IDENTIFICATION OF FACTORS AFFECTING FRONT END ALIGNMENT:

On-Line and Off-Line Analyses

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Recently, managers and engineers at a major Detroit area automotive company recognized the vital importance of identifying the design and production factors which significantly affect the front end camber angle in vehicles produced in one of their assembly plants. The goal of identifying these factors was the eventual establishment of a total process control program to maintain the overall quality of the vehicle front end. This paper contains a summary of the numerous on-line and off-line studies undertaken in the assembly plant during a one-year period to gain an understanding of the factors which affect the front end camber angle. It will be shown that commonly used analyses in both on-line and off-line studies can possess limitations which fail to meet the needs of the quality engineer. Understanding the results from these studies is important to understanding the complexity in establishing a quality control program for currently operating assembly processes.

1. INTRODUCTION

The goal of this paper is to demonstrate the care which must be taken in identifying current assembly line processes which need to be monitored as part of a total process control program. The paper will focus on one specific design and production area, front-end alignment. However, the lessons learned from this specific area can be used in tackling many quality control problems in various assembly processes.

Previous literature on establishing a quality control program to control vehicle alignment in a currently operating assembly process does not mention the problem of identifying the assembly processes having pronounced effects on quality. Bhuyan (1980) advocated a direct application of the well-known Hotelling T^2 statistic, and its associated bivariate control chart, to simultaneously control left and right side vehicle alignment. This statistical technique was developed more that 30 years before Bhuyan's paper by Hotelling (1947), was later described by Jackson (1956), and extended beyond the bivariate case by Jackson (1959).

Bhuyan simply described how the bivariate control chart could be directly applied to control camber and caster. This is, however, only one small part in establishing a comprehensive quality control program. For example, Bhuyan does not discuss what actions need to be take once an out-of-control point is located on the control chart. Although it could be argued that this topic is beyond the scope of Bhuyan's paper, this problem is always central to the application of control charts. Assignable causes can be located and corrective action advocated only <u>after</u> the production processes affecting camber have been identified by means of well designed off-line or on-line studies. This paper will shed some light on the difficulty in identifying these factors.

2. THE IDENTIFICATION PROBLEM AS A GENERAL LINEAR MODEL

Suppose that a production phenomenon of interest can be expressed by the functional relationship

$$\upsilon = f(\xi,\pi) \tag{1}$$

where υ = the phenomenon of interest, and ξ and π represent the entire collection of production factors which determine υ. When the true functional form f and the factors ξ and π are unknown, identification and estimation can be done by assuming a general linear model of the form

$$\mathbf{Y} = \mathbf{X}\beta + \mathbf{Z}\Theta + \varepsilon \tag{2}$$

where

$\mathbf{Y}$ = an (n x 1) vector of observations of the phenomenon υ,

$\mathbf{X}$ and $\mathbf{Z}$ = (n x p) matrices of production input settings,

β and Θ = (p x 1) matrices of production parameters representing ξ and π respectively,

ε = an (n x 1) vector of error terms with $E(\varepsilon)=0$ and $V(\varepsilon)=I\sigma^2$, with I equal to an (n x n) identity matrix.

The error vector ε is included to represent observational errors and a modeling discrepancy by using (2) to estimate (1).

Let us assume that equation (2) sufficiently represents equation (1) to warrant the estimation of β and Θ to gain an understanding of the true relationship expressed in equation (1). That is, $f(\xi,\pi)$ can be equivalently expressed as $\mathbf{X}\beta + \mathbf{Z}\Theta$ and the vector ε is included only to represent observational (measurement) errors. Equation (2) assumes that each component of the vector $\mathbf{Y}$ follows a statistical distribution with a mean value of υ.

Identification of production factors affecting front end alignment is, then, equivalent to the process of estimating β and Θ in equation (2) while assuming that (2) is an adequate representation of (1), where υ is equal to the camber angle. The vector $\mathbf{Y}$ is equal to a vector of camber angle measurements (measured in minutes). Suppose further, however, that a quality engineer believes the factors affecting the camber angle can be adequately investigated by only estimating β. This is equivalent to observing what effect only the X design and production settings have on camber without investigating the effect that the Z production settings have on camber. Therefore the quality engineer assumes that the model

$$Y = X\beta + \varepsilon \tag{3}$$

adequately represents (1). Equation (3) is equivalent to

$$E(Y) = X\beta \tag{4}$$

In classical quality control analysis, it is assumed that production outcomes are random variables. This is basis of control charting. Therefore since the random variables contained in Z are the results of assembly line productions, we can model the observations Z as random variables distributed according to an unknown continuous distribution, with unknown mean and variance. Then the expected value of Y is not equal to equation (4) as assumed by the quality engineer who uses equation (3), but rather

$$\begin{aligned} E(Y) &= \underset{z}{E}(Y \mid Z) \\ &= \underset{z}{E}(X\beta + Z\Theta) \\ &= X\beta + \mu_z\Theta, \end{aligned}$$

where $\mu_z = E(Z)$ and $\underset{z}{E}(\cdot)$ signifies that the expectation is with respect to the random variable Z.

The least squares estimates of the parameters in equation (3) are given by

$$\hat{\beta} = (X'X)^{-1}X'Y$$

assuming X is non-singular. These estimates are, however, potentially biased. Once the observations Z have been observed and assuming that the true model is given by equation (2), we can compute the expectation of the matrix of coefficient estimates. That is,

$$\begin{aligned} E(\hat{\beta} \mid Z) &= (X'X)^{-1}X'E(Y \mid Z) \\ &= (X'X)^{-1}X'(X\beta + Z\Theta) \end{aligned}$$

$$= \beta + A\Theta,$$

where

$$A = (X'X)^{-1}X'Z.$$

This result is well known and **A** is commonly referred to as the *bias* or *alias* matrix (see, for example, Draper and Smith (1981) and Box and Draper (1987)). Unless $A = \mathbf{0}$, $\hat{\beta}$ will not estimate β but rather a function containing both β and Θ. The least squares estimates are biased by the presence of the observations **Z** which are linearly related to Y but disregarded by the quality engineer.

It can also be shown that the expected value of the calculated error sum of squares from using (3) is equal to

$$\begin{aligned} E(SSE \mid Z) &= [n - \mathrm{rank}(X)]\sigma^2 + [E(Y \mid Z)]'[I - X(X'X)^{-1}X'][E(Y \mid Z)] \\ &= [n - \mathrm{rank}(X)]\sigma^2 + (X\beta + Z\Theta)'[I - X(X'X)^{-1}X'](X\beta + Z\Theta) \\ &= [n - \mathrm{rank}(X)]\sigma^2 + \begin{bmatrix} \beta \\ \hline \Theta \end{bmatrix}'[X \mid Z]'[I - X(X'X)^{-1}X'][X \mid Z]\begin{bmatrix} \beta \\ \hline \Theta \end{bmatrix}, \end{aligned}$$

where $[X \mid Z]$ is equal to a partitioned matrix and $\begin{bmatrix} \beta \\ \hline \Theta \end{bmatrix}$ is equal to a partitioned vector. The second term will not be equal to **0** for all cases and, therefore, the error mean square will be a biased estimator of σ^2, the error variance in equation (2).

Thus, the engineer will error in assessing the effects of the production settings by ignoring **Z** which contain factors affecting camber. This type of error occurs when selected areas of the assembly line are observed individually and their affect on camber estimated. This commonly occurs when on-line studies are undertaken since they generate "snapshots" of selected areas of the production process. These snapshots are analogous to only observing **X** and not observing or not controlling for **Z**. By not controlling other variability existent on the assembly line, or by not taking into account other assembly line factors effecting camber, the engineer will obtain a biased view of the assembly process.

The engineer will be unable to obtain unbiased estimates of the effects production factors have on camber. Similarly off-line studies run the potential risk of not obtaining a true representation of the plant since inherent variability existing in the assembly line cannot be reproduced off-line. Examples of these limitations are included in the following sections.

3. RELATIONSHIP BETWEEN SHOCK TOWER LOCATION AND CAMBER

Every white body structure (unpainted sheet metal) in the assembly plant passes through an automated optical measuring station. The optical measuring station is capable of measuring 95 body dimensions using 48 laser sensors. One measurement is the inboard/outboard location of the left and right shock towers relative to nominal (original design). This variable is considered to have a pronounced effect on front wheel camber. Therefore, two on-line studies were undertaken to estimate the predictive power of the automated optical measurements on final front wheel camber measurements.

The current procedure in collecting the optical measures and final on-line front wheel camber data did not provide for an automated linking between the two measurements for specific cars. The analyses presented here were the first studies undertaken in the assembly plant to investigate the relationship between shock tower location using the optical data and final camber readings for the same assembled vehicles.

3.1. Study Procedure

Two on-line studies were undertaken to estimate the predictive power of the automated optical measurements on final front wheel camber measurements. Between those two study dates, the referencing algorithm used at the automated measuring station was revised and considered much improved. Therefore a repeat on the original study was warranted. If we assume that the time periods chosen were randomly selected and reflect normal production operation, then we can assume the data are two random samples of assembled cars.

The first study began on June 24, 1987. All bodies which passed through the automated measuring station between 7:30 AM and 12:15 PM on that date and successfully measured at the automated measuring station were included in the study. The second study began on January 27, 1988. On that date, all bodies which passed through automated measuring station between 12:30 PM and 3:20 PM and successfully measured were included in the study.

In the first study, 69.6% of the bodies passing the automated measuring station were successfully measured. In the second study, the results were dramatically improved. Overall in the second study, 99.3% of the bodies passing the automated measuring station were successfully measured.

3.2. Summary Statistics

Tables 3.1 and 3.2 contain summary statistics of the shock tower location measurements for the first and second study respectively. Measurements are given in millimeters and are referenced from design nominal which is defined as a measure equal to 0.0. Negative measurements signify that the center of the shock tower was located inboard relative to design nominal and positive measurements signify the center was located outboard relative to design nominal.

Model	Side	n	$\bar{X}$ (mm)	Standard Deviation	95% Confidence Interval
A	Left	57	-0.888	.477	(-1.015, -.762)
	Right	57	2.228	.426	(2.115, 2.341)
B	Left	31	-0.682	.535	(-0.878, -.485)
	Right	31	2.274	.576	(2.063, 2.486)
C	Left	27	-0.750	.642	(-1.000, -.496)
	Right	28	2.300	.575	(2.077, 2.522)
D	Left	26	0.053	1.546	(-0.571, .677)
	Right	27	0.244	.979	(-0.143, .631)

Table 3.1. Summary Statistics for Shock Tower Inboard/Outboard Location Measured By The Automated Measuring Station, June 24, 1987.

Model	Side	n	$\bar{X}$ (mm)	Standard Deviation	95% Confidence Interval
A	Left	32	-1.965	.341	(-2.088, -1.842)
	Right	33	3.995	.496	(3.819, 4.171)
B and C	Left	58	-2.431	.348	(-2.523, -2.240)
	Right	58	3.912	.399	(3.807, 4.017)
D	Left	51	-3.386	.525	(-3.534, -3.238)
	Right	51	5.076	.614	(4.904, 5.249)

Table 3.2. Summary Statistics for Shock Tower Inboard/Outboard Location Measured By The Automated Measuring Station, January 27, 1988.

Summary statistics of the final camber measurements for the same vehicles are contained in Tables 3.3 and 3.4 for the first and second study respectively. Estimates of the process mean and associated 95% confidence intervals for the process mean are included in these tables. In comparing these two tables, note that in Table 3.3, five of the eight computed confidence intervals contain the design nominal. However, in Table 3.4, none of the computed confidence intervals contain the design nominal. Therefore it appears that as the process has shifted further away from the design nominal as time progressed.

Model	Specifications	Side	n	$\bar{X}$	Standard Deviation	95% Confidence Interval
A	-30'±20'	Left	54	-33.00'	10.378	(-35.83, -30.17)
		Right	54	-30.56	9.148	(-33.05, -28.06)
B	-30'±20'	Left	29	-26.55	10.838	(-30.68, -22.43)
		Right	29	-37.55	9.912	(-41.32, -33.78)
C	-36'±20'	Left	28	-36.14	7.447	(-39.03, -33.26)
		Right	28	-35.68	10.070	(-39.58, -31.78)
D	-30'±20'	Left	25	-30.56	8.201	(-33.95, -27.17)
		Right	25	-35.72	6.031	(-38.21, -33.23)

Table 3.3. Summary Statistics for Final Camber Measurements, First Study, June 1987.

Model	Specifications	Side	n	$\bar{X}$	Standard Deviation	95% Confidence Interval
A	-30'±20'	Left	29	-22.862'	8.684	(-26.166,-19.559)
		Right	29	-26.724	8.328	(-29.892,-23.556)
B and C	*	Left	53	-21.415	12.662	(-24.906,-17.925)
		Right	52	-24.000	8.088	(-26.252,-21.748)
C	-30'±20'	Left	48	-22.271	9.538	(-25.041,-19.501)
		Right	48	-23.208	9.039	(-25.833,-20.583)

* Includes measures for both models B and C.

Table 3.4. Summary Statistics for Final Camber Measurements, Second Study, January 1988.

Note that the standard deviation estimates for camber tend to be large. In all cases except one, 3 times the standard deviation estimates exceed the tolerance limits. Tables 3.5 and 3.6 contain estimates of the process capability ratio and associated 95% confidence intervals for these estimates. In all cases except one, the estimate of the process capability ratio is less than one. In addition, only four of the twelve computed confidence intervals contain the value one. In comparing Tables 3.5 with Table 3.6, note that the process capability ratios appeared to remain unchanged as the months passed. This is in contrast to the findings noted above in comparing Table 3.3 with Table 3.4.

3.3. Bivariate Relationships Between Shock Tower Location Data and Camber

From a design standpoint, it is assumed that moving the location of the shock tower should directly affect camber, everything else remaining constant. Moving only the shock tower outboard should correspond to a change in the camber angle in the positive direction. Without the ability to control other factors affecting camber, one might expect to see, in general, a positive relationship between shock tower location and camber in the on-line data. To examine the relationship, simple correlation coefficients were computed for all models. These estimates are contained in Table 3.7(a) for the first study and Table 3.7(b) for the second study.

Model	Side	Standard Deviation	Process Capability Ratio	95% Confidence Interval
A	Left	10.378	0.64	(0.51, 0.75)
	Right	9.148	0.73	(0.57, 0.85)
B	Left	10.838	0.62	(0.46, 0.78)
	Right	9.912	0.67	(0.50, 0.85)
C	Left	7.447	0.90	(0.66, 1.13)
	Right	10.070	0.66	(0.49, 0.84)
D	Left	8.201	0.81	(0.59, 1.04)
	Right	6.031	1.11	(0.80, 1.42)

Table 3.5. Process Capability Ratio Estimates and 95% Confidence Intervals for the Process Capability Ratio from Final Camber Readings, First Study, June 1987.

Model	Side	Standard Deviation	Process Capability Ratio	95% Confidence Interval
A	Left	8.864	0.77	(0.57, 0.97)
	Right	8.328	0.80	(0.60, 1.00)
B and C	Left	12.662	-	-
	Right	8.088	-	-
D	Left	9.538	0.70	(0.58, 0.86)
	Right	9.039	0.74	(0.61, 0.91)

* Includes models B and C with different upper and lower specification limits. Therefore, process capability ratios could not be computed.

Table 3.6. Process Capability Ratio Estimates and 95% Confidence Intervals for the Process Capability Ratio from Final Camber Readings, Second Study, January 1988.

The low correlation coefficients, lack of statistical significance, and the estimated negative relationships between shock tower location and camber lead us to conclude that the automated shock tower location measurements have little power when used <u>individually</u> to predict final camber readings. Only one relationship is statistically significant, the location of the left shock tower and the left camber reading for model D in the first study. However, this relationship is weak ($r = .41$) and examination of the scatter plot (not included here) shows that it is heavily affected by one point (a relative outlier). The negative relationships do not appear in the second study and this may be the result of the improved referencing algorithm used at the automated optical measuring station.

Model	Side	n	Correlation Coefficient
A	Left	54	.081
	Right	54	-.012
B	Left	29	-.166
	Right	29	-.168
C	Left	27	.252
	Right	28	.096
D	Left	24	.408*
	Right	25	-.093

* Significant at $\alpha = .05$.

(a)

Model	Side	n	Correlation Coefficient
A	Left	28	.134
	Right	29	.156
B and C**	Left	53	.018
	Right	52	.147
D	Left	47	.269
	Right	47	.074

** Includes measures for models B and C.

(b)

Table 3.7. Estimated Correlation Coefficients Between Shock Tower Location and Final Camber Measurements. Data from first study, June 1987, in Table 3.7(a), and data from second study, January 1988, in Table 3.7(b).

3.4. Predicting the Variability in Camber from the Variability in Shock Tower Location

Using the standard deviation estimates of shock location from the first study, we can begin to investigate the presence of other factors which significantly affect final camber readings. Using model A as an example, assume that the distribution of shock location location for the right side is distributed with a mean and variance given by the estimates in

Table 3.1. That is, assume that the distribution of shock tower location for the right side has a mean equal to 2.228 mm and a variance equal to $(.426)^2$. Assume that the mean of the distribution of final camber readings for the right side is equal to -30.56' as given in Table 3.3. A 1.0 mm movement of the shock tower outboard corresponds to a 6' increase in the camber angle using simple trigonometry from the design angles. Therefore, a one standard deviation movement of the shock tower outboard should correspond to a camber angle equal to -28' since

$$-30.56 + .426(6) = -28.004.$$

Likewise, a two standard deviation movement of the shock tower outboard should correspond to a camber angle equal to -25.448' since

$$-30.56 + 2(.426)(6) = -25.448.$$

Equivalently, this argument would predict that the standard deviation of the right final camber readings should be $(.426 \times 6) = 2.556$. From Table 3.3, however, the estimated standard deviation of final camber right is 9.148 giving a ratio of predicted variance to estimated variance equal to

$$\frac{(2.556)^2}{(9.148)^2} = .078.$$

Table 3.8 contains the estimated and predicted variances of the final camber readings using the above argument. For models A, B, and C, the ratio of the predicted to estimated variance is less than .27. Only for model D is the ratio close to 1.0.

Arguments which employ standard deviations are most informative when the underlying distributions are normal or approximately normal. The distribution of shock tower location and final camber readings do not appear to be normally distributed due to a lack of symmetry and "fatter than normal" tails. Kolmogorov-Smirnov goodness-of-fit tests were performed on shock tower and final camber readings for all models for both the left and the right side. All tests resulted in the rejection of the null hypothesis that the distributions were normal. Thus for the time being ruling out the normal distribution as a good approximation of these distributions, we can choose a worst case scenario in terms of controlling process variability and assume that the distribution of shock tower location is uniform with parameters equal to the minimum and maximum of the sample data (maximum likelihood estimates). Using these estimates and the 1 mm to 6' argument given above, we can obtain predictions of the range of the final camber readings. For example, the range of the automated shock tower location measurements for model A left side is 1.57, see Table 3.8. Thus we would predict that the range in final camber readings for model A left side to be 9.42 (6 multiplied by 1.57).

Model	Side	Camber Standard Deviation	Predicted Camber Standard Deviation	Predicted to Estimated Variance Ratio	Shock Tower Range	Camber Range	Predicted Camber Range
A	Left	10.378	2.862	.076	1.96	43	11.76
	Right	9.148	2.556	.078	1.57	41	9.42
B	Left	10.838	3.21	.088	2.68	39	16.08
	Right	9.912	3.456	.122	2.61	33	15.66
C	Left	7.447	3.852	.268	2.88	34	16.80
	Right	10.070	3.45	.177	2.52	36	15.12
D	Left	8.201	9.276	1.279	8.16	30	48.96
	Right	6.031	5.874	.949	4.08	29	24.48

Table 3.8. Estimated and Predicted Camber Standard Deviations and Ranges, and Ratio of Predicted to Estimated Camber Variance Using Data from the first study, June 1987.

Table 3.8 contains the estimated and predicted ranges of the final camber readings from the first study using the above argument. In models A, B, and C, the predicted ranges are less than one-half the values of the estimated range using the automated optical measures. Only for model D are the ranges close in value. Caution must be used in interpreting the results for model D. Recall that the data from the left side case of model D is greatly affected by the relative outlier mentioned above.

Possible explanations for the great differences between the estimated to predicted variances and between the estimated to predicted ranges are 1) the presence of other factors affecting camber which individually add variability to the final camber readings and the inability to control these factors in such an on-line study, 2) the presence of other factors affecting camber which interact with shock tower location to increase overall variability in the final camber readings and the inability to control these factors in such an on-line study, and 3) measurement error in automated shock tower location measurements and/or camber readings.

4. RELATIONSHIP BETWEEN SHOCK TOWER LOCATION, STRUT ANGLE, BALL JOINT LOCATION, AND FINAL CAMBER DATA:

Two On-line Studies

The inability to clearly establish a relationship between shock tower location and camber using on-line data (as described in Section 3) led to the development of two on-line studies each involving five automobiles. In these studies attempts were made to control additional factors in the assembly process. The first five car study was undertaken in June 1987 and the second in February 1988.

4.1. Study Procedure - First Five Car Study

Five model A vehicles from the June 1987 on-line study described in Section 3 were selected for further detailed investigation. For each of these five cars, automated optical shock tower location measurements was recorded. In addition, the axle face to strut deviations from nominal and the ball joint location deviations from nominal were also measured; both were measured before being installed on the vehicles.

The struts were pre-assembled using standard assembly procedures and the axle face to strut deviation from nominal was measured using standard measuring procedures (the measuring fixture located on the plant floor). Specifications require an axle face to strut vertical distance equal to 206.0 mm ± .3 mm for both the left and the right struts. Negative deviations reflect distances less than 206.0 mm and positive deviations reflect distances greater than 206.0 mm.

Ball joints were attached to control arms using standard assembly procedures. Ball joint location from line center was measured by referencing the control arms to a standard K-frame before assembly. The design nominal specification is for each ball joint to be located 678.0 mm from the center of the K-frame. Reported measurements are deviations from design nominal. Negative deviations reflect distances inboard relative to nominal (distances less than 678.0 mm) and positive deviations reflect distances outboard relative to nominal (distances greater than 678.0 mm). Ball joint measurements were taken off-line.

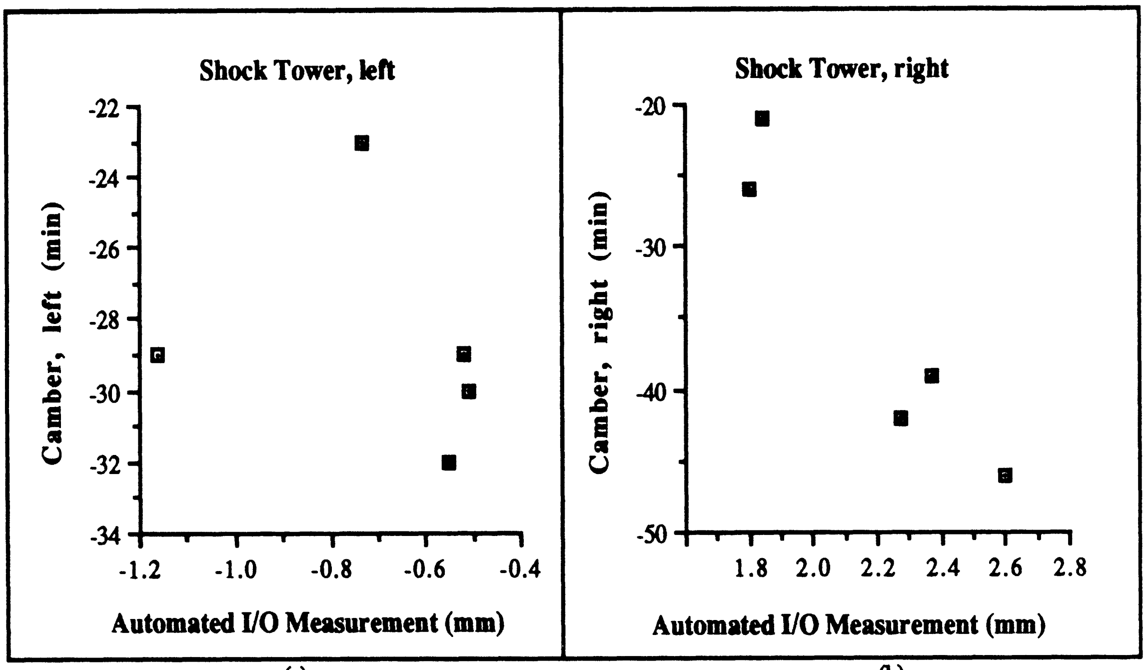
4.2. Relationships Between Front End Measurements and Camber - First Five Car Study

Data recorded for the five vehicles are presented in Table 4.1. Scatter plots were constructed to investigate the bivariate relationships between shock tower location and camber (Figure 4.1), strut deviation and camber (Figure 4.2), and ball joint deviation and camber (Figure 4.3).

Vehicle	Side	Camber	Shock Tower (mm)	Strut Deviation (mm)	Ball Joint Deviation (mm)
1	Left	-29'	-1.16	-0.53	-0.5
	Right	-46'	2.60	0.35	-0.7
2	Left	-23'	-0.73	-0.18	0.8
	Right	-42'	2.27	0.43	-0.7
3	Left	-30'	-0.51	-0.93	-0.2
	Right	-21'	1.84	1.22	-1.8
4	Left	-29'	-0.52	-1.01	0.7
	Right	-26'	1.80	1.31	-0.3
5	Left	-32'	-0.55	-1.98	-0.3
	Right	-39'	2.37	-0.12	-0.9

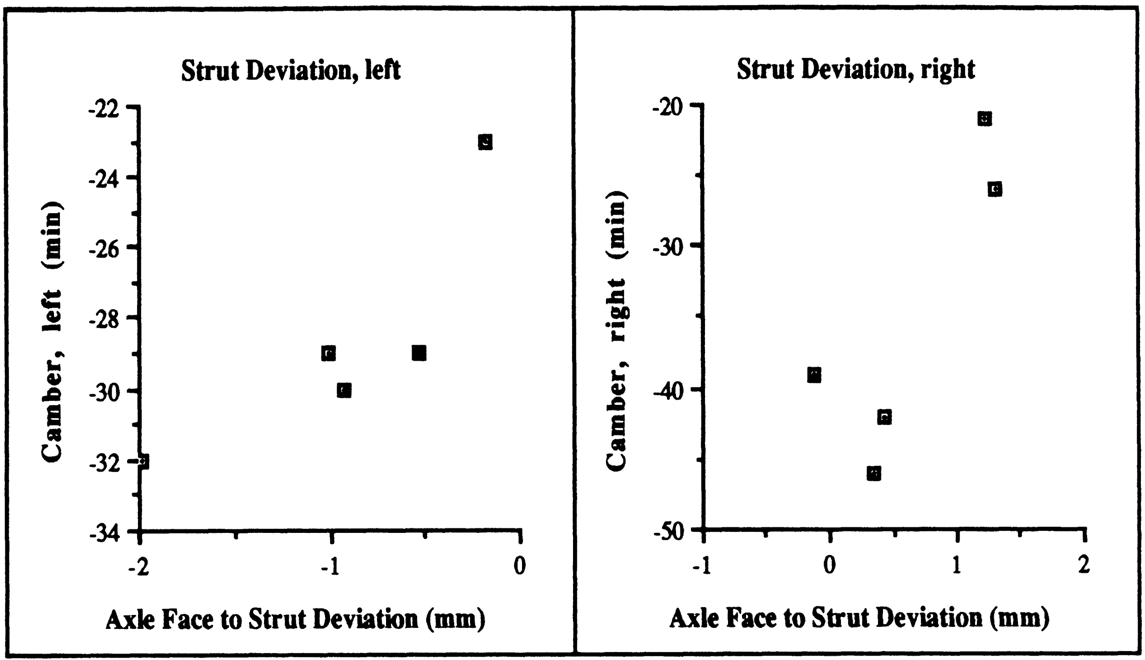
Table 4.1. Measurements in the First Five Car Study: Final Camber Readings, Automated Shock Tower Measurements, and Strut and Ball Joint Deviations.

Although five data points do not permit firm conclusions, we can observe the graphical representations to try and locate the possible existence of factors affecting front wheel camber. Note in Figure 4.1 the apparent negative relationship between shock tower location and camber. This relationship should be positive if all other contributing factors are held constant. Figure 4.2 presents what appears to be a positive relationship between strut location and camber, and this relationship is expected if all other factors are held constant. Also note from the X-axis in Figure 4.2 that the individual right strut deviations tended to be positive but the left strut deviations tended to be negative. The bivariate relationship between ball joint location and camber (all other factors held constant) should be negative but Figure 4.3 appears to show a negative relationship only for the right side. The inconsistency in the ball joint relationship may in part be due to the fact that the ball joint locations were not measured relative to the actual K-frames installed on the vehicles.



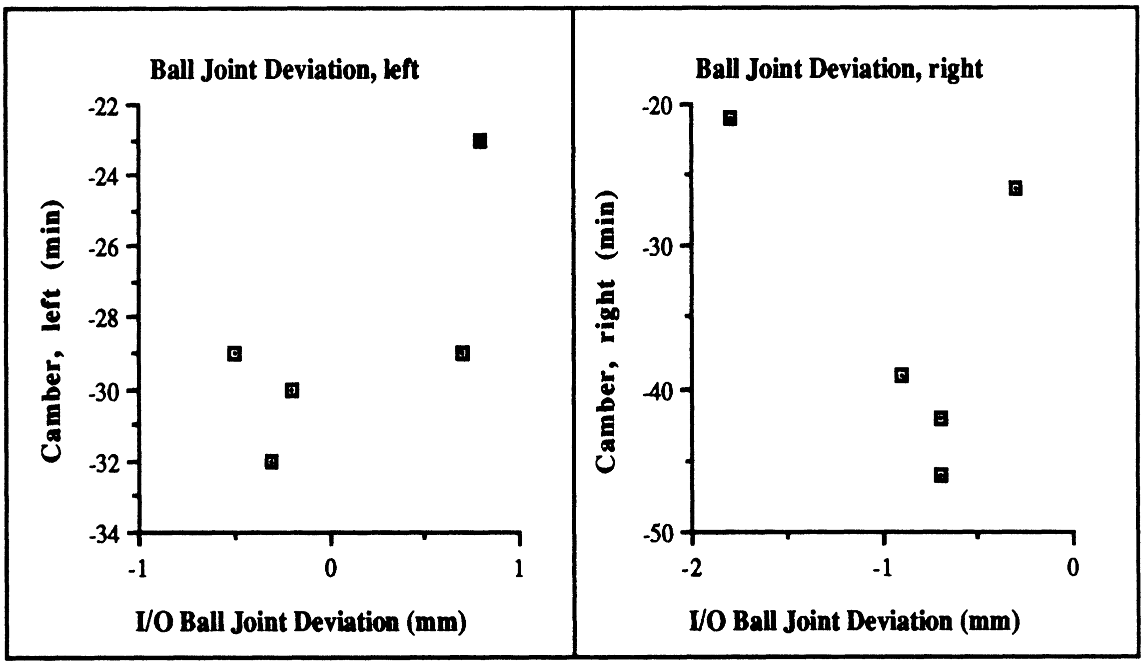
(a) (b)

Figure 4.1. Scatter Plots of Shock Tower Location Versus Final Camber Readings. Left Side in Figure 4.1(a), Right Side in Figure 4.1(b).



(a) (b)

Figure 4.2. Scatter Plots of Strut Deviation Versus Final Camber Readings. Left Side in Figure 4.2(a), Right Side in Figure 4.2(b).



(a) (b)

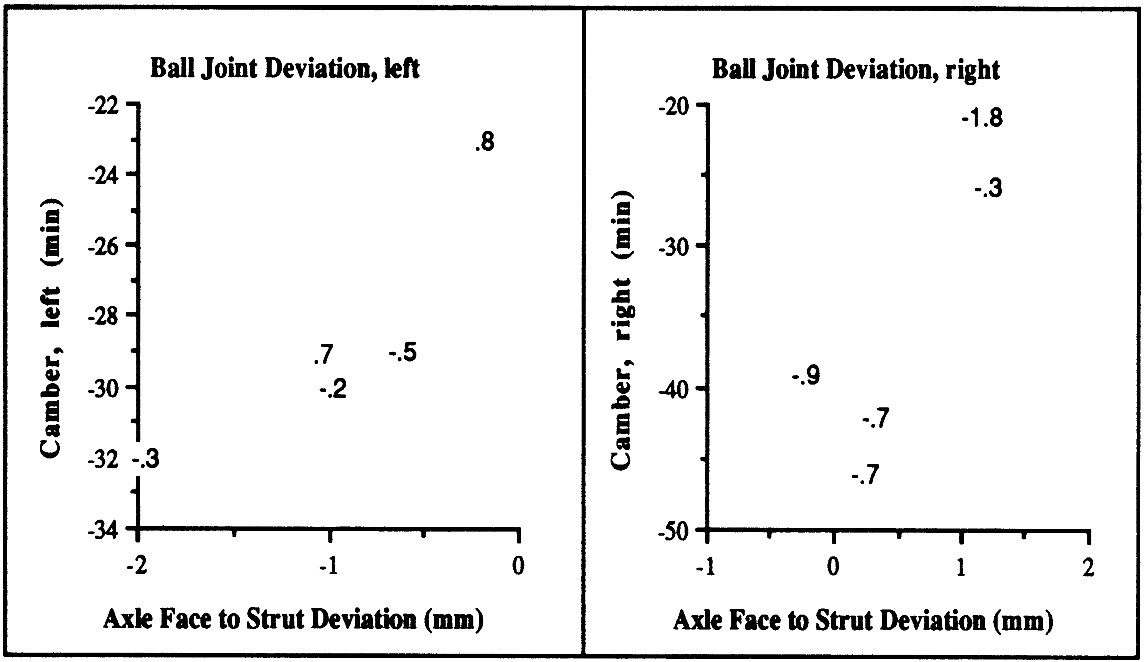
Figure 4.3. Scatter Plots of Ball Joint Deviation Versus Final Camber Readings. Left Side in Figure 4.3(a), Right Side in Figure 4.3(b).

With all other factors held constant, the bivariate relationship between strut deviation and camber should be positive, and the bivariate relationship between ball joint location and camber should be negative. The inverse sign of these relationships may cause a cancelling out of the individual effects when combined to affect camber or they may cause a combined positive or negative effect. For example, a large positive ball joint deviation combined with a large negative strut deviation would cause the camber angle to move in the negative direction. Similarly, a large negative ball joint deviation combined with a large positive strut deviation would cause the camber angle to move in the positive direction. Other strut and ball joint deviations would tend to cancel out the individual effects to a certain degree.

We can investigate if these combined effects appear in the camber readings for the 5 vehicles studied. Figure 4.4 contains the scatter plot of strut deviation and camber readings (as in Figure 4.2) but the scattered points are replaced by the ball joint deviation for the particular vehicle. For example, the scatter plot on the right in Figure 4.4 shows that one of the five vehicles had a right camber reading of -21', a right strut deviation equal to 1.22 mm, and a right ball joint deviation equal to -1.8 mm. From these graphs is appears that the combined effects may be present but not in all cases.

Table 4.2 presents these findings in tabular form. A minus (-) in the strut and ball joint columns of Table 4.2 signify that the measured deviations were negative, while a plus (+) in the strut and ball joint columns signify that the measured deviations were positive. The column labelled "Predicted Camber Effect" specifies the predicted result as described above. The right column of Table 4.2 contains the measured deviation in the camber readings relative to nominal (-30'). Six cases had predictions either in the positive or the negative direction. Note that in only 2 out of these 6 cases is the effect in the direction predicted.

As in Section 3, possible explanations for these inconsistent results are 1) the presence of other factors affecting camber which individually add variability to the final camber readings and the inability to control these factors in such an on-line study, 2) the presence of other factors affecting camber which interact with shock tower location to increase overall variability in the final camber readings and the inability to control these factors in such an on-line study, and 3) measurement error in the automated shock tower locations and/or camber measurements.



(a) (b)

Figure 4.4. Scatter Plots of Strut Deviation Versus Final Camber Readings, Left and Right Sides. Plotted Points are Ball Joint Deviation Measures. Left Side in Figure 4.4(a), Right Side in Figure 4.4(b).

Vehicle	Side	Strut Deviation	Ball Joint Deviation	Predicted Camber Effect	Measured Camber Deviation
1	Left	-	-	Cancel (unknown)	-1
	Right	+	-	+	-16
2	Left	-	+	-	7
	Right	+	-	+	-12
3	Left	-	-	Cancel (unknown)	0
	Right	+	-	+	9*
4	Left	-	+	-	1
	Right	+	-	+	4*
5	Left	-	-	Cancel (unknown)	-2
	Right	-	-	Cancel (unknown)	-9

* Measured deviation in the same direction as the predicted effect.

Table 4.2. Measured and Predicted Camber Deviations Using Inboard (-) and Outboard (+) Strut and Ball Joint Deviations.

4.3. Study Procedure - Second Five Car Study

In an attempt to investigate these possible explanations, a second on-line study was undertaken similar to the one described above. The goal of this second study was to build five vehicles whose shock tower locations, ball joint locations, and strut angles were preset to original design specifications before assembly. The study began on February 5, 1988, in the body shop where shock towers were welded to five white body front structures with their location set as close as possible to 0.0, i.e., original design nominal. Five sets of struts were assembled and measured off-line to achieve the specification equal to 206.0 mm. Five sets of ball joints were attached off-line to control arms, attached to a standard K-frame, and set on the control arms to achieve the design specification equal to 678.0 mm from the center of the K-frame. The five sets of ball joint and control arm assemblies were removed from the standard K-frame and attached to other K-frames online.

Vehicle	Model	Camber Specification	Automated Shock Tower Location (mm)		On-line Camber Measure		Off-line Camber Measure	
			Left	Right	Left	Right	Left	Right
1	C	-36' ± 20'	-.03	.90	-36'	-52'	-35'	-52'
2	A	-30' ± 20'	-.74	4.80	-27'	-32'	-30'	-38'
3	A	-30' ± 20'	-1.03	1.19	0'*	-55'*	-10'	-50'
4	C	-36' ± 20'	.63	.22	-25'	-65'*	-30'	-57'*
5	A	-30' ± 20'	-1.25	.59	-17'	-33'	-35'	-34'

*Outside of Design Specification.

Table 4.3. On-line Camber Measurements, Off-line Camber Measurements, and Automated Shock Tower Location Measurements for Five Vehicles in Second On-line Build Study, February 5, 1988.

Three of the five vehicles were type A models whose camber specifications are equal to -30' ± 20', and two were type C models whose camber specifications are equal to -36' ± 20'. Camber measurements were taken on-line after final assembly in the standard checkpoint area where all front wheel measurements are made on assembled vehicles. In addition, camber was also measured off-line using what is considered to be a more precise measuring device. (Section 5 contains an analysis of the differences between the off-line and on-line camber measurement devices.)

4.4. Results - Second Five Car Study

Table 4.3 contains the camber measurements for the five vehicles. The data in Table 4.3 clearly show that in two of the five vehicles, the camber measurements were far from target. Both of these vehicles were measured to be out of specification using the on-line measuring device while one was measured to be out of specification using the off-line device. Note also that both of these vehicles did not achieve the additional camber specification of a maximum permissible difference between the right and left wheels equal to 30'.

The automated shock tower measurements not only have great variability but appear to have little or no influence on camber. For example in vehicle #2, the right shock tower is measured to be over 4 millimeters outboard while the camber measurement is very close to the target value. This is very different from the automated shock tower and camber measurements for the right side of vehicle #5.

Vehicle #4 was removed from the line after assembly and place on a three-dimensional measuring table to try and explain the out of specification camber measurement. The position of the shock tower was measured to be .6 mm on the left side and .3 mm of the right side. These measurements coincide with the automated shock tower measurements. The position of the K-frame, however, was shifted to the right side of the car due to the deviation in the location of the K-frame attachment points of approximately 1.5 mm.

This study coincides with earlier findings. On-line studies fail in two major regards: 1) the inability to precisely control potentially relevant factors, and 2) the inability to measure the uncontrollable covariates such as the location of the K-frame attachment points. In addition, the possible existence of measurement error in the automated shock tower and camber readings add variability to the results and cloud the influence of the controllable factors. The next section contains a discussion of measurement error in the camber readings.

5. THE ON-LINE AND OFF-LINE CAMBER MEASUREMENT AUDIT

Validity and reliability are two crucial components of any measuring device. An audit policy had been established at the assembly plant to assess the validity and reliability of the final on-line camber measurements. On-line camber measurements were used in the studies contained in Sections 3 and 4. We concluded each of those sections by suggesting that the difficulty in explaining the results may be due to the possible existence of measurement error in the camber measurements. If on-line studies are undertaken, the measurement devices must be reliable and valid, thus measurement error must be at a "minimum." This is equivalent to specifying that the magnitude of the components of the error vector, ε, discussed in Section 2 must be as small as possible (in absolute value). This section contains an analyses of the audit data.

The analyses were performed using audit data collected at two different points in time. In comparing the results from each point in time, we can observe if the trends depicted in the data collected earlier continue to exist at the later time period. In addition, we can observe if any corrective measures taken as a result of the analyses of the earlier data contributed to more welcome results.

5.1. The On-Line/Off-Line Audit Procedure

All vehicles produced at the assembly plant pass through a final on-line wheel alignment inspection station. Among the measurements recorded on-line are right and left front wheel camber. The audit policy stipulates that five cars be selected at random each day and inspected off-line.

In practice modifications are sometimes made on this stipulated policy. Daily sample size are sometimes, but not often, less than five. For example, Table 5.1(a) contains the number of days when the sample sizes were less than five for the period covering March 13 through June 23, 1987. Table 5.1(b) contains the number of days when the sample sizes were less than five for the period covering November 25, 1987 through January 25, 1988. (The sample size variation is due, in part, to the fact that some of the included days were less than full production days.) The small variation in sample sizes should not dramatically affect the inferences which can be made from the analysis of the data.

Another modification involves the type of vehicles selected for each sample. Currently only model C vehicles are selected since the off-line wheel fixture is unable to attach to the tire rim of the other models produced. Measuring front wheel alignment off-line is believed to be more reliable and exact. Inspection time is considerably longer off-line than on-line but more measurements are recorded off-line.

Sample Size	Number of Days
2	2
3	6
4	8
5	43
Total:	59

(a)

Sample Size	Number of Days
2	1
3	1
4	9
5	13
Total:	24

(b)

Table 5.1. Sample Size Variation in Camber Measurement Audit. March 13 through June 23, 1987 in Table 4.1(a), and November 25, 1987, through January 25, 1988, in Table 4.1(b).

5.2. Comparative Analysis of On-line and Off-line Front Camber Measurements

During the period March 13 through June 23, 1987, 59 off-line samples were taken consisting of 269 type C vehicles. During the period November 25, 1987, through January 25, 1988, 24 off-line samples were taken consisting of 106 type C vehicles. Tables 5.2 and 5.3 contains front camber summary statistics for these vehicles, the earlier period in Table 5.2 and the later period in Table 5.3.

In Table 5.2, the mean, standard deviation and skewness estimates for the right side are very similar from both sources, on-line and off-line. The same claim cannot, however, be made about the left side. Note, for example, the discrepancy in the standard deviation and skewness estimates for the left side. The lack of sampling independence and the apparent skewness of the distributions do not permit us to perform conventional statistical tests on the equality of these estimates. Nevertheless, the disparity should be a cause for concern. The results in Table 5.2, however, show that the greatest disparity within the left and right sides is in the estimates of the means.

Side	Source	Camber Mean (minutes)	Standard Deviation	Skewness
Left	Off-line	-49.77	9.41	-.51
	On-line	-34.93	8.58	-.18
Right	Off-line	-33.44	9.94	-.37
	On-line	-34.71	9.74	-.38

Table 5.2. Camber Summary Statistics from 269 Type C Models included in the Camber Audit from March 13 through June 23, 1987.

Side	Source	Camber Mean (minutes)	Standard Deviation	Skewness
Left	Off-line	-35.07	8.76	-.08
	On-line	-27.06	9.02	-.01
Right	Off-line	-19.50	8.49	-.24
	On-line	-21.43	7.49	.17

Table 5.3. Camber Summary Statistics from 269 Type C Models included in the Camber Audit from November 25, 1987 through January 25, 1988.

The estimated correlation coefficients between off-line and on-line front camber measurements for both time periods are presented in Table 5.4. All of the estimated correlations are statistically significant with $\alpha < .01$, and thus it appears that the two measurement sources point in the same general direction. But the strength of the relationships are not strong. For example, a correlation equal to .70 signifies that 51% of the variability in the estimates is still "unexplained" by a linear model.

Correlations only provide a measure of the straight line relationship between the two measures. To assess the possibility of a consistent measurement bias, we need to formally test the hypotheses that off-line and on-line measurements are equal within the same vehicle for both left and right sides. To test these hypotheses, paired t-tests were calculated and the results are presented in Table 5.5. The estimated mean difference between on-line and off-line measurements within vehicles was calculated by defining a difference as the on-line measurement minus the off-line measurement for each vehicle. Mean differences were calculated for both the left and the right sides. Using the March 13 to June 23, 1987, data, the estimated difference within vehicles between on-line and off-line is 14.84' for the left side and -1.27' for the right side, see Table 5.5(a). On both left and right sides, we can reject the null hypothesis that the difference between the two measures within the same vehicles is equal to zero.

The results of hypothesis tests of this nature cannot be considered without the practical problem at hand. The design specifications for front wheel camber for the type C vehicle is -36' ± 20'. Thus, although we can reject the null hypothesis for the right side with an estimated difference equal to -1.27', this small difference is not as alarming as the estimated difference for the left side. The left side estimated difference of 14.84' is 74% of the specified tolerance, a large number by any measurement or design standard. Note in Table 5.5(b) that for the later time period, the estimated difference is equal to 8.01' for the left side. Thus the disparity had improved but an estimated difference of 8.01' is equal to to 40% of the specified tolerance. This is still a wide disparity by most measurement standards.

Side	Correlation Coefficient
Left	.70*
Right	.78*

*Significant at $\alpha < .01$.

(a)

Side	Correlation Coefficient
Left	.65*
Right	.68*

*Significant at $\alpha < .01$.

(b)

Table 5.4. Correlation Coefficients Between On-line and Off-line Camber Measurements for the Left and the Right Sides. March 13 through June 23, 1987 in Table 5.4(a), and November 25, 1987, through January 25, 1988, in Table 5.4(b).

Side	Mean Difference*	Paired t-value
Left	14.84	34.86**
Right	-1.27	-3.19**

** Significant at $\alpha < .01$.

(a)

Side	Mean Difference*	Paired t-value
Left	8.01	11.02**
Right	-1.93	-3.1**

** Significant at $\alpha < .01$.

(b)

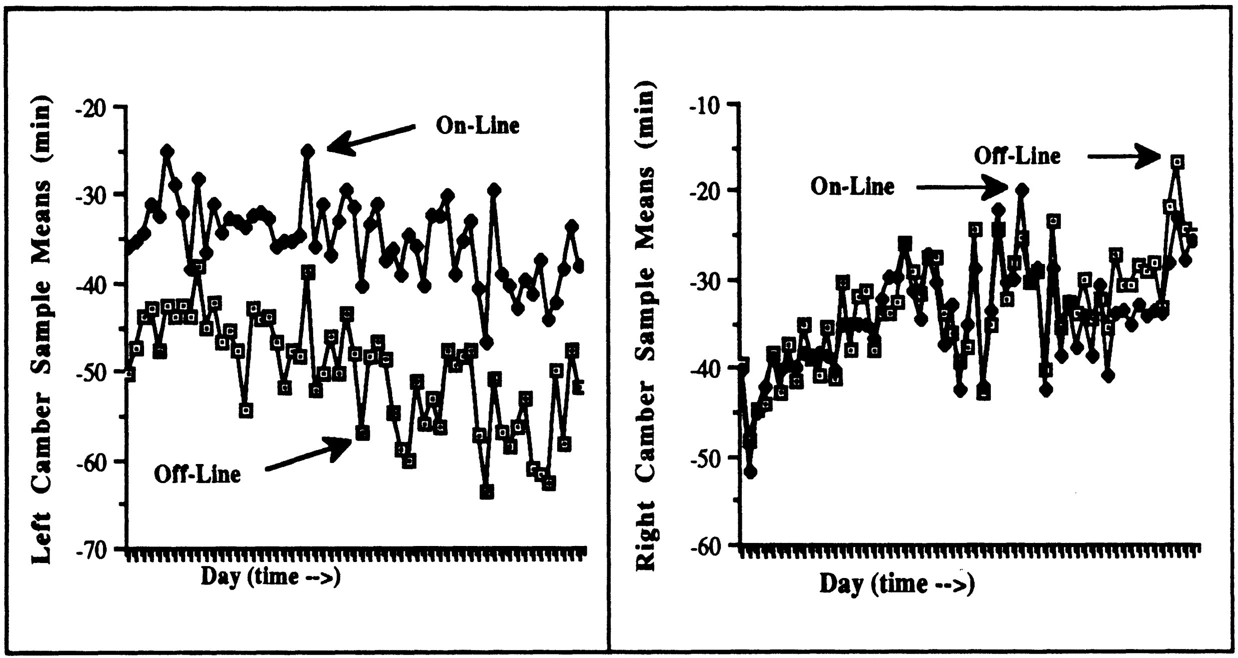
*Equal to $\left[\frac{\sum_{i=1}^{n}(P_i - E_i)}{n}\right]$ where P_i = on-line measure on car i, and E_i = off-line measure on car i, for i = 1,2,...,n.

Table 5.5. Paired t-Tests Between On-line and Off-line Measurements. March 13 through June 23, 1987 in Table 5.5(a), and November 25, 1987, through January 25, 1988, in Table 5.5(b).

This grave inconsistency between off-line and on-line measurements is depicted graphically in Figures 5.1 and 5.2 for the early and later periods respectively. Figure 5.1(a) contains the daily plot of each of the 59 sample means for the left side. In nearly every sample the off-line camber mean was less than the on-line camber mean. Figure 5.1(b) contains the daily plot of the 59 sample means for the right side. It is easy to see from these graphs the consistent positive bias which exists in the on-line left measurements relative to the off-line left measurement, and the more consistent results for the right side. Likewise, Figure 5.2(a) contains the daily plot of each of the 24 sample means for the left side and Figure 5.2(b) contains the daily plot of the 24 sample means for the right side. It is easy to see from these graphs the consistent positive bias which exists in the on-line left measurements relative to the off-line left measurement, and the more consistent results for the right side for both periods of time.

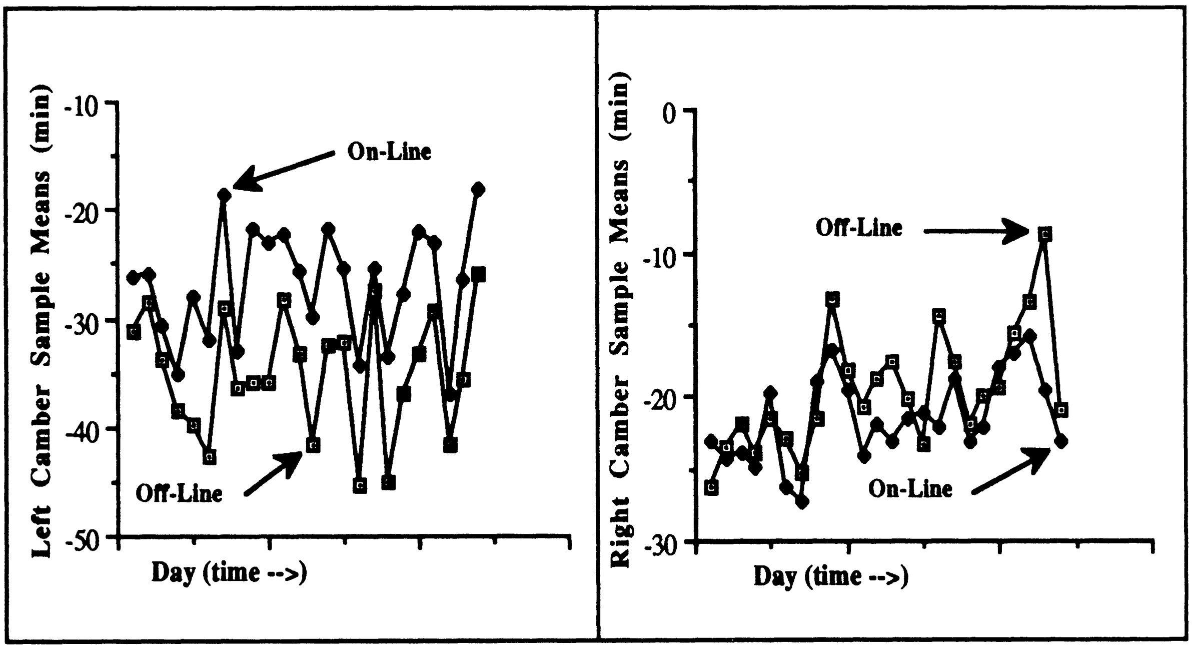
Figures 5.1 and 5.2 not only provide valuable information on the relative differences between on-line and off-line, but they also clearly depict time trends which exist in the camber data. Figure 5.1(a) shows a clear negative trend through time while Figure 5.1(b) shows a trend which is in the positive direction. The magnitude of these apparent linear trends can be statistically assessed by calculating the regression coefficient between the camber sample means and a time trend variable which will be defined as the sample number. For example, the independent variable is 1 for the first sample from March 23, 2 for the next day's sample, and so on with 59 being the independent variable for the last sample.

Using both the off-line and on-line data, these regression coefficients were estimated and are presented in Table 5.6 for the earlier period and in Table 5.7 for the later period. Note that in Table 5.6, all regression coefficients are statistically significant with $\alpha < .001$. The off-line data depicted a more dramatic trend for both the left and right side. The R^2 values for the off-line measures are quite high given the model only contains one independent variable (time). In Table 5.7 we see that the positive trend on the right side continued while on the left side the negative trend disappeared.



(a) (b)

Figure 5.1. Time Series Plots of 59 Camber Audit Means from March 13 through June 23, 1987. Left Side in Figure 5.1(a), Right Side in Figure 51(b).



(a) (b)

Figure 5.2. Time Series Plots of 59 Camber Audit Means from November 25, 1987 through January 25, 1988. Left Side in Figure 5.2(a), Right Side in Figure 5.2(b).

Side	Source	Regression Coefficient	R^2	F-Statistic
Left	Off-line	-.241	.46	47.75*
	On-line	-.139	.29	23.66*
Right	Off-line	.244	.43	43.43*
	On-line	.172	.25	18.71*

*Significant at $\alpha < .001$.

Table 5.6. Regression Analysis of Camber Measurements with a Linear Time Trend as the Independent Variable and the Camber Means as the Dependent Variable. March 13 through June 23, 1987.

Side	Source	Regression Coefficient	R^2	F-Statistic
Left	Off-line	-.004	<.001	<.001
	On-line	-.095	.016	.37
Right	Off-line	.369	.38	13.65*
	On-line	.205	.23	6.70**

*Significant at $\alpha < .01$.

**Significant at $\alpha < .05$.

Table 5.7. Regression Analysis of Camber Measurements with a Linear Time Trend as the Independent Variable and the Camber Means as the Dependent Variable. November 25, 1987 through January 25, 1988.

It should be clear from the preceding analysis that performing on-line studies to estimate a function such as the one given in equation (2) is hampered by the magnitude of the components of the error vector ε as a result of measurement bias and error. Any analysis based on biased measurements can only lead to biased results and, therefore, the inability to clearly identify the magnitude of the factors which affect front end alignment.

6. VARIATION IN STRUT ASSEMBLY

It is believed that the axle face to strut deviation has a direct effect on front end alignment. If it is also believed that on-line studies such as the one conducted in Section 3 are deficient due to the inability to control other important factors affecting camber (i.e., values in the **Z** matrix described in Section 2), then identification of the additioinal variability needs to be done. This section contains a discussion of the process variation present in the strut assembly.

6.1. Data Collection

Struts are assembled on one of two fixtures: the "gold" fixture and the "gray" fixture. At each fixture both left and right side struts are assembled. The gold fixture where left side struts are assembled is designated as Fixture #1, the gold fixture where right side struts are assembled is Fixture #2, the gray fixture where left side struts are assembled is Fixture #3, and the gray fixture where right side struts are assembled is Fixture #4. On each production day, five assembled struts are selected from each of the two fixtures for both the left and right sides. The assembled struts are taken off-line to a measuring fixture (located a few feet from the assembly fixtures) and the axle face to strut deviation from nominal (206.0 mm) is measured and recorded. From these samples, X-bar and R charts are constructed to monitor the process. The analysis presented here is not a discussion of these charts, but rather a simple statistical analysis which more clearly demonstrates the variability between and within the gold and gray fixtures.

Between March 31 and May 26, 1987, 25 samples of size 5 were taken from each of the two fixtures for both the left and right assembled struts. Between November 12, 1987, and January 20, 1988, 25 samples of size 5 were also taken from each of the two fixtures for both the left and right assembled struts. Measurement data were available on each of the 125 assembled struts for each fixture and side recorded between March 31 and May 26, 1987. Thus the analysis can be based on all of these individual measurements. The data available from the later period, November 12, 1987, through January 20, 1988, were the summary statistics (mean and range) from the 25 samples from each fixture and side. Therefore the analysis for this data is based only on these summary measures.

It should be pointed out here that we would expect to see improvements in the process mean and variance in the data from November through January 1988 when compared to the earlier data. During the August 1987 shutdown, the strut assembly fixtures were partially redesigned with the hope of reducing assembly variability.

6.2. Comparison of Assembly Fixtures

Summary statistics for all assembled struts recorded between March 31 and May 26, 1987, are contained in Table 6.1. The difference in the variability in the left and the right sides is reflected in the standard deviation estimates. The variability for the right side is greater than for the left side. Note also the differences in the estimates of the mean deviation between the left and right sides for the same fixture and between fixtures for the same side.

Estimates of the process variability can be obtained directly from the R charts without computing the standard deviation based on the individual struts, as done in Table 6.1. However, estimates of the process variability from on the R charts are based on the assumption that the underlying distribution is normal. Skewness estimates in Table 6.1 and histograms (not included here) demonstrate that the sample distribution for the right side struts is negatively skewed to a considerable degree. Thus all estimates of the process variance based on the average range would tend to underestimate the true process variance.

Tables 6.2 and 6.3 contain computed t-test values to test if the sample means from both sets of data are significantly different from zero. The value zero is equivalent to design nominal (206.0 mm). Note that we can reject the null hypothesis that the sample means are equal to zero in all cases for the March 31 to May 26, 1987, data. For the data from the later period, the situation for the gray left fixture improved dramatically with the process being centered very close to zero.

Fixture	Fixture #	Side	n	$\bar{X}$ (mm)	Standard Deviation	Skewness
Gold	1	Left	125	-0.931	.678	0.198
	2	Right	125	1.122	.938	-1.174
Gray	3	Left	125	-0.574	.631	-0.111
	4	Right	125	0.614	.801	-0.825

Table 6.1. Summary Statistics Using All Strut Assembly Observations. March 31 through May 26, 1987.

Fixture	Fixture #	Side	$\bar{X}$ (mm)	T-Value	p-value (2 tail)
Gold	1	Left	-0.931	-11.31	<.001
	2	Right	1.122	11.35	<.001
Gray	3	Left	-0.574	-8.58	<.001
	4	Right	0.614	6.60	<.001

Table 6.2. T-Test Values to Test of the Sample Means are Significantly Different Form Zero. March 31 through May 26, 1987.

Fixture	Fixture #	Side	$\bar{X}$ (mm)	T-Value	p-value (2 tail)
Gold	1	Left	.300	2.62	.015
	2	Right	1.328	11.69	<.001
Gray	3	Left	.016	.12	.906
	4	Right	.988	16.147	<.001

Table 6.3. T-Test Values to Test of the Sample Means are Significantly Different Form Zero. November 12, 1987 to January 20, 1988.

The differences in these means is also shown in Table 6.4 which contains the results of large sample t-tests. The results in Table 6.4 signify that all of combinations presented in the table have significant mean differences. Thus there are statistically significant differences in the mean and the variance between fixtures for the same side and within for different fixture sides.

Mean Difference Variables	Dependent Variable	Large Sample t-value	p-value (2 tail)
Left vs. Right	Gold Fixture	-19.88	<.0001
Left vs. Right	Gray Fixture	-13.02	<.0001
Gold vs. Gray	Left Side	-4.31	<.001
Gold vs. Gray	Right Side	4.64	<.001

Table 6.4. Large Sample Difference of Means Tests for Both Strut Fixtures and Both Sides. March 31 through May 26, 1987.

Fixture Pairs	Paired T-Value	p-value (2 tail)
#1 vs. #2	6.98	<.001
#1 vs. #3	-1.88	.073
#1 vs. #4	5.43	<.001
#2 vs. #3	-6.59	<.001
#2 vs. #4	-3.03	.006
#3 vs. #4	5.95	<.001

Table 6.5. Paired T-Tests for All Pairs of Fixtures to Test if the Difference in Sample Pairs of Means is Significantly Different From Zero. November 12, 1987 to January 20, 1988.

Table 6.5 contains paired t-test values for all pair combinations to test if the sample pairs are significantly different from zero. Paired t-tests are an important statistical tool to use on this data because it is a measure of the variability that exists between fixtures for the same side and within fixtures for different sides for the same production day. Considerable differences existing within the same production day would mean that large process variability is inherently built into the process, an much unwanted situation.

The paired t-tests demonstrate that the only pairing which did not have significant differences is #1 and #3, the gold fixture building left side struts and the gray fixture building left side struts. Therefore, the significant differences existing in the other pairs clearly demonstrates a lack of control in the assembly process to build struts which are similar and close to the design nominal specification.

Therefore, on-line studies such as the one conducted in Section 3, must take into account the variability present in the strut assembly. In particular, knowledge of where (which fixture) the vehicle's struts were assembled could have reduced the uncertainty which resulted in these on-line studies.

7. OFF-LINE EXPERIMENTS

Off-line experiments are wide used in industry today to design quality into a new product and improve the quality of an existing product. Identification of factors affecting front wheel camber is a quality problem which can and should be researched off-line as well as on-line. This section discusses two experiments performed off-line.

7.1. Experiment #1

An experiment was performed off-line to investigate the relationships between three factors and camber: 1) shock tower inboard/outboard location, 2) strut to axle face angle, and 3) ball joint inboard/outboard location. On one side of a front structure, the engineers attached a K-frame (with a control arm and ball joint attached) and a strut assembly. The location of each of the three factors was changed during the experiment and the resulting camber angles were measured.

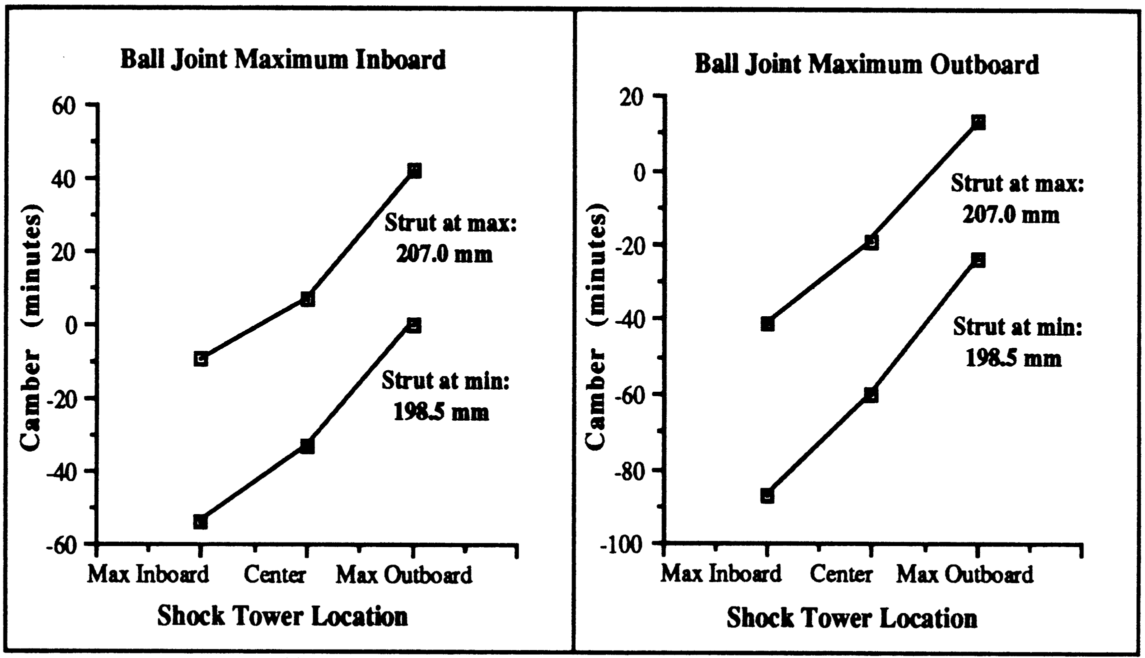
Shock tower location was set at one of three settings: maximum inboard, line center, and maximum outboard. Line center corresponded to an inboard/outboard location which meets the design specification. The exact location of the shock tower at maximum inboard and maximum outboard was not recorded but in personal conversation with one of the engineers performing the experiment, we were told that these settings corresponded to the following approximate locations. Maximum inboard corresponded to an approximate location of -2.5 mm, where the minus sign specifies that the location was inboard relative to the design nominal location. Maximum outboard corresponded to an approximate location of +2.5 mm, where the plus sign specifies that the location was outboard relative to the design nominal location.

The strut to axle face angle was set at one of two locations: a minimum corresponding to a linear distance of 198.5 mm and a maximum corresponding to a linear distance of 207.0 mm. The ball joint location was also set at one of two locations: maximum inboard and maximum outboard. The exact location of the ball joint at maximum inboard and maximum outboard was not recorded, but again we were informed that these locations corresponded to approximately -1.5 mm and +1.5 mm respectively. A location of -1.5 mm specifies that the ball joint was located 1.5 mm inboard relative to the design nominal location, and a location of +1.5 mm specifies that the ball joint was located 1.5 mm outboard relative to the design nominal location.

Given these three factors and their locations, there were 12 possible combinations. All possible combinations were made and the camber angle was recorded at each combination. Thus a full factorial experiment was performed with one observation per combination. The results are shown graphically in Figure 7.1.

The results clearly show that all three factors have a pronounced effect on camber. Analysis of variance (not included here) concludes that all three factors provide statistically significant effects. Note the direction of the bivariate relationships are as expected on average: a positive relationship between strut location and camber, a positive relationship between shock tower location and camber, and a negative relationship between ball joint location and camber. The similar slopes of the lines within and between Figures 7.1(a) and 7.1(b) reflect the absence of interaction effects between these factors. Since the exact locations of the maximum inboard and maximum outboard locations of all three factors were unknown, estimates of the predicted change in camber given a specific inboard or outboard shift could not be made.

Although these results are important, they do not assist plant engineers in authorizing adjustments on the assembly line to achieve desired adjustments in the final camber angle measurements. For example, if an adjustment was needed in the fixture where the shock tower is welded to the front structure, this experiment does not provide the necessary information to determine the precise adjustment. Should the fixture be adjusted so the shock towers are located 0.5 mm outboard, 1.0 mm inboard? Everything else being equal, what would the effect be if such an adjustment was made? The results also do not answer these questions.



(a) (b)

Figure 7.1. Camber angle measurements from off-line experiment #1. Ball joint at maximum inboard in Figure 7.1(a) on the left, ball joint at maximum outboard in Figure 7.1(b) on the right.

In addition, close examination of Figure 7.1 does not provide a combination with the required camber angle: -30'. The possible reasons for this result are numerous: experimental error; not locating the strut to axle face distance at the nominal 206.0 mm; not locating the ball joint at the required nominal inboard/outboard distance; other uncontrollable factors such as the location of the K-frame attachment points, the location of the vehicle long members, and the height of the shock towers. These uncontrollable experimental factors are the result of the particular front structure used in the experiment. If another front structure was used, the results would have been different.

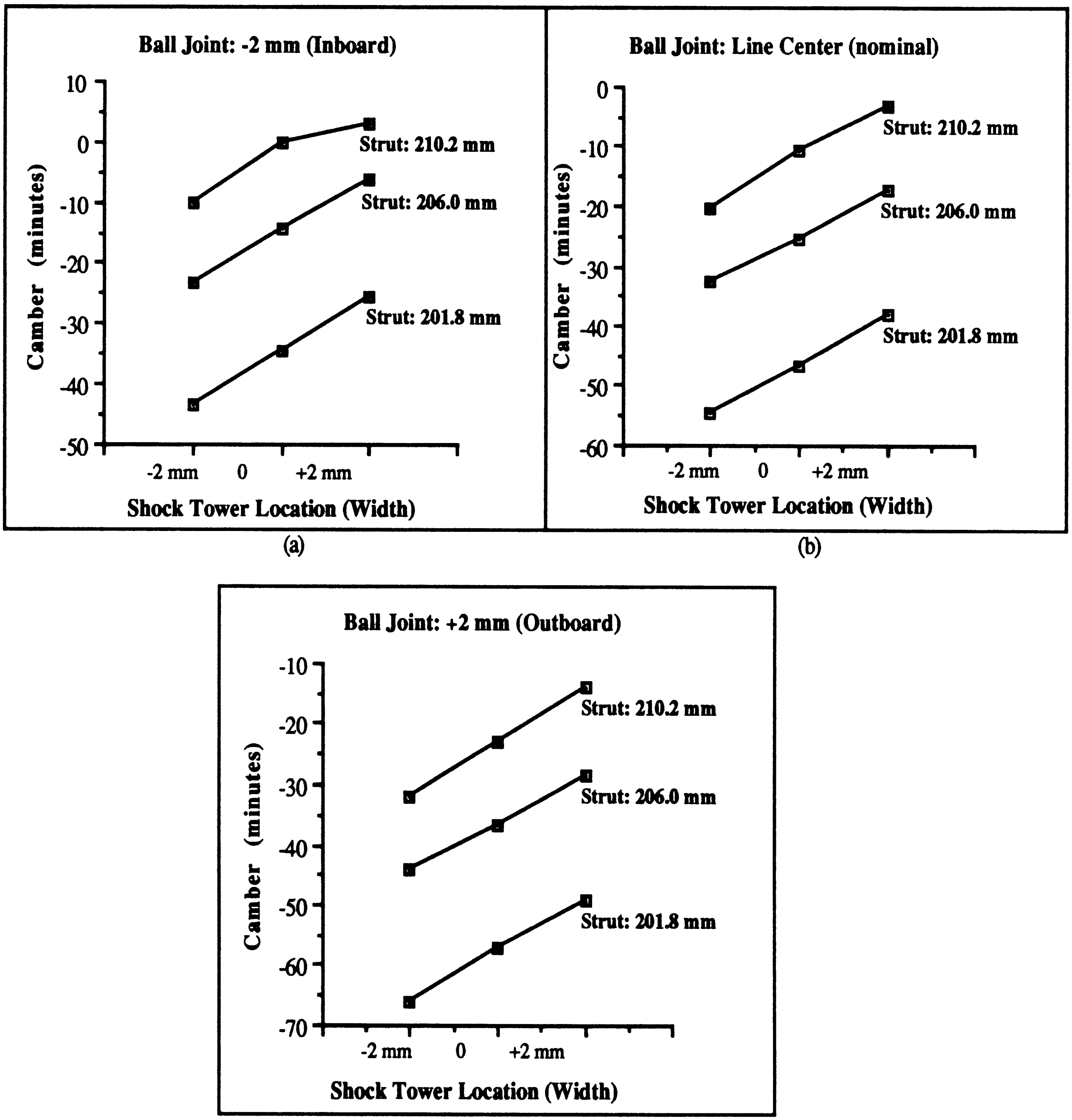
7.2. Experiment #2

Another experiment similar to the one described above was undertaken during the week of January 18, 1988. In this experiment, however, four factors were changed during the experiment to provide estimates of each of the four factor effects. These four factors were: 1) shock tower inboard/outboard location, 2) shock tower fore/aft location, 3) strut to axle face angle, and 4) ball joint inboard/outboard location. On the right side of a front structure, a K-frame (with a control arm and ball joint attached) and a strut assembly were attached. The location of each of the four factors was changed during the experiment and the resulting camber angles were measured. The exact location settings of each of the four factors were determined before the experiment.

Shock tower inboard/outboard location was set at one of three settings: inboard 2 mm, line center (design nominal), and outboard 2 mm. Shock tower fore/aft location was set at one of three settings: forward 2 mm, line center (design nominal), and rearward 2 mm. The strut to axle face angle was set at one of three locations: 201.8 mm, 206.0 mm (design nominal), and 210.2 mm The ball joint location was also set at one of three locations: inboard 2 mm, line center (design nominal), and outboard 2 mm.

All possible combinations of the factor settings sum to a total of 81 experimental runs. All experimental runs were performed and the results measured. Analysis of the results concluded that shock tower fore/aft location had no effect on camber. The effects of the other factors, however, can be easily seen in Figure 7.2. Each point in Figure 7.2 is the average camber angle measured over the three shock tower fore/aft locations.

As in the results of the experiment discussed in Section 7.1, note the direction of the bivariate relationships are as expected on average: a positive relationship between strut location and camber, a positive relationship between shock tower inboard/outboard location and camber, and a negative relationship between ball joint location and camber. The distances between the lines in each graph and the slopes may reflect the presence of interaction effects between these factors.



(a) (b)

(c)

Figure 7.2. Camber angle measurements from off-line experiment #2. Ball joint 2 mm inboard in Figure 7.2(a), ball joint located at line center (design nominal) in Figure 7.2(b), and ball joint 2 mm outboard in Figure 7.2(c).

Parameter	Estimated Value	T-Value	p-value
Constant	-26.787		
X_1 (Strut Deviation)	16.989	64.328	<.001
X_2 (Ball Joint Inboard/Outboard)	-10.889	41.231	<.001
X_3 (Shock Tower Inboard/Outboard)	8.178	30.965	<.001
$X_1 x X_2^2$	-2.563	5.907	<.001
	$R^2 = .989$		

Table 7.1. Least squares regression analysis of experimental data.

Table 7.1 contains the results of fitting a linear model to the data using least squares regression. The fitted equation is

$$Y = -26.787 + 16.989X_1 - 10.889X_2 + 8.178X_3 - 2.583(X_1 x X_2^2)$$

where

Y = camber angle (min),

X_1 = strut to axle face deviation (4.2 mm increments),

X_2 = ball joint inboard/outboard location (2 mm increments), and

X_3 = shock tower inboard/outboard location (2 mm increments).

The meaning of "4.2 mm increments" corresponds to the factor settings of the struts in the experiment. That is $X_1 = -1$ corresponds to a axle face to strut deviation equal to 201.8 mm, $X_1 = 0$ corresponds to a axle face to strut deviation equal to 206.0 mm (design nominal), and $X_1 = 1$ corresponds to a axle face to strut deviation equal to 210.2 mm. For ball joint location, $X_2 = -1$ corresponds to a ball joint location equal to 2 mm inboard, $X_2 = 0$ corresponds to a ball joint located at line center (design nominal), and $X_2 = 1$ corresponds to a ball joint location equal to 2 mm outboard. And for shock tower location, $X_3 = -1$ corresponds to a shock tower location equal to 2 mm inboard, $X_3 = 0$ corresponds to a shock tower located at line center (design nominal), and $X_3 = 1$ corresponds to a shock tower location equal to 2 mm outboard.

Therefore, the estimated effect of moving the shock tower 1.0 mm inboard or outboard is a 4.1 minute change in camber angle; inboard results in a camber change in the negative and outboard results in a camber change in the positive direction. The effect of ball joint and strut locations is complicated by the estimated interaction between strut location and the square of the ball joint variable. Interpretation is as follows.

If the ball joint inboard/outboard location was set at nominal, then decreasing the strut to axle face deviation to a location equal to 201.8 mm results in a 16.989 minute decrease in the camber angle (camber change in the negative direction), or 4.05 minute decrease per millimeter change in the strut deviation. If the ball joint inboard/outboard location was set at nominal, then increasing the strut to axle face deviation to a location equal to 210.2 mm results in a 16.989 minute increase in the camber angle (camber change in the positive direction), or 4.05 minute increase per millimeter change in the strut deviation. If the strut deviation was set at nominal, then moving the ball joint 1 mm inboard results in a 5.4 minute increase in the camber angle (camber change in the positive direction). If the strut deviation was set at nominal, then moving the ball joint 1 mm outboard results in a 5.4 minute decrease in the camber angle (camber change in the negative direction).

However, if the strut or ball joint is not located in the nominal positions, then the interaction term must be added into the predicted change in the camber angle. For example, if the ball joint was set 2 mm inboard, the strut deviation set at 210.2 mm, then the estimated change in camber is 3.5 minutes in the positive direction. But, if the strut deviation was set at 201.8 mm, then estimated change in camber is 8.7 minutes in the negative direction. The estimated ball joint effect of -10.889 in the fitted model is potentially made "worse" by the interaction term of -2.563.

7.3. Further Experimentation

As pointed out at the end of Section 7.1, uncontrollable factors still exists in experiments described in Sections 7.1 and 7.2. Perhaps the most important uncontrolled variable is the location of the K-frame attachment points, the location of the long members, and the height of the shock towers. These uncontrollable factors are the result of the particular front structure used in the experiment. If another front structure was used, the results would have been different. Not only is it hypothesized that these uncontrollable factors have an effect on the experiment, but we would like to know precisely the effect these uncontrollable variables have on the camber angle. Having such knowledge would assist in implementing a complete process control program for vehicle front-end alignment.

Currently no methodology has been developed to assist in designing off-line experiments which contain uncontrollable variables where estimates of the uncontrollable variables are needed. Developing such a methodology is the current research undertaken by the authors of this paper. The proposed methodology would lead to the design of efficient fractional factorial experiments which could provide estimates of the controllable variables as well as the uncontrollable variables.

8. CONCLUSION AND RECOMMENDATIONS

This report has demonstrated that commonly used analyses in both on-line and off-line studies can lead to biased results and inconclusive findings if adequate precautions are not taken in controlling and/or observing relevant factor variables. Section 2 contained a theoretical discussion of this problem in general, and Sections 3 through 7 contained results from a case study in front end alignment. In all studies, variables we described as belonging to the matrix **Z** (in Section 2) were disregarded or components of the vector ε (see Section 2) contained quantities other than pure measurement error.

How can these limitations be overcome? We see two ingredients which must be present to any solution: "good" experimental design, and managerial understanding of the problem complexity. Each of these are discussed briefly below.

Experimental Design - Every quality engineer undertaking on-line as well as off-line studies needs to understand that identification of all assembly problem areas can be modeled by the theoretical models contained in Section 2. Therefore, analysis can only be as good as the generated data. If relevant factors are uncontrolled, on-line (snapshot) studies of selected ares of the assembly line can only cloud the importance of the all factors affecting product quality. Snapshots do not allow the quality engineer to piece together the entire puzzle which make up the entire problem.

Off-line studies cannot be undertaken without controlling or experimentally changing variables related to the outcome variable. Methodologies need to be developed (our current research) to optimally deal with uncontrollable covariates in experimental settings.

Managerial Understanding - Identifying assembly factors which affect front end alignment is but one example of a general problem which exists in many industries. It is a problem which encompasses the <u>entire</u> plant. It is not solely a problem of one department, such as the body shop, chassis, trim, or final assembly. For example, it is not similar to the typical problem of identifying the factors affecting uneven paint applications. This is a problem to be investigated only in the paint department. Front end alignment is a function of the body structure (body shop), steering components (chassis), and final measurement and adjustments (final assembly). Therefore it is a plantwide problem and can only be investigated with the cooperation of all the relevant departments. Plantwide cooperation is not always present due to the fear that one department may be discovered as the "problem area." This is, of course, an example of "managing by fear" which must be continually overcome.

In addition, managers must convey to the plant employees the value of on-line investigations. Many times on-line studies create inconveniences for the line workers, inconveniences that the area manager would rather due without. If on-line investigations were seen as positive undertakings, cooperation would be easy to achieve.

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