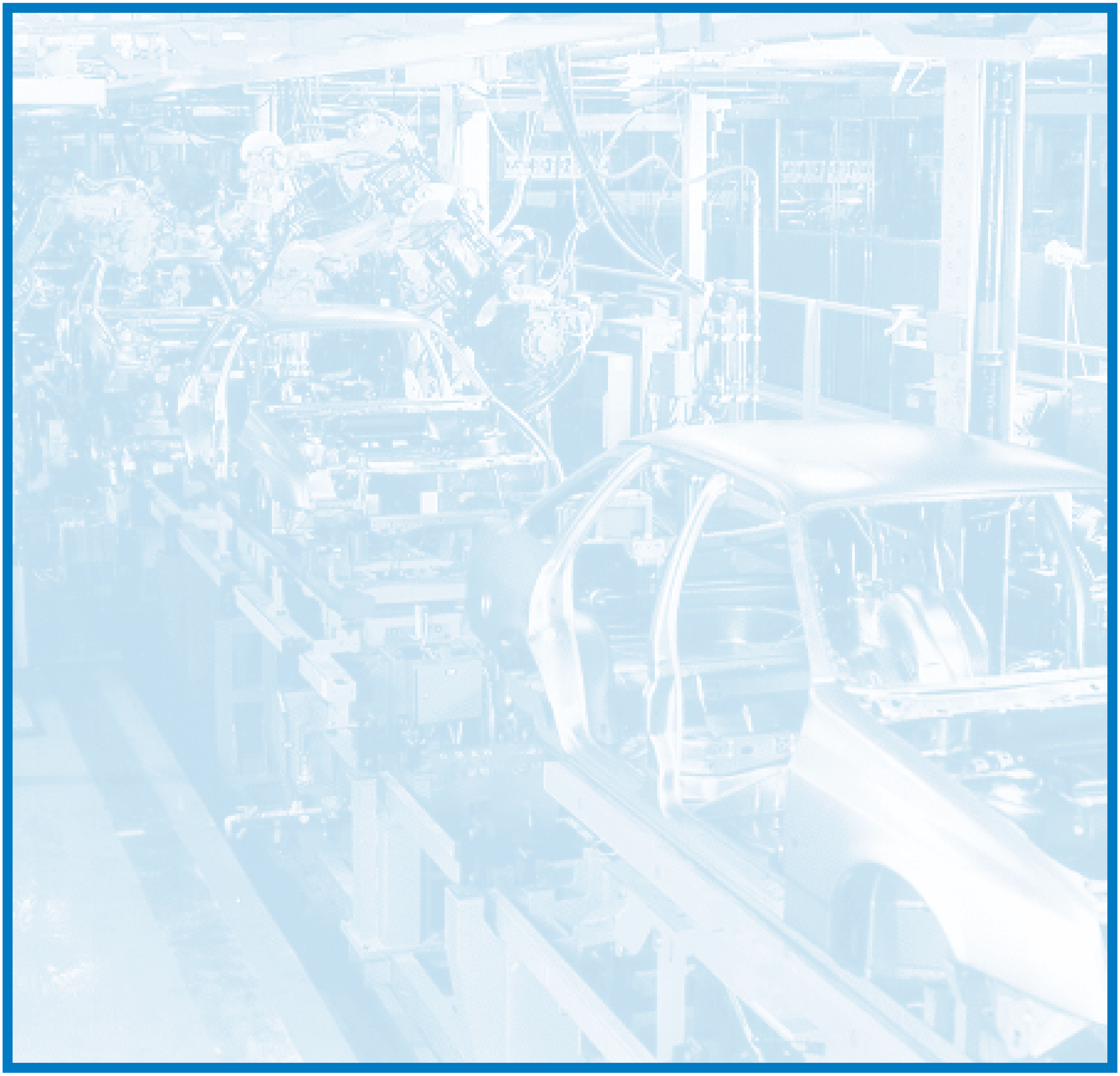

Automotive Body Measurement System Capability

Examining the impact of the measurement system on dimensional evaluation processes.

Auto/Steel Partnership

Automotive Body Measurement System Capability

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Preface

This report is one of a series published by the Auto/Steel Partnership Body Systems Analysis Project Team on stamping and assembly variation, body measurement systems and process validation. These reports provide a summary of the project research and are not intended to be all inclusive of the research effort. Numerous seminars and workshops have been given to individual automotive manufacturers throughout the project to aid in implementation and provide direct technical support. Proprietary observations and implementation details are omitted from the reports.

This automotive body development report, "Automotive Body Measurement System Capability," updates ongoing research activities by the Body Systems Analysis Project Team and the Manufacturing Systems staff at The University of Michigan's Office for the Study of Automotive Transportation. The purpose of this report is to quantify the capability of various body measurement systems and to examine the impact of the measurement system on dimensional evaluation processes.

A primary goal of this research is to develop new paradigms that will drive automotive body-in-white development and manufacture towards a total optimized processing system. Previous reports described fundamental research investigating simultaneous development systems for designing, tooling and assembling bodies, and also flexible body assembly. Since the inception of this research program, considerable emphasis has been focused on dimensional validation of automotive body components. A major factor in the dimensional validation process is the role of the measurement system.

The researchers are indebted to several global automotive manufacturers for their on-going dedication and participation in this research. They are DaimlerChrysler Corporation, Ford Motor Company, General Motors Corporation, Nissan NUMMI, Opel and Renault. Each conducted experiments under production conditions, involving hundreds of hours of effort, often requiring the commitment of numerous production workers and engineering personnel. Although it is impractical to mention each one of these individuals, we do offer our sincere appreciation.

The reports represent a culmination of several years of effort by the Body Systems Analysis Project Team. Team membership, which has evolved over the course of this project, includes:

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Executive Summary

The Auto/Steel Partnership (A/SP) is an innovative international association that includes DaimlerChrysler, Ford, General Motors and eleven North American sheet steel producers. The Partnership was formed in 1987 to leverage the resources of the automotive and steel industries to pursue research projects leading to excellence in the application of sheet steels in the design and manufacture of vehicles. The Partnership has established project teams that examine issues related to steel properties including strength, dent resistance, surface texture and coating weights, as well as manufacturing methods, including stamping, welding and design improvements.

This automotive body development report updates ongoing research activities by the A/SP Body Systems Analysis Project Team and the Manufacturing Systems staff at The University of Michigan's Office for the Study of Automotive Transportation. The purpose of the study is to quantify the capability of various body measurement systems and then to examine the impact of the measurement systems on dimensional evaluation processes.

In the automotive industry, the role of sheet metal measurement systems is critical and costly mistakes can result from poor gage designs and misinterpretation of data. The two most common sheet metal measurement technologies, hard gages and coordinate measuring machines, both tactile (CMM) and optical (OCMM), are used extensively for die buyoff, process validation and process control monitoring. The first step prior to using the measurement system is to verify the repeatability and reproducibility (R&R) of the system and, to determine accuracy.

Achieving acceptable gage R&R for large, non-rigid sheet metal parts is problematic. Non-rigid panels are typically large panels of thinner gauge such as body sides, fenders, quarter panels, etc. Overall, R&R variation is only slightly lower for CMM's than for hard fixtures, and this variation is primarily due to the loading and unloading of parts into the fixture. Reproducibility is the greatest source of R&R variation for both hard fixtures and CMM's, accounting for about 85% and 90% of total R&R variation respectively. The industry rule-of-thumb that gage R&R account for less than 30% of the tolerance is a major factor influencing part tolerances, check point locations and checking fixture design, particularly for panels that are not rigid. In order to comply with the 30% R&R rule, check points on non-rigid parts often require minimum tolerances of +/- 0.75 mm, and +/- 0.5 mm on rigid parts. Because gage R&R accounts for a significant portion of the tolerance, measurement fixtures, especially hard gages are more effective at detecting process mean shifts for process control than they are at identifying changes in process variation.

Since non-rigid panels deflect with clamping pressure and from their own weight, redundant locators and clamps are often used to establish the reference plane once the panel is loaded onto the checking fixture. The use of multiple or redundant locators provides both an opportunity and a dilemma. The problem of over-constraining parts for measurement is that the checking fixture distorts the part and introduces stresses. The problem when measuring over-constrained parts is that they can be held as they would be during the assembly process, and therefore the measurement system can help anticipate build quality. The datum or clamping sequence can be altered in order to shift variation to areas of the part that may not be as critical as the interface between two mating flanges, for example. De-emphasizing the actual process variation and measurement accuracy and focusing attention on how parts will assemble is consistent with a functional build philosophy.

The functional build philosophy for part measuring advocates that the measurement fixture reflects the assembly of the part with respect to locating and holding clamps. Areas of the part where measurements are concentrated are critical assembly areas such as mating flanges, cut lines and possible interference points. Since gage R&R and accuracy are difficult to attain and verify accurately, die rework decisions are not based solely on measurement data, except in obvious cases where deviations are extreme. In some cases, critical areas can be “netted” first, or fixed to their

desired location, and variation transferred to other non-critical areas of the part, both in the measurement fixture and in the assembly fixture. Although the measurement locations focus on the ability to assemble parts, over-stressing of panels must be minimized. The ideal functional build fixture minimizes the amount of over-constraining, yet has sufficient constraints so that part loading and unloading results in consistent assembly quality with minimal inherent stress.

1.0 Introduction

To evaluate automotive body quality, North American manufacturers are incorporating more data-based decisions to replace subjective opinions. Inherent in to this approach, however, is an understanding of the quality of the data collected, and hence the effectiveness of the measurement systems used. This report assesses the strengths and limitations of automotive body measurement systems and considers their impact on dimensional evaluation strategies.

An ideal measurement system produces results that agree exactly with a master standard. Unfortunately, measurement systems with such properties are rare. These systems routinely produce data with measurement biases and variation. Measurement biases are deviations between measured values and the true values obtained by using more precise measuring equipment. Measurement variation relates to the inability to obtain the same value for repeated measurements of the same part. Automotive manufacturers typically evaluate the impact of measurement system variation using gage capability studies, gage repeatability and reproducibility studies, and other analysis methods outlined in the “Measurement Systems Analysis” reference manual(1) published by the Automotive Industry Action Group (AIAG).

The measurement system plays a critical role in any dimensional evaluation process. In the case of the automotive body, its role is particularly influential. Body manufacturers measure most part features in absolute space using X, Y, and Z coordinates rather than as relative distances between points. Absolute space measurements are more complex, particularly for angled surfaces. They are also heavily dependent upon the part locating system, or datum scheme, which often is difficult for parts lacking rigidity. Manufacturers frequently have to over-constrain a part in order to meet gage capability requirements. Adding or moving a locator in a part holding fixture, however, may significantly change the dimensional mean and variation for a particular part feature. In some cases, these measurement system effects limit the ability to identify real dimensional problems, as some mean deviations are attributable to the part locating system rather than the stamping die.

The purpose of this report is to examine the capability and limitations of the various body measurement systems, including hard checking fixtures and coordinate measuring machines. The supporting data are based primarily on studies at the noted manufacturers

In this report, the various measurement systems used in automotive body manufacturing are described first. Section 3 provides typical levels of gage capability for the most widely used checking fixture and coordinate measurement systems. Section 4 examines sources of gage error and compares gage variation and inherent part-part variation. Section 5 considers the impact of the measurement system on dimensional measurement strategies. The impact of the measurement system on the assignment of part tolerances is examined, along with the use of over-constrained fixtures to measure non-rigid detail components.

This report will show that although body measurement systems typically have sufficiently low gage error, they have limitations in terms of measurement biases. The lack of rigidity of stamped parts requires manufacturers to violate standard part locating principles. Although violating these principles by adding secondary locators reduces gage variation, it also creates measurement biases. In other words, the location of part features in measurement fixtures may not correlate to part positioning in assembly tools. The effect of these measurement biases is that manufacturers should not simply evaluate a part characteristic relative to its gage readings, but also in relation to assembly processes.

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[1] “Measurement Systems Analysis: Reference Manual,” Second Edition, February 1995, Automotive Industry Action Group (AIAG).

2.0 Body Measurement Systems

2.1 Measurement System Applications

The most widely used systems to measure automotive bodies and their stamped components are checking fixtures, often called hard gages, and coordinate measuring machines, the CMMs. CMMs may either be mechanical or optical. Mechanical CMMs are usually stationary, that is, fixed plates, although portable CMM systems are seeing increased usage. Figure 1 below illustrates a checking fixture and a stationary coordinate measurement machine.


Body Side - Check Fixture

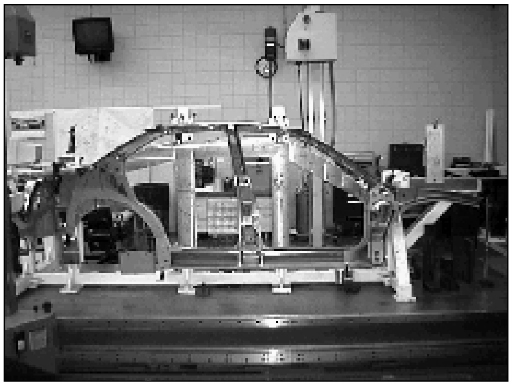
Body Side - CMM

Figure 1. Measurement Systems

The use of a particular measurement system depends largely on application and measurement objectives. Typically, manufacturers use coordinate measuring machines for larger, complex parts requiring numerous dimensional checks. Of the coordinate measuring machines, stationary systems in environmentally controlled-rooms are the most common, and are considered the most accurate and repeatable. Other benefits are their flexibility, in terms of adding dimensional checks, and that they may be operated using automated programs, thereby reducing the need for measurement personnel to be present.

Portable CMMs are even more flexible than stationary CMMs because adding dimensional checks does not require programming, and they can be moved to the process. This flexibility allows manufacturers to use these systems for problem solving during stamping tryout. Some manufacturers also use them on the shop floor to measure assembly-tooling locators. The principal concern with portable CMMs is their limitations in measuring the exact location of a part characteristic across a large sample of parts. They also are more operator intensive. Thus, portable CMMs are used primarily to measure only one or two parts.

Another type of coordinate measuring machine common in body manufacturing is the optical version (OCMM). Typically, these machines are used for on-line measurement because their reduced cycle time allows them to be used at production speeds. These on-line OCMMs make real-time, 100% inspection of bodies and major sub-assemblies possible. OCMMs also eliminate material handling problems that result from transporting large, complex-shaped assemblies to a special CMM inspection room. One concern with OCMMs, however, is their accuracy or measurement bias. Manufacturers often program mean offsets to coordinate OCMM actual readings with CMM data. Accuracy issues often result from problems with camera alignment and controlling the environment, including shadow effects, under production conditions. Another potential problem with OCMMs is part locating. Some OCMM users align parts mathematically by measuring locator holes and surfaces. They then reference part characteristics to this datum scheme. Unfortunately, part measurements based on mathematical alignment often differ from fixture measurements due to problems created by locator hole distortions, part movement during clamping in fixtures or the effects of gravity.

Although coordinate measurement systems offer tremendous flexibility and data collection efficiency, they often are not used for process control in press shops. Generally, OCMMs are considered too expensive and impractical for widespread use in stamping. CMMs often are considered impractical for smaller stamped parts with few dimensions because of their long processing times. CMM processing time includes transportation to a special inspection room, wait time for a measuring machine to become available, set up time, and machine cycle time. Long CMM processing times delay feedback of measurement information which impairs process control effectiveness.

Most manufacturers rely on hard checking fixtures to measure stamped parts for process control. The principal advantage of checking fixtures is that manufacturers can locate them near a press or a sub-assembly line, thus providing quick feedback on process performance. The principal concerns for manufacturers using checking fixtures are cost and measurement capability. Checking fixtures generally cost more than CMM holding fixtures because manufacturers have to mount checking rails and data collection bushings at dimensional locations. In terms of gage capability, checking fixtures generally are considered less accurate and repeatable than coordinate measurement systems. This capability generalization will be examined further in the next section.

2.2 Part Locating System

One of the main components of a measurement system is the part reference or locating system. Regardless of the measurement technology, nearly all part measurements are relative to a part datum scheme described on Geometric Dimensioning and Tolerancing (GD&T) drawings. These datum schemes provide a reference system for all part surfaces and features using body coordinates. Figure 2 below illustrates a typical body coordinate system. This system replaces the traditional X, Y, and Z directional designations with fore/aft (X), in/out (Y), and up/down or high/low (Z). The 0,0,0 point of the car is the front, lower, center position.

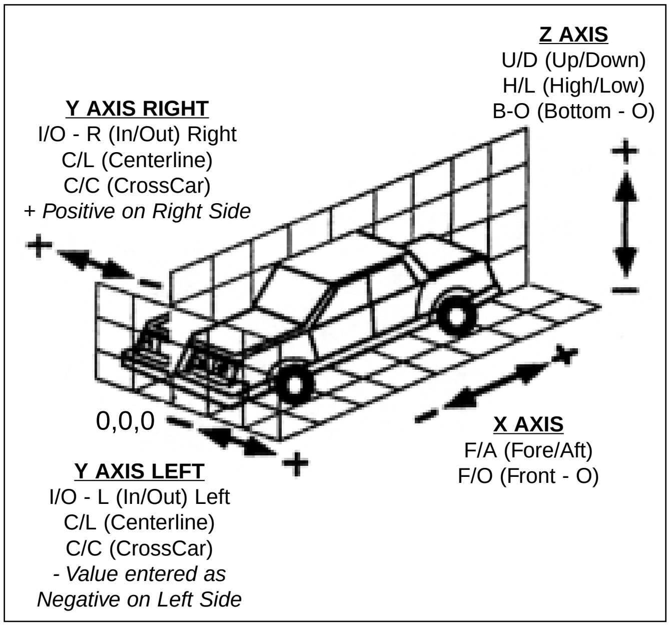

Figure 2. Body Coordinate System

Holding fixtures used in measuring systems and assembly operations often follow a 3-2-1 locating scheme to position parts. Under this scheme, three locators position a part in a primary plane or direction. Two locators then position the part in a secondary direction leaving one locator for the tertiary direction. This approach fixes the part in 3-dimensional space and satisfies the six degrees of freedom constraint. For some product designs, manufacturers replace the three locators for the secondary and tertiary directions by using two round pins, one fitting a circular hole and the other a slot. The pin locates the part in two directions, in/out and fore/aft. The slot then becomes the other locator for the secondary direction. Figure 3 below is a schematic representation of the 3-2-1 principle using the hole/slot combination.

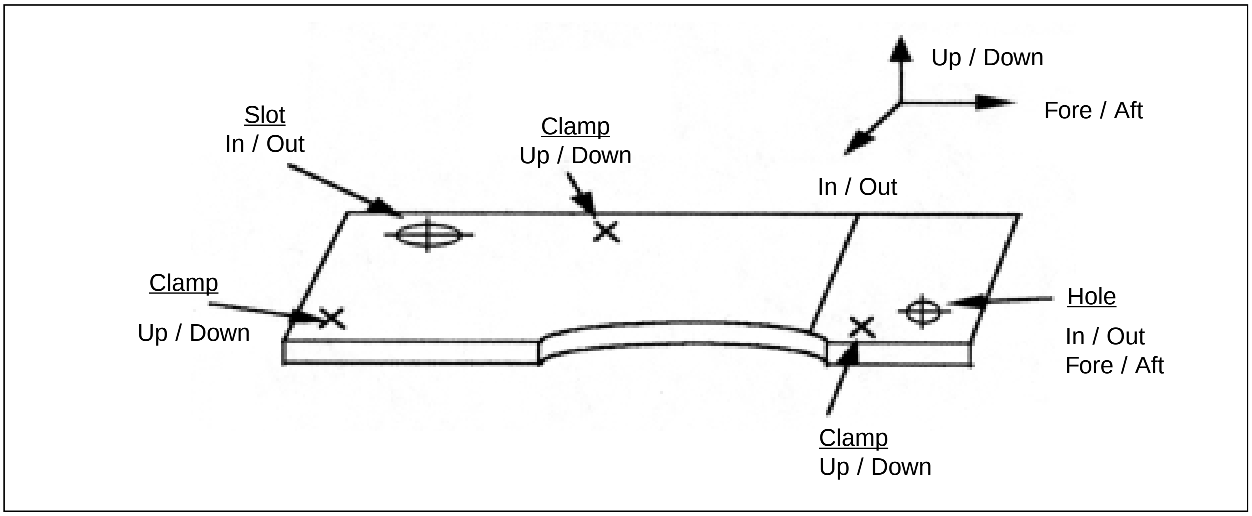

Figure 3. The 3-2-1 Locating Scheme

The lack of rigidity for many stamped components and assemblies often forces manufacturers to violate the 3-2-1 locating scheme and use additional locators to position parts in a stable and repeatable manner. As a result, the locating scheme for sheet metal is sometimes referred to as *n*-2-1. The *n* denotes the three or more locators needed to position a part in a primary plane. The number of additional constraints may vary greatly between manufacturers. For example, Figure 4 below shows a similar body side outer panel design at two manufacturers. Company C has ten primary locators in the in/out direction while company E has twenty. The effects of different part locating schemes on gage error are examined in subsequent sections.

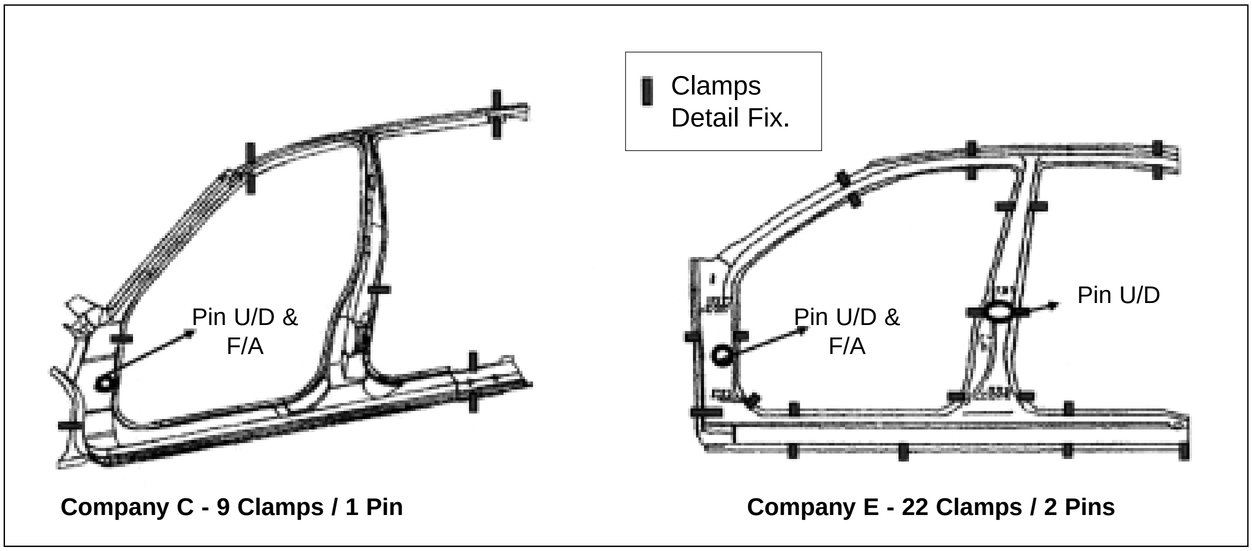

Figure 4. Number of Locator Clamps at Company C versus Company E

3.0 Gage Capability

3.1 Gage Capability for Check Fixture Data

Measurement systems are subject to variation and therefore, dimensional analysis of a process first, requires an evaluation of gage capability. Most manufacturers evaluate capability using gage R&R studies. gage repeatability refers to the variation in measurements obtained when one operator uses the same gage for measuring identical characteristics of the same parts. Gage reproducibility refers to the variation in the average of measurements made by different operators using the same gage to measure identical characteristics of the same parts. The total gage variation, Equation 1, is based on repeatability and reproducibility. To compute the capability of a measuring device, manufacturers typically compare the range of gage variation, estimated by 5.15 x σ_{gage}, to the tolerances, Equation 2.

Equation 1

$$\text{Total Gage Variation: } \sigma_{gage} = \sqrt{\sigma^2_{repetability} + \sigma^2_{reproducibility}}$$

Equation 2

$$\text{\% Gage Capability (Gage R\&R)} = \frac{5.15\,\sigma_{gage}}{Tolerance} * 100\%$$

To assess gage capability, the automotive industry typically uses a 30% rule. This rule states that the range of gage variation must be less than 30% of the total tolerance for a part dimension, or gage R&R < 30%. For instance, if the tolerance for some part characteristic is +/- 0.7 mm, the gage standard deviation must be less than 0.08 mm (30% x 1.4 / 5.15 < .08).

Table 1 and Figure 5 below summarize gage variation across several parts in three case studies. Overall, these studies suggest that manufacturers achieve similar levels of gage variation. Note that although Case Study II had a higher 95th percentile value, it exhibited a similar median sigma gage. Since this case study considered significantly more parts, it likely provides the best estimate of the distribution of gage error.

Case Study	# Parts / (# Dimensions)	Median σ_{gage}	95th Percentile σ_{gage}
I	4 (34)	0.04	0.06
II	61 (428)	0.03	0.11
III	12 (309)	0.03	0.07
All	77 (771)	0.03	0.09

Table 1. Gage Variation by Manufacturer

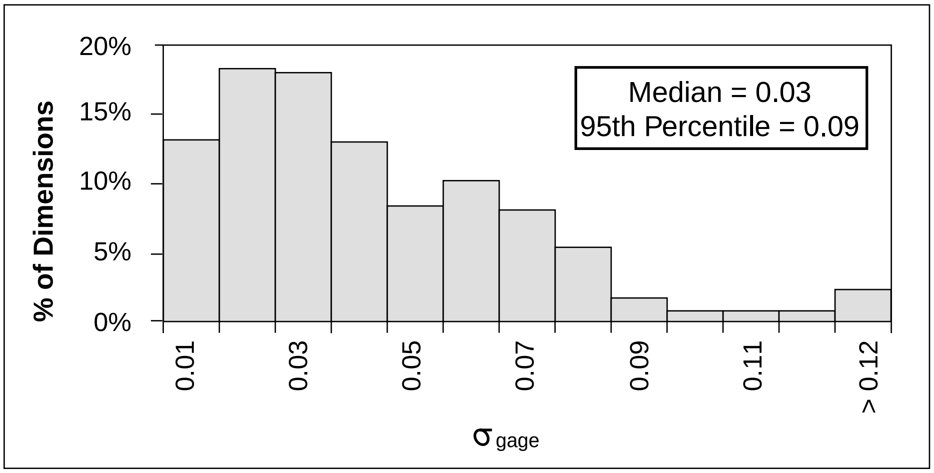

Figure 5. Histogram of Gage Standard Deviation for Checking Fixtures

Figure 6 below shows the distribution of gage capability for the 700 part dimensions presented in Figure 5. Over 90% of the dimensions exhibited a gage R&R less than 30%. In addition, more than 50% of the dimensions had a gage R&R less than 10%. Although the inherent gage variation is usually acceptable, a small percentage of dimensions still have gage error concerns. The following section discusses why certain dimensions have larger gage variation.

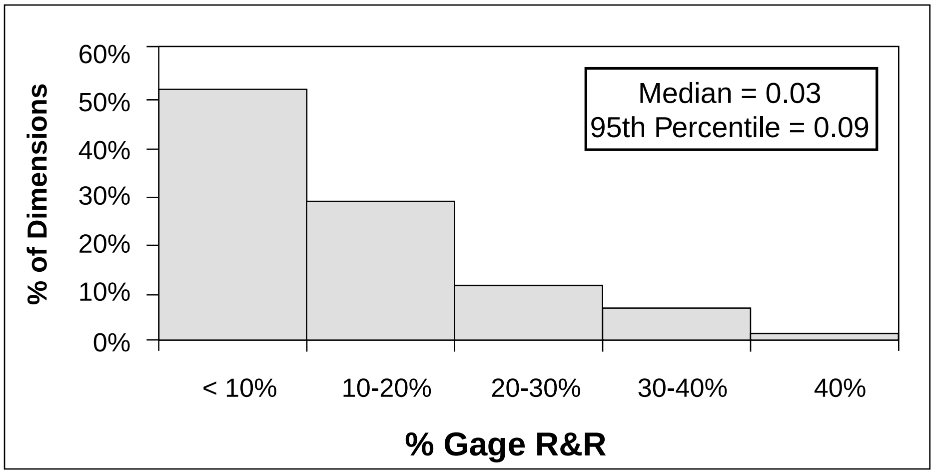

Figure 6. Distribution of % Gage R&R (Goal < 30%)

The next step is to determine which of the two components of gage variation, repeatability or reproducibility, account for the greater proportion of the gage variance. The data in Figure 7 below, based on Case Study III, suggest that nearly 85% of the observed gage error may be attributed to repeatability. The principal cause of this gage repeatability error relates to the loading/ unloading of parts in the fixture and not the variability in the measurement probe. Once a part is located in a fixture, measurement probes are quite repeatable, with $\sigma_{repeatability}$ less than 0.01 mm without loading/ unloading between measurement trials.

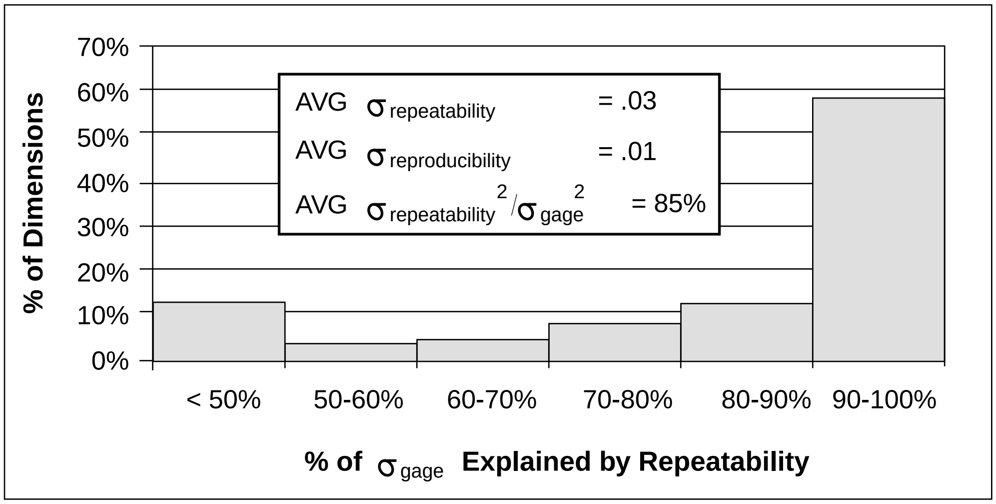

Figure 7. Percent of Gage Variation Explained by Repeatability Error

3.2 Gage Capability for CMM Data

Evaluating the capability of a CMM differs slightly from a check fixture. Since CMM measurements are taken using automatic programs, manufacturers generally are not concerned with the operator or reproducibility effect. In this instance, the gage variability for a CMM consists primarily of repeatability. Some manufacturers, however, break CMM gage repeatability down to static repeatability and dynamic repeatability. Dynamic repeatability, or setup error, represents the ability to measure identical part characteristics using the same gage on the same part with loading and unloading between measurement trials. In the case of static repeatability, the part is not unloaded or unclamped between trials. Thus, static repeatability represents the pure error in the measurement instrument. The breakdown of CMM gage repeatability may be represented mathematically using Equation 3.

Equation 3

CMM gage error: $\sigma_{repeatability} = \sqrt{\sigma^2_{static} + \sigma^2_{setup\text{-}dyanamic}}$

Figure 8 below separates CMM repeatability into static and dynamic repeatability. These data suggest that the dynamic repeatability, based on the setup or loading/unloading of the part in the holding fixture, is the main source of CMM gage error. Here, more than 90% of the repeatability error σ_{repeat} may be attributed to loading and unloading of the part between measurement trials.

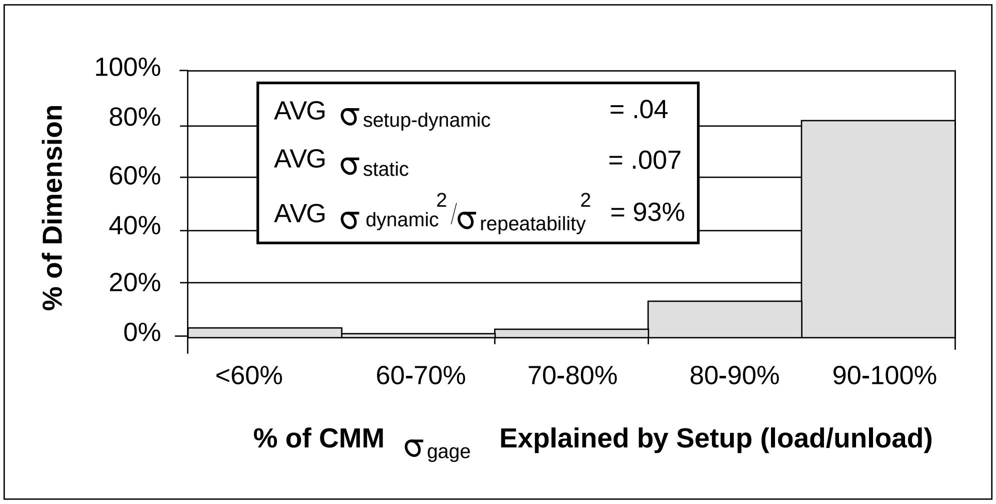

Figure 8. Static versus Dynamic CMM Gage Repeatability Error

The next step is to compare the repeatability of a CMM to that of checking fixtures or hard gages. Unfortunately, data based on identical parts and holding fixtures are not available to make these comparisons. Thus, the following analysis represents a general comparison of measurement systems. Table 2 below summarizes the repeatability for integrated or one-piece body side outer panels at four manufacturers. These data indicate that for similar clamping strategies, gage repeatability error appears only slightly better for a CMM. This result is not surprising given that gage variation relates primarily to the load/unload operation and not the static repeatability of the measurement probe. These data also suggest that using more over-constrained holding fixtures tends to have a greater influence than the measurement technology in terms of reducing gage error. For example, although companies A and B have similar one-piece body side designs, with integrated quarter panels, the CMM gage repeatability error at company B is higher than at company A. One explanation is that company B uses significantly less clamps in their measurement fixture, 5 versus 11 cross-car clamps.

Company	**Measurement System**	**# Cross Car Clamps**	**Median** $\sigma_{\text{repeatability}}$	**95th Percentile** $\sigma_{\text{repeatability}}$
A	CMM	11	0.04	0.06
B	CMM	5	0.04	0.13
C	Check Fixture	10	0.05	0.08
G	CMM	17	0.01	0.03

Table 2. CMM vs. Checking Fixture Gage Repeatability for One-Piece Body Sides

(Note: Body Side for company C in this table is different than in prior tables)

4.0 Measurement System Analysis

A fundamental question in evaluating measurement systems is whether to separate the analysis of the gage from the part characteristics. Some manufacturers maintain that evaluating gage capability should be independent of the part features. Here, manufacturers use a subset of part characteristics to evaluate gage capability. Unfortunately, the distribution of gage error shown previously does not support this strategy. In the following sub-sections, several issues are identified that affect gage error and measurement biases.

4.1 Gage Error and Type of Part

Figure 9 below compares the distribution of gage variability of large/complex and small/simple parts. Large/complex parts tend to have a wider distribution of gage variation than small/simple parts. One reason for this difference is the effect of the measurement system clamps on individual dimensional characteristics. Small/simple parts typically may be constrained using the basic 3-2-1 approach. In this situation, the clamping effect does not appear to significantly affect gage error. For large/complex parts, however, the use of additional clamps (*n*-2-1) can significantly reduce gage error in certain localized areas within a part. For example, dimensions in stable areas, either due to proximity to locator clamps or rigidity of localized part area, often have less gage variation than non-stable areas. These issues are explored in the next sub-section.

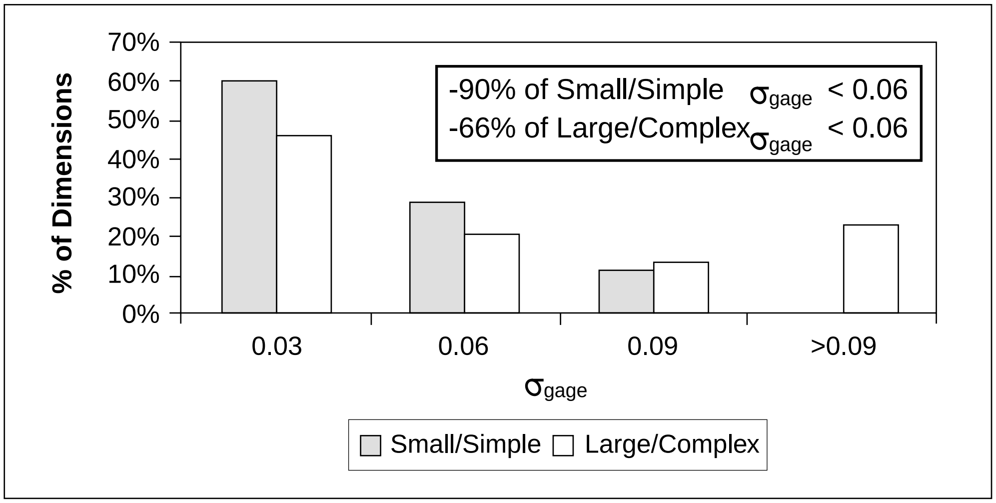

Figure 9. Distribution of Gage Error for Small/Simple and Large/Complex Parts

4.2 Gage Error and Dimensional Characteristics

Figure 10 on page 12 compares the gage variation for respective dimensions on ten right and left mirror image components. If gage error is truly independent of the characteristics being measured, then low correlation between right and left mirror dimensions might be expected. Figure 10, however, shows a significant correlation of R=0.75, suggesting a relationship between gage error and individual part characteristics.

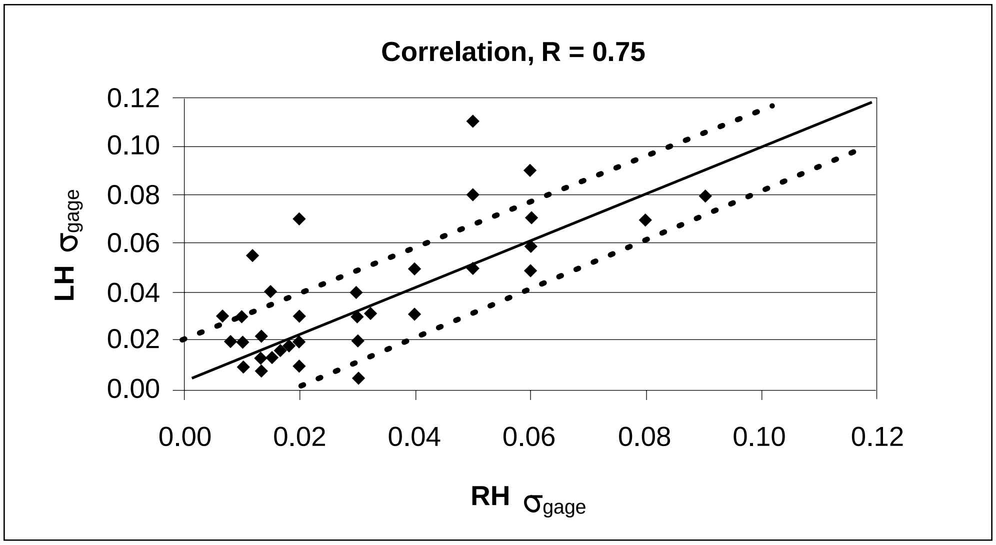

Figure 10. Correlation of Gage Error for Right and Left Coordinated Dimensions

Even within a single part, considerable variability in gage error may exist. Figure 11 below shows the gage error distribution for a relatively unconstrained body side of company B. This histogram suggests that gage error across a part is not independent of the part characteristic being measured.

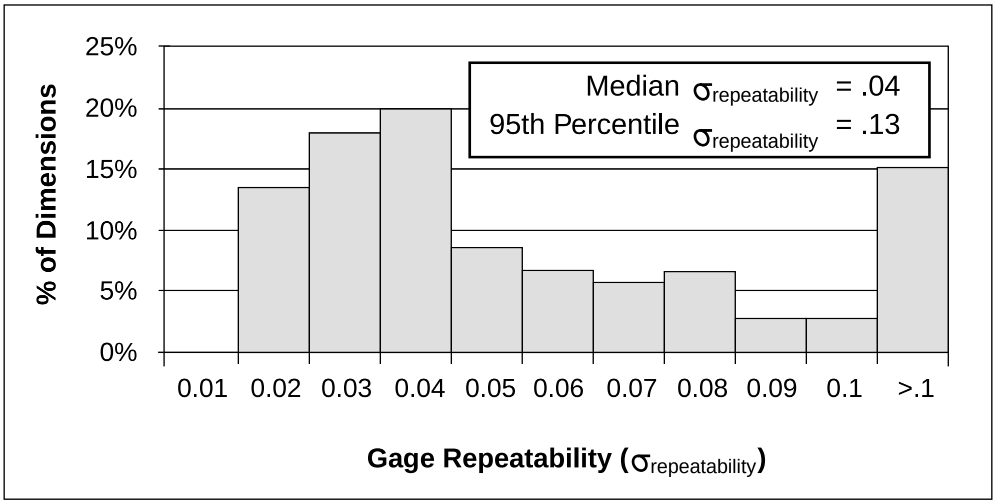

Figure 11. Histogram of CMM Gage Variation for a One-Piece Body Side Outer Panel

(Based on 105 dimensions)

To further explore this lack of independence, Figure 12 below illustrates high and low gage variation areas for a body side outer in relation to part locating clamps. Again, one predominant theory to explain why certain dimensions have higher gage variation is lack of part constraint in certain local regions and not the measurement technology. For this body side, those areas located close to clamps are well constrained and exhibit low sigma gage measurements ranging from 0.01 to 0.04. In contrast, areas of the part that are less-constrained exhibit significantly larger sigma gage measurements, as high as 0.15. This lack of constraint and the resulting gage variation can cause certain areas of the part that are not well constrained to also exhibit higher part variation.

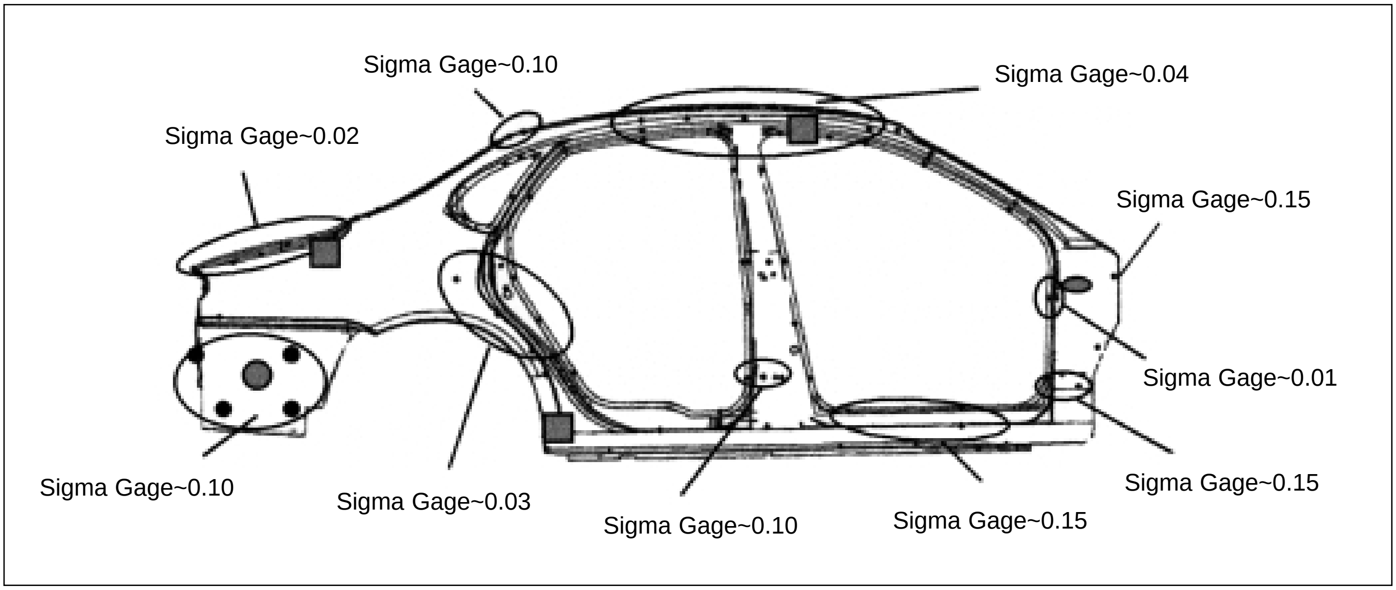

Figure 12. High Gage Error vs. Datum Scheme

(Clamps designated by □)

Figure 13 on page 14 illustrates gage error and localized part rigidity for another body side outer panel. This figure also suggests that gage error is not independent of the part characteristic being measured. More stable dimensions in heavily formed areas, such as the B-pillar, typically exhibit less gage variation than less stable measurement areas in the quarter panel and wheelhouse. Because of this greater gage variation, these less rigid areas of large/complex parts typically have greater part variation than those in more stable measurement areas.

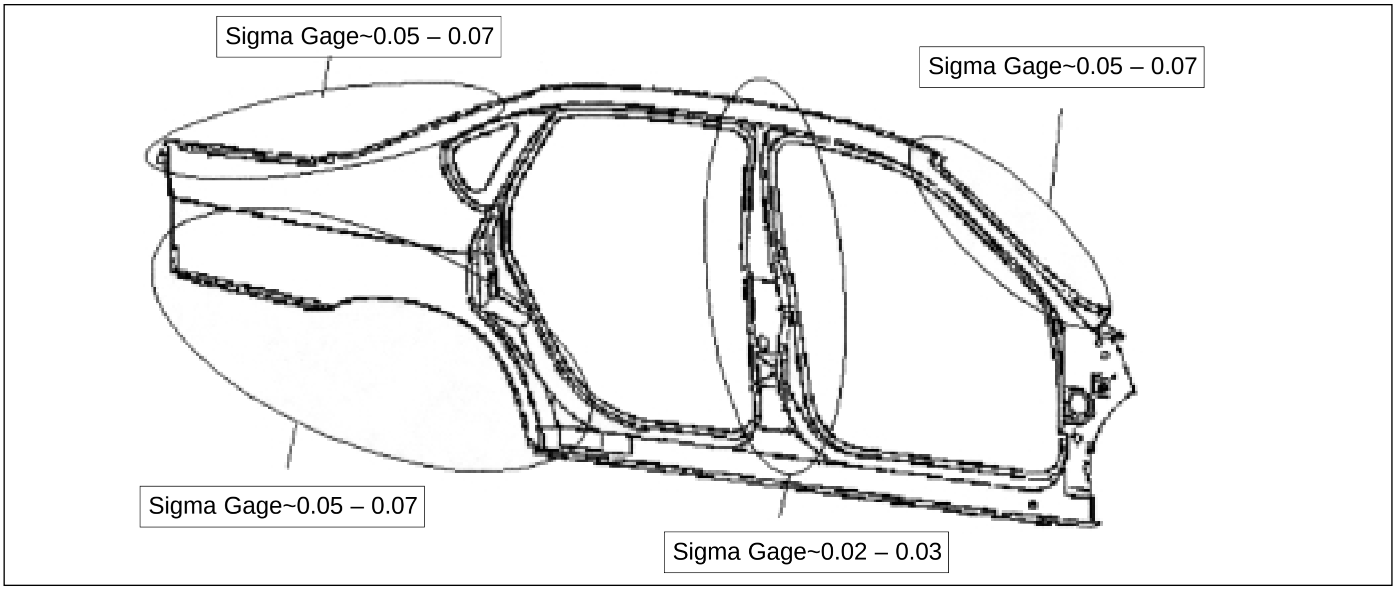

Figure 13. Gage Error by Part Area

4.3 Effect of Dimensioning and Part Locating System (GD&T) on Accuracy

In addition to repeatability and reproducibility, whether for a CMM or check fixture, manufacturers should also evaluate dimensional measurement biases. For instance, they should examine whether the observed measurement mean biases accurately reflect their true means. Manufacturers often use additional clamps beyond the 3-2-1 locating scheme to hold a panel in a stable position. As mentioned previously, this approach can introduce measurement biases for certain dimensions. This bias is the deviation of the observed mean from its true mean.

Traditionally, manufacturers assess the true mean of a part characteristic by using more precise measurement equipment. However, given the unique influence of the part locating system on stamping measurements, it is recommended that body manufacturers consider part positioning in the assembly operations to identify the true mean. Manufacturers use GD&T in body manufacturing because the positioning of the parts or the location of a mating part dimension is as critical as the actual part size. Thus, body measurement systems must strive to yield dimensions that accurately reflect the positioning of a part characteristic, such as a mating flange, at time of assembly. Inconsistencies between assembly fixtures and detail measurement fixtures result in discrepancies between measurement data and part positioning at time of assembly.

Many of these discrepancies are related to part datum schemes. Part holding fixtures using additional clamps beyond 3-2-1 often create measurement biases by temporarily bending a part during clamping. This bending may shift a dimension either toward or away from its target or nominal specification. Thus, the observed mean for a dimension can reflect its actual position plus a fixture effect.

Similarly, the observed part variation may also include a fixture effect. Non-rigid sheet metal components typically conform to their holding fixtures based on their clamping sequence, or the order in which locator pins and clamps are engaged to hold a part during measurement. Dimensions near those clamps engaged first may exhibit less variation than those engaged last. These observed variations change for different clamping sequences.

When the locating system of a fixture affects both the observed mean and variation of non-rigid part dimensions, it becomes an active part of the measurement system. This contrasts with a passive measurement system where dimensional means are not dependent on the checking fixture locating scheme or clamping sequence. For instance, if a manufacturer measures the relative distance between two features, the actual locating scheme may become less critical if the fixture is not deforming the part.

Two case studies are presented, showing the effects of the part locating system on measurement biases and variation.

4.3.1 Case Study I: Effect of Clamping Sequence

In Case Study I, the effect of clamping sequence on gage error for a quarter inner panel was considered. This experiment studied the effect of altering the clamping sequence by changing the order of the last three clamps (see Figure 14, below). In the second sequence, the clamp near dimension #4 was engaged before the two clamps located next to dimensions #1 and #3. The purpose of this second sequence was to determine if variation in dimension #4 might be reduced since it has the smallest assigned tolerance of dimensions #1, #3, and #4. The same ten panels were measured for each clamping sequence.

Figure 15 on page 16 summarizes the differences in the mean and variability for various dimensions using the two clamping sequences. Both the mean and standard deviation for dimension #4 changed by altering the clamping sequence as seen in Figure 16, also on page 16. As a result of a decrease in the standard deviation, the C_p index for this point increased. The second sequence, however, did result in increased variation for dimensions 1 and 3, but these points have larger tolerances than # 4. The mean and variation for the dimensions did not change for those located near clamps 6 and 7, where the sequence was not altered.

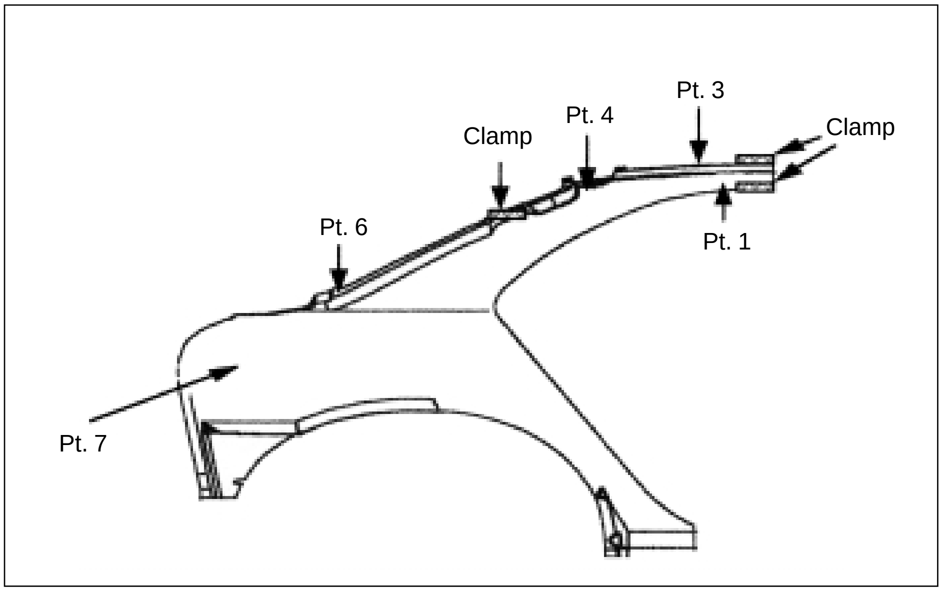

Figure 14. Dimensional Measurements for an Inner Quarter Panel

This study shows that by changing the clamping sequences, manufacturers can shift variation to less critical areas without actually changing the part. It also confirms the widely held belief that clamping sequence affects dimensional measurements. For non-rigid parts, manufacturers can produce different estimates for dimensional means and variation depending upon the clamping sequence. The ramifications of these findings are significant. Since clamping in assembly tooling typically occurs simultaneously as opposed to manually in measurement holding fixtures, manufacturers must accept some potential measurement biases and variation inconsistencies in their stamping data. They should exercise caution before reworking or adjusting a process closer to nominal because of the potential lack of a relationship between measurement data and part positioning at time of assembly.

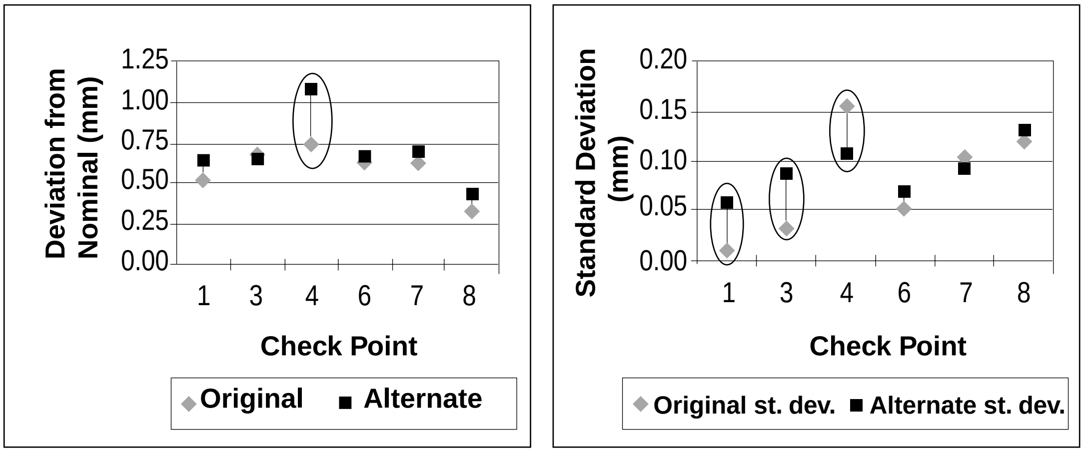

Figure 15. Differences in Mean and Variation for Alternate Clamping Sequence

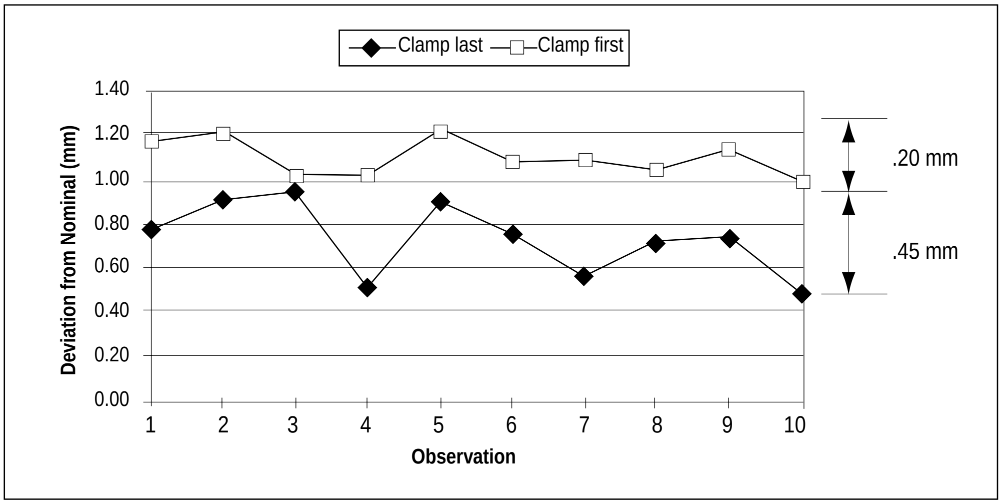

Figure 16. Effects Of Clamping Sequence on Dimension #4

4.3.2 Case Study II: Effect of Additional Clamping Locators

Case Study II compared constrained versus over-constrained clamping strategies. Figure 17 below illustrates ten dimensions on a body side inner panel and the location of two sets of clamps. The constrained system uses 9 cross-car clamps, and the over-constrained system uses 17. In this experiment, ten body sides were measured using both a CMM and a feeler gage for the two clamping systems.

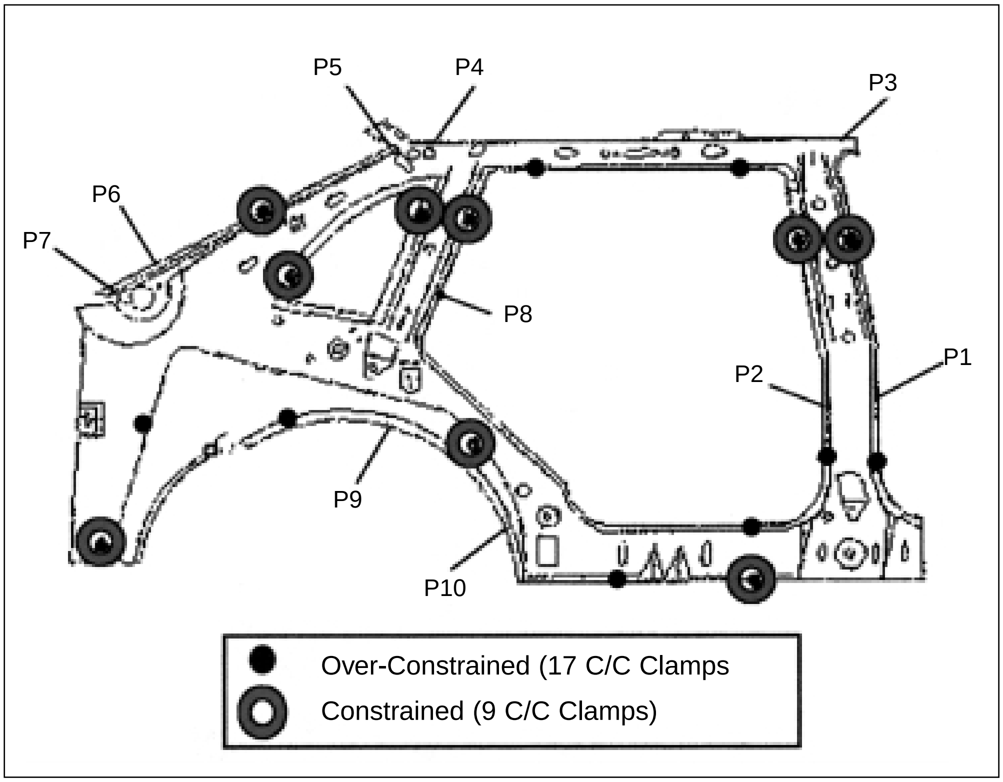

Figure 17. Body Side Conformance and Clamping Strategies

Table 3 on page 18 indicates that the use of additional clamps may significantly shift mean dimensions and reduce variation. In this study, three of the ten dimensions shifted more than 0.5 mm. Interestingly, these mean shifts were not always toward nominal. One dimension, P10, shifted away from nominal using the more constrained clamping system. The point of this case study was not simply to show dimensional changes due to clamping, but to question the ability to accurately assess mean deviations.

This experiment also indicates significant variation reductions for several dimensions using the more constrained clamping system, particularly in the center pillar and wheelhouse area check points P1, P2, P6, and P9.

	Average Deviation from Nominal (mm) by Panel Dimension										
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Median Difference
Constrain (9 clamps)	-0.54	-0.96	-0.46	0.09	0.10	-0.29	0.70	-0.06	-0.74	0.56	
Over-Constrain (17 clamps)	-0.20	-0.45	0.15	0.38	0.43	-0.23	0.67	-0.09	-0.55	1.60	
Mean Difference	0.34	0.51	0.61	0.29	0.33	0.06	0.03	0.03	0.19	1.04	0.31

	Standard Deviation (mm) by Panel Dimension										
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Average Sigma
Constrain (9 clamps)	0.23	0.21	0.19	0.18	0.21	0.16	0.31	0.09	0.15	0.22	0.20
Over-Constrain (17 clamps)	0.08	0.03	0.14	0.14	0.25	0.07	0.20	0.17	0.06	0.16	0.13
Statistical Difference? (based F-test,α=.05)	Dec	Dec	–	–	–	Dec	–	–	Dec	–	

Table 3. Mean and Variation Conformance by Clamping Approach

Table 4 below compares mean dimensional measurements between CMM data and feeler gage data using both constrained and over-constrained systems. These data suggest that the CMM had a significant effect on mean values. Four dimensions shifted over 0.5 mm between the CMM data and the feeler gage data. Furthermore, in all cases where dimensions shifted, the CMM mean dimensions had greater mean deviations than the feeler gage data. Table 5 below examines the potential impact of the measurement gage on variation. The results of this analysis are mixed. Two dimensions show significant reductions using feeler gages, although the overall observed product variation does not differ significantly between measurement instruments.

	Average Deviation from Nominal (mm) by Panel Dimension										
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Median Difference
CMM (17 clamps)	-0.36	-0.47	-0.76	0.07	-0.08	-0.19	0.61	0.17	-0.49	1.60	
Feeler (17 clamps)	-0.04	-0.13	0.18	0.20	0.00	-0.10	0.14	0.04	-0.34	-0.07	
Mean Difference	0.32	0.60	0.58	0.13	0.08	0.09	0.47	0.13	0.15	1.67	0.24

Table 4. Effect of Measurement Instrument on Mean Values: CMM vs. Feeler Gages

	Standard Deviation (mm) by Panel Dimension										
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Average Sigma
CMM (17 clamps)	0.08	0.03	0.14	0.22	0.25	0.07	0.20	0.17	0.06	0.16	0.14
Feeler (17 clamps)	0.11	0.12	0.04	0.09	0.25	0.11	0.28	0.10	0.07	0.08	0.13
Statistical Difference? (based F-test,α=.05)	–	Inc	Dec	Dec	–	–	–	–	–	–	

Table 5. Effect of Measurement Instrument on Variation: CMM vs. Feeler Gage Data

In practice, manufacturers try to maintain consistent locating schemes and clamping sequences between checking fixtures and assembly tooling. This consistency is needed to obtain measurements that are valid or representative of stamping quality. Maintaining this consistency, however, is not always feasible. First, many assembly operations use only a subset of the measurement system locators. Second, when automating assembly operations, manufacturers may have to change the position of datum locators. The lack of consistency between locating schemes and clamping sequences may result in observed measurements for stamped parts that are not reflective of their positioning in assembly tooling. This has led some manufacturers to wait until after an assembly evaluation before altering stamped parts, or employ a functional build approach.

Due to the limitations with measuring non-rigid parts, observed mean deviations may not indicate a problem with a set of dies or a press line. Therefore, manufacturers using a traditional build-to-nominal approach may rework dies unnecessarily to correct deviations that result from measurement system problems. This research is not suggesting that all deviations from nominal are a result of measurement problems, but rather that approving a stamped part for production is more complex than simply comparing individual part measurements to design specifications. In many cases, manufacturers must wait until after a part becomes more rigid in sub-assemblies before deciding on whether observed stamping dimensional measurements are reflective of body quality.

4.4 Gage Variability and Part-to-Part Variation

Most manufacturers conduct gage R&R studies to verify the capability of their measuring instruments. However, they should also consider the ability of the measurement system to separate product variation and gage error. Equation 4 is a common mathematical relationship assumed between the observed variation and gage variation.

Equation 4 $\sigma^2_{observed} = \sigma_{product} + \sigma_{gage}$

Observed variation is the variation across a sample of parts, a sample standard deviation. Observed variation may be separated into the measurement system and true product variability. Equation 5 estimates the contribution of gage variability to the observed process variability.

Equation 5

$$\%\text{Gage Contribution} = \sigma^2_{gage} / \sigma^2_{observed} \text{ x100\%}$$

As the gage error represents a larger percentage of the observed variation, the conclusion is that the gage is unable to separate product variation from that of the gage. The significance of a high contribution is that little value is gained by measurement. In other words, if the gage error is nearly equal to short term part-to-part variation, then little information is gained by actually measuring several parts over a short run.

Figure 18 on page 20 compares the percent gage contribution to the part-to-part standard deviation, $\sigma_{part\text{-}part}$, for over 450 part dimensions. Part-to-part standard deviation is computed based on a sample of at least 50 panels from a single stamping run. This figure shows that when the variation is small, or $\sigma_{part\text{-}part} < 0.15$ mm, measurement error can explain a large portion of the observed variability. Of the dimensions with a part-to-part standard deviation less than 0.15 mm, one-third have a gage contribution over 50%. For these dimensions, the usefulness of checking fixtures at distinguishing part-to-part variation from measurement error is questionable. This figure also shows that when part-to-part standard deviation is high, $\sigma_{part\text{-}part} > 0.30$ mm, the gage contribution is less than 20%. This indicates that checking fixtures are capable of detecting large differences or mean shifts between panels.

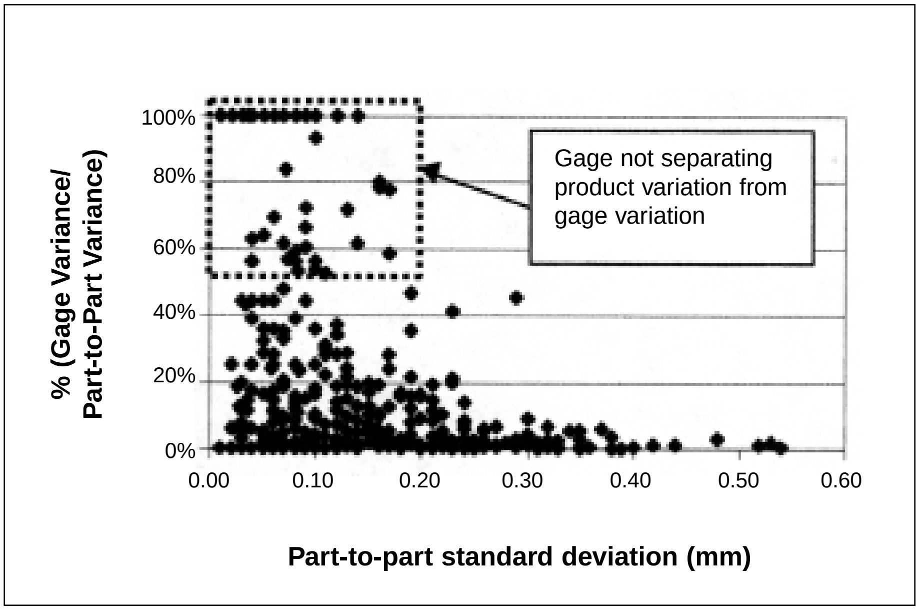

Figure 18. Contribution of Gage Variation to Part-to-Part Variation

Understanding the effects of gage error has implications for determining the number of panels to sample for a tryout or production run. For most stamping dimensions, the short term part-to-part variation is low, $\sigma_{pp} < 0.15$ mm, and thus, measuring large samples of panels from a single run typically yields minimal value due to the inability to separate product and gage variation. This finding does not suggest, however, that measuring stamped parts is non-value added, but rather that measuring large samples over short periods within a single run yields minimal value.

5.0 The Effect of the Measurement System on Dimensional Evaluation Processes

5.1 Gage Capability and Tolerances

One effect of the gage error distribution across a part relates to the assigning of dimensional tolerances. This research suggest that σ_{gage} may range from 0.01 to 0.09 mm (median = 0.03) depending on the part characteristic. Table 6 below derives minimum tolerance requirements, given this range of inherent gage variation, in order to meet a 30% gage error/tolerance ratio. This analysis suggests minimum tolerances of +/- 0.3 to +/- 0.75 are needed to meet these gage R&R requirements. Less stable measurement areas on a part would require the larger minimum tolerances of +/- 0.75 mm.

Gage Error σ_{gage}	**Minimum Tolerance (Gage R&R > 30%)**
0.03	+/- 0.3 mm
0.05	+/- 0.45 mm
0.07	+/- 0.6 mm
0.09	+/- 0.75 mm

Table 6. Inherent Gage Error and Minimum Tolerance Requirements

5.2 Constrained versus Over-Constrained Clamping Systems

A major difference among manufacturers is their use of secondary locator clamps for larger non-rigid parts. Some manufacturers use nearly twice as many clamps as others for similarly designed body side panels. This finding suggests two clearly different strategies. On the one hand, some manufacturers try to minimize the number of secondary locator clamps to reduce their potential effect on part movement. Although these manufacturers strive for 3-2-1, in practice they typically add some secondary locators for large non-rigid parts in order to meet gage capability requirements. This approach is referred to as constrained measurement because it violates 3-2-1 locating principles. In contrast, other manufacturers are less concerned about adding secondary locators, as long as similar clamping strategies are used in assembly tools and that part holding fixtures are not over-stressing the part. This alternative approach is referred to as over-constraining because some of the secondary locators are added even though they are not necessary to meet gage capability requirements. These secondary clamps are used to control metal movement during assembly and subsequently are added to component part holding fixtures to simulate this movement and maintain coordinated datum schemes. Note that manufacturers using these over-constrained systems typically examine parts in a free state, prior to engaging clamps, to insure that no part areas are over-stressed.

One question raised by this analysis is which approach is better. The benefit of using an over-constrained system is typically lower observed part and gage variation. In some cases, the additional secondary locators will mask stamping variation, allowing assignment of tighter part tolerances. Not surprisingly, of the seven manufacturers in the body side experiment, the three manufacturers with the tightest tolerances all use over-constrained measurement systems. One potential drawback of an over-constrained system is that additional locators may adversely deform metal in the part holding fixture. Part dimensional means may significantly shift due to clamping forces. Historically, some of these shifts may be closer to nominal, but others may be further away depending upon the relationship between clamping position and the area of the part being measured.

In contrast to the over-constraining approach, certain manufacturers seek a minimum number of secondary locators. The principal benefit of this approach is that manufacturers reduce the potential to over-stress parts during measurements.

Determining whether to constrain versus over-constrain means recognizing certain basic practices. First, regardless of the clamping approach, manufacturers must have consistent datum schemes between stamping measurement fixtures and assembly process tooling to insure measurements reflect part positioning at time of assembly. Second, manufacturers must be cautious of over-stressing panels. Most manufacturers acknowledge the need to verify that parts fit the fixture before engaging clamps and taking measurements. Manufacturers should also recognize that the effective use of over-constraining only applies to large, non-rigid panels such as body sides, quarter inners, quarter outers, hoods, roofs fenders, floor pans, rear compartment pans and dash panels. This assertion is important because manufacturers should not infer that adopting over-constraining systems will drastically reduce overall variation as it would likely only impact a relatively small percentage of body parts that are heavily influenced by clamping strategy. Nevertheless, these large, non-rigid parts typically are the most difficult to approve for production use.

One hypothesis is that over-constraining large non-rigid parts may provide the best predictor of metal movement during assembly. The addition of spot welds deforms non-stable part dimensions during assembly. The use of additional secondary locators could help predict part positioning and movement during assembly because they constitute additional control points. If the principal objective of stamping measurements is to assess the potential to build dimensionally correct sub-assemblies, then over-constraining may offer a better approach. This Project Team intends to explore more fully the ramifications of using over-constrained measurement systems in future research.

6.0 Conclusions

In devising a dimensional evaluation strategy for the automotive body, manufacturers must carefully consider the effects of the measurement system. This research found that checking fixtures and coordinate measuring machines are capable of measuring most stamping dimensions with a six sigma gage spread of 0.24 mm (6 x 0.04). Since most stamping tolerances are at least +/- 0.5 mm, manufacturers can generally meet gage R&R requirements of less than 30%. For certain large, non-rigid parts, however, they typically have to violate 3-2-1 locating principles by adding secondary locators to stabilize the part during measurement.

Although body measurement systems meet gage requirements for the large majority of part dimensions, manufacturers cannot universally separate measurement system analysis from individual data collection points. Dimensions in unstable measurement areas may yield sigma gage errors of 0.10 mm. For these high gage variation errors, manufacturers must either add secondary locators or assign larger tolerances (+/- 1 mm). Fortunately, dimensions in unstable measurement areas with high gage variation often conform to mating components during assembly, minimizing the need to control them at tight tolerances of less than +/- 0.5 mm.

Another finding of this study is that CMMs and checking fixtures exhibit similar levels of gage variation because the principal source of gage error relates to the ability to consistently load/unload parts in fixtures. The static repeatability of CMMs or check fixture probes are quite good, with $\sigma_{\text{static-repeatability}}$ is less than 0.01 mm.

Although body measurement systems may have low gage variation, they are not necessarily accurate or representative of part positioning in assembly tooling, particularly for larger, non-rigid parts. This research recommends greater emphasis on improving the correlation between detail part measurements in holding fixtures, whether CMM or check fixture, and part positioning at time of assembly. Some manufacturers are trying to achieve this by over-constraining large, non-rigid parts. This contrasts with the traditional approach of trying to develop datum schemes that meet gage capability requirements using only a minimum number of secondary locators beyond 3-2-1.

One concern with measurement biases of mean dimensions at the detail part level is their impact on dimensional evaluation processes. Manufacturers using a build-to-nominal approach may unnecessarily rework mating part flanges based on measurements that do not reflect part positioning in assembly operations. This potential impact of measurement systems on mean dimensions further supports the implementation of a functional build strategy, in which manufacturers evaluate part dimensions relative to their mating part dimensions and not solely to the datum scheme used in stamping check fixtures.

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DaimlerChrysler Corporation

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