Stamping Process Variation:

An Analysis of Stamping Process Capability and Implications for Design, Die Tryout and Process Control

July 1999

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Final Report – July 1999

Preface

This report is one of a series of several reports 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 intervention support. Proprietary observations and implementation details are omitted from the reports.

This automotive body development report "*Stamping Process Variation: An Analysis of Stamping Process Capability and Implications for Design, Die Tryout and Process Control,*" updates ongoing research activities by the Body Systems Analysis Team and the Manufacturing Systems staff at The University of Michigan's Office for the Study of Automotive Transportation.

An over-riding goal of this research is to develop new paradigms that will drive automotive body-in-white development and production 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 benchmarking key world class body development and production processes. These benchmarks created foundation elements upon which further advances could be researched and developed.

This report summarizes stamping variation observations that support moving toward a new "functional build" paradigm that integrates the many individual activities ranging from body design and engineering, on through process and tooling engineering. Revised stamping die tryout and buyoff processes receive special emphasis in addition to the launch of stamping and assembly tools.

The researchers are indebted to several global automotive manufacturers for their on-going dedication and participation in this research. They include Daimler-Chrysler, Ford, General Motors, Nissan, Opel, Renault, and Toyota. Each conducted experiments under production conditions, involving hundreds of hours of effort, often requiring the commitment of many production workers and engineering personnel. Although it may be impractical to mention each one of these people individually, we do offer our sincere appreciation.

These reports represent a culmination of several years of effort by the Body Systems Analysis Project Team. Team membership has evolved over the course of this project. They include:

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Executive Summary

Automotive manufacturers have struggled with the challenge of how to identify when a process is capable of producing dimensionally acceptable stamped panels. The flimsy nature of stamped parts has always made them difficult to measure, and they often do not achieve the lofty dimensional quality objectives, as measured by C_{pk}, seen in many other vehicle components. In fact, **no manufacturer** has successfully achieved a C_{pk} of 1.33 on all part dimensions using the originally assigned specifications, particularly on the larger, thin body panels. Furthermore, achieving a high C_{pk} value alone is not necessarily a good predictor of final dimensional quality. Many factors such as the rigidity of the mating panels, the assembly locating process, and the clamp and welding effects influence how body panels build into an assembly. Consequently, a number of automotive manufacturers have opted not to use C_{pk} as the principal measure of panel quality.

This stamping report analyzes dimensional data to characterize stamping variation by short-term (part-to-part), long-term (die set to die set), and mean bias (long term deviation from design nominal) to better understand process capability. Numerous factors affect the observed variation in a stamping process, making stamping one of the most difficult processes to operate. The complexity of stamping makes it extremely difficult to conduct rigorous experimental studies that can be generalized beyond a given part and process configuration. Thus, the knowledge base of stamping variation is very sparse, and a great opportunity exists to both learn and apply this knowledge to automotive body evaluation processes including die "buy-off", production validation, and long-term process capability analysis. Working within the constraints of the production environment, this research evaluated stamping variation for several processes across seven manufacturers. The research has found that stamping variation is related to:

- Check point location on a part (more rigid areas tend to be closer to nominal and have less variation).
- Measurement fixture design (checking fixtures with more clamps tend to reflect lower variation).
- Part size, complexity and thickness (smaller, less complex and thicker parts have lower variation).

- Press process control (different press lines demonstrate higher die set to die set mean shift control which often is reflected in the control of process variables such as draw press tonnage).
- Shipping and handling (the shipping and handling of parts tends to increase variation and shift dimensions on the parts).
- Changes in stamping presses (for example, some dimensional shifts occur as dies are moved from a tryout press line to the home production press line).

Different automotive manufacturers manage variation, in part, by how they manage these factors; several examples are cited in this report. Although the effects of steel material properties (gauge, yield strength, percent elongation, and n-value) were investigated, this factor is not included in the list above because it had minimal influence on variation. All of the automotive manufacturers that supplied steel coupons in this study had material properties sufficiently controlled to virtually eliminate any influence on stamping variation.

One of the objectives of this research is to understand the amount of variation experienced at different manufacturers and how they manage variation issues. Together, this information may be used to improve the overall validation process for stamping and sheet metal assembly. The uncertainty of sheet metal assembly clearly supports a functional build approach where component quality is determined by how it influences the assembly. These methods are outlined in other reports by the Body Systems Analysis Task Force.

1.0 Introduction

1.1 Motivation for Research

Leading automotive manufacturers around the world have been challenged with applying traditional, fundamental design practices to sheet metal design and assembly. The goal behind this effort is to help achieve high quality car bodies with minimal lead-time and development costs. These practices include geometric dimensioning and tolerancing (GD&T), variation simulation analysis, tolerance stack-up analysis and setting quality standard targets for process capability such as Cp and Cpk. Most manufacturers have expressed concerns over the limited success these methods have had on sheet metal processes including the assignment of dimensional part tolerances, translating component designs into tools that can make them and predicting assembly conformance based on stamping capability. Several important observations account for the limited success of applying traditional design principles to these processes:

- Manufacturers experience difficulties estimating mean part dimensions (relative to nominal) and process variation because these attributes are product and process co-dependent. Potential attributes affecting variation include material properties (steel variations in gage, grade, and coatings), part geometry (size and shape), die engineering and construction, and stamping press variables. The infinite number of design and process possibilities make it nearly impossible to accumulate sufficient historical knowledge for a designer to accurately assign, a priori, tolerances that meet future process capability consistently.
- The lack of component rigidity allows more flimsy panels to conform to more rigid ones, making it difficult to predict final assembly dimensions based on component quality.
- Component dimensions that deviate from their design nominal cannot always be predictably centered (shifted) to the desired nominal without excessive rework costs. Moreover, this rework may correct one particular deviation but then adversely affect correlated points on the same part.
- Part measurement systems often have limited capability to measure non-rigid parts without additional clamps beyond 3-2-1 requirements. These additional clamps in the fixtures over-constrain parts, shifting mean dimensions.

- Stamping processes have so many input variables affecting variation (some estimates are well over 100) that even world-class stamping operations routinely operate out-of-statistical control (i.e., with non-stable process means between die sets), especially on larger flimsy parts. Consequently, measuring several parts from a single die set (run) does not provide sufficient information about the expected long-term variation of the process.
- Assembly processes often distort parts (sometimes closer to and sometime further away from nominal) during assembly because of clamping, spot welding, and inconsistencies of part locating schemes. These distortions can shift panel mean dimensions and affect process variation resulting in a low correlation between stamping dimensions and assembly dimensions.

A purpose of this report is to provide a basic understanding of stamping variation. The data in this report are intended to illustrate general characteristics of stamping variation, and are not intended to be a comprehensive data base to support design. World-class automotive manufacturers that are most adept at designing and assembling sheet metal are those who have effectively learned from past designs, while managing the variation in new parts/processes as they become known. By looking at a number of stamping and assembly processes across several manufacturers, this report begins to establish boundaries for the limits of variation that can be expected under different situations. This report examines the implications of this inherent stamping variation on several design and validation activities including:

- Tolerance assignment,
- Check point selection,
- Stamping process control limits,
- Process validation – die tryout,
- Production part approval process – stamping,
- Part measurement systems and measurement strategies, and
- Assembly strategies with respect to part locating and clamping.

The majority of the data in this report is collected under production conditions, resulting in several advantages and disadvantages over a more controlled experimentation approach. The advantages are that the data actually reflect what can be expected in production, at normal line rates and with typical levels of process control of the overall process. In cases where similar observations are seen over several case studies, generalizations about process variation are made. The disadvantages are that the data cannot be used, in most cases, to show direct cause-and-effect conclusions, thus often limiting observations to hypotheses. However, given the infinite number of design options (part design and process design), controlled experiments in stamping and assembly often have a limited value in generalizing results.

1.2 Study Background

Seven companies participated in this study by providing data about their stamping and assembly processes. These companies, and their vehicle studied are shown in Table 1 below (Note: Companies are referred to as A, B, C, D, E, F, and G in this report; they do not correspond to the order presented in the table below).

Company	Model	Data Collection	Stamping Location	Assembly Location
GM	Grand Am	1996	Lansing, MI	Lansing, MI
NUMMI (Toyota)	Corolla	1996	Fremont, CA	Fremont, CA
Chrysler	Neon	1997	Twinsburg, OH Belevidere, IL	Belevidere, IL
Nissan	Altima	1997	Smyrna, TN	Smyrna, TN
Ford	Taurus	1997	Chicago, IL	Chicago, IL
Opel	Vectra	1998	Ruesselsheim, Germany	Ruesselsheim, Germany
Renault	Clio II	1998	Flins, France	Flins, France

Table 1. Participating automotive manufacturers

Dimensional studies at each company are based on the body side assembly and its major stamped components. One company provided data for panels on both the right and left body side, resulting in a total of eight body-side assembly studies. A difference among companies was the type of body side outer. Three companies used body side outers with an integrated quarter panel (i.e., one piece); the remaining companies used two-piece body sides. The other panels chosen in each body side assembly study (typically 4-5 mating parts) depended on the design, but with the goal to include rigid (thicker gage, greater than 1.25mm), critical structural reinforcements. The scope of body panels included from all the automotive manufacturers are:

- One-piece body side outer,
- Two-piece body side outer,
- Center pillar reinforcement (i.e., B-pillar),
- Front pillar reinforcement (i.e., A-pillar),
- Quarter outer panel,
- Quarter inner panel
- Roof rail outer,
- Wheelhouse outer and
- Windshield frame reinforcement.

Figure 1 below illustrates a typical body side case study for a two-piece body side.

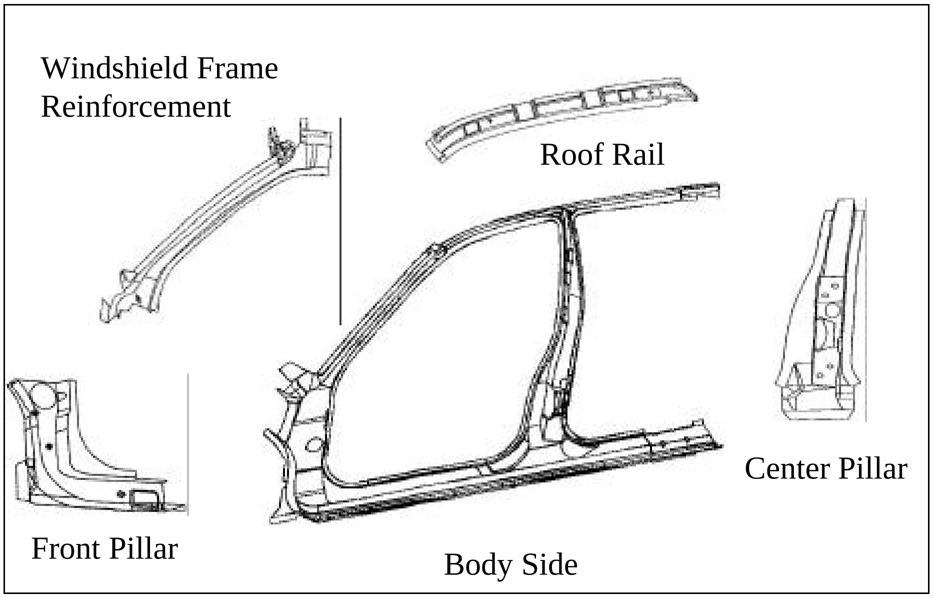

Figure 1. Body side components chosen for Company C

Table 2 lists the body side components chosen from each of the automotive manufacturers for this study. The identifier letter (A through G) is used consistently for the same company throughout this report. (See Appendix for pictures of components in study).

Company Identifier	Part Description	Number of Dimensions	Steel Gauge	Steel Coupons
A	Body Side - One Piece	39	0.69	yes
	Quarter Inner	76	0.90	
	Wheelhouse Outer	38	0.61	
	Front Pillar Reinf	69	1.70	
	Center Pillar Reinf	60	1.44	
B	Body Side - One Piece	104	0.90	yes
	Body Side Inner	54	0.80	
	Wheelhouse Outer	42	0.75	
	Center Pillar Reinf	17	1.00	
	Cowl Side	24	1.10	
	Roof Rail Inner	8	0.80	
	Roof Rail Outer	13	1.00	
C	Body Side - Two Piece	60	1.10	yes
	Roof Rail Outer	22	0.90	
	Front Pillar Upper	9	1.85	
	Front Pillar Lower	8	1.85	
	Center Pillar Reinf	14	1.87	
	Windshield Side Inner	30	2.70	
D	Body Side - Two Piece	17	0.73	yes
	Quarter Outer	14	0.82	
	Front Pillar Lower	6		
	Center Pillar Lower	6		
	Front Pillar Upper	15		
	Center Pillar Upper	4		
E	Body Side - Two Piece	35		no
	Front Pillar Lower	2		
	Center Pillar Lower	2		
	Roof Rail	2		
F	Body Side - One Piece	38	0.90	no
	Quarter Outer	11		
	Body Side Inner	6		
	Center Pillar	6		
G	Body Side - Two Piece (tailor welded blank)	54	Frt: 1.17; Rr:0.77	yes
	Body Side Inner	13	0.67	
	Windshield Side Inner	5	1.17	
	Front Pillar Reinf	6	0.97	
	Center Pillar Reinf	10	1.17	

Table 2. Components studied at each auto company

A consistent sampling plan was applied to each of the stamped panels. This plan was designed to ascertain both short-term and longer-term variation, under production conditions. Six panels were taken during each die set (production run) for a given part; three consecutive panels near the beginning of the run and three consecutive panels near the end of the run. This six panel sampling plan was then repeated over six separate die sets, thus producing a total case study of 36 panels (6 per die set x 6 die sets = 36 panels total). This sampling plan was executed on <u>all</u> of the major panels in each case study (Note: a few smaller reinforcements had less than 6 die sets). The length of each die set varied by company, but tended to be greater than four hours in most cases. The time between each die setup also varied typically between 2 and 7 days. This sampling plan allowed the calculations of short-term variation (variation across consecutive panels) and long-term variation (variation both within and between die sets).

Several of the companies also collected panel coupons and process variable data to see if relationships could be found between the material or equipment setup and stamped panel variation. These companies collected a steel blank (at the de-stacking side of the press) at the same time that a contiguous sample of 3 panels was collected. Also at this time, several companies collected data on the process, such as tonnage and cushion pressure in the draw die. The actual variables collected at each manufacturer varied by part and die design. The steel coupons (12 per panel in several cases since one was collected for each sample of 3 panels) were collected and tested for several metallurgical properties including R-value, n-value and blank gage variation.

The measuring of parts was conducted in a manner to help reduce measurement error. The 36 samples were collected over a period of several weeks and set aside for measurement at one time. This approach was intended to reduce potential measurement errors by using a single operator and a standard measurement protocol (loading, clamping and measurement sequence routine). To measure the body side outer and many of the other inner panels, five companies used CMM (E and F used hard fixtures). However, a few of the smaller parts were measured on “hard” checking fixtures using datamyte collection devices and measurement probes. In all cases, part locating was based on the standard checking fixtures used by each company for internal quality monitoring. A few companies chose to modify their CMM measurement routines to include additional dimensions to provide a more comprehensive geometric database.

One challenge with comparing companies in this study was the significant differences in measurement systems. These differences relate primarily to the locating and clamping of parts in the fixtures. For instance, some companies attempt to minimize the influence of the fixture on the part by minimizing the number of clamps and clamping pressure, other companies intentionally over-constrain their parts for measurement. Companies attempting to reduce the influence of the measurement system use a minimal number of clamps and locators to obtain an adequate measurement system repeatability and reproducibility (gage R&R). Other companies more readily obtain high gage repeatability and reproducibility by adding a larger number of clamps. However, this approach masks variation in the panel making the measurement system less able to detect variation. The difference in measurement systems requires caution when generalizing variation across companies.

2.0 Stamping Variation

2.1 Components of Variation Explained

Dimensional variation from the stamping process may be broken down into a number of components (i.e., components of variation). For the most part, different variation components are attributable to different sources and often have a different impact on downstream operations. The following are the general components of variation that will be used throughout this report (see Figure 2 for illustrations of each variation component).

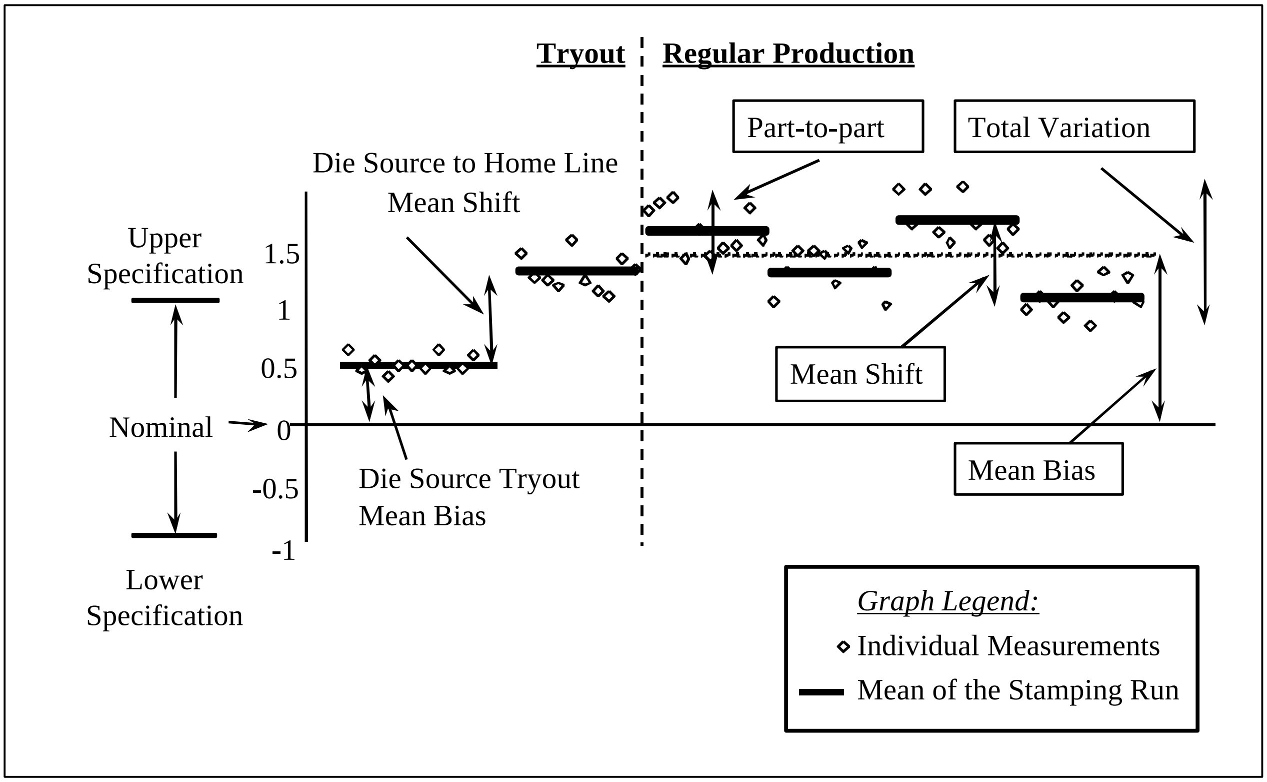

Figure 2. Components of variation

> **Mean bias** deviation is the process bias relative to the design nominal. Mean bias is the absolute value of the average deviation from nominal. When a process is centered exactly at its nominal dimension, its mean bias is zero. If after a single die set (e.g., at the die source tryout) a mean dimension is -0.65 mm or 0.65mm, then its mean bias is 0.65 mm. If the mean from two die sets are -0.40 mm and 0.10 mm (assuming equal sample size from each die set), then the grand

mean is –0.15 and the mean bias of those two die sets is 0.15 mm (|-0.40 + 0.10| ÷ 2 = 0.15)

Part-to-part variation is also referred to as the short-term or inherent variation. It is the amount of variation that can be expected across consecutive parts produced by the process during a die set. The assumption is that the variation is a reflection of numerous incidental random variables over a short-term and is not affected by any special causes of variation such as a change in the steel coil or process settings. This part-to-part variation will be denoted as $\sigma_{\text{part-part}}$.

Estimates for part-to-part variation for the 36-panel study are based on the 12 subgroups of 3 consecutive panels. Again, the assumption is that the process is stable during three consecutive parts.

Run-to-run variation is commonly referred to as mean-shift variation. It is the measure of the repeatability of the die setting process and its derivation is based on the variation of the mean dimension across two or more die sets. We denote run-to-run variation as $\sigma_{\text{run-to-run}}$. Estimates for run-to-run variation are based on the variations in mean dimensions between die sets.

Begin-end of run variation is another type of mean-shift variation in that it is a measure of the stability of the process mean within a die set. Since stamping production runs can be long, the mean of the run can change from the beginning to the end, some several hours later. This change in a mean dimension may occur due to process changes during a run such as a steel coil change, changes in operating speeds or tonnage, or adjustments to draw lubrication. If a mean dimension significantly shifts during a run due to some special cause, the stable mean assumption is violated and begin-end variation is greater than part-to-part variation. We denote this variation as $\sigma_{\text{begin-end}}$. Estimates for begin-end of run variation are based on the variation of the mean dimension from the beginning to the end of each die set.

Figure 3 illustrates a run chart for a single stamping dimension with unusually large variation. Each of the three variation components: part-to-part, run-to-run, and begin-end variation is illustrated in the plot.

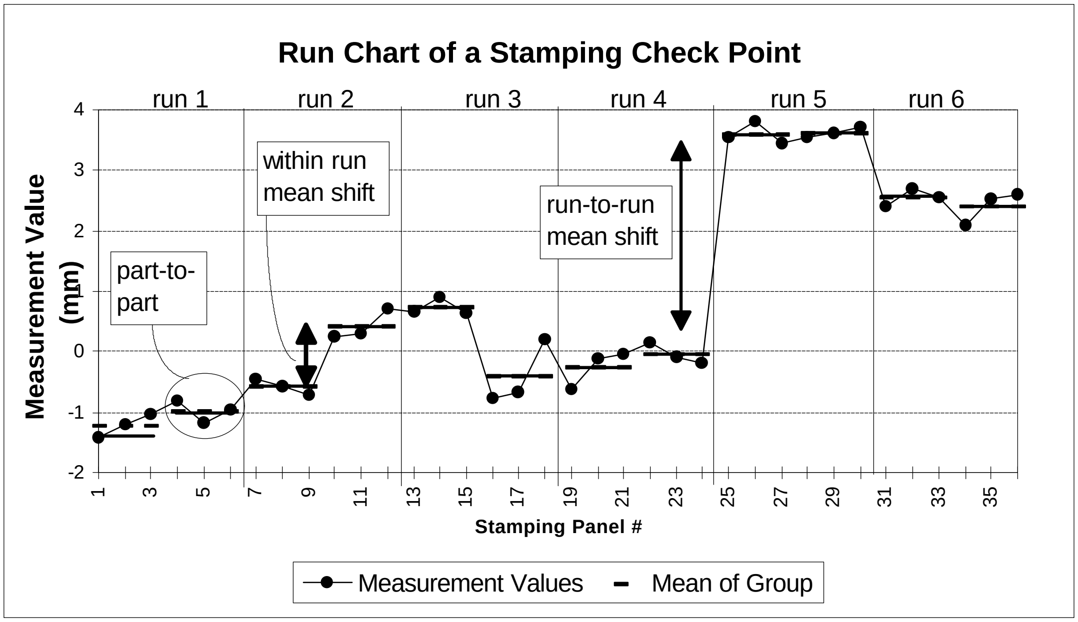

Figure 3. Potential sources of stamping variation

Mean shift variation is the sum of the run-to-run variation and begin-end of run variation. Since run-to-run variation and begin-end variation are both forms of mean instability, they can be combined into one variation number that is called the mean shift variation. The mean shift variation is denoted by $\sigma_{\text{mean shift}}$, where $\sigma^2_{\text{mean shift}} = \sigma^2_{\text{run-to-run}} + \sigma^2_{\text{begin-end}}$. In most cases with stamping, the run-to-run variation dominates the within run variation ($\sigma^2_{\text{run-to-run}} >> \sigma^2_{\text{begin-end}}$), so rather than separate the two, the total mean shift variation ($\sigma^2_{\text{mean shift}}$) is used.

Total variation is the sum of part-to-part variation and mean shift variation. This represents the total variation that the downstream assembly process is subject to over the long-term. The total variation is denoted σ_{total}. Equation 1 below and Figure 4 summarize the decomposition of variation into components.

Total variation is equal to the sum of the components of variation:

$$\sigma^2_{\text{total}} = \sigma^2_{\text{part-to-part}} + \sigma^2_{\text{mean shift}}, \text{ or}$$

Equation 1 $$\sigma^2_{\text{total}} = \sigma^2_{\text{part-to-part}} + \sigma^2_{\text{run-to-run}} + \sigma^2_{\text{begin-end}}.$$

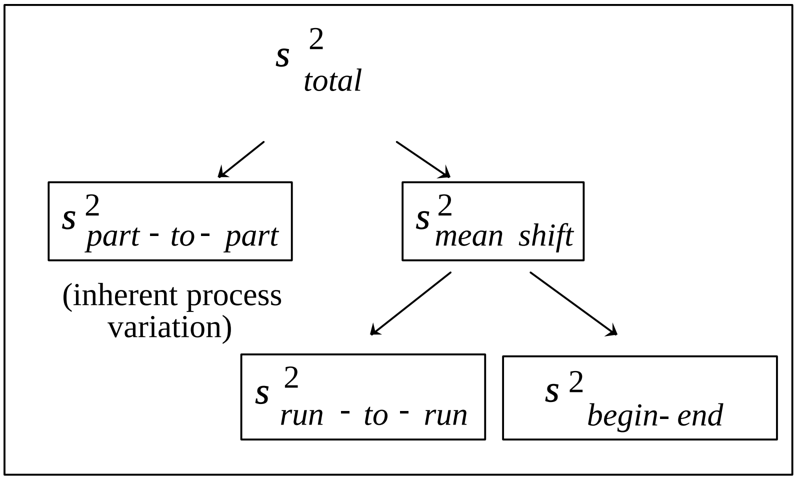

Figure 4. Total variation partitioned into components

2.2 Calculating Components of Variation Using ANOVA

An efficient method for estimating the components of variation is through analysis of variance (ANOVA). (ANOVA software is readily available in most statistical analysis software programs.) Briefly, the parameters for an ANOVA model for this sampling plan may be defined in the following way:

d = number of die sets = 6 (die sets)
s = number of groups per die set = 2 (samples of 3 per batch)
n = sample size per group = 3 (consecutive panels)

The total number of panels sampled is equal to dsn (6x2x3 = 36). This ANOVA model estimates part-to-part, run-to-run and begin-to-end of run variation using the expected Mean Squares (MS). The following equations shown in Table 3 may be used to estimate the various sources of variation. If both of the factors (i.e., run-run and begin-end of run) are statistically significant, then a begin-end of run and a run-run variance may be calculated. If only one of the two factors is significant, then only that variable will have a variance estimate. Finally, if neither of the two factors is significant, then all of the total variance may be attributed to part-part variation. The equations used to estimate the components of variance are:

	Variation		Formula	Description
Equation 2	$\sigma^2_{\text{part-to-part}}$	=	MSE	mean squared error
Equation 3	$\sigma^2_{\text{begin-end run}}$	=	$\frac{\text{(MSBE – MSE)}}{n}$	(mean squared $_{\text{begin-end}}$ – mean squared error) ÷ sample size
Equation 4a*	$\sigma^2_{\text{run-to-run}}$	=	$\frac{\text{(MSRR – MSBE)}}{sn}$	(mean squared $_{\text{run-to-run}}$ – mean squared error $_{\text{begin-end}}$) ÷ (number of samples x sample size)
Equation 4b*	$\sigma^2_{\text{run-to-run}}$	=	$\frac{\text{(MSRR – MSE)}}{sn}$	(mean squared $_{\text{run-to-run}}$ – mean squared error) ÷ (number of samples x sample size)

*Note: If all variation sources are significant, use Equation 4a. If begin-end factor is not significant, use Equation 4b.

Table 3. Formulas for Calculating Components of Variation

The following example illustrates an application of an ANOVA analysis for a stamping dimension. Table 4 summarizes the observed data for a stamping dimension.

Die Set	Group	Panel 1	Panel 2	Panel 3	Sample Average
1	begin run	0.13	0.16	0.17	0.15
1	end run	0.10	0.03	0.03	0.05
2	begin run	0.06	0.16	0.08	0.10
2	end run	0.13	0.08	0.23	0.15
3	begin run	0.18	0.72	0.14	0.34
3	end run	0.19	0.49	0.16	0.28
4	begin run	-0.35	-0.43	-0.47	-0.42
4	end run	-0.41	-0.39	-0.38	-0.40
5	begin run	-0.32	-0.31	-0.35	-0.33
5	end run	-0.32	-0.33	-0.29	-0.31
6	begin run	-0.16	-0.10	-0.21	-0.16
6	end run	-0.20	-0.17	-0.20	-0.19
				Grand Mean (Mean Bias)	-0.06 (.06)

Table 4. 36-data samples for a stamping dimension

The ANOVA output for this data is summarized in Table 5 (note: analysis performed using SPSS based on Type I error, $\alpha = 0.05$). Note: a significant variable has a significance value less than α (0.05). For this data set, the Mean Squared Error for the begin-end factor is not significant. In other words, the mean does not significantly change from the beginning to the end of the stamping run. (Note: The begin-end factor is a nested variable within the run or die set factor, and thus should be examined as an interaction effect.)

Source		df	Mean Square	F	Significance
Run-Run	Hypothesis	5	.479[a]	103.81	.000
	Error	6	4.6E-03[b]		
Run-Run x Begin-End Run	Hypothesis	6	4.6E-03[b]	.352	.901
	Error	24	0.013[c]		

a. Mean square run-to-run
b. Mean square begin-run of run
c. Mean squared error

Table 5. SPSS output calculations for mean squared errors (all factors)

Since the begin-end factor is not significant, we must revise the ANOVA model and re-calculate the Mean Square Errors. The revised SPSS output is shown below in Table 6 (again significance is based on a Type I error of $\alpha = 0.05$).

Source		df	Mean Square	F	Significance
Run-Run	Hypothesis	5	.479	25.836	.000
	Error	30	0.011		

Table 6. SPSS output calculations for mean squared errors without begin-end factor

The mean squared errors in Table 6 may be used to estimate the variation for each of the components of variation present using equations 2-4 (note: $\sigma_{\text{begin-end}} = 0$ because this factor is not significant for this dimension). The variation estimates are shown in Table 7.

Variation Source	Mean Squared Error Calculation	Variance (mm^2)	Standard Deviation (mm)
Part-to-part	MSE	0.011	0.11
Begin-end run	not significant	0.00	0.00
Run-to-run	(0.479 – 0.011) ÷ (2)(3)	0.078	0.28
Total Process	(.078+.011)	0.089	0.30

Table 7. Summary of components of variation calculations

Table 8 summarizes the components of variation and the mean bias at 12 measurement locations for the Body Side Outer at Company A (see Figure 5 below). One interesting finding is the large range in variation for part-to-part (0.01 to 0.48) and run-to-run (0.00 to 0.18) across different measurement locations. This contrast is attributable to the differences in location/axis on the part and to the proximity of measurement system clamps. It will be shown in the next section that as the number of clamps increases on a checking fixture, the amount of observed variation decreases due to the masking of variation by the clamps. Table 8 also indicates that part-to-part variation (65.4%) and run-to-run variation (30.3%) are much greater than begin-end run variation (4.3%) for these dimensions.

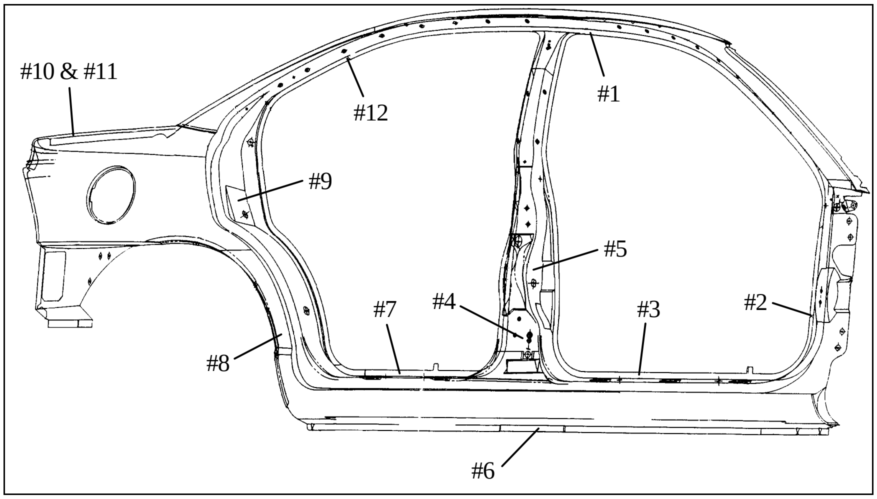

Figure 5. Body Side Outer for Company A: 12 measurement locations

Measurement		**Component of Variation (mm^2)**				**Mean Bias (mm)**
Location	**Direction**	**Part-to-part** ($\sigma^2_{\text{part-to-part}}$)	**Begin-end** ($\sigma^2_{\text{begin-end}}$)	**Run-to-run** ($\sigma^2_{\text{run-to-run}}$)	**Total Process** (σ^2_{total})	
1	Y	0.09	0.00	0.06	0.16	0.313
2	Y	0.04	0.00	0.00	0.04	0.342
3	Z	0.01	0.01	0.00	0.02	0.786
4	Y	0.05	0.03	0.00	0.08	1.187
5	X	0.48	0.00	0.00	0.48	0.851
6	Z	0.05	0.05	0.00	0.10	3.673
7	Z	0.06	0.00	0.03	0.09	1.609
8	Y	0.14	0.00	0.18	0.32	2.530
9	X	0.34	0.00	0.17	0.51	1.139
10	Y	0.01	0.00	0.00	0.01	0.618
11	Z	0.02	0.00	0.03	0.05	0.837
12	Y	0.14	0.00	0.18	0.32	0.675
Average		**0.12**	**0.01**	**0.05**	**0.18**	**1.130**
Percent of Total		**65.4%**	**4.3%**	**30.3%**	**100.0**	**---**

Table 8. Variance Summary for 12 Body Side Dimensions

2.3 Description of the Sources of Stamping Variation

Extensive research has been conducted on identifying and eliminating the sources of variation associated with stamping sheet metal. The stamping process is complex, with many variables that can influence variation. One related research effort by John Siekirk[1] identified 30 major factors, and then classified them into the following seven categories:

- Blank condition,
- Blank lubrication,
- Stamping press variables,

---

[1] Process Variable Effects on Sheet Metal Quality," Journal of Applied Metalworking, American Society for Metals, July 1986

- Metal properties,
- Die condition,
- Miscellaneous and
- Interactive variables.

This body side research project investigated process variation under production conditions. Consequently, only a limited number of process and material variables could be collected. More importantly, process variables were not purposely altered. Thus, we only can make inferences between stamping variation and the observed variability in process variables. In many of these case studies, the control of process and material variables was quite good. As a result, our findings do not necessarily identify those variables that could affect part variation, but rather which variables explain the dimensional mean shifts in these case studies.

One area of this research that is often not examined is the effect of process variables on mean conformance. Most of the research on reducing stamping mean biases has been directed toward metal forming and die design. Unfortunately, little research exists on eliminating mean biases once a die has been made and the actual mean biases become known. Even less attention has been given to non-die related influences on mean bias such as the measurement system effects. Among the factors that influence mean bias include:

The Measurement System:	Clamping sequence
	Clamping forces
	Part locating (datum)
Product Design:	Part geometry (size and complexity)
	Part rigidity (shape and gage)
	Check point location
Process:	Press setup and control of process variables (see above)
	Changes in stamping presses (e.g., tryout to production presses)
	Material handling and storage

3.0 Analysis of Stamping Variation

3.1 Mean Conformance

One of the greatest challenges in die making and stamping is minimizing *mean biases* for dimensions on stamped parts. As defined earlier, **the mean bias is the absolute value of the average deviation from nominal**. Ideally, a manufacturer would produce every stamped component such that each dimension is, on the average, at the specification nominal. By doing so, design capability (C_{pk}) would be maximized for a given level of process variation. Achieving minimal mean biases in stamping also facilitates the "tune-in" of assembly tooling (which is initially designed for parts at nominal) and increases the likelihood of producing dimensionally acceptable assemblies within the shortest possible lead time. The problem is that no manufacturer in the world has demonstrated that they are capable of producing stamped body parts without mean biases.

Manufacturers who have minimized their mean biases relative to their competition appear to maintain a competitive advantage in terms of cost, quality and lead-time. To achieve lower mean biases, companies employ a combination of technology (e.g., finite element analysis), applied learning (using historical experience) and limit the evolution of product design to reduce uncertainty. Future product designs with uncertain forming challenges might be subject to soft tool evaluation in order to evaluate metal forming and die design before production tools are machined.

Modifying hard tool dies (die rework) after they have been machined to reduce mean biases represents one of the most difficult tasks in getting dies approved for production. Companies attempting to rework dimensions to reduce mean biases face several challenges. First, since a stamped part has a continuous surface, reworking a die to shift one dimension may affect inadvertently other areas of the part. Many areas of a part are inter-dependent, so that when one dimension changes another area does as well, sometimes in an unpredictable way. Another difficulty is trying to rework dimensions exactly to their design nominal. In other words, there is a limited ability to hit the nominal dimension even after rework. A final difficulty is concerned with the ability to measure a part and to know precisely what the mean bias really is. In addition to die processing, mean dimensions also are affected by the number and positioning of clamps in measurement fixtures. Because of the many variables in forming a part (variations in stamping press variables and steel properties) and the limited ability to measure sheet metal, ascertaining the precise mean bias can be very difficult – both before and after a die change. Manufacturers often face a complicated decision in determining when to rework a die versus allowing a mean bias to remain (see Body Systems Analysis Task Force Report on Functional Build).

3.1.1 Benchmark Comparison – Body Side Outer and Inner Panels

Figure 6 shows a histogram for 143 mean dimensions across 5 parts at Company C. Several observations may be made from these data:

1. The distribution of mean dimensions is approximately normal. Assuming the measurement system does not unfairly influence mean deviations, this finding suggests an inherent variation in the ability to design and construct dies to produce part dimensions at nominal.
2. The distribution of mean dimensions is centered approximately at zero (i.e., average mean bias is near zero). This is not surprising since the distribution is normal and the die maker's target is to have zero bias.
3. Approximately 10% of mean values have a bias greater than 1.0mm (and about 35% have a bias greater than 0.5mm).

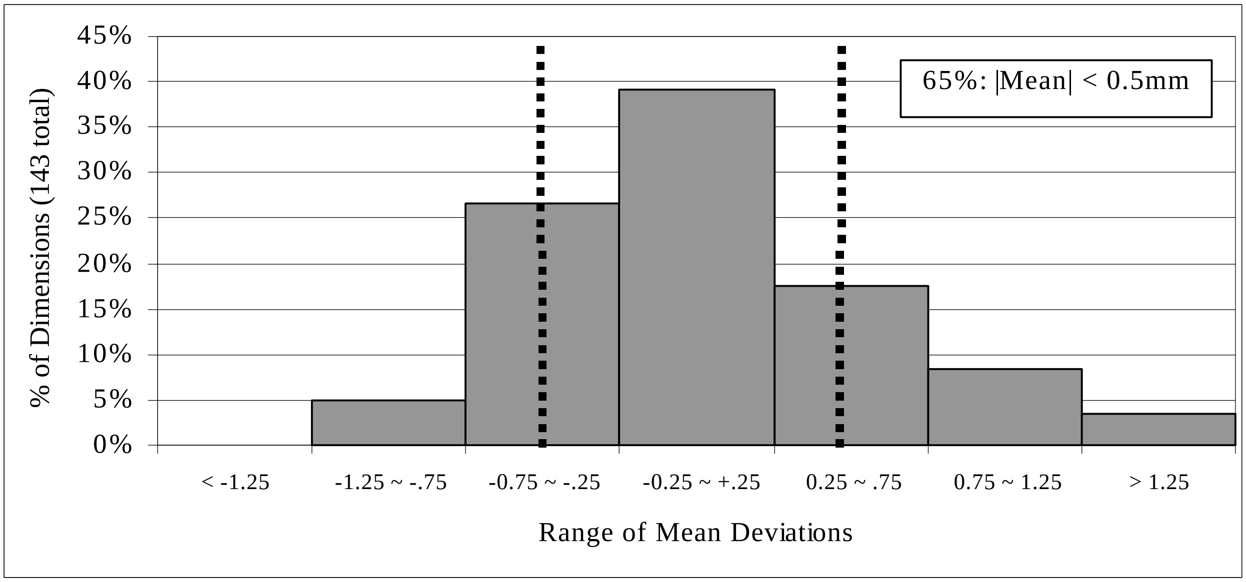

Figure 6. Histogram of mean values across 5 parts for Company C

In general, the amount of *spread* in the mean distribution will vary significantly by type of part. Larger, more flimsy panels like the body side outer often have significantly more dimensions with large mean biases than rigid panels (blank thickness > 1.5mm).

Figure 7 compares the mean deviations for smaller rigid reinforcement panels at Company A to larger more flimsy panels (i.e., A and B pillar reinforcements versus one-piece body side outer and quarter inner). The less rigid panels have larger mean biases and also a greater dispersion in mean deviations than the rigid panels. This is evident in comparing reinforcements to a one-piece body side, and it also occurs in comparing a one-piece body side (0.69mm gauge) to a two-piece body side (1.10mm gauge). (See Figure 8)

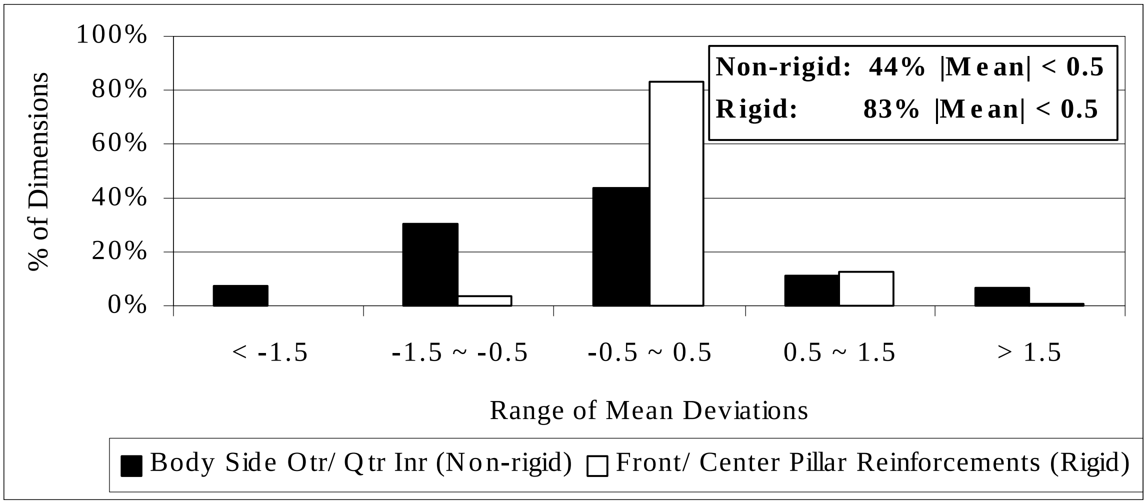

Figure 7. Mean Conformance: Rigid vs. Non-Rigid Panels

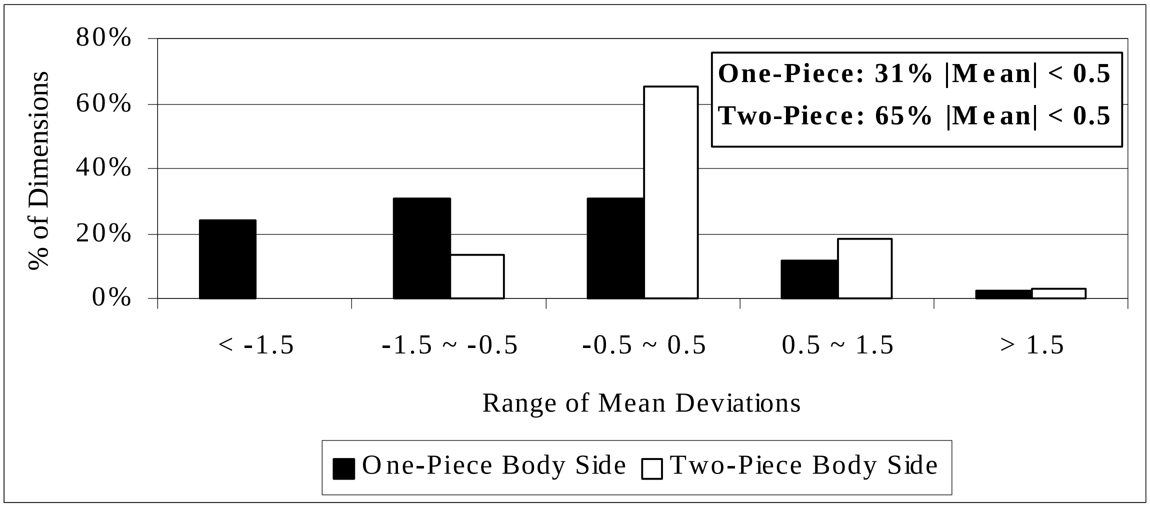

Figure 8. Mean Conformance: Two-Piece Body Side Panel vs. One-Piece

Table 9 below summarizes the mean bias for the body side outer panels at each of the automotive manufacturers. These data suggest several generalizations. First, larger one-piece body side outers (with integrated quarters) tend to exhibit greater biases than two-piece body sides. Second, companies using constrained measurement systems (i.e., excess part locating clamps) have significantly less mean deviations. Companies E, F, and G use constrained measurement systems, and all have lower biases for the body side out panel. In addition, the same body side panels at company B exhibited less mean bias when measuring the parts in a more constrained fixture. A major influence of the constrained checking system is that extreme mean biases (greater than 1.0mm) are greatly reduced.

Company	**Body Side Type**	**# cross/car clamps in fixture**	**Average | Mean |**	**% Dimensions |Mean| < .5**	**% Dimensions |Mean| > 1**	**% Dimensions |Mean| > tol (t)**
A	Integrated Quarter	11	1.10	34%	56%	66%
B (remeasured)	Integrated Quarter	14	0.73	49%	29%	39%
C	Two-piece	7	0.51	65%	15%	5%
D	Two-piece	8	0.88	42%	39%	39%
E*	Two-piece	22	0.36	74%	3%	14%
F*	Two-piece	16	0.31	84%	3%	39%
G*	Integrated Quarter	17	0.37	69%	2%	28%

* Over-constrained (excess clamps) during measuring

Table 9. Mean conformance by Company

The effect of a constrained measurement system is limited to larger, less rigid panels since additional clamps beyond 3-2-1 on rigid parts (gauge > 1.5mm) have little or no effect. Table 10 compares mean conformance across several part types. Although the clamping strategy may be correlated with mean bias in the body outer panels, the same cannot be done for rigid panels.

	Body Side Outer	**Non-Rigid Inner Panels**	**Rigid Inner Panels**	**Body Side Outer**	**Non-Rigid Inner Panels**	**Rigid Inner Panels**
Company	**Average | Mean |**	**Average | Mean |**	**Average | Mean |**	**% Dimensions |Mean| > 1**	**% Dimensions |Mean| > 1**	**% Dimensions |Mean| > 1**
A	1.10	0.79	0.22	56%	30%	1%
B	0.90	0.56	no data	33%	16%	no data
C	0.51	0.31	0.34	15%	0%	3%
D	0.88	0.32	0.27	39%	0%	0%
E*	0.36	0.35	no data	3%	0%	no data
F*	0.31	0.38	no data	3%	17%	no data
G*	0.37	0.39	no data	2%	6%	no data

* Over-constrained (excess clamps) during measuring

Table 10. Mean bias by type of part

3.1.2 Mean Bias and Part Tolerances

Another interesting contrast across companies is the assignment of part tolerances. When comparing manufacturers, the same physical dimension on a body side may have a tolerance of +/- 0.3mm at one manufacturer and +/- 1.25mm at another. Table 11 shows the typical tolerance for the body side panel and the percentage of dimensions whose mean bias exceeds the tolerance limit. On average, more than 30% of the dimensions (companies A through G) have their mean bias outside of the tolerance. It is important to note that whenever the mean bias exceeds the tolerance limit, at least 50% of the physical panels have that dimension outside of tolerance. *It is clear that a significant number of vehicles are being produced with acceptable final body quality, but with a significant number of body panel dimensions out of tolerance.*

Another observation across companies is that although companies A through C use Cpk as their principal buyoff criteria, they do not achieve greater mean conformance. In fact, it might be argued that the use of Cpk at Company C has lead primarily to wider tolerances (to achieve greater Cpk conformance), not greater mean conformance. Another finding is that only those companies using constrained measurement systems assigned tolerances less than ± 0.70 mm. Company F assigns the tightest tolerance (± 0.3), but uses a constrained measurement system and also has a two-piece body side which tends to have lower mean bias than the larger one-piece design.

Company	Body Side Type	Typical tolerance	# cross/car clamps in fixture	Average | Mean |	% Dimensions |Mean| > tol (t)	% Dimensions Cpk > 1.33
A	Integrated Quarter	+/- 0.7	11	1.10	66%	15%
B	Integrated Quarter	+/- 0.7	14	0.73	39%	80%
C	Two-piece	+/- 1.25	7	0.51	5%	75%
D	Two-piece	+/- 1.0	8	0.88	39%	23%
E	Two-piece	+/- 0.5	22	0.36	14%	43%
F	Two-piece	+/- 0.3	16	0.31	39%	29%
G	Integrated Quarter	+/- 0.5	17	0.37	28%	37%

Table 11. Mean conformance and tolerances

3.1.3 Benchmark Comparison – Tryout versus Production

Many companies apply common dimensional validation procedures and criteria to all body panels, even though the expected mean bias differs by type of panel (e.g., rigid versus non-rigid, small/simple form versus large/complex). Table 12 depicts mean conformance across multiple parts during regular production at three Companies (A through C). These data suggest that manufacturers produce stamped parts with 50-70% of dimensions within 0.5mm. If we compare these findings with mean biases experienced at production buyoff, the data are consistent. Although the other four companies did not provide tryout data, discussions with their personnel suggest that their mean conformance distributions in production also corresponded to die tryout. The main point is that even though manufacturers may adjust some mean biases to correct build concerns, the overall ability to produce mean dimensions at nominal does not significantly change from die tryout.

	Tryout	**Production**	**Tryout**	**Production**
Company	**% Dimensions |Mean| < 0.5**	**% Dimensions |Mean| < 0.5**	**% Dimensions |Mean| > 1**	**% Dimensions |Mean| > 1**
A	59%	63%	26%	22%
B	51%	53%	15%	23%
C	64%	66%	13%	10%

Table 12. Summary of mean bias: tryout vs. production (case study parts)

3.1.4 Mean Bias Stability over Time

Another important consideration about mean bias concerns its stability over time. Most automotive manufacturers first evaluate mean bias during die source tryout. A decision is eventually made to advance the die to the production press (often referred to as the "home line") where another estimate of the mean bias is made. Then finally, as the dies are repeatedly run on the home line for production, each die set up provides another opportunity to estimate the mean bias. Most of the data in this study was collected during production, a year or more after the dies were initially brought to the home line. An important question affecting dimensional validation is how does the estimate of mean bias change from tryout to the home line, and then to future production.

Table 13 examines changes in part dimensional means between die source tryout and home line tryout. The first two data sets are based on the case study parts at two of the manufacturers. Two more extensive studies of die source to home line mean shifts are also included. These data suggest that approximately 30% of dimensions shift at least 0.5mm when the dies are moved from the tryout press to the home line. The amount and uncertainty of change is one reason that manufacturers recognize that it is necessary to re-evaluate the dimensions on a part when the dies are transferred to the home line. Interestingly, a similar number of dimensions shift **toward nominal as opposed to away from nominal** (i.e., the shift in mean bias from tryout to the home line appears random.).

		Die Source to Home Line			
Company	# of Parts/ # Dimensions	Median Shift |Die source mean - Home line Mean|	% Dimensions |Mean Shift| > 0.5	Of the Dimensions with shift > 0.5 % closer	% away
B - 1	4 /104	0.30	30%	40%	60%
C - 1	5 / 86	0.20	25%	68%	32%
C - 2	47 / 652	0.23	30%	63%	37%
C - 3	26 / 182	0.27	28%	50%	50%
	Overall	0.25			

Table 13. Comparisons of the change in mean bias from tryout to home line

Figure 9 below compares the mean dimension at time of part approval versus the production mean approximately one year later at Company C. For the parts in this study, nearly 50% of the dimensions shifted more than 0.5mm over the life of the program. Table 14 further shows that of the dimensions with significant mean differences, a similar number shifted closer to nominal versus away from nominal.

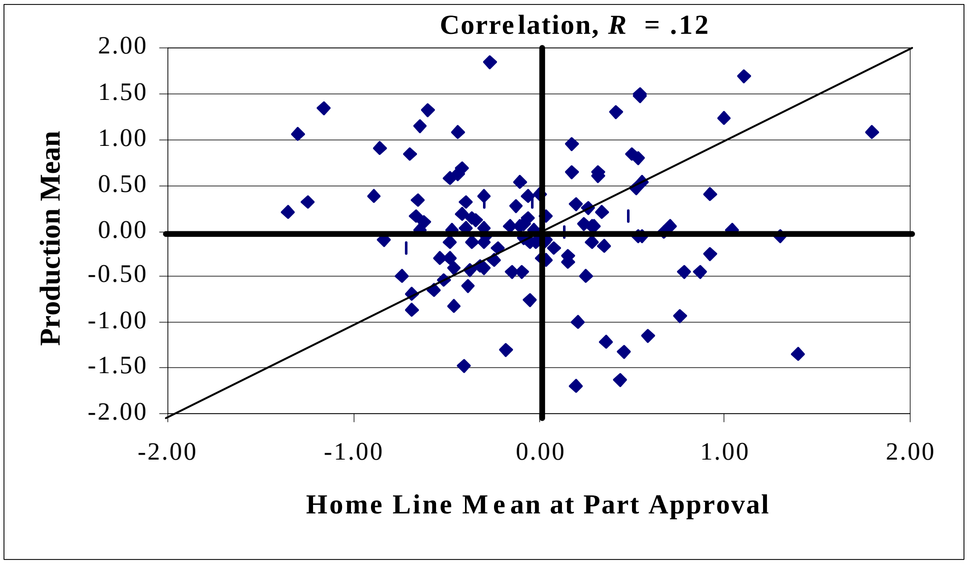

Figure 9. Correlation of mean at part approval vs. production

	Home Line Approval Mean to Production Mean			
Company	Median Shift |Home line Mean - Production Mean|	% Dimensions |Mean Shift| > 0.5	Of the Dimensions with shift > 0.5 % closer	% away
A	0.48	48%	41%	59%
B	0.57	53%	45%	55%
C	0.35	40%	44%	56%

Table 14. Change in mean from home line to long term production

These findings suggest that automotive-body parts continue to evolve from die source tryout, through home line tryout, and even through regular production. Although some of these dimensional changes are intentional (i.e., based on die rework to correct a problem), the majority are not. They shift because of lack of process control or die rework/ maintenance in another related dimensional area.

Interestingly, some dimensions shift away from nominal with no apparent impact on the assembly process. In addition, some dimensions may shift significantly closer to nominal (greater than 1mm), but with an adverse affect on the final assembly. Figure 10 depicts a stamping dimension that shifts 1.3mm between stamping runs four and five. Even though this shift is toward nominal, the variation observed in assembly actually becomes higher.

In this example, maintaining a stable mean over time appears more important than the magnitude of the mean deviation. Similar to stamping, assembly processes evolve over time to match stamping mean deviations. If these mean deviations change significantly, assembly processes will likely experience problems. Thus, manufacturers must develop a better understanding of how to minimize mean instability. Fortunately, mean instability is not inherent to a process like part-part variation, it is caused by some special influence such as a process variable change or die rework. Thus, a potential exists to control these special causes.

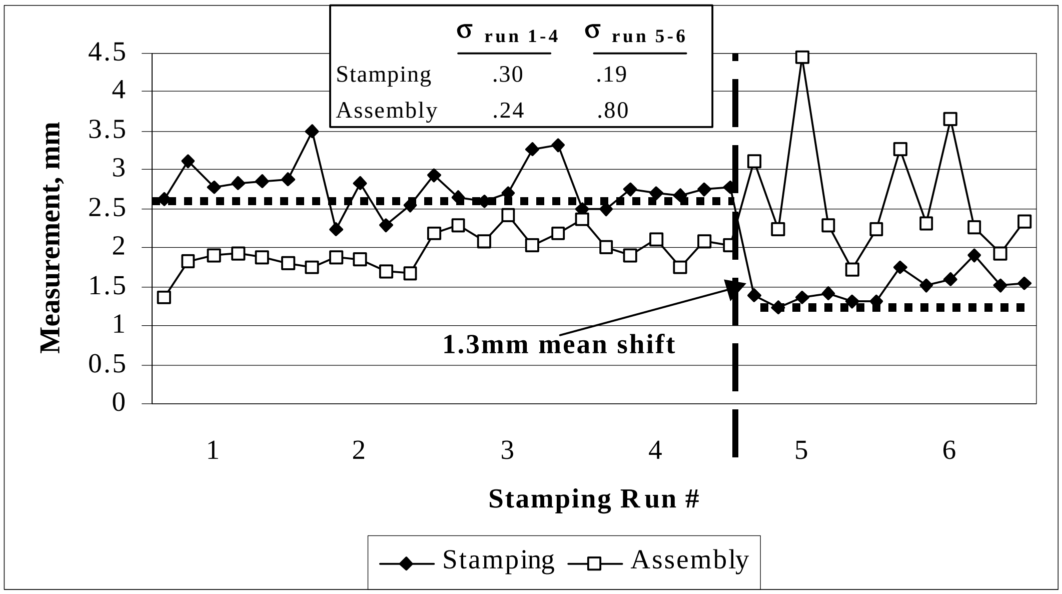

Figure 10. Effect of Stamping Mean Shift on Body Side Assembly
(Note: above dimension is coordinated between stamping and assembly)

3.1.5 Impact of Shipping on Mean Bias

One final investigation into the factors influencing mean bias looked at the impact of material handling. Factors related to material handling and the impact on mean bias include:

- Racking of parts (pallet design, etc.) – for consistency and impact resistance,
- Time lag – as stressed parts become stress relieved and
- Movement of parts – including manual, forklift, and mass transit (truck and rail) all which impact the shaking and distortion of parts.

An experiment was performed at Company A where four inner panels were measured both before and after shipment. The measurement system used the same locating fixtures and CMM programs at both the production and assembly plants, however, different operators performed the actual measurements. The panels were shipped in their production pallets (tote bins for all parts) via truck over several hundred miles. Two small parts had their panels dropped into bins, one larger part (wheelhouse outer) had panels stacked on top of each other in the bins and the fourth part, the quarter inner, was shipped in a special rack. The results are shown in Table 15.

Part	Number of Check Points	Average Mean Bias Shift (mm)	% of Dimensions With Mean Bias Shift > 0.2mm
Wheelhouse Outer	69	0.89	76 %
Quarter Inner	91	0.10	15 %
B-pillar Reinforcement	59	0.16	19 %
A-pillar Reinforcement	70	0.08	6 %

Table 15. Summary of panels measured before and after shipping

This experiment shows a potential significant impact of shipping on mean bias. One caveat, however, is that the impact of shipping is confounded by different measurement operators. Reproducibility is a potential source of gage error in this study because the same operator did not measure the panels before and after shipping. Reproducibility of a CMM based on an automatic program, however, is generally insignificant.

Of these parts, the wheelhouse outer suffered the greatest mean shift with an average shift of 0.89mm. The wheelhouse panels at the bottom of the stack had the largest dimensional differences, indicating a racking problem. For the quarter inner, special racks are used which clearly helps reduce the shipping effect. The more rigid panels also experienced less shipping impact, with most mean dimensions shifting less than 0.2mm. Similar to the die source tryout to home line analysis, the direction of the mean shift appears random, or equally likely to get closer or further away from nominal.

3.2 Stamping Process Variation

3.2.1 Benchmark Comparison – Part-to-Part Variation

Part-to-part or short-term variation is a measure of the *inherent* variation for a particular product (set of dies) and process (stamping press line). Here, key variables such as set-up parameters (shut height, lubrication, cushion pressure, etc.) and incoming steel coils or blanks are presumed to be constant or consistent. Several variables may explain differences in part-part variation across companies. Several of these differences were investigated, including:

- measurement and clamping system,
- check point location/axis on the part, and
- part rigidity, size and material thickness.

Table 16 summarizes part-to-part variation for the body side outer panels for each of the manufacturers studied. A contrast in variation across manufacturers is again difficult because of the different measurement strategies as demonstrated by the number of clamps. The three companies using the most clamps (E, F, and G) have the lowest part-part variation. In addition, part-part variation at Company B is significantly lower when using a more constrained measurement system. These data suggest that **adding measurement clamps will likely reduce the observed part-to-part variation for large, non-rigid parts.** Both the average and the extreme variation points (i.e., $6\sigma_{\text{part-to-part}} > 1.5\text{mm}$) appear to be significantly reduced by the additional secondary locator clamps.

Company	**Body Side Type**	**# cross/car clamps in fixture**	**Average $6\sigma_{\text{part-part}}$**	**95th Percentile $6\sigma_{\text{part-part}}$**	**% Dimensions $6\sigma_{\text{part-part}} > 1.5$**
A	Integrated Quarter	11	1.14	2.90	20%
B (remeasured)	Integrated Quarter	14	1.09	2.35	23%
C	Two-piece	7	0.99	1.89	18%
D	Two-piece	8	0.99	1.57	10%
E*	Two-piece	22	0.48	0.81	0%
F*	Two-piece	16	0.32	0.50	0%
G*	Integrated Quarter	17	0.40	1.08	0%

* Over-constrained (excess clamps) during measuring

Table 16. Part-to-part variation for body side outer panels

Note: 95th percentile is the level of variation where 95% of the dimensions on the part are less than this amount.

The type of body side style (one-piece versus two-piece) also appears to affect variation. Companies A through D use roughly the same number of clamps, but have two different body side styles, integrated quarter panel and two-piece. **It appears that the two-piece body side results in lower average part-to-part variation than the larger and more complex integrated quarter body side by about 10%.** The same relationship is seen amongst companies E, F, and G using the more constrained measurement approach. Of these companies, Company G with the larger body side has the highest 95^{th} percentile part-part variation. Follow-up analysis at Company

G indicates that most of their high variation dimensions are in non-stable measurement areas in the tail area of the body side outer panel.

Since part-to-part variation differs according to body side style, it would be expected to vary according to part size and rigidity for non-body side outer panels. The panels in these case studies may be grouped into three categories: body side outer panel, non-rigid body side inner panels and rigid body side inner panels. The body side outer panel is the largest and one of the thinnest gauge panels, varying from between 0.69mm to 0.90mm thickness. The non-rigid body side inner panels are arbitrarily limited to 1.5mm thickness and are smaller than the outer panel. These panels include the quarter inner, wheelhouse outer and roof rail, for example. The third category consists of small, heavy-gage parts. These panels include the A- and B-pillar reinforcements.

Figure 11 plots the average standard deviation (sigma) for all parts studied at the seven manufacturers. The changes in these groupings from large and flimsy to smaller and/or more rigid can be seen to correlate with the average amount of part-to-part variation. **As panels become smaller and more rigid, their part-to-part variation decreases.** In addition, Figure 11 suggests that the body side panels with the lowest variation are from companies using more measurement clamps, thus masking some of the actual process variation.

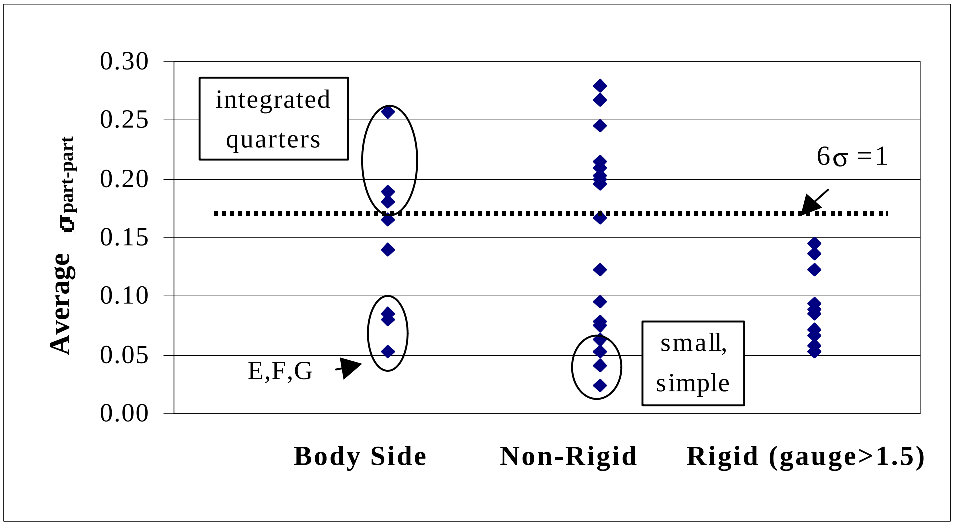

Figure 11. Average variation (standard deviation) by type of part

Another difference among manufacturers is the number and location of dimensions measured. Two manufacturers, D and E, collect **less** data on their stamped panels (i.e., fewer measurement dimensions) than the other manufacturers, and primarily collect data from points located in more rigid localized part areas. Although a body side outer panel tends to be flimsy, certain areas in highly formed sections of the part, such as the door openings of a body side, typically are more rigid than in the tail or wheelhouse areas. Control of these more rigid areas often is more important than other areas because they are less likely to conform to reinforcements during assembly. As has been shown, dimensions on less rigid parts tend to have greater variation. In order to illustrate the impact of dimension location, Table 17 shows the body side variation for Companies D and C. At Company D, 24% of their body side dimensions have an average standard deviation greater than 0.2mm. Company D measures near the A- and B- pillars and on the flanges in the door openings. In contrast, Company C measures dimension throughout the body side and has 73% of their dimensions exceeding 0.2mm. However, when comparing dimensions in similar locations, the variability at Company C more closely resembles Company D. **Thus, the expected variation on a stamped panel appears dependent upon where the dimension is located and how rigid the part is in that location.**

Company	**Selected Dimensions**	$\sigma < 0.2$	$\sigma > 0.2$
D	14	76%	24%
C	40	27%	73%
C	14 (common with D)	60%	40%

Table 17. Effect of dimension location on variation

3.2.2 Variation Over Time

Theoretically, part-to-part variation produced from a set of dies on the same press line should remain constant over time. In practice, part-part variation does vary for some dimensions. Variables that may affect part-to-part variation over time include:

- The condition of the press line (depending on the level of maintenance of the press),
- The condition of the dies (depending on die maintenance and deliberate changes to implement engineering changes) and
- Processing variables such as the control over cushion pressure, material handling automation between presses, etc., and

Although many of these changes often are associated with mean shifts, part-to-part variation can be affected as well. Table 18 shows that part-part variation typically increases from part approval runs to regular production. These data suggest that average six sigma increases from 0.8mm to 1.2mm after more than a year in production. The most likely explanation for this difference is that operating conditions at buyoff are substantially more controlled than in regular production. Although the overall variation increases, not every dimension exhibits an increase. Figure 12 compares the observed part-part standard deviation at buyoff versus regular production. This figure indicates a general lack of correlation between part approval variation and regular production. For some dimensions, the variation increases and for others, it decreases, although more dimensions have higher part-part variation in production overall.

		Home Line	**Production**	**Home Line**	**Production**
Company	**# Parts (# Dimensions)**	**Average $6\sigma_{\text{part-part}}$**	**Average $6\sigma_{\text{part-part}}$**	**% Dimensions $6\sigma_{\text{part-part}} > 1$**	**% Dimensions $6\sigma_{\text{part-part}} > 1$**
A	1 (37)	0.79	1.16	14%	48%
B	5 (132)	0.96	1.32	26%	48%
C	39 (327)	0.84	1.14	23%	38%

Table 18. Part-part variation: home line approval vs. production by Company

Note: production data (1 year + after home line buyoff

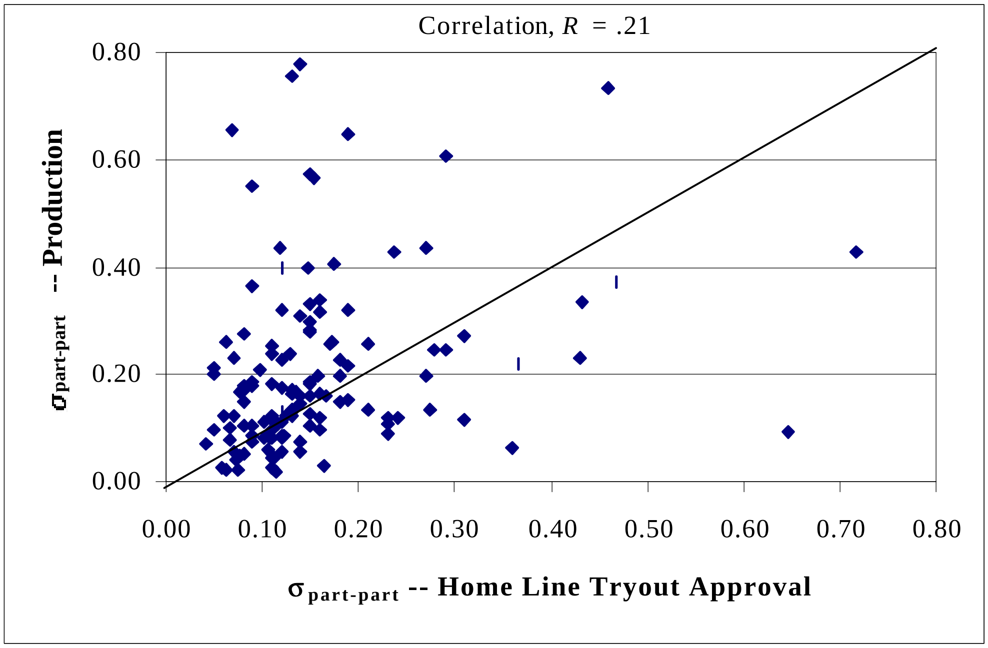

Figure 12. Part-part variation: home line tryout approval vs. production by dimension

3.2.3 Impact of Shipping on Variation

As mentioned previously, part shipping caused several mean dimensions to shift from the stamping to the assembly plant, particularly for the non-rigid wheelhouse outer panels. This section examines the effects of shipping on variation. (Note: some potential operator noise exists because different operators measured the panels before and after shipping. However, this operator effect is unlikely significant, as the panels were measured using the same fixtures and automated CMM programs.)

Table 19 indicates that **part-to-part variation increased on 87% of the dimensions for the four parts: wheelhouse outer, quarter inner, A-pillar reinforcement, and the B-pillar reinforcement**. Variation increased less on the more rigid components (A and B pillar reinforcements). Clearly, part shipment increases part-part variation.

Panel	Measurement Points	Variation Increased
Wheelhouse Outer	69	91 %
Quarter Inner	91	92 %
B-pillar Reinforcement	59	86 %
A-pillar Reinforcement	70	76 %

Table 19. Summary of re-measured data before and after shipping (via truck)

3.2.4 Components of Variation: Part-to-Part, Run-to-run, and Begin-End of Run

Stamping variation may be broken down into three components of variation: part-to-part, run-to-run, and begin-end of run (see Section 2.0). Total variation (σ_{total}) is a statistical summation of these three variation components. One reason for looking at the components of variation individually is that the each is a reflection of different root-causes. Table 20 shows the part-to-part and total variation for each auto company's body side outer panel.

Company	**Body Side Type**	**# cross/car clamps in fixture**	**Average $6\sigma_{part-part}$**	**Average $6\sigma_{total}$**	**% Dimensions $6\sigma_{total} > 1.5$**
A	Integrated Quarter	11	1.14	1.41	29%
B	Integrated Quarter	14	1.09	1.93	57%
C	Two-piece	7	0.99	1.88	42%
D	Two-piece	8	0.99	1.21	23%
E	Two-piece	22	0.48	0.52	0%
F	Two-piece	16	0.32	0.49	0%
G	Integrated Quarter	17	0.40	0.77	3%

Table 20. Summary of part-to-part and total variation for the body side outers

Companies E, F, and G, which used the most constrained measurement systems (16, 17, and 22 clamps, respectively on the body side outer panel), have the lowest part-to-part and total variation. Comparing Companies C and D, excluding the clamping effect, showed that even the two companies exhibit similar part-part variation, Company C has much higher total variation. Figure 13 shows that Company C has significantly more run-run and begin-end of run mean shifts. Thus, Company C does not appear to control their process as well as Company D. We observe a similar finding in comparing companies A and B, with Company D. Companies A and B's total variation increases more over their part-to-part variation. Among companies E, F, and G (constrained measurement companies), Company G appears to have less control over their mean shift variation. In general, companies with similar panels and similar checking systems should have similar levels of dimensional variation. When they do not have similar levels of variation, the difference typically is not related to inherent part-part variation, but rather to how well one company controls their process over time.

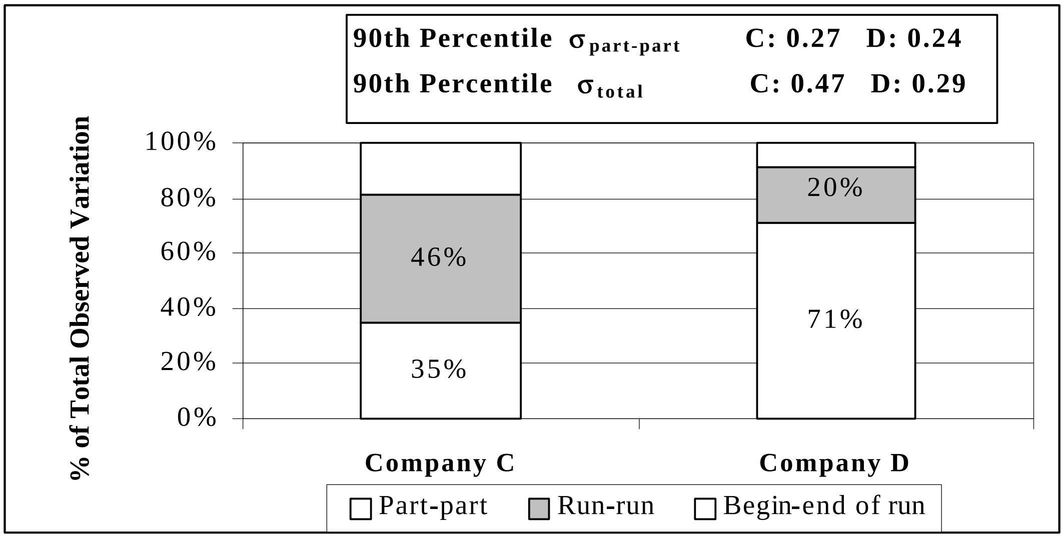

Figure 13. Components of variation for body side panel at Company C and D
(Note: σ_{total} is greater at Company C due to mean shifts not part-part variation)

Table 21 shows the amount of variation for each of the parts studied at Company A, broken down by the source of variation. The sample size for each type of panel is 36 right and 36 left (72 total for each type). (Note: numbers expressed in Table 21 are averages across all the dimensions on a part and therefore are non-additive). These data indicate that less-rigid panels exhibited the largest part-to-part and mean shift variation. Interestingly, the variation for a particular component is not always the same for right and left mirror image parts. At Company A, the right hand body side outer exhibits significantly less variation than the left side. Overall, variation at Company A is relatively low with the exception of the left body side. Although part-part variation is typically larger for a one-piece body side, the principal reason that the left side has significantly higher variation than the right side is due to mean shifts between stamping runs.

Part	Average $\sigma_{run\text{-}run}$	Average $\sigma_{begin\text{-}end}$	Average $\sigma_{part\text{-}part}$	Average σ_{total}	% of Variation Explained by Mean Shifts
Body Side - RH	-	0.15	0.19	0.24	31%
Body Side - LH	0.26	0.15	0.26	0.34	43%
Quarter Inner	0.07	0.07	0.08	0.10	43%
Wheelhouse Outer	0.11	0.09	0.09	0.14	50%
A-Pillar Reinforcement	0.04	0.07	0.05	0.08	59%
B-Pillar Reinforcement	0.06	0.05	0.07	0.08	28%

Table 21. Sources of Variation by part for Company A

Table 22 shows the percentage of total variation at Company C according to variation source: part-to-part and mean-shift (run-run and/or begin-end). The effects of mean shifts at Company C are more significant than Company A. The variation of the body side, front pillar and center pillar reinforcements are approximately doubled due to mean shifts. An analysis of the roof rail and windshield frame suggests one potential challenge with assessing mean shifts. Because analysis of variance methods are used to estimate mean shift variation, higher part-part variation will mask mean shift variation. In other words, the true mean shift variation cannot be effectively evaluated if the inherent variation is unstable (violation of the homogeneity of variance assumption used in analysis of variance (ANOVA) models).

Part	Average $\sigma_{mean\text{-}shift}$	Average $\sigma_{part\text{-}part}$	Average σ_{total}	% of Variation Explained by Mean Shifts
Body Side - RH	0.26	0.17	0.31	79%
Roof Rail	0.23	0.28	0.34	32%
Front Pillar Upper	0.16	0.09	0.18	76%
Front Pillar Lower	0.15	0.09	0.18	76%
Center Pillar	0.21	0.08	0.23	92%
Windshield Frame	0.15	0.20	0.23	22%

Table 22. Sources of variation by part for Company C

3.2.5 Steel Properties and Press Setup Control and Stamping Variation

These observational case studies under production conditions provide an opportunity to investigate possible root-causes of mean shift variation. Short-term or part-part variation (i.e., part-to-part variation) is assumed to result from several factors related to product design (e.g., part size and rigidity), die design, stamping press condition or the measurement system. Mean shift variation (run-to-run and within run), however, is generally related to *changes* in the process over time, such as the repeatability of press setup or changes to material properties. Although this observational study did not provide an opportunity to rigorously control variables to ascertain direct cause-and-effect relationships between process input variables and variation, it does allow for some general conclusions regarding the causes of mean shifts.

Five companies (Companies A through D and G did not participate) collected input data for both process and material variables across thirty parts. They collected this data for each sampling of three panels, or in some cases once per run. The material coupons were analyzed later, either at an independent test laboratory (three companies) or in-house (two automotive manufacturers). The following variables were collected when possible:

- Process data (at each setup)
    - Draw press shut height
    - Draw Tonnage
    - Die cushion pressure (if present)
    - Outer ram tonnage (if two-action press was used)
- Material data (a steel coupon was sampled when a sample of parts was taken from the production run)
    - Gage
    - Yield strength
    - Ultimate strength
    - n-value
    - Percent elongation

Due to data collection limitations, it was not possible to match process and material variable data directly to a particular panel. For example, the material properties of the steel for each individual panel are unknown. Thus, the analysis is limited to trying to explain mean shift variation and not part-part variation. For instance, if mean-shifts account for only 20% of the total observed variation, then the most variation that can be explained with the input variables collected is 20%. In other words, this analysis only identifies relationships between control of input variables and mean-shifts.

Of the thirty parts with process input data, approximately 30% of the dimensions (330 out of 1135 total dimensions) had at least one large mean shift (greater than 0.5mm) over the data collection period. Thus, prior to any mean-shift analysis, over two-thirds of the dimensions studied were found robust to the variability of their respective process and material input variables.

The next step was to examine the relationship between process variable control and mean-shift variation. Table 23 compares mean shift variation with process input variation using allowed ranges. Allowed ranges are essentially the tolerances of the process and material input variables. Thus, if manufacturers control their process-input variables within these ranges, they should not observe significant mean shifts related to these variables. Generic *allowed ranges* are used instead of tolerances to permit comparison among manufacturers with different process and material variable specifications. Furthermore, since this analysis only looks for relative variation differences, the nominal or average value of each variable is not important.

Variable	**Robust Range**	**% Parts within Robust Range**	**Correlation, *R*, to $\sigma_{\text{mean-shift}}$**
Material Gauge	0.06 mm	96%	0.23
Yield Strength	6 ksi	95%	0.22
Ulimate Strength	6 ksi	92%	0.24
% elongation	9%	100%	0.19
n-value	0.04	100%	0.09
Inner Tonnage	60 tons	45%	0.69
Outer Tonnage/ Cushion Pressure	50 tons/ +/- 10%	48%	0.47

Table 23. Summary of product and process variation compliance

Table 23 shows that most steel variables (from 92% to 100%) fall well within their expected ranges of variation. Consequently, it is not surprising to see that their correlation with mean shifts is relatively low (correlation values ranged from 0.09 to 0.24, where 0 has no correlation, 1.0 is a perfect correlation and a value greater than 0.6 is considered correlated). In general, the steel manufacturers studied had relatively good control of their variation, and even when they did not, material property variability could not be correlated with dimensional mean shifts.

The two process variables, inner tonnage and outer tonnage/ cushion pressure (outer tonnage if double-action press, cushion pressure if single-action), had considerably more variation and operated within the allowed range only 45% to 48% of the time. The result was a much higher correlation to mean shifts. Presumably, the opportunity for variation reduction for these part dimensions is significant if press setup (tonnage and cushion pressure) can be controlled tighter than is currently done. Figure 14 suggests an observed threshold of around 75 tons as the limit to the allowable range of variation for controlling dimensional mean shifts. Note that these observed ranges relate only to dimensional mean shifts and do not consider potential impacts on formability issues such as splits or wrinkles.

A few additional caveats with respect to this analysis are worth mentioning. First, tonnage readings may be affected by several setup variables such as lubrication, die placement in press, shut height, etc. and thus the correlation to mean shifts should be viewed principally as an indicator of lack of process control. Second, the relationship between tonnage and mean shifts over a continuous range of tonnage settings was not analyzed scientifically for every part. Thus, these data should not be used to identify tonnage specifications for a particular part. Rather, simply recognize that those parts in this study exhibiting large mean shifts tended to have relatively poor control of the process variables but good control of the material variables.

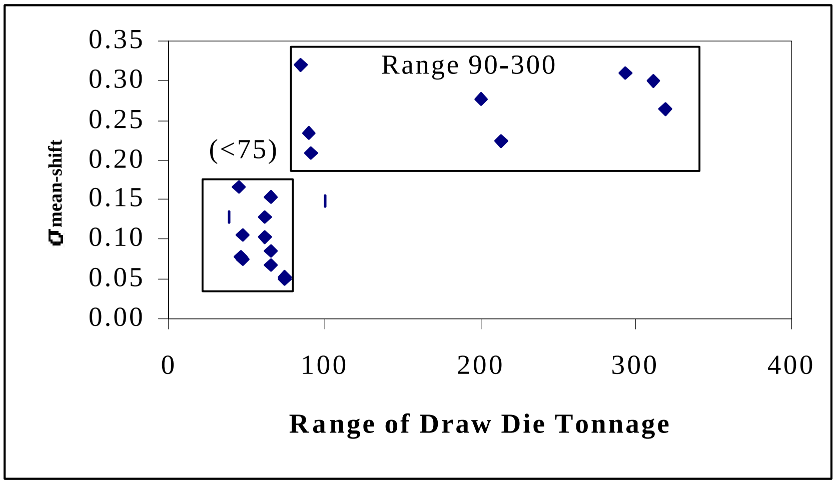

Figure 14. Relationship between press tonnage and mean shift variation ($\sigma_{\text{mean shift}}$)

3.2.6 Effect of Mean Shifts on Statistical Process Control Techniques

All companies in the benchmark study exhibited some level of mean shift variation for the majority of their part dimensions (see Table 24). Of the 1287 dimensions examined, approximately 80% would have at least one subgroup plot out-of-control on an X-bar chart. However, only 20% of the dimensions had a mean shift greater than 0.5mm (note: the majority of these mean shifts occurred on the parts at Companies B and C). Again, these mean shifts largely explain why certain companies have more variation in their process than others.

Company	**# of Dimensions**	**Average σ_{total}**	**% Dimensions w/ Significant Mean Shift**	**% Dimensions |mean shift> .5|**
A - RH	329	0.12	80%	3%
A - LH	282	0.15	88%	12%
B	262	0.36	80%	51%
C	143	0.28	84%	31%
D	62	0.19	85%	3%
E	41	0.09	34%	0%
F	61	0.10	82%	3%
G	107	0.15	82%	14%
Total	1287	0.18	81%	19%

Table 24. Summary of mean shift variation across companies

The fact that such a large percentage of dimensions would plot out-of-control on an X-bar chart (Statistical Process Control Chart used to assess mean stability) has serious implications for process control. One interpretation is that stamping and die processes by nature are not stable enough to produce parts with stable mean dimensions, even at world-class facilities. Another interpretation is that the inherent or part-part variation of a stamping process often is so low, that even well maintained processes will exhibit some process drifts over time. Assuming, for example, that the inherent standard deviation of a stamping process is 0.10mm, a process will be deemed statistically out-of-control if a mean shifts by more than **0.15mm**[2]**.** Most manufacturers would not want to adjust a process for a 0.15mm mean shift.

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[2] The control limit for an X-bar chart is equal to $A_2(n)$ x $d_2(n)$ x $\sigma_{part-part}$, where A_2 and d_2 are functions of subgroup size. If the subgroup size, n, is equal to 4, then the control limits are +/- 0.729 x 2.059 x 0.1 or +/- 0.15mm

Assuming that small mean shifts are inevitable with the die changeover process, the traditional use of X-bar charts to assess mean stability may be unnecessarily stringent. The small part-part variation results in tight control limits, and this in turn results in many out-of-control dimensions. Since small, mean shifts rarely effect assembly builds, manufacturers using control charts often ignore the results. Unfortunately, they often ignore the results even if larger shifts are observed. The main concern with X-bar/ Range charts for stamping is that they do not effectively separate problems from insignificant process changes. One approach to desensitize charts is to replace X-bar/ Range charts with Individuals and Moving Range charts.

Individuals and Moving Range charts are based on subgroup sizes of one. Control limits to assess mean stability are then based on moving ranges. Because moving range values are based on consecutive subgroups, variation estimates reflect the part-part variation and some mean-shift variation. Table 25 presents process control data for a stamping dimension. Using traditional X-bar charts, this process would be considered unstable or out-of-control (see Figure 15). Interestingly, if only the first observation in each subgroup is measured and Individual and Moving Range charts are used, this same process would be deemed in-control. The reason is that Individual charts based on moving ranges are less sensitive than X-bar charts if small mean shifts are inherent to the process. Of course, with individual and moving range charts, large significant mean shifts may still be identified.

Subgroup (i)	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Xbar (i)**	**Range (i)**	**X (i=2)**	**Rm (i)**
1	0.40	0.30	0.20	0.50	0.35	0.30	0.30	0.00
2	0.25	0.50	0.40	0.30	0.36	0.25	0.50	0.20
3	0.25	0.25	0.05	0.15	0.18	0.20	0.25	0.25
4	0.50	0.20	0.10	0.20	0.25	0.40	0.20	0.05
5	0.90	0.75	0.85	0.70	0.80	0.20	0.75	0.55
6	0.65	0.40	0.50	0.90	0.61	0.50	0.40	0.35
7	0.20	0.40	0.25	0.25	0.28	0.20	0.40	0.00
8	-0.10	0.10	0.25	0.20	0.11	0.35	0.10	0.30
9	0.25	0.30	0.30	0.25	0.28	0.05	0.30	0.20
10	0.40	0.25	0.10	0.20	0.24	0.30	0.25	0.05
11	0.40	0.65	0.50	0.30	0.46	0.35	0.65	0.40
12	0.30	0.25	0.20	0.25	0.25	0.10	0.25	0.40
13	0.10	0.10	0.00	0.10	0.08	0.10	0.10	0.15
14	0.40	0.30	0.70	0.50	0.48	0.40	0.30	0.20
15	0.30	0.25	0.30	0.30	0.29	0.05	0.25	0.05
16	0.35	0.60	0.50	0.40	0.46	0.25	0.60	0.35
17	0.15	0.15	-0.05	0.05	0.08	0.20	0.15	0.45
18	0.60	0.30	0.20	0.30	0.35	0.40	0.30	0.15
19	0.70	0.55	0.65	0.50	0.60	0.20	0.55	0.25
20	0.75	0.60	0.90	1.00	0.81	0.40	0.60	0.05
21	0.15	0.20	0.35	0.40	0.28	0.25	0.20	0.40
22	0.30	0.50	0.25	0.60	0.41	0.35	0.50	0.30
23	0.15	0.20	0.20	0.15	0.18	0.05	0.20	0.30
24	0.30	0.55	0.40	0.50	0.44	0.25	0.55	0.35
25	0.75	1.00	0.85	0.65	0.81	0.35	1.00	0.45
Average					0.38	0.26	0.39	0.25

Table 25. Process Control Data

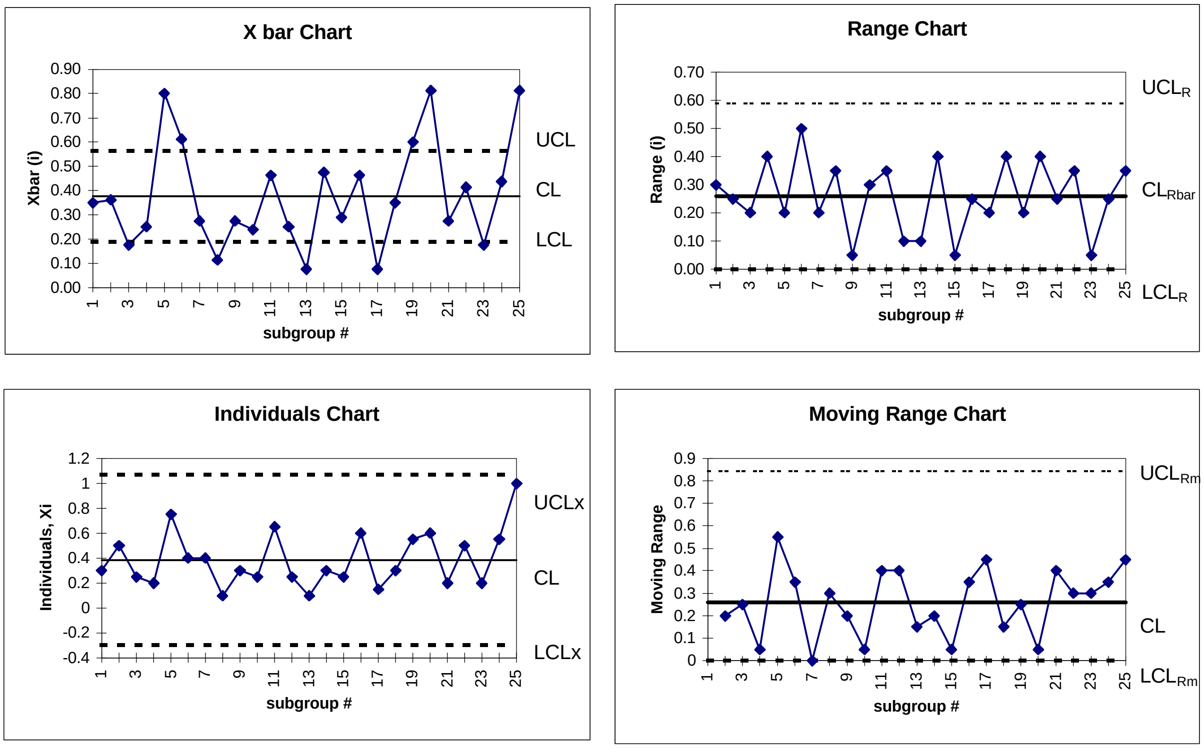


Figure 15. X-Bar/Range Chart vs. Individuals/ Moving Range Charts
(Note: charts based on the same process data)

The use of Individuals and Moving Range charts for stamping processes solves the problem of over-sensitive control charts; however, it does not necessarily result in better process control. The fundamental problem with statistical process control charts for stamping is that they merely expose mean shifts. Effective process control requires an understanding of the robustness of dimensional measurements to input variables and then the discipline to control the variation within these robust levels. For example, manufacturers should identify safe operating windows for draw tonnage, cushion pressure, shut height, counterbalance pressure, air pressure, n-value, material thickness etc. Then, they need to operate their processes within these windows. If they can meet this objective, there is little need to measure stamped parts during regular production. Unfortunately, many companies either have insufficient knowledge of the robustness of their processes to input variables or are not consistent in monitoring them.

Ultimately, whether a non-stable mean is acceptable depends on the influence that the variation will have on the assembly. In these case studies, most assembly dimensions were robust to the variability of their coordinated stamping dimensions. Table 26 indicates that relatively few dimensions (i.e., less than 5%) exhibited strong correlation. Although stamping-to-assembly correlation is low, some stamping dimensions with mean shifts greater than 0.5mm corresponded with assembly dimensions with higher variation (see Table 26). Thus, the elimination of large stamping mean shifts would likely lead to a reduction in some assembly variation.

				Effect of Stamping Mean Shifts	
Company	**# Coordinated Dimensions**	**# Dimensions w/ Significant Correlation**	**# Dimensions w/ Stamping Mean Shift > 0.5**	**Median $\sigma_{assembly}$ if shift < .5**	**Median $\sigma_{assembly}$ if shift >= .5**
A	33	1	1	0.18	0.30
B	104	8	62	0.16	0.23
C	32	2	14	0.19	0.38
D	31	0	1	0.22	0.21
E	32	0	0	0.16	none
F	8	2	0	0.20	none
G	77	1	9	0.13	0.13
Totals	**317**	**14 (4%)**	**87 (27%)**	**Average =0.16**	**Average = 0.25**

Table 26. Effect of Stamping Mean Shifts on Assembly Variation

4.0 Tolerance Considerations

4.1 Tolerances

Two objectives for assigning sheet metal tolerances are to help insure that final assembly quality will be met and to minimize productivity losses during assembly because of large stamping variation. Assigning tight tolerances help achieve this goal. The tradeoff to assigning *overly* tight tolerances, however, is that die and stamping costs may become excessive trying to meet them. In some respects, the tolerance has the effect of shifting costs from stamping to assembly or from assembly to stamping, depending on the tolerance assigned. A reasonable and meaningful sheet metal tolerance needs to consider the following three factors:

- **Stamping process capability** – the tolerance must reflect what a stamping process is capable of achieving, otherwise unnecessarily high stamping costs will accrue. There are many instances today where stamped parts are out of tolerance, but are being assembled successfully (all of the benchmark automotive manufacturers had body side outer panels with a significant number of points out of tolerance). This is evidence that companies tend to assign unnecessarily tight tolerances on stamped parts, particularly for less-rigid outer panels. When stamping plants have difficulty meeting assigned tolerances, there is a tendency to overlook the tolerance and wait to hear if assembly experiences build problems. This wait-and-see approach would be improved upon if the tolerances were known to be meaningful.
- **Impact on assembly** – unlike many other rigid assembly processes, the <u>assembly</u> of sheet metal affects final part geometry. The assembly process has the ability to add or reduce variation depending on the components and assembly process. Many assembly processes are robust to a wide range of stamping variation showing virtually no impact on assembly quality due to stamping variation. In these instances, it would behoove the manufacturer to widen stamping tolerances – at least up to the point where they begin to impact assembly.
- **Measurement system limitations** – because of the impact that the measurement system has on our ability to measure stamped panels, part tolerances need to reflect the measurement system design. It was shown earlier that measurement fixtures with more clamps tended to have parts with tighter tolerances than those measured with fixtures

that had fewer clamps. The amount of observed variation with constrained checking fixtures is less than that of less-constrained fixtures and therefore tighter tolerances can be achieved.

4.2 C_p and C_{pk} (P_p and P_{pk})

The predominant tolerance strategy used by automotive manufacturers is to assign tolerances, which may be difficult to achieve, but are believed to help final assembly quality while reducing assembly problems. In some cases, overly tight tolerances are assigned; if not readily achieved, they can be re-evaluated during development. An advantage of this strategy is that certain parts where all the tolerances are met are approved without special intervention. One concern with this strategy, however, is that many dies are unnecessarily reworked to meet the original tolerances even though they may not impact assembly build. This unnecessary rework then leads to timing delays. Since these companies often use process capability indices (C_p and C_{pk}) to measure conformance to tolerance, they will be discussed next.

Two process capability indices often used to compare how well a process is achieving the design tolerances are C_p and C_{pk}. These indices are a function of the tolerances, part-to-part variation and mean bias. The C_p (process capability) and C_{pk} (design capability) indices were developed to measure the capability of a process relative to design intent. The formula for C_p is:

Equation 5

$$C_p = \frac{USL - Nominal}{3\sigma_{part-part}}$$

The C_p index is determined by dividing one half of the tolerance (one half the tolerance = the upper specification limit minus the nominal = USL – Nominal) by three standard deviations of part-to-part variation. The formula for C_{pk} is:

Equation 6

$$C_{pk} = \frac{USL - Mean\ Bias}{3\sigma_{part-part}}$$

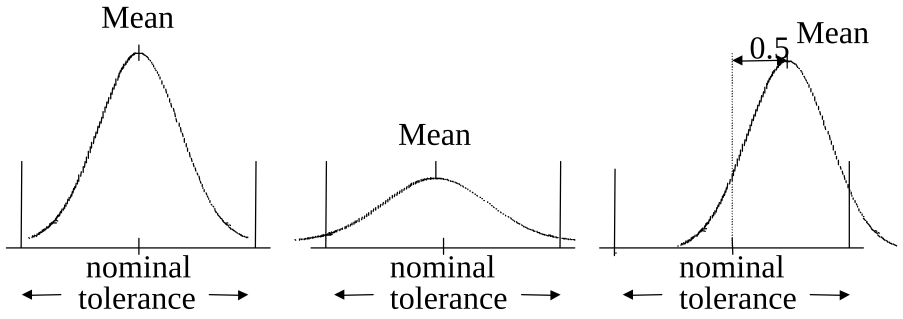
(Note: mean bias = | process mean – nominal |)

The C_{pk} index is determined similarly to C_p, except that any mean bias is first subtracted from the numerator. If there is no mean bias and the process is operating exactly at the design nominal, then $C_p = C_{pk}$. For the purpose of these calculations, $\sigma_{\text{part-to-part}}$ is estimated using statistical tables and the formula:

Equation 7

$$s_{part-part} = \frac{\overline{R}}{d_2}$$

If the sample standard deviation is used to estimate $\sigma_{\text{part-to-part}}$ rather than the above formula, then the C_p and C_{pk} indices are referred to as P_p and P_{pk}. Their interpretation, however, is the same regardless of the method used to estimate $\sigma_{\text{part-to-part}}$. Figure 16 illustrates differences in Cp and Cpk for three different scenarios.



Tol.	±1.0	±1.0	±1.0
σ	0.25	0.33	0.25
Cp	1.33	1.0	1.33
Cpk	1.33	1.0	0.67

Figure 16. Illustration of Cp and Cpk calculations for three scenarios

4.3 Recommended Tolerances for Sheet Metal

The tolerance guidelines shown in Table 27 are based on these empirical benchmark studies. These guidelines allow consideration for process capability (achieving a $C_p = 1.33$), influence on assembly dimensions and measurement system limitations. They also assume that the data is obtained without over-constrained measurement systems. Furthermore, these tolerances only reflect manufacturing variation (about the long-term process mean) and do not consider the ability to hit the design nominal. Since dimensions routinely deviate from design nominal, initial specifications may account for both mean bias and process variation, resulting in wider tolerances than shown in Table 27.

These case studies also suggest that rigid components (typically with material gauges greater than 1.5mm) have greater process capability (i.e., smaller variation) and exhibit more influence on the assembly, and therefore warrant smaller tolerances. Rigid components also tend to exhibit greater repeatability from die set to die set, so both short-term and long-term tolerances are smaller than other components. Dimensions for non-rigid panels are divided into two groups, mating surfaces and non-mating surfaces. Mating surfaces often are more critical for assembly, and thus may have tighter tolerances than non-mating surfaces. In all cases represented in Table 27, a tolerance range is shown because the ability to control variation may differ by dimension around the part. These general tolerances are a function of the inherent sigma and assume that a C_p of 1.67 is desired. For all three categories, manufacturers should be able to at least meet the high end of the tolerance guideline based on the inherent capability of stamping processes.

Part Rigidity	**Location of Dimension**	**Inherent Sigma**	**Tolerance to Achieve $C_p > 1.67$ (tol > $3C_p\sigma$ or +/- 5sigma)**
rigid dimensions (~gauge > 1.5mm)	all	.06 ~ .15	0.3 to 0.75
non-rigid dimensions (~gauge < 1.5mm)	Mating Surface	.10 ~ .20	0.5 to 1.0
	Non-Mating Surface	.10 ~ .25	0.5 to 1.25

Table 27. General recommended tolerances for stamped parts based on process capability
(Note: data based on measurements systems without over-constrained clamping)

4.4 Part Tolerances and Functional Build

The assignment of part tolerances often hinges on whether to allow for mean bias (deviation from nominal). The previous section recommended part tolerances based on manufacturing variation without consideration of mean bias. Since mean bias is not considered, the C_p index may be used to measure conformance to design, but C_{pk} is **not** used. This development strategy relies on two steps. First minimize variation to an acceptable level, and then evaluate the impact of mean bias on the assembly to determine which points, if any, require a rework. Here, the assembly build is used to identify dimensional shifts and not product specifications. Several manufacturers use this functional build strategy. Advantages of this strategy include:

- Less die rework is needed because only dimensions that adversely affect the final assembly are identified for rework.
- Development lead-time is saved because less die rework is required.
- Lower overall process variation is achieved both in stamping and in assembly. Many engineers believe that as the amount of die rework increases from shifting many dimensions toward nominal, the less robust the die becomes.

This functional build strategy may also help improve process control because the final specifications for mean bias and process variation are determined during tryout, and thus better reflect process capability and the influence on assembly. The consequence of not meeting the final tolerances is better understood without waiting to hear from assembly.

5.0 Conclusions and Summary

The following conclusions are based on the analysis shown in this report, and from observations made throughout the study. Since much of the data collection was obtained under production conditions in a non-statistically structured manner, the analysis is not sufficiently rigorous to establish conclusive results in many areas. Due to the enormous number of product and process variables seen at a single manufacturer, rigorous experimentation would have severely limited the breadth of analysis. The following general conclusions provide insight from several manufacturers and reflect different design and manufacturing strategies structured around common operating principles of sheet metal design, die construction and metal forming. The following general observations provide guidelines to developing more rigorous research deemed necessary at particular companies choosing to develop more science around stamping variation and measurement.

1. An important distinction across companies was the type of panel measuring system used on large, non-rigid parts like the body side and wheelhouse outer panels. The greater the number of clamps, the less observed variation and mean biases that was seen in the measurement data. Constrained measurement systems had between 16 and 22 in/out clamps, whereas the unconstrained (lesser-constrained) systems used from 5 to 11 clamps. The use of clamps and their location is indicative of different dimensional validation and process control strategies (not discussed in this report). However, it is important to note the difference because of the impact on the measurement data for large panels. Companies using constrained measurement systems also assigned tighter tolerances to the body side. The constrained tolerances varied from ± 0.3mm to ± 0.50mm, where the unconstrained tolerances varied from ± 0.70mm to ± 1.25mm.
2. There are significant differences in the amount of variation seen in larger, less-rigid parts (e.g., body side outer panel) versus smaller reinforcements (e.g., A and B pillar reinforcements). Larger parts experience from 20% to over five times more **mean bias** on the average (averaging from 0.5mm to more than 1.0mm for unconstrained measured parts). The amount of mean bias varies considerably across manufacturers depending on many factors. Several factors include measurement strategy (constrained versus unconstrained), panel size (one-piece body side versus two-piece) and die buyoff strategy (e.g., their willingness to accept dimensions to vary based on a functional build dimensional validation strategy versus a

conventional "build-to-specification" strategy). Large parts also experience about twice as much variation than small parts, and the variation is distributed across part-to-part and mean shift variation.

3. Short-term variation (part-to-part) is relatively small with the 95% 6-sigma less than 1.0mm for rigid parts and less than about 2.0mm for the body side outer (using unconstrained measuring). If the mean bias could be eliminated, many parts would readily achieve a C_{pk} = 1.33 without much difficulty. A significant challenge during dimensional validation is eliminating mean bias, particularly for large or small complex panels.
4. Large, less-rigid panels also are more susceptible to changes in variation due to transferring the dies from the tryout source to the home line and from home line tryout versus future production. In both cases, their mean bias and amount of variation are likely to increase. Small, rigid panels have smaller changes in variation when transferring from tryout presses to the home line. In some cases during production, they show a decrease in mean bias from the home line tryout. (It is likely that die re-work has taken place during the production life to reduce mean bias, and attention may have been focused more on the rigid panels than on the larger ones.) Small, rigid panels are also less susceptible to increased variation and mean bias due to shipping than are larger panels. Several small panels experienced from 6% to 19% of the dimensions shifting at least 0.2mm due to shipping, whereas the wheelhouse outer had 76% of the dimensions shift at least 0.2mm. The difference in the variation increase was not as significant, where the small panels averaged 85% of their dimensions increasing in variation and the wheelhouse experienced 91%.
5. Companies with similar part design and measurement systems, but with different levels of total variation usually experience different amounts of run-to-run mean shifts. As expected, part-to-part variation is similar for companies with similar measuring strategies and product designs. The two setup-related variables investigated in this study, tonnage and cushion pressure, showed a correlation with dimensional mean shifts. No significant relationship could be found between material property variation and mean shift variation.
6. All stamping processes in this study operated out of statistical control. Stamping processes have inherent complexity making it difficult or impossible in production to set up repeatedly with a constant mean dimension on all panel dimensions. For this reason, conventional X-bar and R charts are inappropriate for process control because they would routinely indicate that

the processes are out of control, in spite of their ability to assemble into acceptable bodies. Some companies are better than others at minimizing mean shift variation, but all companies in this study are producing a significant percentage of parts with dimensions outside of their assigned tolerances. The meaningfulness of currently assigned tolerances to sheet metal part dimensions is suspect, particularly for less rigid panels.

Appendix A – Part Sketches by Company

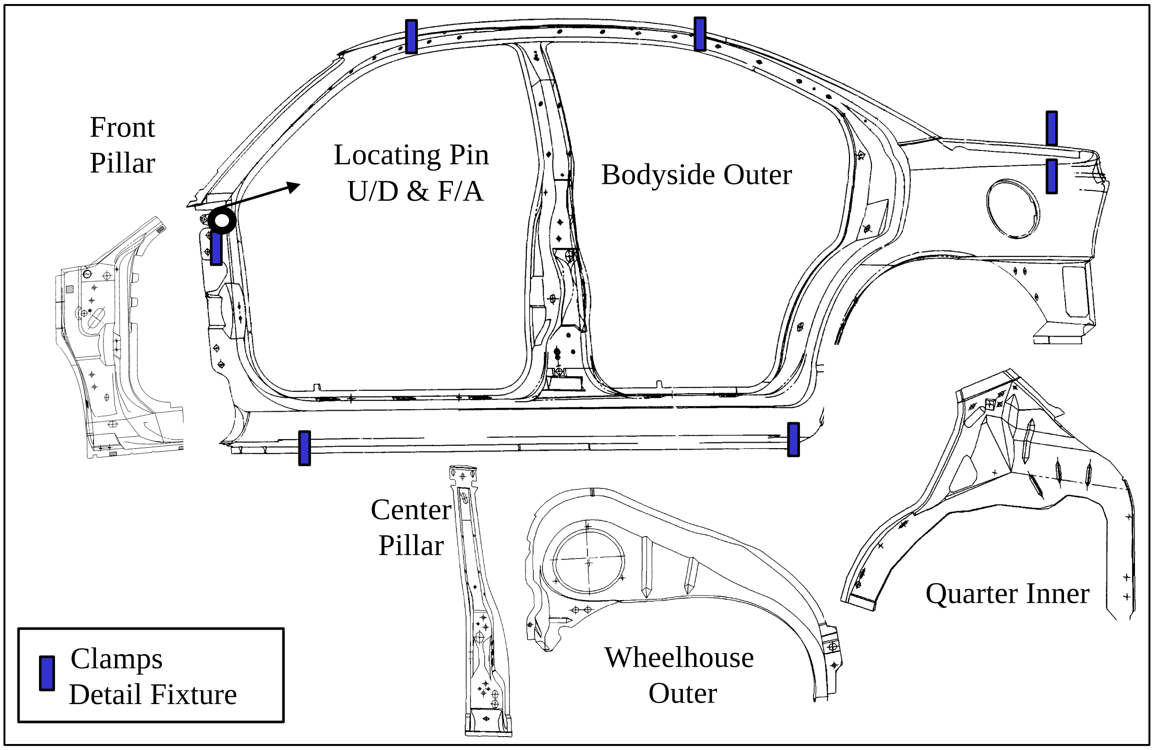


Figure 17. Part Sketches at Company A

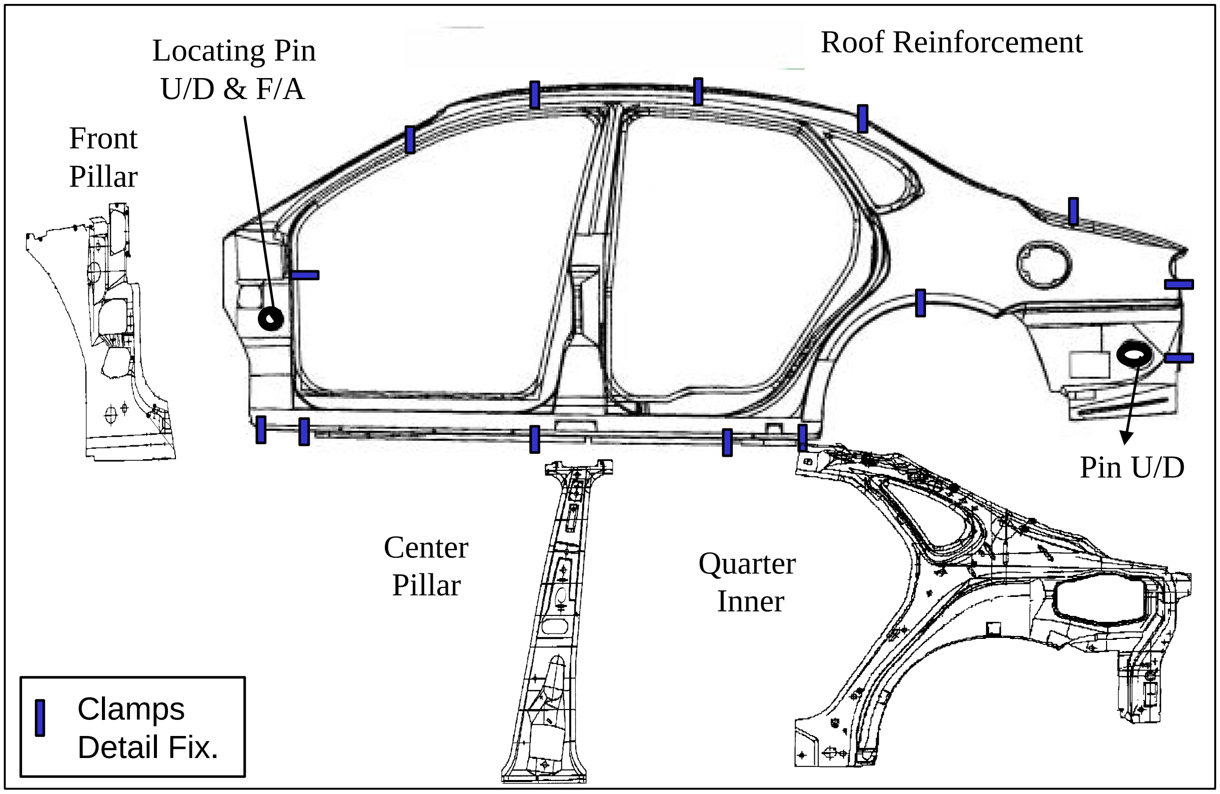


Figure 18. Part Sketches at Company B

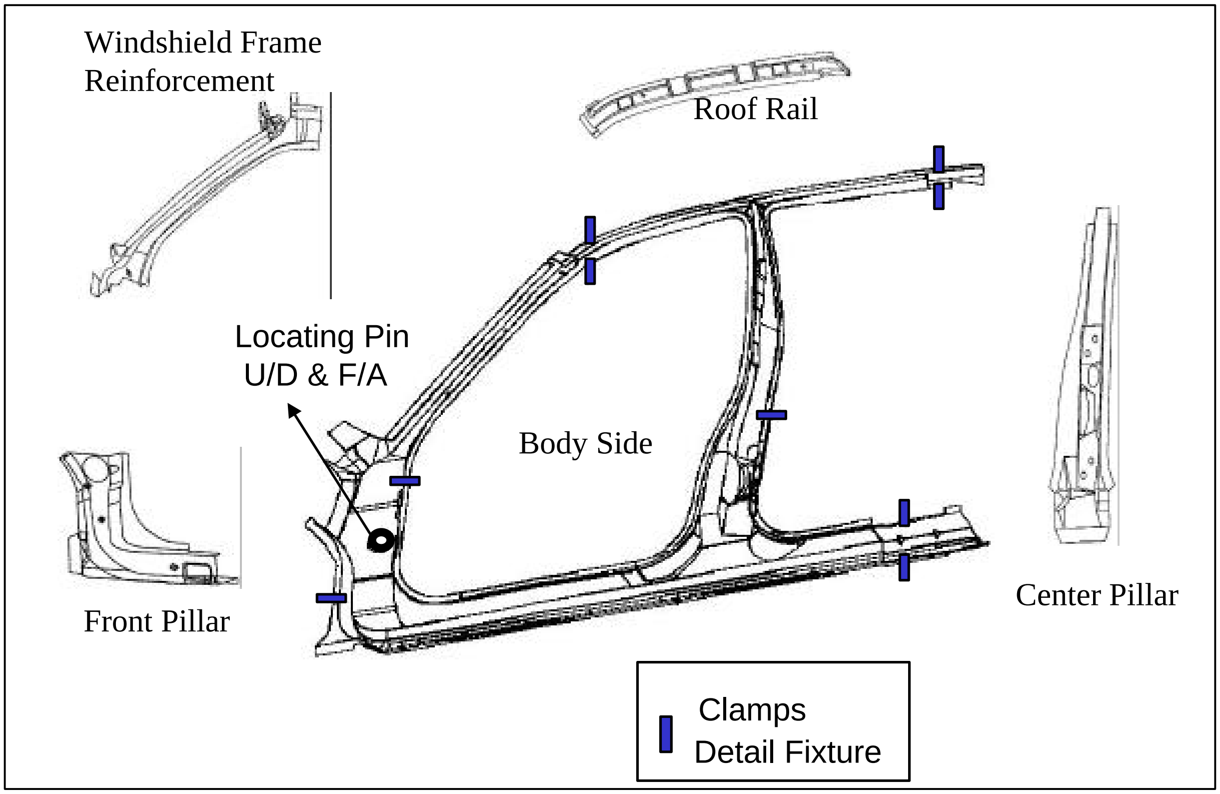
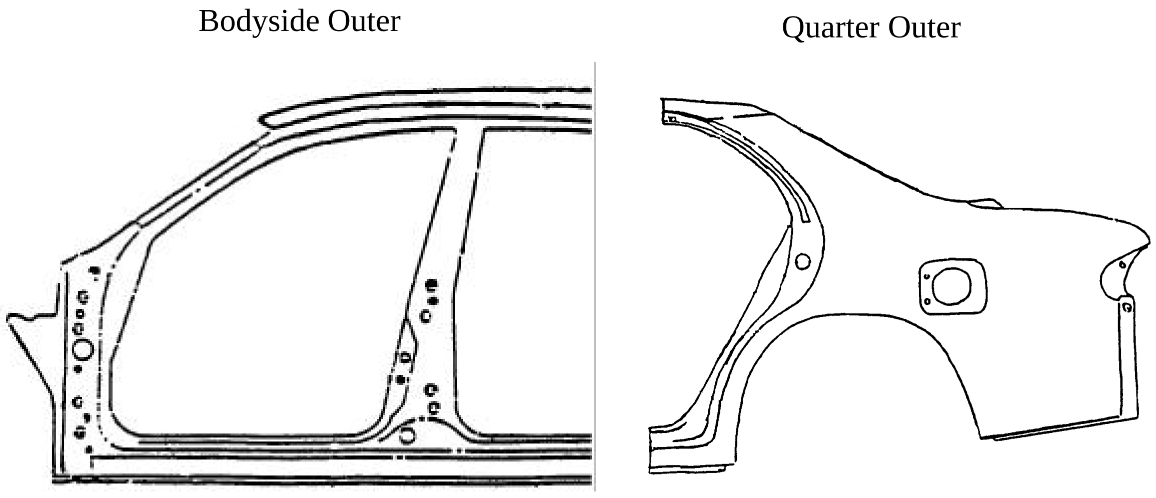


Figure 19. Part Sketches at Company C



<u>Not included:</u>
A-Pillar Upper and Lower Reinforcement
B-Pillar Upper and Lower Reinforcement

Figure 20. Part Sketches at Company D

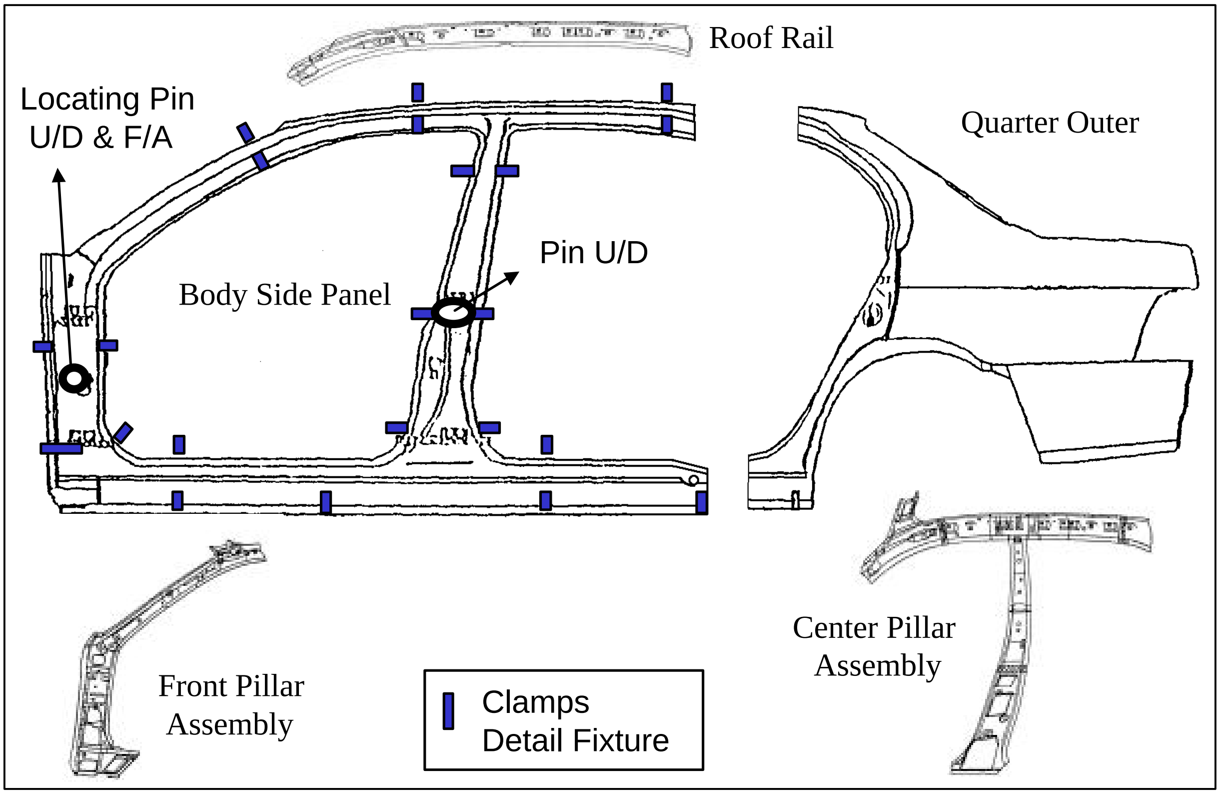


Figure 21. Part Sketches at Company E

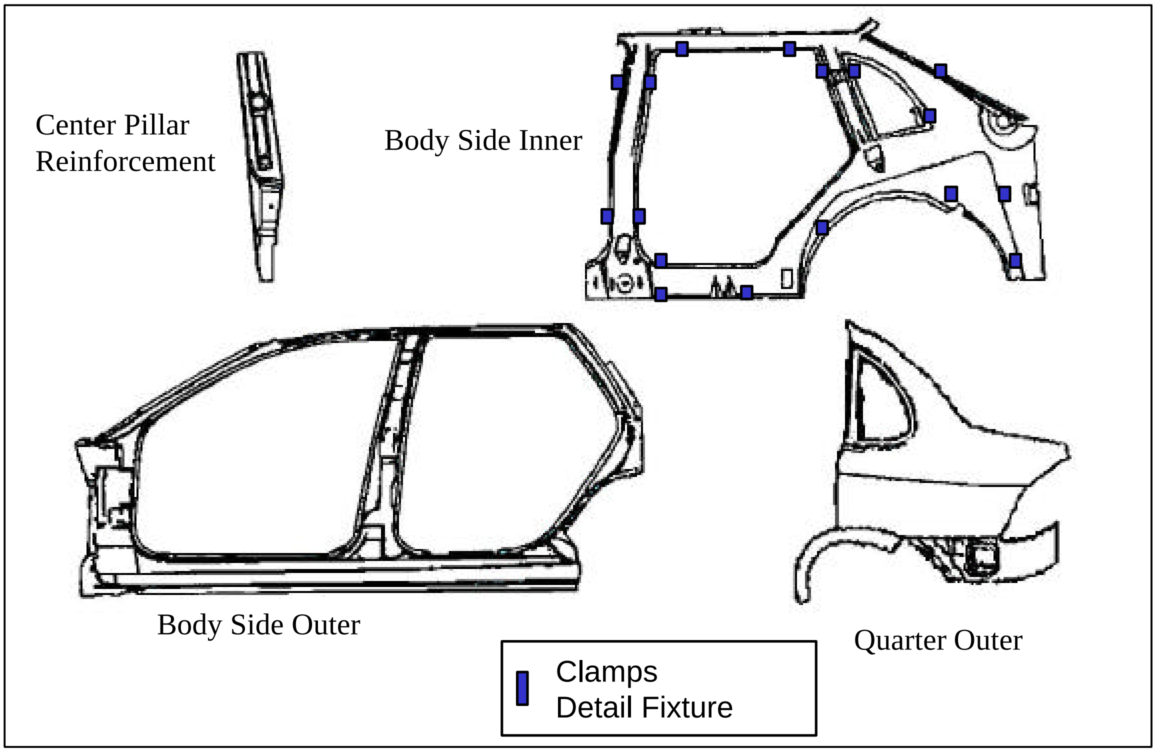


Figure 22. Part Sketches at Company F

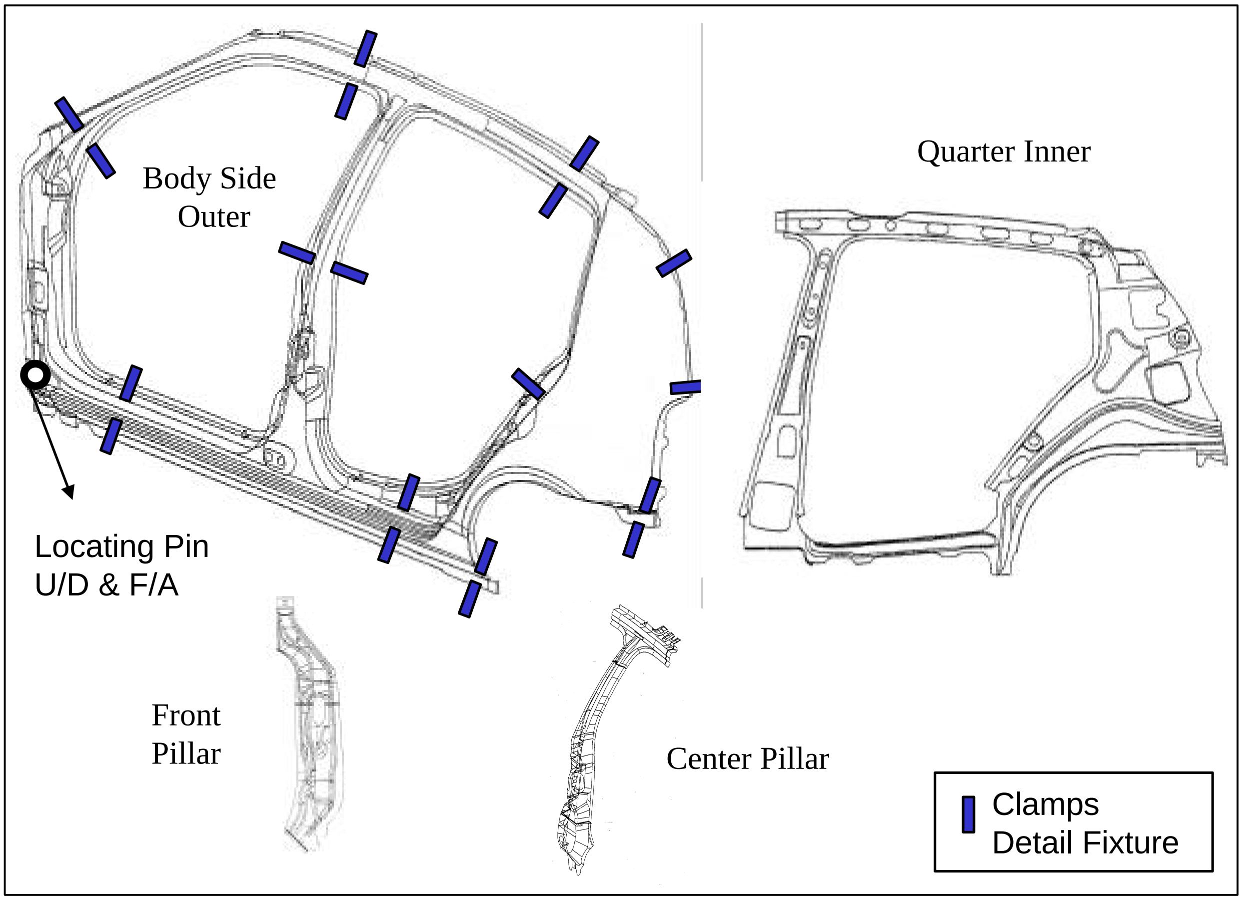


Figure 23. Part Sketches at Company G