Effective Convergence Type Problem-solving Technique for North American Automotive Products and Manufacturing Processes

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Automotive systems and components have shown a pattern toward increasing complexity, stricter tolerances, and shorter product cycles. To meet market requirements, excellence in automotive design and manufacturing practices must rise accordingly to ensure the reliability of such evolved mechanical systems. Product failure investigations must be fast, efficient, and exact. The increasing complexity of mechanical systems can create an attribute failure problem (i.e., damage) that is often harder to solve than a failure that comes from a continuous feature such as dimensional variation. Consequently, convergent problem-solving methods for finding the source of various failure types have been utilized effectively in North America.

Introduced in this paper will be problem solving techniques that specifically address attribute failures.

Key Words: *contrast, energy, strength, Concentration Chart, destructive events, malfunctions*

1. Introduction

Automotive components that fail in the application can potentially compromise operator safety as well as comfort. It is therefore critical that problem solvers tasked with improving the reliability of automotive components have quick and exact methods that can reveal and eliminate the precise source of the failures. The techniques being used in North America that are presented in this paper will show investigators how to diagnose multiple failure modes accurately and by order of influence.

The first step in an efficient investigation is to choose a strategy for how the problem will be solved and then implement that strategy using techniques that will make the task easier. Effective strategies begin with a precise categorization of the response under study[1]:

1) *Feature* (a continuous response: typically dimensions referenced against a datum)
2) *Defect* (an attribute response: scratches, chips, cracks, etc.)
3) *Event* (an attribute response: field failures, Durability test etc.)
4) *Property* (a continuous response: decibels, density, tensile strength, etc.)

The second step is to choose a technique that is appropriate for that category. If, for example, Y is a property or a feature, the X-Y relationship should be evaluated by plotting Y against several potential variables (X) on either a Multi-Vari chart or a Scatterplot. These graphs will expose the family of variables that harbor the root cause.

At this point, that family is split into two or more groups of variables, followed by another test to ascertain which of those groups harbors the root cause. This sequence of splits continues progressively until the offending variable (X) is found.[2]

If the failure is an event and the product is an assembled unit, then a typical next step might be to use a technique known as Component Search[3]. This method will show if the assembly process caused the failure or if it was one of the components, and if one of the components, which one.

If the response is a defect such as a scratch, inclusion, crack, etc., then the starting point is to map the defects with a Concentration Chart[4] to see if the defects are concentrated. If they are, then either a strength problem exists at that location or the concentration correlates with some position in the manufacturing process (or to a position within the application). If the defects are distributed randomly, then they were probably caused by an energy spike from the manufacturing process or the application itself. Concentrated defects tend to result from the way the part is made; randomly distributed defects tend to result from the way the part is used.

2. Converging Onto Important Factors: the Attribute-to-Continuous Transform

When defects such as cracks or scratches are found on tested parts, it is prudent to transform those defects and events (attribute responses) into continuous responses early in the problem-solving investigation (**Fig. 1**).

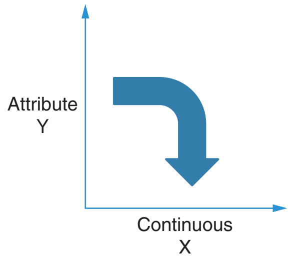


Fig. 1 Attribute-to-Continuous transform

Attribute-to-continuous transformations come in many forms: Defect to Feature, Defect to Property, Event to Feature, etc. Below is an example of an attribute-to-continuous transform.

The raceway of a transmission thrust bearing was spalling at the inner diameter where the edge curls downward. The spall was categorized as a defect (an attribute response) based on actual tested parts. Since the response is a defect, the investigation began with the mapping of spall locations onto a Concentration Chart (**Fig. 2**).

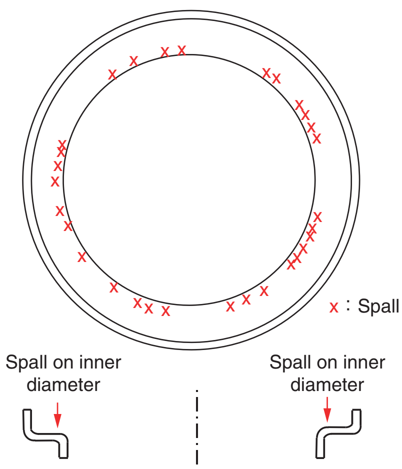


Fig. 2 Concentration chart of spall on a thrust bearing raceway

The progressive search pattern is shown on a search tree (**Fig. 3**). The concentration chart answered the first question: are the defects concentrated or distributed randomly?

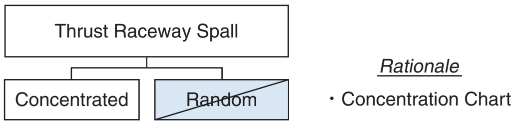


Fig. 3 Search tree

The fact that the defects are concentrated suggests the material is too weak to withstand system energy. The reason why the material is too weak can be answered by leveraging the contrast between spalled and non-spalled raceways. Twelve raceways were sampled, six with spall at the inner diameter (the WOW, or worst-of-worst location) and six with no spall at the inner diameter (BOB, or best-of-best, parts). Taper and surface finish features were measured on the WOW parts near the spall indications. **Table 1** shows the original, unsorted data (BOBs in green, WOWs in red). **Table 2** shows each column sorted independently from low to high in a Group Comparison analysis[5]. The data in the interaction column is the product of the taper and surface finish values.

Table 1 Group comparison (unsorted)

Taper	Surface Finish	Taper × Surface Finish Interaction
−0.022	0.136	−0.0030
−0.026	0.111	−0.0029
−0.028	0.119	−0.0034
−0.031	0.115	−0.0035
−0.029	0.114	−0.0033
−0.027	0.112	−0.0030
−0.035	0.133	−0.0046
−0.028	0.158	−0.0044
−0.028	0.15	−0.0043
−0.032	0.141	−0.0045
−0.029	0.145	−0.0042
−0.034	0.132	−0.0045
Original column order		

(BOBs in green, WOWs in red)

Table 2 Group comparison (sorted)

Taper	Surface Finish	Taper × Surface Finish Interaction
−0.035	0.111	−0.0046
−0.034	0.112	−0.0045
−0.032	0.114	−0.0045
−0.031	0.115	−0.0044
−0.029	0.119	−0.0043
−0.029	0.132	−0.0042
−0.028	0.133	−0.0035
−0.028	0.136	−0.0034
−0.028	0.141	−0.0033
−0.027	0.145	−0.0030
−0.026	0.150	−0.0030
−0.022	0.158	−0.0029
End-count = 6	End-count = 9	End-count = 12
90% Confidence	95% Confidence	99% Confidence
Each column sorted independently		

(BOBs in green, WOWs in red)

The sum of each column's end-counts determines significance. Data are analyzed by ranks, not values, which makes the technique suitable for both variables and attributes data. Sample sizes can be as small as six parts (three BOBs, three WOWs) for finding significance and confirming effects.

Larger end-counts provide higher significance. End-counts of seven to nine are significant with 95% confidence; from ten to twelve: 99% confidence; and greater than twelve: 99.9% confidence.

Based on the end-counts in **Table 2**, it is clear that taper and surface finishes are significant. Surface finish was the stronger of the two effects. However, the strongest effect was the taper-by-surface finish interaction. **Figure 4** shows a contour plot of the taper and surface finish variables against the response (no spall = 1, spall = 2). Diverging contour lines indicate the presence of the taper-by-surface finish interaction.

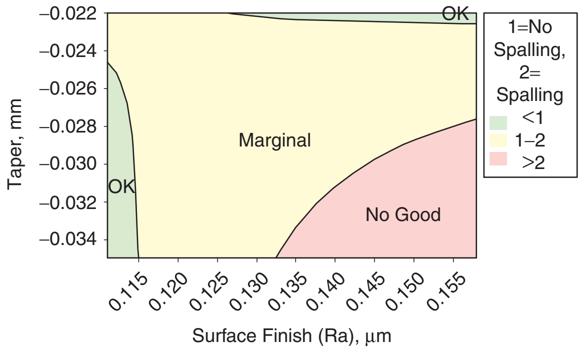


Fig. 4 Contour plot of taper, surface finish

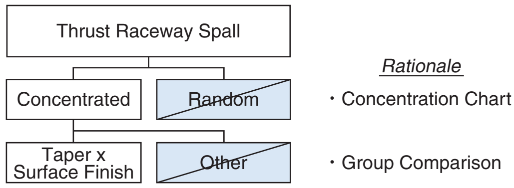


Fig. 5 Search tree (updated)

The Search Tree (**Fig. 5**) is updated per the new information. The attribute response Y (spall) has now been transformed into a continuous response X (taper, surface finish).

Now that the attribute response Y has been transformed into a continuous response X, the next step in the progressive search is to apply Multi-Vari and Scatterplot techniques to taper, surface finish, and their interaction.

Starting with the taper variable, the question was asked if Heat Treat was causing its variation or some process before Heat Treat. Taper was measured before Heat Treat and then re-measured after Heat Treat. The data was plotted on a Scatterplot (**Fig. 6**).

It was clear from the correlation (**Fig. 6**) that taper variation after Heat Treat depended on the variation the parts had before Heat Treat. A similar analysis was done with surface finish data as well (for this response, parts were measured before and after the tumble process).

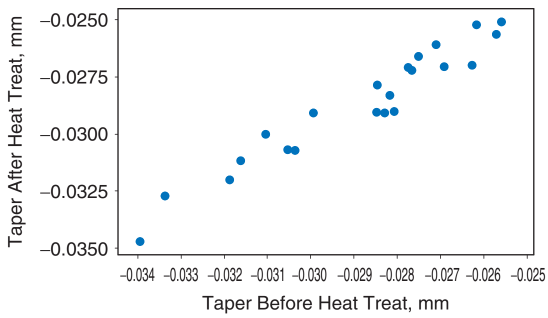


Fig. 6 Scatterplot

Note that if the spall had been distributed randomly over the surface of the raceway, the problem solver should consider using a Weibull analysis to understand the nature of the failure.

A Weibull analysis of miles-to-failure data (from vehicles) or hours-to-failure data (from bench tests) will generate a slope (β) that will show if the spall resulted from part weakness ($\beta<1$), energy spikes ($\beta=1$), or premature wear-out ($\beta>1$). If the wear-out time is significantly less than what was intended by design, then either the part was designed incorrectly or the application energy was too high for the part's design.

In another example, the outer diameter of a thrust-bearing raceway was spalling. Specifically, the spall resulted when the rollers repeatedly hit the high edge of the dip in the raceway (**Fig. 7**). An attribute-to-continuous transform connected the spall to raceway thickness variation.

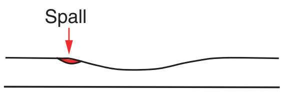


Fig. 7 Spall location on raceway

The updated search tree is shown in **Fig. 8**.

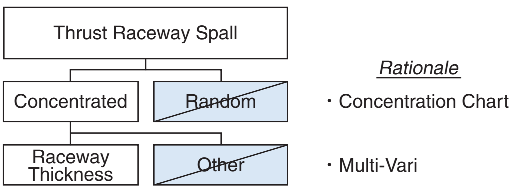


Fig. 8 Search tree

The next split asked if raceway thickness variation was originating at or before the stamping operation or after the stamping operation. The raceway thicknesses of a sample of parts were measured after they were stamped and then they were re-measured after Heat Treat. The data correlated (Scatterplot), identifying Stamping as the source of thickness variation (**Fig. 9**).

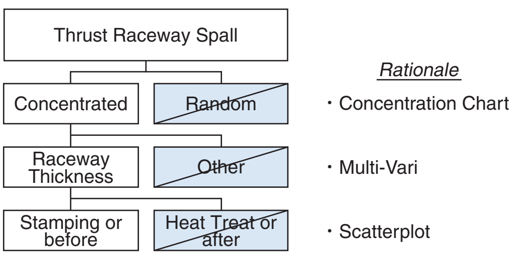


Fig. 9 Search tree (updated)

For the next split, raceways were sampled from all seven cavities of the stamping die. The thickness variation was the same for each part, up to and including the first cavity (the piercing step), suggesting the variation existed in the incoming strip material. Additionally, the thin areas on the raceways were concentrated on the same side with respect to the strip feed direction (**Fig. 10**).

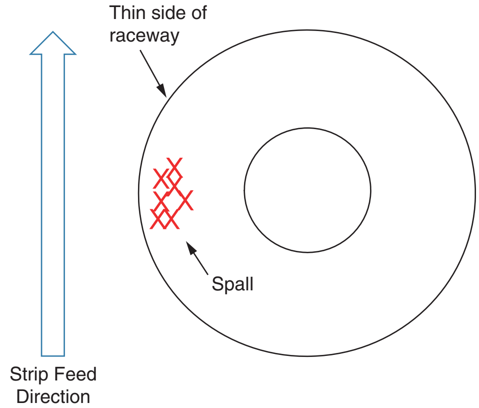


Fig. 10 Concentration chart

To investigate the strip material influence, a ten-foot strip was cut, reversed in direction, and fed back into the stamping machine and die. Raceways stamped from that strip showed that the thin area of the raceway had shifted to the opposite side (**Fig. 11**). This reversal of concentration location proved that the thickness variation was coming entirely from the strip material and not the stamping process. (A common technique in convergent searches is to "move" a family of variables similar to what was done in this example to see if it will move the location of the concentration.)

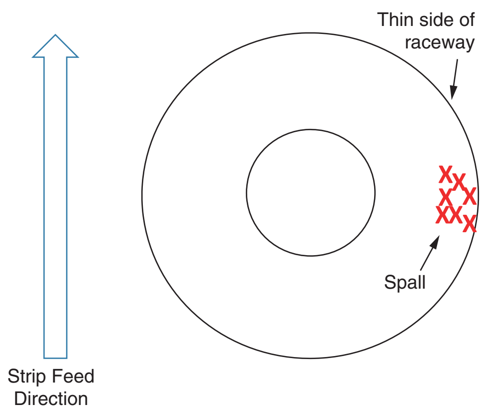


Fig. 11 Thin side shifts from left to right

Thin areas in the strip correlated with thin areas in the raceway. Hence, it was found that the root cause of raceway spall (attribute response Y) was strip thickness variation (taper, continuous response X). See **Fig. 12**.

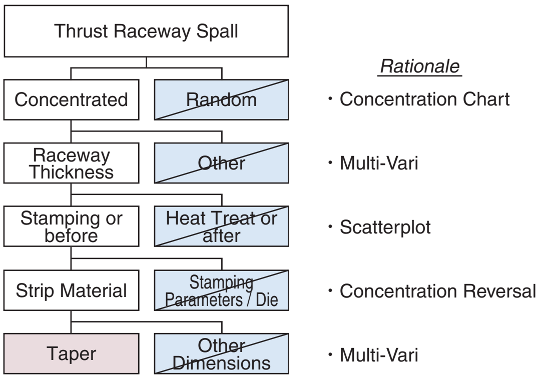


Fig. 12 Final search tree

3. Part Strength vs. System Energy

Components fail when system energy overwhelms part strength. Investigators must decide if a part's failure is due to excessive system energy or insufficient part strength.[3)]The answer can be found by either understanding or changing both system energy and part strength in the various steps of the manufacturing process.

When defects are distributed randomly over a part, one should ask how much energy is needed to make that defect and which step of the process produces that much energy. This approach can lead the investigator to the source of the problem.

Consider the cracked washer example. This low failure rate problem (19 ppm) was solved by understanding how part strength and process energy (and their relationship) changed throughout the value stream.

It was noted that rectangular and uniformly wide indentations were made at the base of the cracks (**Fig. 13**). This characteristic was an important clue as to what was cracking the washers. Any suspected root cause would have to be capable of making a dent of the same dimensions.

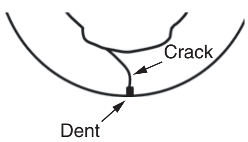


Fig. 13 Characteristic indentation

To understand how much energy it took to crack a washer, several washers were broken with a tensile machine and the average strain energy density (area beneath the stress-strain curve[5)] was calculated. It was seen that typical washer strength was greater than all sources of energy produced by the value stream.

The investigators first approach was to reduce washer strength. An additional process step was added to weaken the washers (i.e., change the correct relationship between system energy and part strength) so they would break effortlessly and increase the number of failures. This result would make it easier to find out where in the process the washers were breaking. Specifically, a notch was cut into six hundred washers taken from the stamping machine (**Fig. 14**) and then re-inserted into the remaining process.

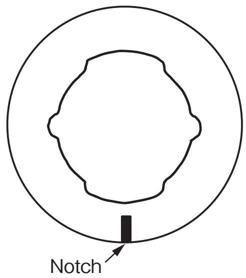


Fig. 14 Weakened washer

Most of them cracked, albeit in the tumble process where the tumbling energy was too low to crack a full-strength washer, but high enough to crack a weakened washer. None of the cracks had the characteristic dents that were seen on the original cracked washers. Consequently, a new problem-solving approach was taken.

Since energy leaves impressions that have specific timing, identity, location, and magnitude, investigators asked what exists in the process that can make that specific dent at that location to that extent. They also asked if part strength changes throughout the process, and if so, where?

By using a tensile machine to crack washers after every process step, it was found that washers were the weakest after quenching. When the investigators checked the oil quench tank, they found a clearance at the rotation position of the conveyor belt (**Fig. 15**) with a section shape that was the same as the dents seen on cracked washers. It was suspected that the sidewall plates were pinching the washers. To confirm this suspicion, quenched washers were dropped between the converging side plates during belt rotation. A crack with the characteristic dent was made. It was concluded that pinching sidewall plates was the root cause of washer cracks.

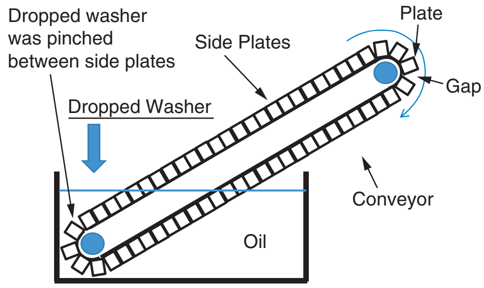


Fig. 15 Quench tank with conveyor

This effect explained all the contrasts: the brittle cracks, their random locations (implying energy spikes), the low failure rate, and the size and shape of the dents.

By examining energy impressions and the relationship between the component strength and system energy, the root cause of defects can be found quickly and effectively.

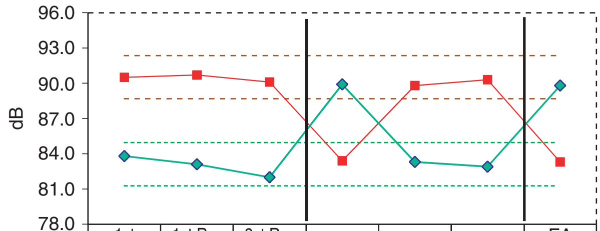
4. Catastrophic Failures vs. Malfunctions

All examples discussed thus far have dealt with catastrophic failures: defects that remain after energy is removed. Another kind of failure is the malfunction: defects that *disappear* when energy is removed.

Malfunctions can occur intermittently (unpredictably) or repeat under specific operating conditions. Sometimes a malfunction can be continual, presenting symptoms such as excessive noise, heat, and vibration, and yet create no physical damage.

Solving malfunction problems can be approached by leveraging the first law of thermodynamics (conservation of energy): supplied energy (E1) = work done (E2) + energy loss (E3). Determine which of these three forms of energy is causing the malfunction event.

If the malfunction is continual while energy is being applied, the root cause can be found using the Component Search technique. The response is decibels, which is a measure of energy loss (E3). **Figure 16** shows an example of part swapping between a noisy and a quiet thrust bearing. Two assembled units are used in this study: a BOB, and a WOW, unit.



	1st Assembly	1st Re-assembly	2st Re-assembly	FA	JK	JF	FA Confirm
WOW's	90.5	90.7	90.1	83.40	89.80	90.30	83.3
BOB's	83.8	83.1	82.0	89.90	83.30	82.90	89.8

Fig. 16 Component search

The three stages of the graph show:

1st Stage: the normal variation for each of the BOB and WOW units when they were disassembled and re-assembled

2nd Stage: how the causal component(s) were found through part swapping

3rd Stage: how reversals that occurred during the part swapping were confirmed

In the first stage, the noise (dB) of the BOB unit was measured. The unit was disassembled, re-assembled, and re-measured. This step was repeated, yielding three measurements for the BOB unit. The same procedure was applied to the WOW unit, producing six measurements in all. The BOB unit remained good (low dB) and the WOW unit remained bad (high dB). The conclusion drawn from the first stage was that assembly variation was not causing the noise; it was coming from one of the components.

The data for the first stage were used to establish decision limits, lines meant to show what is “normal” for each unit based on assembly variation.

In the second stage, the investigator swapped Components 2 and 3 between the BOB and the WOW assemblies. The trend line reversed for Component 1 only, which showed that the root cause was coming from that component alone (**Fig. 16**).

In the third stage, the investigator swapped Component 1 again to confirm the original reversal. The result confirmed the correlation between noise and Component 1.

Without a detailed investigation of all components, Component 1 was taken from eight BOB assemblies and eight WOW assemblies. An inspection of Component 1 found scratches on all of the WOW parts but none on the BOB parts.

Below is the final Search Tree for the noisy bearing malfunction problem (**Fig. 17**):

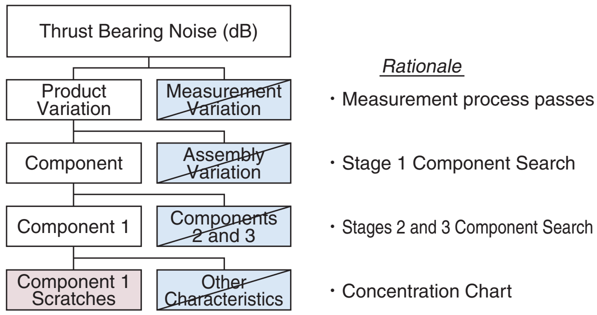


Fig. 17 Thrust bearing noise search tree

Malfunctions are easier to solve when the contrast is known between what a good unit is supposed to do and what a defective unit is actually doing. Malfunctioning units will usually emit some kind of energy loss such as heat, noise, vibration, etc., which can be used as a response at the beginning of the convergent search tree.

If product failures are catastrophic such that no features can be measured on the damaged parts, the root cause can be found by pre-measuring features prior to testing the parts. The data from parts that failed the test are then compared with the data of parts that passed the test (a Group Comparison analysis – see examples in **Tables 1 and 2**).

Another method for dealing with catastrophic failures is to monitor a variable that changes with time that usually reaches a predictable level prior to a product failing. BOBs and WOWs can then be chosen based on the length of time that passed before the indicator variable has reached its failure limit.

5. Conclusion

In recent years, convergent search techniques have been used in North America for solving complex problems in automotive products and processes. A few of those methods were introduced in this paper. These were:

1) Categorization of the response of failed parts to determine how an investigation should begin
2) Transformation from an attribute response to a continuous response and then convergence to a root cause
3) Convergence to a root cause based on the relationship between system energy and part strength
4) Convergence to a defective component within a product assembly by swapping BOB and WOW components

By using these techniques, complex problems can be solved fast and effectively.

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