performance and quality.

The soft brake condition is described by the driver perceiving the brake pedal feel to be "soft" or "mushy" during braking. In other words, when the driver applies force to the brake pedal the driver feels less resistance and/or more movement from the brake pedal then the driver expects. So instead of a smooth and coordinated braking effort, the driver must compensate for the difference between the expected and actual brake pedal feel. Furthermore, there are other customer comments that are often linked to the soft brake problem, such as, "brake pedal goes to the floor," "excessive brake pedal travel," and "insufficient stopping power." Thus there is ambiguity with what customers may consider a soft brake problem.

Thus one dimension of the soft brake problem is the customer's perception of the brake pedal feel. Customer satisfaction with the brake pedal feel not only depends on an objective measure (i.e. force applied by the driver per distance of brake pedal movement), or performance intrinsic to a vehicle's brake system, but also on a subjective measure (i.e. the brake pedal feels soft to me) that is extrinsic and depends on the customer's preferences and senses. Even for the exact same vehicle, different drivers will have different perceptions of the brake pedal feel depending on their previous experiences with brakes on other vehicles, body type, leg strength, braking style, and many other factors. Figure 2 shows the various contributing factors to the soft brake problem grouped into the two components of brake pedal feel quality.

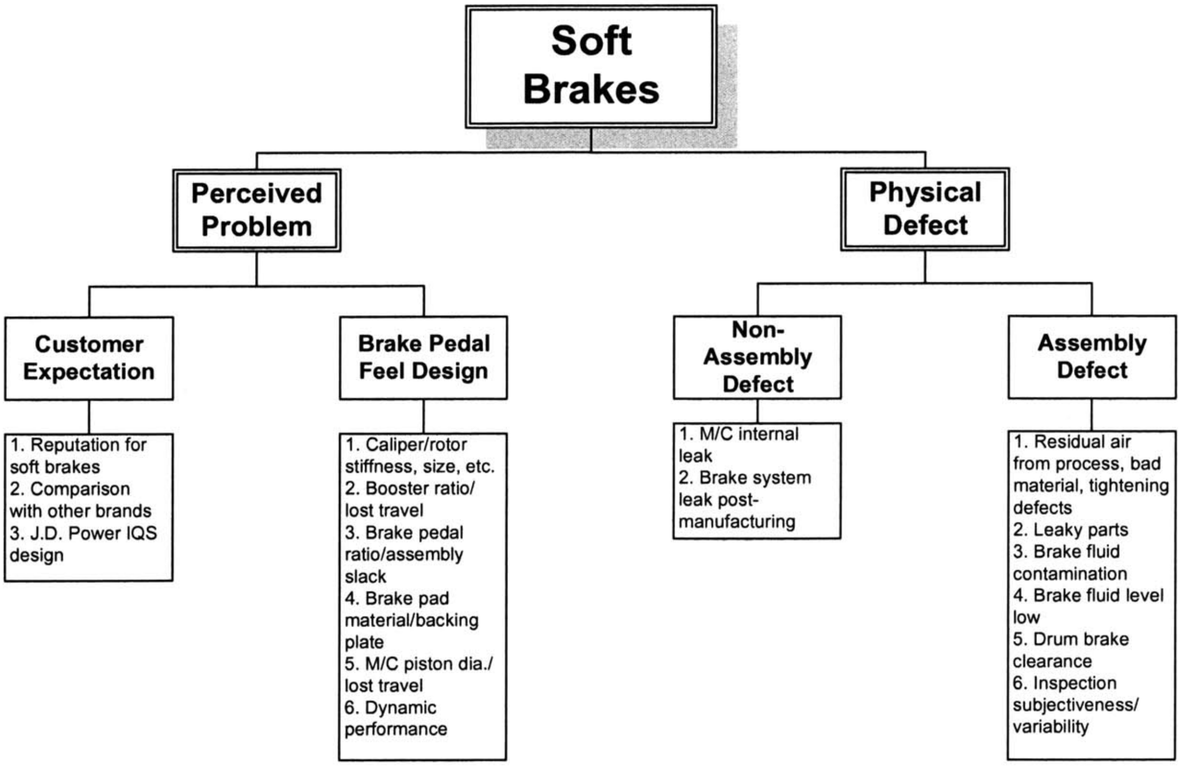

Figure 2. Components of brake pedal feel quality – soft brake problem.

The process of achieving high customer satisfaction begins with correctly defining customer requirements and translating those requirements to matching design attributes. For example, a customer requirement that the brake pedal needs to feel "predictable" may be translated by the design engineer into a linear brake pedal feel. Then those design attributes must be further translated into well-defined product specifications and manufacturing process specifications so that manufacturing can build the product according to the original design intent. Once again in our example, linear brake pedal feel may be defined as a constant slope of 5 kgf per cm. Finally, manufacturing's role in this process is to ensure that the product can be built to those specifications, and to have quality control systems in place to ensure that the manufactured product meets all necessary specifications. Ideally, early collaboration will lead to a design that makes it easier for manufacturing to build a high quality product.

2.1.2 Measuring customer satisfaction – J.D. Power IQS

The automobile industry standard for measuring vehicle initial quality is the J.D. Power IQS produced by the influential marketing information services firm J.D. Power and Associates. In its 18th year in 2004, the 2004 IQS is based on responses from more than 51,000 purchasers and lessees of new 2004 model-year cars and trucks, who were surveyed after 90 days of ownership. According to J.D. Power and Associates, the IQS measures "a broad range of quality problems, heavily weighted towards defects and malfunctions, quality of workmanship, drivability, human factors in engineering (i.e. ease of use) and safety-related problems." The IQS ranks automakers, nameplates, models, and plants by the number of initial quality problems reported by customers, and automakers use the rankings as important marketing and benchmarking tools.

A section of the IQS asks about the automobile's "Ride, Brake, and Handling" performance, and in this section there are many questions regarding the customer's perception of the automobile's braking performance. One question specifically asks whether the brake pedal feels soft or mushy to the customer. For the 2004 IQS, a comparison of total brake problems between different models in the premium mid-size car segment shows that customers identified a much higher level of brake problems on the Toyota Camry, with 8.1 problems per hundred vehicles (PPHV), than the segment average of 5.3 PPHV (see Figure 3). In addition, the Camry fared worse than the other two models, the Toyota Avalon and Toyota Solara, currently being produced at TMMK. A pareto chart of the Camry's brake problems showed that the most significant brake problem in the eyes of the customers was the soft brake problem, with 2.2 PPHV, followed closely by the noisy brake problem, with 2.0 PPHV.

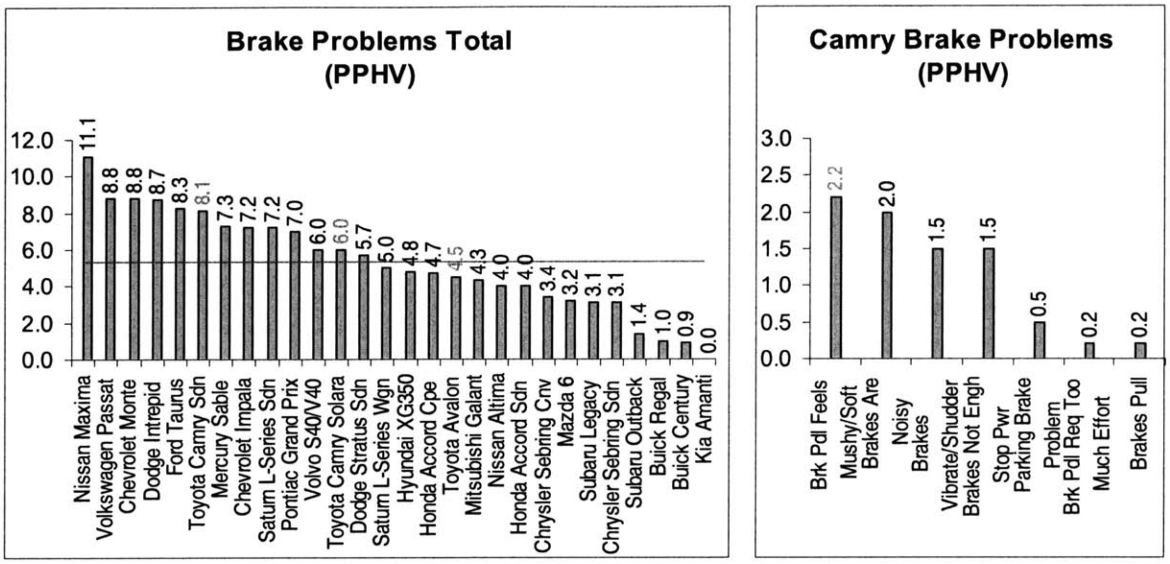

Figure 3. Total brake problems comparison of models in the premium mid-size car segment (left) and pareto chart of Camry brake problems (right). Source: J.D. Power IQS 2004.

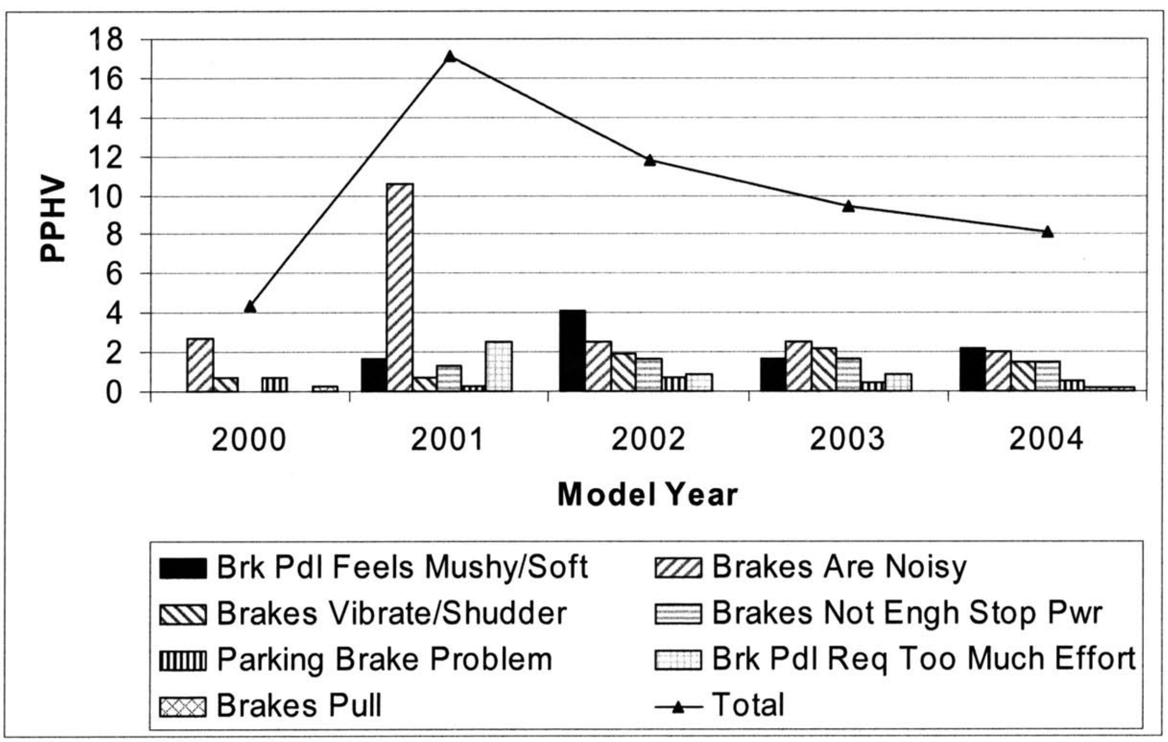

Figure 4. Camry brake problems trend for model-years 2000-2004. Source: J.D. Power IQS 2000-2004.

The soft brake problem on the Camry first appeared as a major problem during the 2002 model year (see Figure 4). At that time, the problem was blamed largely on the introduction of a linked brake pedal design. Although the contribution of the linked brake pedal design was never conclusively measured, many dealers and manufacturing team members still believe that the Camry's brake design has an inherently soft brake pedal feel. Another suspected cause of the soft brake problem was an internal leak within the master cylinder unit (an integral part of the brake system). Again, although some defective master cylinders were found and parts quality control was consequently improved, it could not be established as the root cause of the soft brake problem. Nonetheless, a concerted improvement effort dramatically reduced the severity of the problem, although it has never completely disappeared. As the 2004 IQS showed, the soft brake problem continues to be the most significant brake-related problem on the Camry.

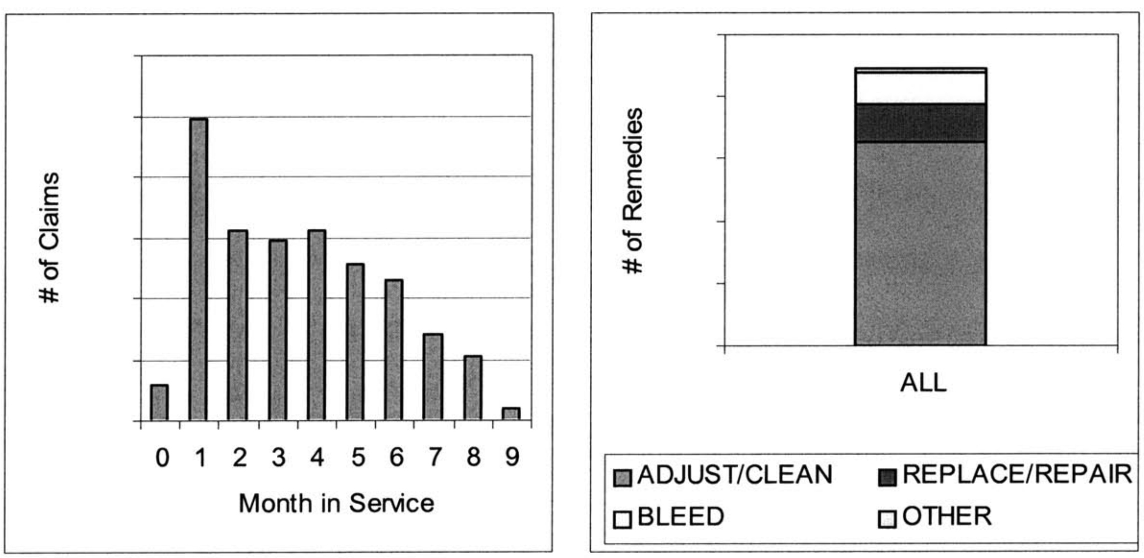

Figure 5. Soft brakes warranty claims by month in service (left) and soft brakes warranty remedies (right).

2.1.3 Measuring customer satisfaction – warranty claims

A careful study of brake-related warranty claims, including verbatim comments recorded by dealer service departments, confirmed the prevalence of the soft brake problem on the Camry. The Avalon, manufactured alongside the Camry on one of TMMK's production lines, had a much lower level of warranty claims. The frequency of claims was highest in a vehicle's first month in service (see Figure 5), potentially indicating a manufacturing problem. On the other hand, another plausible explanation is that customers simply did not like the brake pedal feel as designed, and that there were no manufacturing problems. A look at the remedies performed by the dealer service departments for the warranty claims suggests the latter scenario. The vast majority of the remedies were categorized as adjustment or cleaning. The next highest was air bleeding of the brake system, and then the replacement or repair of a part in the brake system.

One reason adjustment or cleaning may have been the highest is the Camry's reputation for having the soft brake problem. Many dealers dismiss the problem as inherent in the Camry, and now feel that no repair can correct this problem. Perhaps the dealers reason that if they at least do something on the vehicle it may be enough to assuage the worries of the customers. The verbatim comments suggested rear drum brake clearance to be the most frequently adjusted item, but there is no indication of a widespread problem with the drum brakes and the soft brake problem occurs even with vehicles that do not have drum brakes (i.e. 4-wheel disc brakes). Air in the brake system is a well known cause of soft brakes, so air bleeding of the brake system is a standard procedure attempted for a soft brake problem. The replacement or repair of parts was mostly comprised of the replacement of an internally leaking master cylinder.

Analysis of returned master cylinders performed by Toyota's quality group and the parts supplier showed some evidence of a parts problem, but the quality group estimates only a 5-10% contribution from leaky master cylinders to the soft brake problem. The quality group is working closely with the parts supplier to improve parts quality. Since brake pedal feel is not objectively measured before and after the service remedy (the mechanic only steps on the brake and makes a judgment), it is difficult to determine whether these remedies actually improved the brake pedal feel.

2.2 The Soft Brake Problem and the Typical Brake System

2.2.1 The typical brake system

A typical automobile brake system operates by transmitting the force applied by the driver on the brake pedal, via hydraulic brake fluid, to the brake at each wheel (see Figure 6). Since brake fluid can be considered to be practically incompressible, in a closed system the brake fluid can transmit fully the force applied at the brake pedal to the brakes. In the brakes at each wheel, the increase in brake fluid pressure causes pistons attached to brake pads (or shoes) to move against rotating rotors (or drums) attached to the wheels, which results in friction that slows the wheels. The automobile then slows through friction between the tires (mounted on the slowing wheels) and the ground.

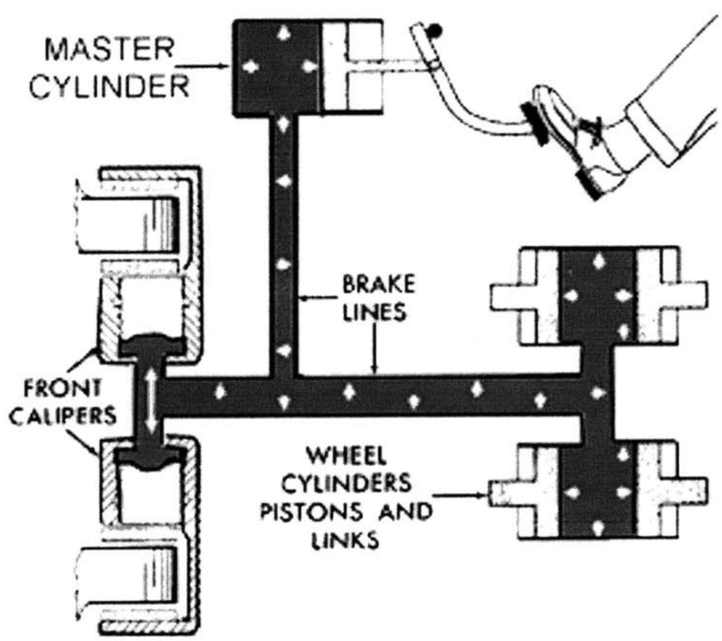

Figure 6. Typical automobile brake system.

Since the pressure required by the brakes to slow and stop an automobile is much greater than the pressure that drivers could physically apply with their foot, several force multiplication mechanisms aid to increase the braking pressure. First, the brake pedal itself is designed to multiply the force applied by the driver's foot through mechanical leverage. Second, most modern automobile brake systems employ a vacuum booster unit to assist braking. The vacuum booster uses differential pressure between two sides separated by a diaphragm to help move a piston attached between the brake pedal and master cylinder. Third, the relative surface areas of the master cylinder pistons, which actually push on the brake fluid and are connected to the brake pedal, and the pistons in the brakes determine the hydraulic multiplication factor. As a result, a driver's foot force of several tens of pounds becomes several thousands of pounds at the brakes.

The typical brake system comprises not only of the brake pedal, master cylinder, vacuum booster, and brakes, but also of the p-valve, numerous different brake lines, several brake hoses, and usually in modern automobiles some type of Anti-lock Braking System (ABS). The p-valve, or proportioning valve, proportions the braking power between the front and rear brakes to achieve stable braking. The brake lines and hoses carry brake fluid from the master cylinder, through the ABS and p-valve, to the brake at each wheel. The ABS unit is controlled by a computer and prevents the brakes from locking by automatically engaging and disengaging the brakes many times per second. There are many parts, connections, constrictions and bends in the brake system which makes it difficult to manufacture the brake system and many things can go wrong that result in a soft brake problem.

2.2.2 Brake system problems and the soft brake problem

The following defects in the brake system can affect brake pedal feel:

- Flexing of the brake pedal or vehicle dash panel where the brake pedal is connected
- Air in the brake system
- Leaks in the brake system

- Flexing of the brake lines and hoses
- Flexing of the brake calipers, rotors, brake pads, and brake pad backing

Figure 7 shows a fishbone diagram of the different factors that may contribute to a soft brake condition. The analysis was based on looking at the 5M's of production: man, machine, method, measure, and material. In our case, man referred to the manufacturing team members (T/M); machine, the brake system; method, the brake fluid evacuation and fill process; measure, both the IQS and inline inspection; and material, the parts and the brake fluid. We then investigated several of the significant factors in manufacturing that contributed to the soft brake problem, and attempted to find solutions for each factor (see also Appendix 1).

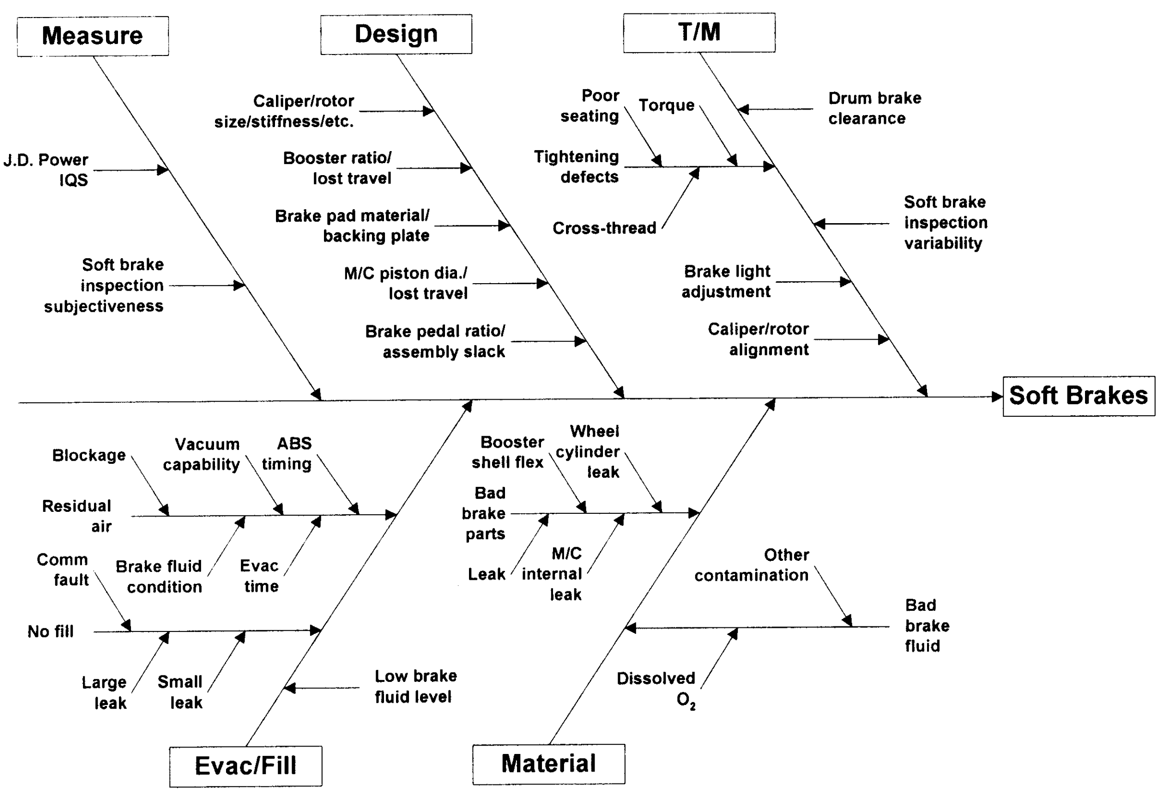

Figure 7. Fishbone diagram of the soft brake problem.

In automobile manufacturing, the soft brake problem is usually attributed to air in the brake system. Air, unlike brake fluid, is compressible. Thus air in the brake system acts like a damper that softens the feel of the brake pedal when it is depressed. Residual air in the brake system is difficult to diagnose since the only certain method to detect air in the brake system is to bleed the brake system and see the air that comes out. Brake bleeding involves forcing brake fluid out through bleeder valves (small valves on the brake wheel cylinder wall used to remove trapped air from the brake system) and separating the air from the fluid in a measuring cylinder. Brake fluid leaks are also common but these problems are easier to diagnose since the brake system can be visually checked for gross leaks.

2.3 The Soft Brake Problem and the Manufacturing Process

2.3.1 Vehicle final assembly

At TMMK, vehicle final assembly is performed on several continuous flow lines. The total process is roughly split into three sequential groups: Trim, Chassis, and Final. As is typical in a Toyota assembly plant employing the Toyota Production System (TPS), the total assembly work is subdivided into stations of equal takt time. One or more team members work at each station to complete the required assembly work for that station within the specified takt time. Since the TPS philosophy is to build in quality and not pass on sub-standard work to the next station, every team member is expected to check the quality of their own work. When problems occur, any team member on the assembly line can call for assistance and stop the line by pulling on the andon cord running along the assembly line. Standardized work, where everybody performs the work in the specified way, ensures consistent quality and visibility of abnormal conditions.

Parts are delivered to the assembly line "just-in-time" at regular time intervals. Several feeder lines and sub-assembly work cells are also used where production can be modularized.

For the brake system the following assemblies are prepared separately before being delivered to the main assembly line:

- Brake and strut assembly
- Brake pedal assembly
- ABS unit assembly

Toyota also buys some parts, such as the master cylinder and vacuum booster assembly, preassembled by the parts supplier.

2.3.2 *Brake system assembly process*

The brake system is assembled at various stations along the assembly line. From the attachment of the brake pedal to the automobile body which occurs almost at the beginning of the assembly process, to the air evacuation and filling of the brake system with brake fluid near the end, the process involves many team members and parts.

As the fishbone analysis showed, the soft brake problem can arise from assembly defects such as loose fittings, cross-threads, and bad parts/materials. The problem is that in marginal cases it is very difficult to detect such defects until the brake system is attempted to be evacuated in the brake fluid evacuation/fill process, or even until the inline braking test at the end-of-the-line. When a problem is detected, feedback to the responsible group is rapidly accomplished through extensive plant quality systems.

2.3.3 *Brake fluid evacuation and fill process*

The completed brake system is evacuated of air and filled with brake fluid at the brake system evacuation and brake fluid fill step. The brake system is evacuated of air by powerful vacuum pumps (to a vacuum pressure of ~ 2 Torr), before being filled with brake fluid to an appropriate level in the brake fluid reservoir. The process is completely automated, with the assembly team member simply attaching an adapter to the brake fluid reservoir opening, connecting a communication cable to the ABS unit, if appropriate, and pressing a button to start the process.

Step	Time (s)
Adapter Attach	8
Vacuum-1	33
Lg. Leak Check	4
Sm. Leak Check	2
Vacuum-2	21
Fluid Fill	17
Purge/scavenge	3
Adapter Detach	8
Dolly Return	10
Total Cycle	106

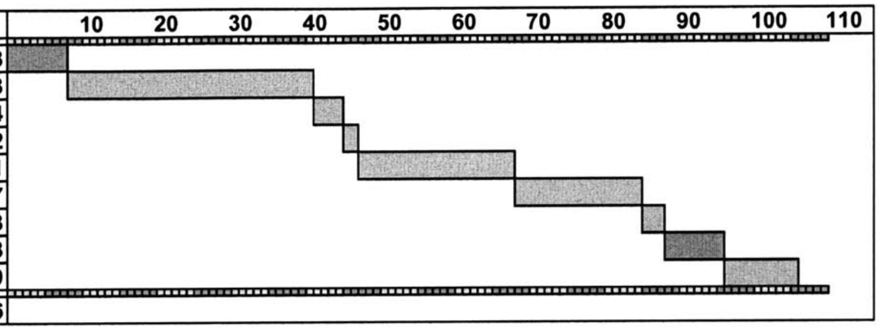

Figure 8. Brake fluid evacuation and fill timing chart.

The brake fill equipment performs the vacuum evacuation, checks to make sure the system is below a specified pressure, fills the system full with brake fluid to a specified pressure, and then scavenges back the extra brake fluid back to a specified level in the brake fluid reservoir. Interlocks in the computer logic causes the equipment to alarm and stop its operation if the specified vacuum pressure is not met, the leak check fails, etc. The timing chart for the brake fluid evacuation and fill process is shown in Figure 8.

The brake fill equipment is available from several commercial vendors specializing in assembly process equipment. A survey of brake fill equipment from several vendors (see Appendix 2) showed very little differentiation in the equipment, and essentially every vendor used the same process technology (as described above). A patent search of brake fluid evacuation and filling yielded only a single patent by GM on the use of a Venturi pump at the adapter (U.S. Patent 5,088,529). We were unable to find any commercial application of this patent. Vendors instead competed along other dimensions such as ease of use, ease of maintenance, reliability, customizability, service, and equipment cost.

Perhaps the biggest failure mode for this process is the system not reaching or maintaining the specified vacuum pressure. This failure mode usually occurs due to leaks in the brake system from bad parts or poor part fit from poor assembly (cross-threads, loss connections, improper fit, etc…). Other possible causes are a bad o-ring on the adapter head causing poor sealing between the adapter and brake fluid reservoir, and problems with the vacuum system causing poor air evacuation.

2.3.4 Inline soft brake measurement

Inline soft brake measurement is performed by a qualified team member right after completion of assembly as the vehicle is being driven to the test line. The team member accelerates the completed vehicle off the moving conveyer at the end of the line and quickly performs a hard brake, then repeats the maneuver a second time. Team members performing this test subjectively determine if the vehicle has a soft brake problem using their "calibrated foot." Due to the subjective nature of the test, it is difficult to verify the consistency of the results of this test, or the true level of the soft brake problem. There are certainly team member to team member differences, as well as shift to shift differences due to the different interpretations of what constitutes an acceptable level of softness in the brake pedal feel.

Figure 9 shows the inline measurement of soft brakes. It also shows that the level detected in the plant is about 10 times less than the J.D. Power level. This indicates that the detection capabilities at the plant are inadequate, or the metrics are not calibrated with customer expectations, or the less likely scenario that the problem occurs after leaving the plant but within 90 days.

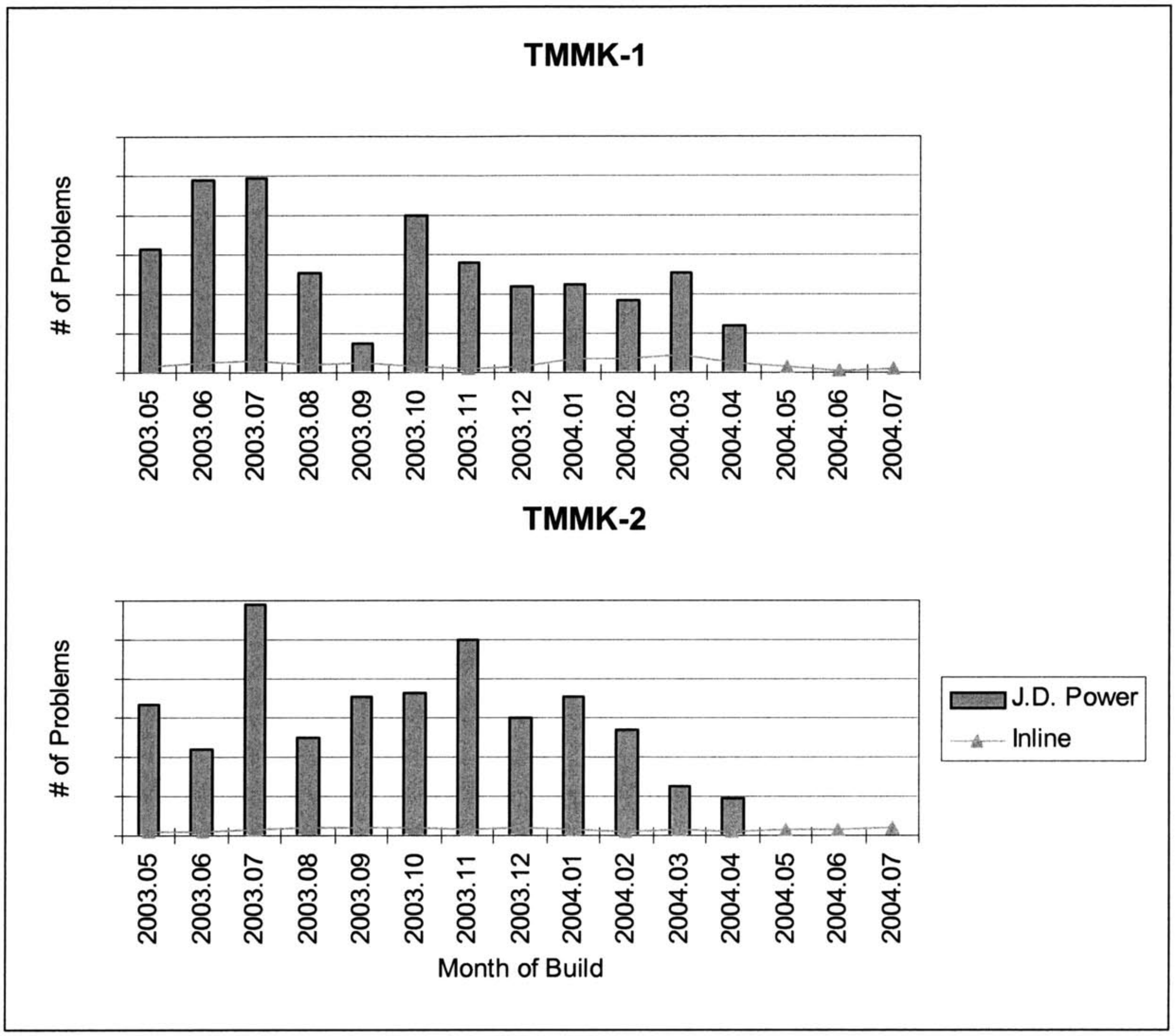

Figure 9. Inline soft brake measurement for production lines TMMK-1 and TMMK-2 compared to J.D. Power IQS scores.

2.3.5 Offline soft brake measurement and repair

Offline soft brake measurement is similarly performed subjectively by feel but by a different team member belonging to the offline repair team. The brake system is quickly checked for obvious leaks or cross-threads, and the brake system is bled if no other problems are found. During brake bleeding, obvious residual air problems can be spotted by the air forced out of the brake system but marginal problems are very hard to detect. A highly accurate bubble test could also be performed, but it is exclusively reserved for engineering tests (usually during the pilot of a new vehicle or model change) due to the difficulty and time consuming nature of the test. Commercial systems (inline and offline) to objectively measure the brake pedal force/displacement curve are available but they require a significant capital investment and add to the manufacturing cycle time.

2.4 Summary

The soft brake condition is a sensory perception by the driver that the brake pedal feels "soft" or "mushy" when braking. The soft brake problem can occur from two components: how well designers can define and translate customer needs for brake pedal feel into appropriate brake design attributes, and how well manufacturing can conform to the required product and process specifications. Our analysis of the 2004 IQS showed that the Camry had a greater occurrence of brake-related problems compared to both the segment average and the other cars produced at TMMK. A pareto chart of the Camry brake problems showed that the soft brake problem was the number one contributor to customer complaints of braking performance.

In manufacturing the most common causes of the soft brake problem were: residual air in the brake system, leaks, and bad parts. Although these problems do occur at TMMK, the failure rates for these defects are much lower than the IQS data exhibits. There is strong anecdotal data that suggests the major cause of customer complaints regarding soft brakes appear to be related to the original design of the brake system. Improvements in manufacturing can only marginally improve the situation with soft brakes.

3 Testing and Results

3.1 Introduction

Based on the fishbone analysis of the soft brake problem, we decided to concentrate further on those factors that could be controlled by the manufacturing organization. Particularly, we analyzed the soft brake measurement and the brake fluid evacuation and fill process. Ideally, a more systematic solution encompassing all the contributing factors to the soft brake problem should have been investigated, but problems with the current organizational processes (discussed in Chapter 4) precluded such a broader initiative.

Inline measurement of the soft brake problem, as discussed previously, depended solely on a team member's perception of the brake pedal feel. We felt that any improvement efforts would require an accurate measurement of the baseline condition for the soft brake problem, and thus a more objective measurement tool and method was required. With the new measurement tool we could run controlled experiments to see the effects of changing the various factors contributing to the soft brake problem.

In automobile manufacturing, we felt that residual air in the brake system and leaks were the primary factors contributing to the soft brake problem. Manufacturing problems with team member induced defects and parts/materials defects were well controlled under existing plant quality systems. Leaks were obvious problems easily spotted at the end-of-the-line repair station, and this information could be rapidly fed back to the responsible group for corrective actions. The brake fluid evacuation and fill process on the other hand was more of a "black box" process that was not well understood or characterized. We thus chose to focus on this operation for potential process improvements.

3.2 Brake Pedal Feel Characterization

3.2.1 Brake pedal feel measurement tool and method

Brake pedal feel can be modeled in terms of the force applied by the driver to the brake pedal and the displacement of the brake pedal under the applied force. In fact, there are commercial brake pedal feel test units available to measure such a force/displacement curve. However, commercial systems cost anywhere from $60,000 for a single engineering test unit, to over $150,000 for a system capable of being deployed in a full-scale assembly plant. The engineering team members at the plant instead built a custom tester unit comprised of a load cell mounted on a telescoping threaded rod (see Figure 10). The tester could be mounted between the brake pedal and the steering wheel to measure the force applied on the brake pedal at regular brake pedal displacement intervals (adjusted by turning a nut on the threaded rod). Although the brake pedal-steering wheel geometry of this custom tester does not exactly match the geometry of a human leg, we were able to obtain relative measures of brake pedal feel and draw meaningful conclusions from our results.

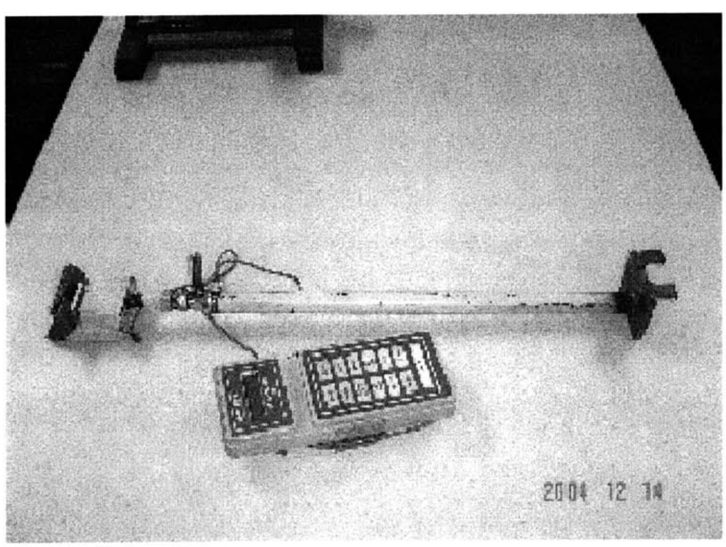

Figure 10. Brake pedal feel measurement tool.

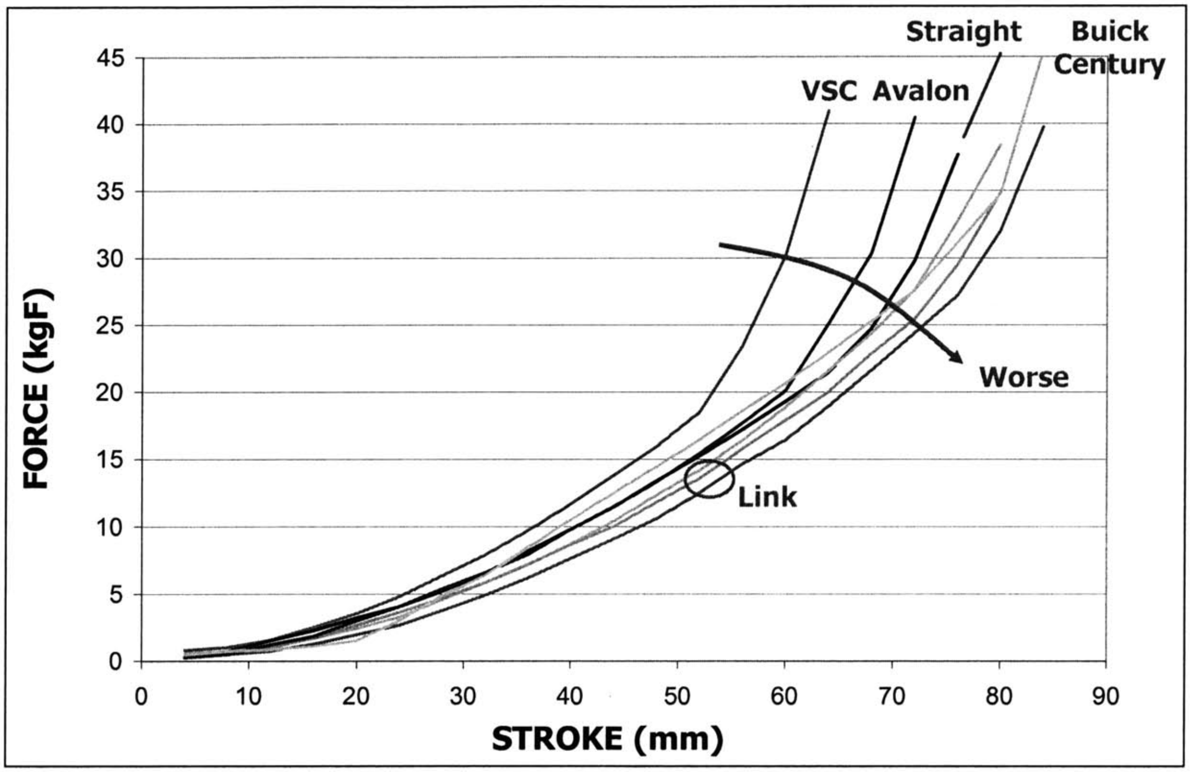

Figure 11. Brake pedal feel profiles.

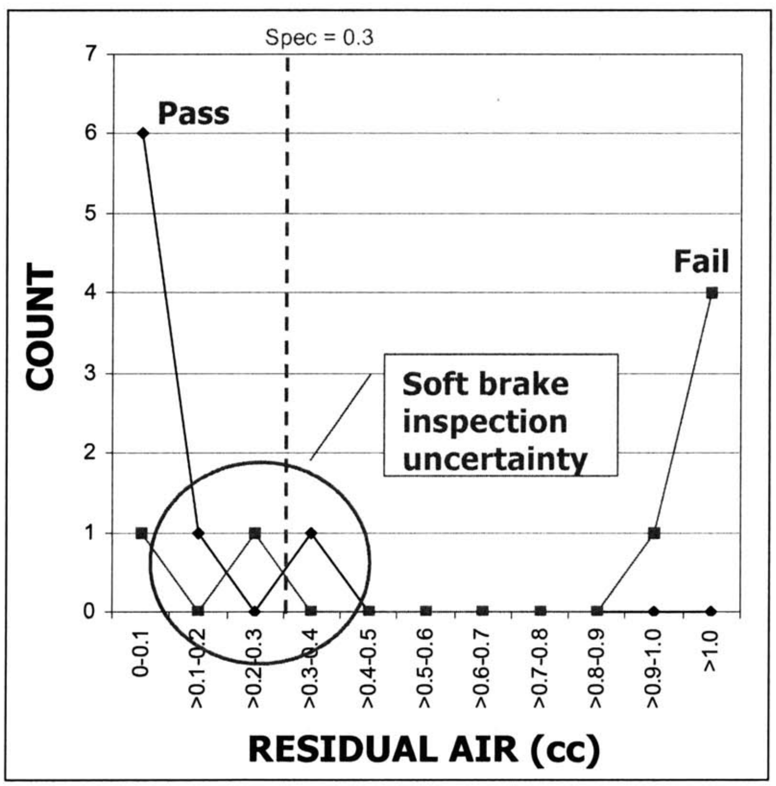

Figure 12. Histogram of residual air in the brake system.

3.2.2 Brake pedal feel characterization

We ran a series of experiments to prove the capability and repeatability of our brake pedal feel tester. Although the tester exhibited some variation depending on the exact placement of the tester in the vehicle and variation between vehicles, consistent testing procedures and careful testing produced repeatable results.

We next measured the brake pedal feel of different models and brake system configurations (see Figure 11). The following vehicles were measured: Buick Century, Avalon, Camry with a Vehicle Stability Control (VSC) unit, Camry with a straight-type brake pedal, Camry with a link-type brake pedal and several types of Camrys with a link-type brake pedal. We found that the Camry with a VSC unit had the hardest brake pedal feel. This is probably due to the more constricted nature of the brake fluid path through the VSC unit. The Avalon was next hardest, followed by the Camry with a straight-type brake pedal, and the various Camrys with a link-type brake pedal had the softest brake pedal feel. The Buick Century, a competitor's model that ranked higher in our IQS comparison of total brake problems, had a very different brake pedal feel profile than those of the Toyota vehicles. The Buick Century exhibited a harder brake pedal feel than the Toyota vehicles for most of the its brake pedal displacement range, but the brake pedal feel became softer than the Toyota vehicles towards the end of the range due to a longer brake pedal range.

3.2.3 Brake pedal feel and residual air in the brake system

We first measured the residual air in the brake systems of random vehicles pulled off the line, some considered normal and some tagged as having the soft brake problem, by the bubble test method (see Figure 12). The results show that team members testing for the soft brake problem correctly identify vehicles with high levels of residual air in the brake system, greater than 0.9 mL, that far exceed the specification limit of 0.3 mL. Team members did however have trouble determining the residual air conditions near the specification limit. Team members failed to detect one vehicle that had marginally failed the specification limit, and misidentified two vehicles as having the soft brake problem even though the vehicles had passed the specification limit. The results show that testing by team members is adequate for gross failures of residual air but uncertain close to or below the specification limit.

We next determined the effect of residual air on the brake pedal feel (see Figure 13). At the very low failure rates of the soft brake problem, single-digit defects per thousand vehicles, it is nearly impossible to correlate the soft brake condition to any one contributing factor from the production data. The sample size is simply too small to be able to draw statistically significant conclusions. Thus, in our experiments on the effect of residual air on the brake pedal feel, we were forced to run controlled experiments on a test vehicle by introducing known amounts of air into the brake system, and not simply measure the residual air and brake pedal feel on a random sample of vehicles pulled from the production line. After we measured the brake pedal feel with air in the brake system, we measured the amount of the air by the bubble test method.

We found a linear relationship between the amount of residual air in the brake system and the brake pedal force for a given brake pedal displacement (see Figure 14). Interestingly, even for the worst-case where the drop in force with residual air was steepest (at the end of the brake pedal stroke), the force only dropped 3.3% with residual air at the specification limit of 0.3 mL. To achieve a 10% drop in force, a residual air of 0.9 mL, or three times the specification limit, is needed. The effect of residual air on brake pedal force is even less for short to medium brake pedal displacements. When this result is integrated with our earlier findings that the team members are capable of detecting gross levels of residual air, we must conclude that the current inline inspection measurement is adequate for detecting the soft brake problem due to residual air.

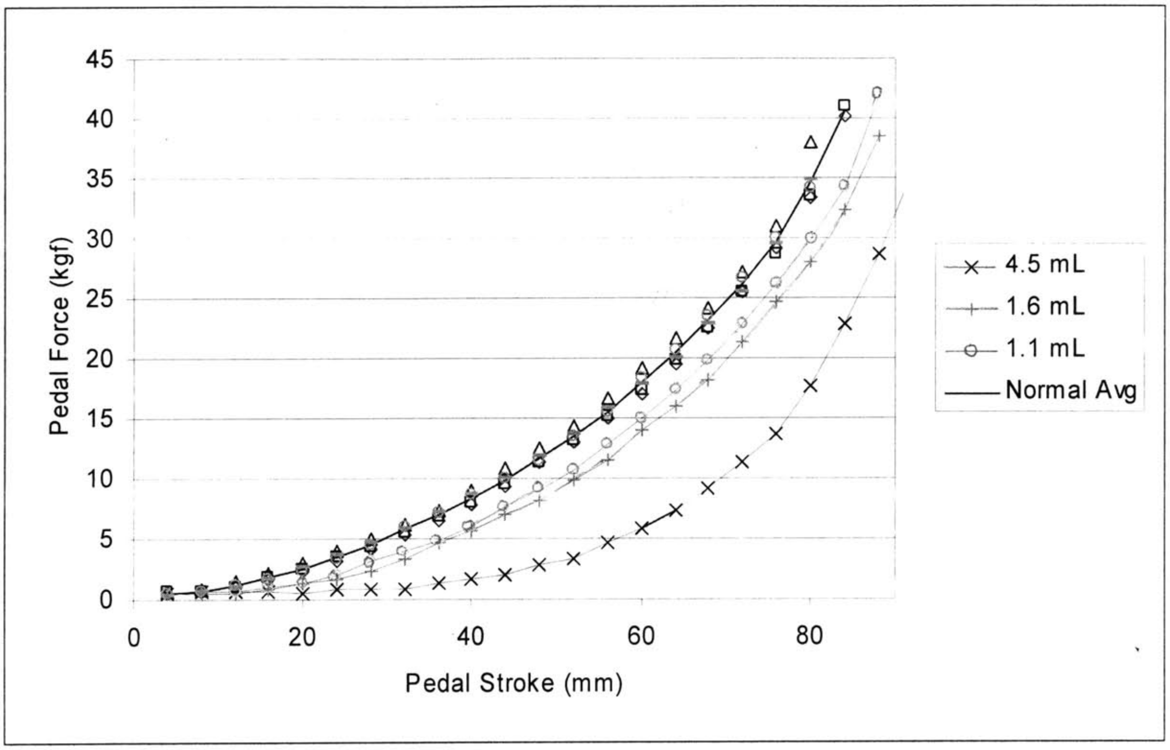

Figure 13. Brake pedal feel profiles for different levels of residual air in the brake system.

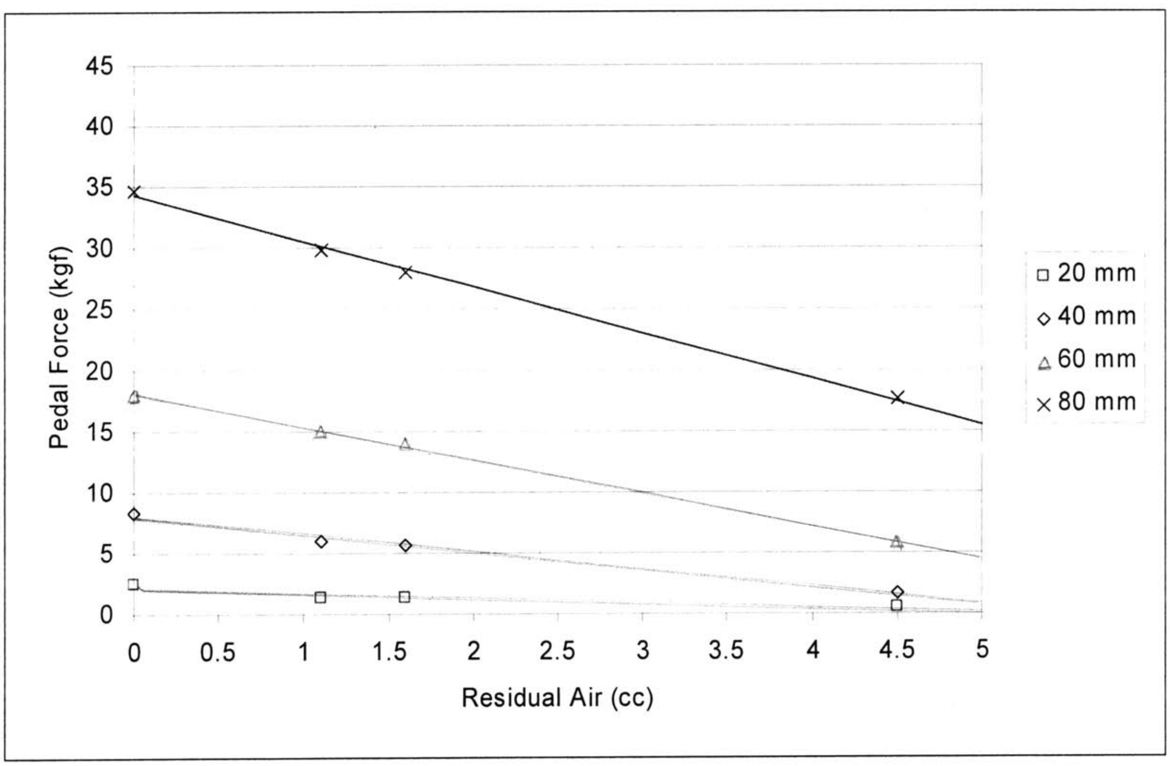

Figure 14. Effect of residual air on brake pedal feel for various brake pedal strokes.

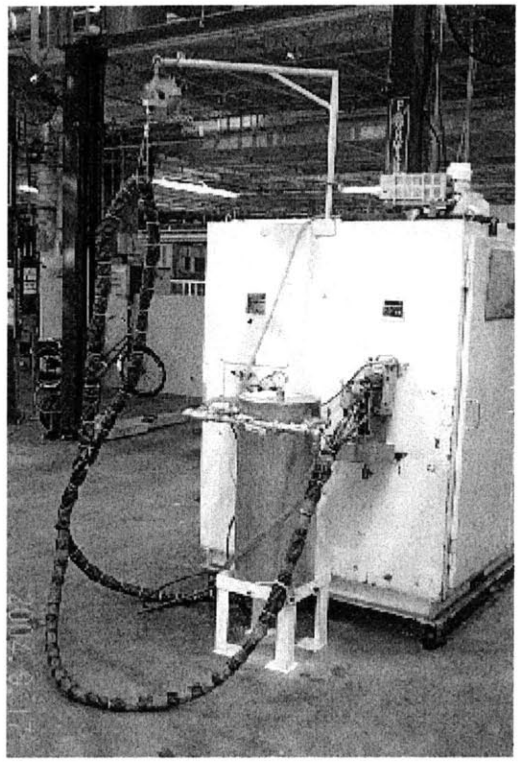

Figure 15. Vacuum accumulator tank attached to the offline brake fluid filling equipment.

3.3 Brake Fluid Evacuation and Fill Process Improvement

The foremost concern with the brake fluid evacuation/fill process was the ability of the system to reach the required pressure in the specified time. The plant was already experimenting with higher capacity vacuum pumps in the hopes that they could either reduce the air evacuation time or compensate for leaks and contamination in the brake system. Another potential low-cost solution was the addition of a vacuum accumulator tank between the vacuum pumps and the vacuum line leading out to the vehicle (see Figure 15). We surmised that the addition of the accumulator tank would help reduce the initial spike in vacuum pressure as the air is first evacuated, and this would keep a constant vacuum pressure applied to the brake system.

We tested the vacuum tank setup on a brake system test stand. The vacuum pressure profiles, measured both at the gun head and brake caliper, showed a miniscule improvement in the vacuum profile (see Figure 16). The air evacuation time was reduced by less than a second.

Our result with the accumulator tank was consistent with the results obtained by maintenance on the use of higher capacity vacuum pumps. Air evacuation, or conductance, is controlled by both the differential pressure (which we were trying to increase with the higher capacity pumps and keep constant with the accumulator tank) and the diameter of the air path in the brake system (i.e. brake lines). We can conclude that the air evacuation of the brake system is not controlled by the vacuum pressure, but by the very small diameters (some less than 1 mm) and constrictions of the parts in the brake system.

Brake systems on these vehicles have become higher in volume, longer, and more complicated, with the addition of ABS units, and harder to evacuate. Physical limitations of the production process necessitate a better design for manufacturability approach in brake system design.

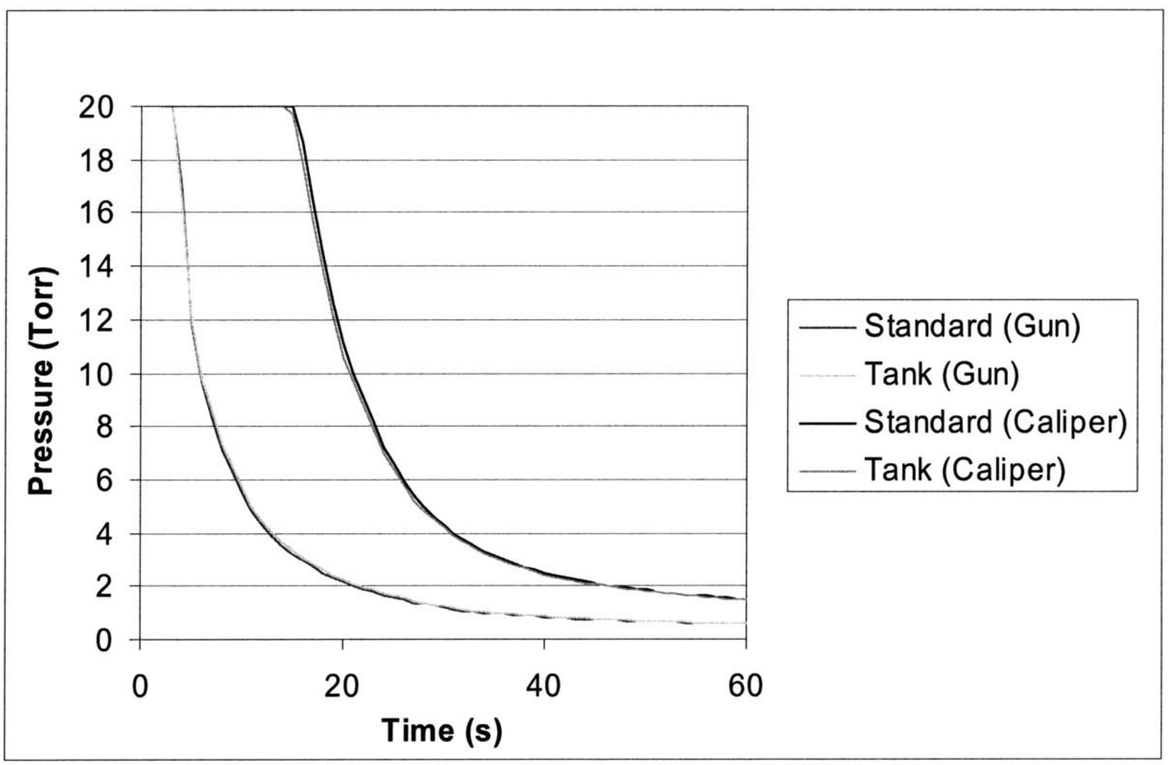

Figure 16. Vacuum pressure profiles for the vacuum accumulator tank test.

3.4 Summary

Plant engineering was able to build a low-cost brake pedal feel test tool that could measure the force applied to the brake pedal for the full brake pedal stroke. This tool allowed us to measure the brake pedal feel of different models and brake system configurations, and investigate the effects of residual air in the brake system on the brake pedal feel. The results show that Camrys with a VSC unit installed had the hardest brake pedal feel, followed by the Avalon, then Camrys with straight-type brake pedals, and trailed by the Camrys with link-type brake pedals.

We found a negative linear correlation between residual air and brake pedal force. However, even for the worst case at the end of the brake pedal stroke, the brake pedal force dropped an unremarkable 3.3% with residual air at the specification limit. This indicates that residual air results in the soft brake condition only at high residual air levels. Measurements taken of the residual air levels in the brake systems of randomly sampled vehicles confirm these findings. Team members were quite accurate at detecting soft brakes on vehicles with high residual air levels, but incorrectly diagnosed vehicles close to the residual air specification limit.

We tested the addition of a vacuum accumulator tank to the air evacuation system of the brake fluid filling equipment in the hopes of reducing the air evacuation time. However, the accumulator tank had virtually no effect of the vacuum profile. This result, in combination with similar results obtained by maintenance from of using higher capacity vacuum pumps, indicates that conductance of air out of the brake system depends on the diameters and constrictions of the brake system and not on the vacuum pressure. With the existing brake system design the physical limits of the vacuum evacuation equipment has been reached.

4 Organizational Processes Analysis

4.1 Project Context

4.1.1 TMMK as "plant of choice" in North America and self-reliance

Founded in 1986, TMMK was Toyota's first fully-owned manufacturing plant in the United States.[1] Today it employs over 7,000 people and produces almost 500,000 vehicles per year on two production lines. At the time of this project TMMK was producing the Camry, Avalon and Solara models. To date, TMMK has been a very successful plant, and it has even garnered eight prestigious Initial Quality Plant Awards from J.D. Power and Associates, including four Gold Plant Quality Awards. However, TMMK last received a J.D. Power Award in 2001, and with an increasing number of Toyota plants in North America, TMMK is currently working hard to become Toyota's "plant of choice" in North America by further improving its quality and productivity.

Even as Toyota's North American manufacturing organization continues to grow, and with the workload increasing proportionally, the amount of support available from Toyota Motor Corporation (TMC), Toyota's worldwide headquarters in Japan, has decreased. Toyota's TPS experts in Japan are now busy ramping up operations around the world in emerging markets such as China. As Fujio Cho, TMC's president, observed in his keynote speech at the 2004 Management Briefing Seminars:

> There used to be a time when we could handle everything from Japan. But starting in the 1980s, our own business started to move at turbo speed, and it has been accelerating ever since...Obviously, using only Japanese advisors cannot be done any more. We are stretched thin here and elsewhere around the world.

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[1] New United Motor Manufacturing, Inc. (NUMMI), a joint venture between the General Motors Corporation and Toyota Motor Corporation founded in 1984, was Toyota's first experience with manufacturing automobiles in the United States.

After close to two decades of manufacturing operations in the United States, the North American manufacturing organization is increasingly being asked to become more self-reliant. With the process of weaning away from Japanese support have come great organizational changes and the need to develop new skills.

4.1.2 The soft brake improvement team

Multifunctional teams, made up of engineers, maintenance specialists, and quality engineers, were formed to address specific customer satisfaction problems such as the soft brake problem. However, the members on the team were largely confined to team members at TMMK. In fact, before the author joined the soft brake improvement team there was no representative from TMMNA in the group, even though the author discovered a lot of people knowledgeable about the soft brake problem amongst those at TMMNA. The executive project champion for the customer satisfaction improvement initiative sub-group which included the soft brake improvement project was the manufacturing head of powertrain manufacturing. This created an interesting dynamic in which a problem largely located in assembly manufacturing and a team comprised mostly of assembly manufacturing team members had to report up to the head of another manufacturing group.

The author joined the soft brake team several months after the formation of the team. The team had been formed in response to a spike in the level of soft brake problems at TMMK, but there was no longer any sense of urgency in this team after seeing the frequency of soft brake problems decrease back to the baseline level. The sense was that the soft brake problem was back to being just another unresolved quality issue that could be lived with. They blamed the design of the brake system and thought that the problem would not be eliminated until the brake systems were redesigned in a future model. The team met periodically, but it appeared that individuals from different functions largely worked independently on their already assigned action items and simply used the meetings to report back their results. There was not much real collaboration between the functional groups.

4.1.3 Customer satisfaction improvement and organizational processes

Designing and building quality products is an inherently cross-functional exercise due to the need to translate often ambiguous customer requirements into suitable design attributes, and then well-matched product and process specifications. This translation requires communication and coordination between marketing, design, engineering, manufacturing and quality functions. Similarly, improving the customer satisfaction for products in full production should be a collaborative effort, and not left solely the responsibility of the manufacturing organization. The manufacturing organization, lacking channels to the customer, marketing, service and design, is forced to focus solely on meeting the specified quality metrics at the plant level. The real root causes of customer dissatisfaction may be missed if the original assumptions of the product design and development are unknown or ignored. It is clear from this project's analysis of the soft brake problem that although manufacturing problems contribute to the problem, they are not the major root cause of the problem.

4.2 Three Lenses Analysis of the Organizational Processes

As with any improvement effort, understanding the organizational processes of the organization provides insights into factors that may contribute to and perpetuate the problem. Such an analysis also provides guidance on how to successfully implement any necessary changes. The organizational processes are analyzed here using three perspectives: strategic design, political and culture (Ancona et al. 2004).

4.2.1 Strategic lens

The strategic design perspective looks at how organizations are structured to implement the strategies and goals of the organization. The formal structure of Toyota's North American manufacturing organization is highly siloed. In fact there are two levels of silos: functional silos between manufacturing, engineering, maintenance and quality groups, and geographical silos between groups based at the TMMNA headquarters and groups attached to each plant. Increasing the scope further, the North American manufacturing organization itself is separate from TMC, Toyota Motor Sales, U.S.A. (TMS), and until recently Toyota's North American research and development organization, Toyota Technical Center, USA (TTC).

Toyota's traditional structure of functional silos has offered it the advantage of concentrating expertise and developing specialists in individual functions. However, quality improvement for systems problems like the soft brake problem requires greater coordination and collaboration between functions. W. Edwards Deming, the quality guru influential in the ascendance of Japanese manufacturing after World War II, addresses this issue with Point 9, "Break down barriers between staff areas," in his 14 Points of Quality (Deming 1982). He says, "Break down barriers between departments. People in research, design, sales and production must work as a team to foresee problems of production and in use that may be encountered with the product or service." (24)

TMMK did form cross-functional teams for projects like the soft brake improvement project as part of their customer satisfaction improvement initiative. What was missing was the expertise that only someone in the design group could provide. Although the engineering drawings provided significant detail not only with regard to dimensional specifications but also on performance specifications and assembly instructions, the team was often at a loss when trying to compare different brake system configurations. Testing by plant engineering on caliper flex suggested excessive flexing, but we did not know how the caliper flex interacted with other parts of the brake system and we could not be sure whether the brake system was purposely designed that way. Systems thinking is required in solving complex problems like the soft brake problem, and experts from design as well as marketing must be included in the cross-functional team.

TMMK's geographical isolation largely developed from being the first and only fully-owned manufacturing plant in the United States for over a decade. With the growth of the Toyota manufacturing organization in North America, what was once a single manufacturing organization, TMMK in Georgetown, Kentucky, has grown into one headquarters company, TMMNA in Erlanger, Kentucky, and multiple assembly/parts manufacturing companies (North American Manufacturing Companies, or NAMCs). Some functions and responsibilities have been moved to or consolidated at TMMNA in an effort to increase coordination and standardization between the various NAMCs. However, the delineations between the roles and responsibilities of the headquarters groups and those at the NAMCs remain unclear.

4.2.2 Political lens

The political lens informs us on how power and influence is distributed and wielded by various groups within the organization. At Toyota it is clear that the manufacturing group holds the most power. Nobody can dispute Toyota's manufacturing prowess through the dedicated refinement and application of TPS. Especially at the plant, engineering and maintenance are considered support groups to manufacturing. Those groups have to be responsive to manufacturing needs and they are often subservient to manufacturing decisions. Perhaps the only group with much influence on manufacturing is the quality group. Toyota prides itself as the quality leader, and they will not accept any compromises on quality. Nonetheless, manufacturing is the number one stakeholder in every change initiative at the plant.

Decisions are made by consensus through a consensus building process called "nemawashi." Nemawashi usually involves circulating a proposal for feedback from all the managers with a stake in the proposal. The proposal is revised based on the feedback from the stakeholders until an agreement is reached in principle. Only then after the decision has already been made to go ahead does the proposal go up to management for formal approval. This process is a powerful linking mechanism between siloed groups, but the danger is that groups acting in their own group's interest may manipulate or block proposals without consideration for the goals of the whole organization. Although team members are empowered to propose changes for continuous improvement through TPS, power at Toyota still resides at the top with a bureaucratic, top-down management system. In the case of cross-functional teams, the decision making process and the nemawashi should be pushed down to the team level. Paul Adler, an organizational theory expert who has studied Toyota's NUUMI plant in California, talks about an enabling bureaucracy where organizational systems are not used for command and control but as tools to empower employees and enable innovation (Adler 1999).

4.2.3 Cultural lens

The culture lens shows how a company's history, norms, and collective values guide its actions. Toyota's fundamental DNA, the common values and beliefs shared by all employees, was codified in 2001 as the "Toyota Way 2001." It is supported by two main pillars: "Continuous Improvement" and "Respect for People." Continuous Improvement expresses the sentiment that the people at Toyota are never satisfied with the status quo and are always seeking to improve all aspects of their business. In fact, "2001" was added to the "Toyota Way" title to indicate that this particular written articulation of the company DNA was a snapshot in time and that the expectation was for the Toyota Way to continue to improve in the future. Respect for People conveys the idea that business success stems from respect for people and effective teamwork.

Under Continuous Improvement are three more principles: Challenge, Kaizen and Genchi Genbutsu. Challenge refers to forming a long-term vision to meet great challenges in creating exceptional value. Kaizen is a Japanese word meaning incremental or continuous improvement, and it refers to Toyota's attitude of continuously driving improvement. Genchi Genbutsu is another Japanese term meaning actual place and thing, and it refers to Toyota's belief that one must go to the source of things to find the true facts to make correct decisions. Under Respect for People are two principles: Respect and Teamwork. Respect includes respect for stakeholders, building mutual trust and accepting mutual responsibility, and communicating sincerely. Teamwork stresses the power of effective teamwork while fostering respect for individual development and achievement.

The Toyota Way 2001 is Toyota's attempt to train its growing number of employees worldwide on the shared values that have led to Toyota's success. It helps break down the various silos by establishing a common value system and behavioral expectations. At TMMK, The Toyota Way culture is very strong in manufacturing. However, the strength of the culture wanes as team members are further removed from manufacturing. Groups such as engineering are trained in the Toyota Way and understand the concepts, but they do not seem to have internalized it and live it everyday. For example, there is much more of a "make it work" mentality in engineering than an attitude of continuous improvement.

4.3 Change Initiative

The biggest challenge with the customer satisfaction improvement initiative at TMMK was organizational ossification. TMMK was Toyota's first fully-owned manufacturing plant in the United States, and it had largely grown up as the only Toyota manufacturing organization in the United States. Compared to some of the other Toyota manufacturing sites, there is a sense that TMMK has already been successful and that there was no great need to change. What was lacking was a sense of urgency to devote fully to the quality improvement efforts. Again, Fuijo Cho comments in his speech:

> But a few years ago, we realized we needed to develop a greater sense of urgency in our business. Steady success is good, but it can foster serious weaknesses. Complacency sets in...customer focus declines...creative ideas dry up...and...before you know it...you are in trouble.

In an increasingly competitive automobile market, it is imperative that TMMK continues to improve its quality and productivity to stay ahead of its competitors.

4.4 Summary

This project was started in an environment of increasing competition on quality in the automobile industry, and the need for Toyota's North American organization to become more self-reliant. TMMK was striving to improve its quality and productivity in order to become

Toyota's "plant of choice" in North America. However, for the soft brake problem, there was little urgency in solving the problem. Once the spike in soft brake problems had passed, the team members gravitated back to their more immediate concerns, and they where content to wait for design to fix the problem with the next model change. Much of the organizational problem stemmed from the lack of communication channels back to the design and marketing groups. Quality improvement projects for a complex system like the brake system necessitates close communication and great collaboration between all functions.

All the organizational processes for success are already in the Toyota Way:

- Challenge to form a long-term vision of quality improvement and realize it with a spirit of challenge and creativity
- Kaizen to continually improve and combat complacency
- Genchi Genbutsu to go to the source of the problem, whether it be in manufacturing or design or the customer
- Respect to build mutual trust between functions, share responsibility for team results, and promote open communication
- Teamwork to realize the power of cross-functional teams

The organization must continue to train, promote, and internalize the principles of the Toyota Way, especially with support groups such as the engineering and maintenance groups that have historically not been in the center of TPS.

5 Recommendations and Conclusions

This chapter summarizes the recommendations and conclusions reached regarding the soft brake quality problem at TMMK. A soft brake mitigation plan, based on the project findings regarding the contributing factors of the soft brake condition, is presented in Figure 17. Since the soft brake problem in manufacturing is largely a result of leaks and gross amounts of residual air in the brake system, the components of this plan are:

1. Detect leaky brake systems before the vehicles goes on to the brake fluid evacuation and fill step
2. Fix any problems inline when possible, but if not possible, tag the vehicle to skip the brake fluid evacuation and fill step, and perform offline repair at the end of the line
3. Strictly monitor and control the brake fluid evacuation and fill process to ensure that the process is operating under nominal conditions
4. Request brake pedal feel benchmarking and brake system design reassessment from the design group

Below are listed the recommendations for specific changes in manufacturing to enable better measurement and control of the soft brake problem, and more general suggestions for improving the organizational processes as related to customer satisfaction improvement projects.

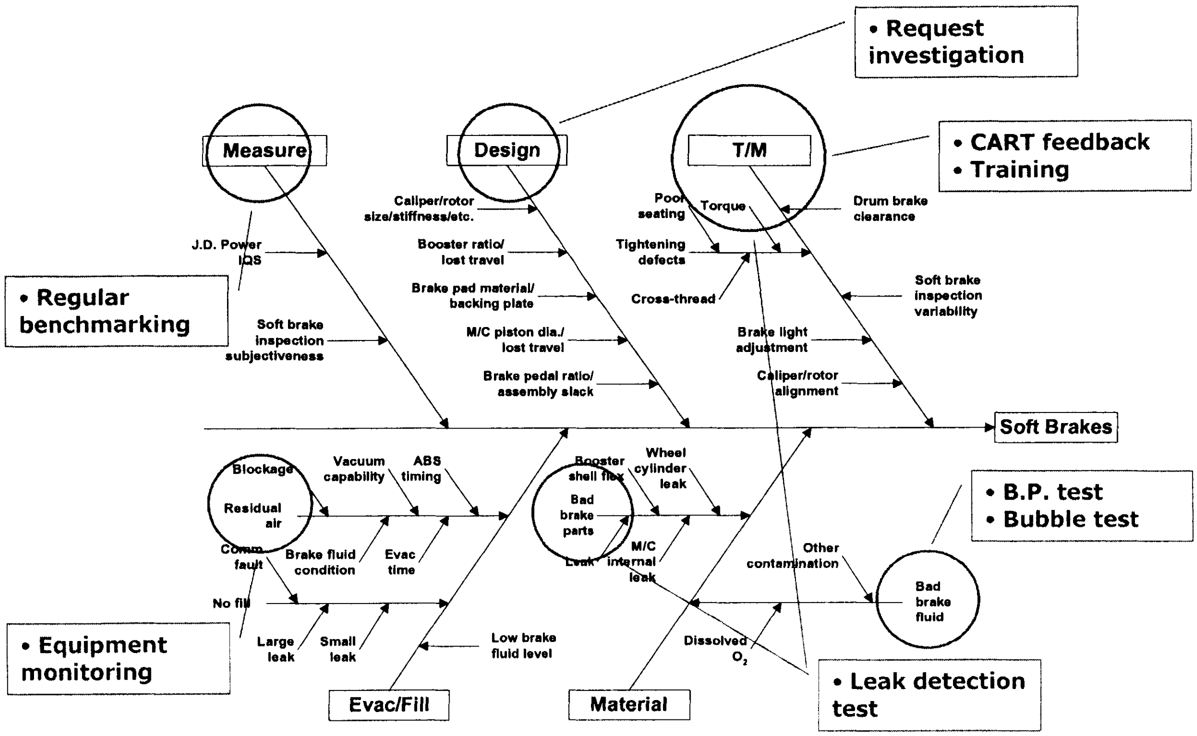

Figure 17. Fishbone diagram of the soft brake problem showing items to mitigate the soft brake problem.

5.1 Recommendations

5.1.1 Addition of a leak detection step

Currently at Toyota Motor Manufacturing Indiana (TMMI), leak detection is performed after the brake system has completed assembly and before the brake fluid evacuation and fill step. The leak detection step detects vehicles with leaky brake systems that may lead to the soft brake condition. The process involves applying a positive pressure to the brake system and measuring any pressure decay due to leaks. It may also find blockages in the brake system by detecting a spike in pressure.

The positive pressure test is different from the leak check performed during the air evacuation process in that the system is tested under a positive pressure instead of a vacuum pressure. This test is more sensitive to slow leaks at the far ends of the brake system. Testing performed by plant engineering and maintenance showed that a minor but significant leak at the furthest brake from the injection head (where the pressure sensor is located) did not appear on the air evacuation vacuum profiles. Since there is no possible way to prevent the brake fluid filling tool from filling a vehicle with a leak that it cannot detect, a prior leak detection step is necessary.

The positive pressure test also more accurately reflects the pressure condition of the brake system under the brake fluid filling process and during braking, when the brake system is stressed under a positive pressure. Under vacuum pressure potential leaks are closed as loose fittings and seals constrict inward, but the positive pressure test exposes those same leaks by pressing outward on them. The positive pressure test is much better in ensuring proper brake fluid filling, and revealing potential leaks under braking.

When possible any problems found at the leak detection step are corrected before air evacuation and brake fluid filling is attempted. This is consistent with the TPS philosophy of building in quality and not passing on defects to the downstream step. For large leaks, it prevents vacuum failures from occurring during attempted air evacuation, and for small leaks, it prevents problems with residual air in the brake system. Even if the problem cannot be corrected inline, the vehicle can be tagged to skip the brake fluid evacuation and fill step, and repaired offline at the end of the line. The leak detection step is the only reliable method of ensuring that no vehicles with leaky brake systems get filled with brake fluid, thus preventing potential soft brake problems.

One comment the author received from a senior Japanese advisor, on assignment at TMMNA, was whether the addition of this step is consistent with the principles of TPS. He was specifically referring to the tenet in TPS that states problems should be corrected at the root of the problem. Since the root causes of any leaky brake systems originate with upstream processes, such as with the team members involved in the assembly of the brake system, or with bad parts from suppliers, the leak detection step merely helps to control the problem but not eliminate it. The addition of a leak detection step is a bandage that serves to cover up the weaknesses in the upstream processes.

However, for brake systems there is a fundamental trade-off between testing individual components at each step and testing the fully assembled system. Unlike with visual defects where team members can assure quality by use of their own eyes, brake system leaks require the use of sophisticated equipment to detect them. For the soft brake problem, the added cost of leak testing at each step can not be justified. In addition, the complexity of the brake system may mean that some problems do not manifest themselves unless the whole system is tested. Although the leak detection step is a non-ideal form of a poka-yoke (a device that prevents errors) since it merely catches the leak problem, it nonetheless prevents the problem from propagating and growing into the bigger soft brake problem.

Instead of problems remaining hidden under the broad umbrella of a soft brake problem, the addition of the leak detection step reveals important information to drive root cause analysis and improvement. Perhaps with rigorous improvement efforts this step could be a temporary solution and eliminated in the future. However, we must ensure that brake systems entering the brake fluid evacuation and fill step be free of defects, otherwise the soft brake problem can never be controlled.

5.1.2 Improvement of process monitoring and control

Ideally, we would be able to measure residual air in the brake system by an inline measurement system to get instant feedback on the result of the brake fluid evacuation and fill process. We tested one idea using ultrasonic waves that proved unsuccessful, and we know of no practical systems capable of doing so. In the absence of the ability to directly measure the product to determine the brake fluid filling process result, we are forced to control the process by ensuring that the inputs to the process are problem free (using the added leak detection step) and controlling the equipment and process parameters to nominal targets. A defect free product processed under nominal process conditions should yield a problem free result.

Key parameters (such as vacuum profiles, vacuum pump base pressures, brake fluid fill levels, etc) must be identified, monitored and controlled to ensure that the equipment is running under the nominal conditions. Other factors, such as assembly defects and parts/materials quality assurance, are already monitored and controlled under existing quality systems.

5.1.3 Reassessment of the brake system design

There is large agreement within the manufacturing organization, and anecdotal evidence from dealers, that the brake system design on the Camry models do not possess the brake pedal feel attributes desired by many customers. It is fundamental that companies design products according to the needs and preferences of its target customers. TMMNA should not only request a thorough review of the brake system design to determine what customers think of the brake pedal feel, but it should also insist on a quantified measurement of the desired brake pedal feel. This information is critical when running experiments to improve the brake pedal feel so that a target can be established. In addition, manufacturing must work together with design and development to determine the appropriate metrics that must be followed to ensure that quality vehicles are manufactured with the brake pedal feel desired by customers.

Second, the brake system must be designed for manufacturability. Manufacturing must identify problems with the brake design that makes it difficult to manufacture the product. Often, design for manufacturability is driven by potential productivity gains in manufacturing, but as this case demonstrates, manufacturability problems can also lead to significant quality issues. The brake fluid evacuation and filling process appears to be running at the physical limitations of the brake system design. Problems identified by manufacturing needs to be quickly fed back to design and development to reassess the trade-offs between performance, cost, and manufacturability. Luckily, the brake system is largely modular, so simple improvements can be more easily made, and revisions can often be deployed at any time without waiting for a major model change event.

5.1.4 Standardize the brake assembly process across all plants

Standardized work is a foundation principle of TPS. It enables the creation of a baseline for continuous improvement and the visualization of problems. Jeffrey Liker, author of "The Toyota Way," says about standardized work:

> Capture the accumulated learning about a process up to a point in time by standardizing today's best practices. Allow creative and individual expression to improve upon the standard; then incorporate it into the new standard so that when a person moves on you can hand off the learning to the next person. (38)

Likewise, Intel's "copy exactly" philosophy, which states that, "everything which might affect the process, or how it is run is to be copied down to the finest detail, unless it is either physically impossible to do so, or there is an overwhelming competitive benefit to introducing a change," encapsulates a similar idea. The processes for manufacturing semiconductors are complex (involving interactions with many steps and process parameters), and the processes are not fully characterized. In such an environment, the only way to ensure that a process runs as expected is to copy and maintain every aspect of a successful process as originally developed. Using copy exactly, Intel was able to achieve fast production ramps and high quality.

The brake assembly processes at the different plants are not standardized (see Appendix 3). As each plant evolved separately, each plant was largely free to determine their selection for equipment and process layouts. TMMK, being the oldest plant, suffers from having outdated equipment that have since been modified in an ad hoc manner. In fact, TMMK, TMMI and TMMC all use brake fluid filling equipment from different equipment vendors. With the differences it is difficult to compare the process results, as well as apply improvements from one plant into the other plants. There was very little information sharing between the plants, even when two plants were both working on the soft brake problem, and knowledge was dispersed between individual experts.

Standardized work or manufacturing processes must be embraced not only by the manufacturing group but also by the engineering and maintenance groups. Engineers and technicians have a natural tendency to tinker with processes and try to make changes to improve them. However, these changes must be made in a controlled manner and across all the plants to avoid the problems stated above. The mentality in setting up the manufacturing process needs to change, in Intel parlance, from "make it work" to "copy exactly" (or to standardized work in TPS). Only by doing so can continuous improvement initiatives succeed.

5.1.5 Improvement of communication and localization of design (support)

To improve the effectiveness of customer satisfaction improvement projects, there must be greater communication and collaboration between marketing, design, engineering, manufacturing and quality. To break down the existing silos, TMMNA should organize an in-depth study of brake pedal feel quality with participation from all the other functional groups and separate companies. Starting with market research, followed by design and product development, and ending with the manufacturing implementation, a small dedicated team of experts from every function should complete the study. While such an exercise is not feasible for every improvement project, it should illustrate the importance of collaboration, and given closer relationships between the functions, lead to increased communication between the groups.

In the spirit of greater North American self-reliance, TMMNA must localize the technical knowledge and support for brake systems in its North American technical center. While it may still be necessary to design the brake systems in Japan for reasons such as greater expertise or economies of scale/scope, there must still be a local presence capable of investigating design related quality problems and reporting the information back to the original design teams back in Japan. Without this support, the manufacturing organization can only improve conformance to the given product and process specifications, even if better conformance only leads to marginal improvements in customer satisfaction.

5.2 Future Work

5.2.1 What is the ideal brake pedal feel that customers desire?

The most intriguing unanswered question of this project is, "What is the ideal brake pedal feel that customers desire?" A simple market research study of this question, using the brake pedal feel measurement tool and method described in this thesis, would establish an objective specification by which both design and manufacturing could operate. Communication between the two groups would also improve since they would be able to quantify any soft brake problem as an exact force per distance measurement, instead of vague comments such as "soft" or "mushy."

In the future this question will continue to grow in importance as electro-hydraulic and fully electronic brake systems (so called "brake-by-wire" systems) increasingly replace the traditional mechanical-hydraulic brake systems. Since the electronic systems use electrical signals to transmit brake pedal movement to the brakes, these systems use a brake pedal simulator to simulate the feel and feedback of a traditional brake pedal. Designers will no longer be constrained by the physics of the brake system in designing the brake pedal feel; they will be able to deliver exactly what customers desire. It is conceivable that individual drivers may be able to customize the brake pedal feel of their vehicles, and thus every driver will have their ideal brake pedal feel.

5.2.2 How does different factors affect brake pedal feel?

This project established a correlation between residual air and brake pedal feel. However, residual air is clearly not the only significant factor to the soft brake problem. It would also be interesting to expand the testing to try and find correlations of brake pedal feel with other factors such as the drum brake clearance mentioned in many of the warranty claims. Our testing also showed differences in brake pedal feel between different brake configurations. Further testing could determine the effect of the design choices for individual parts on brake pedal feel.

The brake fluid evacuation and fill process is still a "black box," and so a series of design of experiments should be run to better characterize the process. The effects of different process parameters, such as air evacuation time, and process conditions, such as humidity, on residual air needs to be analyzed to identify the key parameters of the process, and determine appropriate control targets.

5.2.3 Feasibility of a simple inline brake pedal feel tester

Although the high capital costs prohibit the deployment of a commercial brake pedal feel test system, slight modifications to the low-cost brake pedal feel test tool produced for this project by plant engineering may permit its use in production, replacing the current subjective test method. For example, the tool could be modified to measure the force on the brake pedal at a specified brake pedal stroke. A simple threshold test at this one point may be enough to detect vehicles with the soft brake condition. Even if the sensitivity of this test is no greater than the current method, as long as the repeatability and reproducibility of the test is proven, it would be a vast improvement over the current test based on an individual's sense of feel.

5.3 Conclusion

Although the recommended changes in manufacturing should help control manufacturing quality, the broader changes in organizational and business processes are necessary to completely eliminate the soft brake problem and improve quality in general. Quality cannot be improved by the manufacturing organization alone but must involve all the groups responsible for translating customer needs into a quality finished product. This is particularly true for complex quality problems like the soft brake problem, where a systems view is needed to determine the interactions between the contributing factors.

As the clockspeed of the automobile industry has dramatically increased, more and more models are being launched every year. With an abundance of alternatives in the marketplace, customers will no longer wait an extended time for quality problems to be fixed. Quality must be designed into the product with early manufacturing input, as well as being built into it. However, when quality problems have unclear standards of quality, communication and collaboration with design and marketing are required to once again determine how best to meet the actual customer requirements. In this way, manufacturing can truly satisfy its customers.

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Appendix 1: Contributing Factors to the Soft Brake Condition

Factor	Description	Control	Remedy
Incorrect brake light switch adjustment	Slightly depressed brake pedal causes pistons in the master cylinder to be positioned forward, and this blocks air evacuation	Vacuum profile check during air evacuation	Correct brake light switch adjustment
Brake system leaks	Poor fit Bad parts	Visual check for leaks	Retighten fittings or replace bad parts
Residual air in the brake system	Dissolved air/moisture in the brake fluid Poor air evacuation Leaks	B.P. Test Leak check	Air bleeding of the brake system
Internal leak in the master cylinder	Scratches on the pistons or poor seals cause brake fluid to leak back through the pistons	Soft brake inspection	Replace master cylinder
Drum brake seal leak	Seals leaked back brake fluid	Soft brake inspection	Redesigned seal
Brake hose flex	Brake hoses flex when brakes are applied	Soft brake inspection	Replace brake hose or upgrade to wire mesh
Caliper flex	Brake calipers flex when brakes are applied	Soft brake inspection	Redesign brakes
Dash panel flex	Dash panel flexes when brakes are applied	Soft brake inspection	Redesign dash panel

Appendix 2: Comparison of Brake Fluid Filling Equipment Vendors

	Dürr Production Systems (DPS)	Production Control Units (PCU)
Description	DPS is part of the German Dürr group, a leading supplier of production systems and manufacturing support services to the automotive industry. DPS is focused on fluid fill, end-of-line-test, and tire & wheel assembly.	PCU is an established supplier of automated fluid, gas, refrigerant fill and processing equipment.
Business Areas	• Paint Finishing systems • Final Assembly Systems • Manufacturing Support • Measuring Systems	• Fluid Fill and Processing Systems
Customers	TMMC; DCX, MBUSI, GM, Hyundai, Mitsubishi	TMMK; GM, Ford, DCX, Honda
Fluid Filling Equipment Features	• Pressure transducer in charge tool • Coriolis flow meter for temperature sensitive processes • Diaphragm valve	• Pressure transducer in charge tool
Other	"Turnkey" production system design, planning, implementation and manufacturing support Portable brake pedal tester with or without base station	Portable brake pedal tester with base station
Locations	Farmington, MI: HQ, manufacturing, engineering, service and support Atlanta, GA: service and support Oakville, Canada: service and support	Dayton, OH

Comparison of Brake Fluid Filling Equipment Vendors, cont.

Serv-I-Quip (SIQ)	Fori Automation	Dominion Technology Group
SIQ was spun-off from duPont in 1981. Started in charging and reclamation equipment for the HVAC and appliance industries, but is a growing player in vehicle fluid fill systems.	Fori supplies a wide array of assembly automation and process equipment. Fori has previously modified TMMK's original brake fill equipment.	Dominion is an established assembly automation and process equipment supplier. Dominion supplied TMMK's original brake fluid fill equipment.
• HVAC and Appliance Process Equipment • Vehicle Fluid Fill Systems	• Automation Systems • Fluid Fill • Glass & Urethane Apply Systems • Manipulators • Tire Wheel Processing • Test Equipment	• Alignment • Fluid Fill • Roll Test • Tire Wheel Processing
Mitsubishi, Honda	TMMK (upgrade)	TMMK (original); GM, Ford, DCX
• Sophisticated process control and data acquisition system • Simple charge tool design with modular extensions	• Not interested in doing new fluid filling equipment (per Mike Scott)	
N/A	Portable brake pedal tester with base station	N/A
Dowington, PA	Shelby Twp., MI	Roseville, MI

Appendix 3: Comparison of Brake Fluid Evacuation and Fill Processes at Different Assembly Plants

	TMMK	TMMI	TMMC
Equipment	Dominion/Fori	Decker	Decker, currently evaluating Durr
Positive pressure test	No, currently under evaluation	Yes	No, currently under evaluation
Process monitoring	TMMK-1: equipment alarms only, TMMK-2: adding vacuum profile high/low limits	Equipment alarms only	Vacuum profile collected for every vehicle
Equipment monitoring	Reactive – vacuum calibration, vacuum base pressure, vacuum time, leak rate	Reactive – vacuum calibration, vacuum base pressure, vacuum time, leak rate	Proactive – equipment condition based monitoring triggers preventative maintenance

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