CASE 35

Clear Vision by Robust Design

Abstract: Clear vision is as the angle of the steering wheel while a vehicle is being driven in a straight line. Since the process of measuring CV introduces measurement variability and to ensure that the setting process is stable, the CV angle is audited on several vehicles at each shift and corrective action is taken if the CV average is outside SPC limits. A Ford gauge repeatability study indicated that gauge measurement error was approximately 100% of the tolerance of the CV specification. Due to the large measurement error, corrective actions were taken too often, not often enough, or incorrectly. This study used methods developed by Taguchi to reduce the gauge error by developing a process robust to noise factors that are present during the measurement process.

1. Introduction

Clear vision (CV) is the perceived angle of the steering wheel while a vehicle is being driven in a straight line (Figure 1). The perception of this angle is influenced strongly by the design of the steering wheel hub as well as by the design of the instrument panel. Clear vision for each vehicle is set in conjunction with the vehicle's alignment in the assembly plant at a near-zero setting determined by a customer acceptance study. Since the process of measuring CV introduces measurement variability to ensure that the setting process is stable, the CV angle is audited on several vehicles at each shift using the following audit process:

1. A CV audit tool is mounted to the steering wheel. The tool measures the inclination (i.e., rotation) angle of the wheel.
2. The vehicle is driven along a straight path while the CV tool collects and stores data.
3. At the completion of the drive, the CV tool algorithm calculates the average CV angle, and corrective action is taken if the CV average is outside SPC limits.

Currently, CV is audited by driving a vehicle along a straight path (Figure 2). The driver mounts a gauge on the steering wheel which measures the inclination (rotation) of the steering wheel and stores the data. When the drive is complete, the average CV reading for the drive is calculated using the gauge.

Quality Concerns

Historical gauge repeatability and reproducibility metrics indicated that gauge measurement error was approximately 100% of the tolerance of the CV specification. Due to the large measurement error in the facility, corrective actions were taken too often, not often enough, or incorrectly.

Measurement studies conducted in two different facilities indicated errors of 95 and 108%, respectively. These errors indicated that the facilities were not capable of accurate tracking of their own performance setting of clear vision. Most important, without the ability to track their own progress accurately, the facility was unable to respond properly to CV setting problems. Improving the robustness of the measurement system would reduce the variability of the audit measurements and allow the facilities to monitor and correct the setting process more accurately when required. This would lead to

 Taguchi's Quality Engineering Handbook. Genichi Taguchi, Subir Chowdhury and Yuin Wu

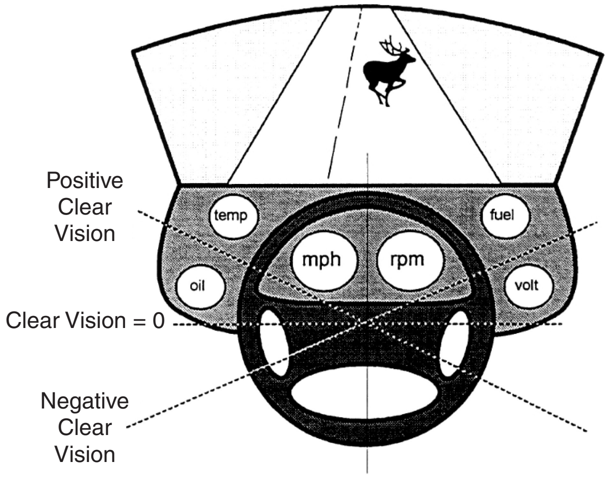

Figure 1
Clear vision: driver's view

improved customer satisfaction and reduce CV warranty cost.

2. Parameter Design

Ideal Function

The objective of this study was to reduce the measurement error of the CV tool from 100% of the clear vision tolerance. The ideal function (Figure 3) of the CV audit process is to produce an accurate and repeatable measurement of the actual steering wheel angle using the CV audit tool. The purpose of this tool is to indicate a CV angle response that reflects the actual clear vision angle condition.

The signal, actual clear vision angle, was set at two levels. The first signal, M_1, was the CV value of the vehicle as it was built at the assembly plant. M_2 was achieved by removing the steering wheel, rotating it clockwise approximately 15° from the original position, and reassembling it to the column.

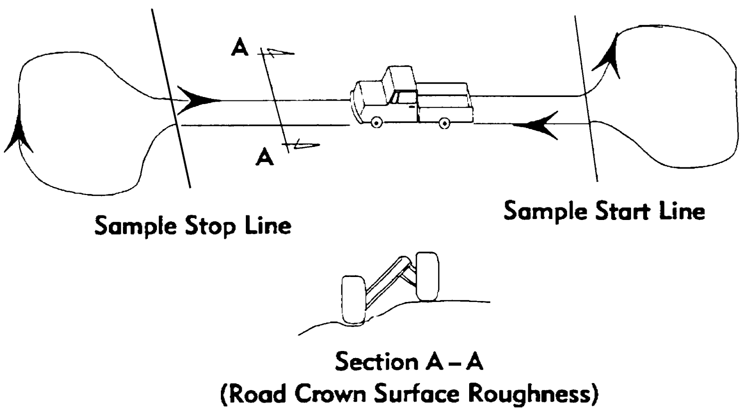

Figure 2
Testing diagram

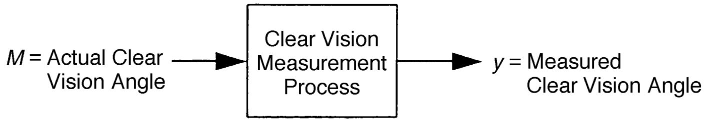

Figure 3
Ideal function

In traditional engineering, we do not typically change the signal to look at the linearity of the response to the changing signal level. Testing at different signal levels is a fundamental strategy of the robust design method, and testing at more than two signal levels is desirable. However, the spline (steering wheel attachment) was designed such that the allowable attachment rotation was in 15° increments. If the steering wheel was moved two notches in either direction, the total degree of movement would have been outside the limitations of the measurement tool.

The true value for the M_1 condition was not known, but the change in signal, M_2, was known. Also, the midpoint between positive and negative M was not zero. Therefore, reference-point proportional analysis was recommended as being most appropriate (Figure 4). (See the Appendix for the original data analysis process.)

Noise Strategy

As in every design, noise factors can induce a relatively large amount of variability and cannot be controlled easily. The noise strategy selected for this study included driver skill and driver weight. These factors were compounded as N_1 = skilled, lightweight driver and N_2 = unskilled, heavyweight driver.

Experimental Layout

The experimental layout was completed in two phases. The first phase was the execution of parameter design to determine the best combination of control factors to reduce the measurement system variability. An L_{18} orthogonal array (Figure 5) was used to define the control factor configuration for each of the 18 tests. The experiment was conducted at two signal levels, M_1 and M_2. The control factors

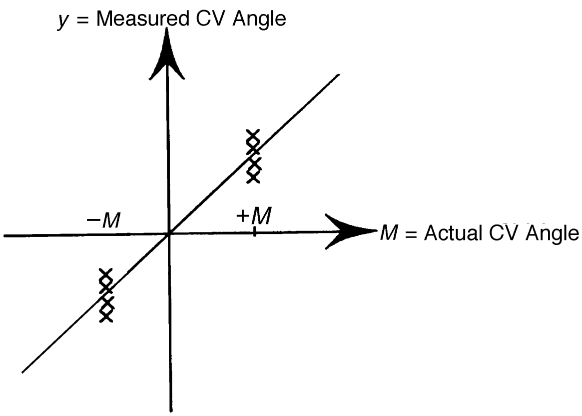

Figure 4
Measured CV angle versus actual CV angle: reference-point proportional

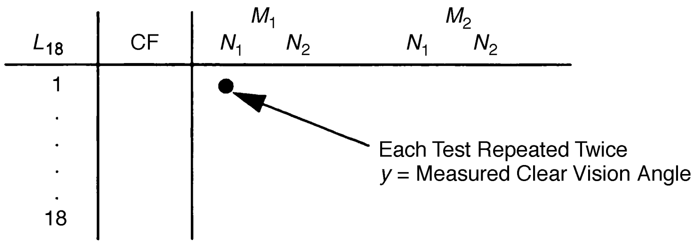

Figure 5
Experimental layout

were road service (A), navigational signs (B), route type (C), drive distance (D), drive speed (E), tool mounting (F), steering wheel tilt (G), and algorithm (H). Table 1 defines the control factor levels. Test results are shown in Table 2. Signal-to-noise (SN) and beta values were calculated for each configuration based on four responses. Response plots are shown in Figures 6 and 7.

The current process (baseline configuration) was $A_1B_1C_2D_3E_1F_2G_3H_1$. The optimum configuration selected was $A_1B_1C_1D_3E_2F_1G_3H_1$. The optimum combination has an SN ratio of −6.06 dB; the baseline method yielded a −16.42 dB ratio. The improvement predicted was 10.36 dB, which corresponds to a 70% reduction in variability. Time constraints did not allow a confirmation run at both signal levels. Instead, a gauge repeatability and reproducibility study which measures the standard deviation at one signal level was conducted using the optimum configuration. Results (Table 3) indicated that measurement error was reduced to 39% versus the predicted error of 30% (based on a 70% reduction in variability).

Sensitivity Analysis

The second phase of this experiment was a sensitivity analysis conducted by performing CV audit drives with configurations of vehicle factors and operators, as specified by an L_{16} orthogonal array. The sensitivity analysis was undertaken to determine how different vehicles and operator factors biased the actual CV setting. The percent contribution of each factor to the total system variability was calculated.

Completion of this analysis showed that the CV audit measurement was affected significantly by operator weight, caster split values, and steering system hysteresis. Since the audit driver cannot affect the caster split values or steering system hysteresis, it was decided to confirm only the effect of differences in operator weight. By eliminating differences in operator weights, the measurement system error was reduced further from 39% to 32%.

Table 1
Control factors and levels

	Factor							
Level	***A***	***B***	***C***	***D***	***E***	***F***	***G***	***H***
1	Smooth	Line	Loop	50 ft	10 mph	BHND WHL	Bottom	Current
2	Rough	Diam. sign	Modified	150 ft	20 mph	FRT WHL	Center	New 1
3	—	Goalpost	Modified	300 ft	30 mph	BHND WHL	Top	New 2

Table 2
Raw data, SN ratio, and beta values

	$M_1 = -1$				$M_2 = 1$					
	N_1	N_1	N_2	N_2	N_1	N_1	N_2	N_2	SN	β
1	−2.80	−5.90	−7.30	−5.10	10.70	9.20	11.10	9.40	15.38	17.27
2	−6.30	−4.10	−5.60	−5.50	9.90	10.40	10.10	11.40	15.83	22.87
3	−4.90	−5.80	−7.40	−6.20	12.20	9.80	9.10	9.10	16.13	19.04
4	−2.10	−6.40	−1.60	−3.80	11.10	9.90	10.90	17.80	15.90	11.44
5	−5.10	−5.80	−4.60	−3.40	8.80	10.60	11.10	12.20	15.40	18.93
6	−7.20	−7.40	−6.40	−7.20	8.80	9.10	9.00	8.60	15.93	30.13
7	−9.10	−9.50	−6.20	−11.60	13.00	4.60	12.10	17.80	20.98	10.95
8	−6.50	−6.70	−6.00	−5.80	8.00	8.80	9.40	9.50	15.18	25.48
9	−0.40	−1.00	−8.30	7.30	15.70	11.50	17.10	17.80	11.98	6.44
10	−5.90	−4.60	−5.10	−5.40	9.40	9.70	10.50	9.00	14.90	25.01
11	−6.10	−6.90	−5.70	−6.00	7.30	7.80	8.80	8.10	14.18	24.86
12	−5.30	−5.30	−6.20	−6.80	9.70	8.20	10.00	10.30	15.45	22.28
13	−5.50	−4.70	−3.70	−1.10	7.00	11.20	13.90	11.90	14.75	12.52
14	−6.50	−7.60	−5.60	−7.90	10.20	13.60	11.50	2.90	16.45	10.66
15	−4.30	−4.60	−3.40	−1.60	9.50	8.50	11.40	12.90	14.05	15.41
16	−5.30	−5.50	−5.70	−6.10	8.80	10.30	10.00	9.80	15.38	26.42
17	−7.30	−5.00	17.80	5.40	10.20	11.30	17.80	17.80	11.55	−0.80
18	−7.90	−6.50	−5.40	−5.40	8.50	8.50	9.00	10.00	15.30	20.89

Deviation of SN and β

$$\text{SN} = 10 \log_{10} \frac{(1/r)(S_\beta - V_e)}{V_N} = 10 \log_{10} \frac{\beta_2}{\sigma^2}$$

$$\beta = \sqrt{\frac{1}{r}(S_\beta - V_e)}$$

In the following equations, m is the number of signal levels, r_0 the number of repetitions at each noise level, and n the number of noise levels.

$$M'_i = M_i - M_{\text{ref}} \qquad i = 1, 2, 3, \ldots, m$$

$$y'_{ijk} = y_{ijk} - Y_{\text{ref}} \qquad i = 1, 2, 3, \ldots, m;$$

$$j = 1, 2, 3, \ldots, n; \quad k = 1, 2, 3, \ldots, r_0$$

$$Y_{ij} = \sum_{k=1}^{r_0} y'_{ijk} \qquad i = 1, 2, 3, \ldots, m;$$

$$j = 1, 2, 3, \ldots, n$$

$$L_j = \sum_{i=1}^{k} M_i'^2$$

$$r = nr_0 \sum_{i=1}^{k} M_i'^2$$

$$S_\beta = \frac{1}{r}\left(\sum_{j=1}^{n} L_j\right)^2 \qquad (f_\beta = 1)$$

$$S_N = \sum_{j=1}^{n} \frac{L_j^2}{r/n} - S_\beta \qquad (f_N = n - 1)$$

$$S_T = \sum_{k=1}^{r_0} \sum_{j=1}^{n} \sum_{i=1}^{m} (y'_{ijk})^2 \qquad (f_T = nkr_0)$$

$$S_e = S_T - S_N - S_\beta \qquad [f_e = n(kr_0 - 1)]$$

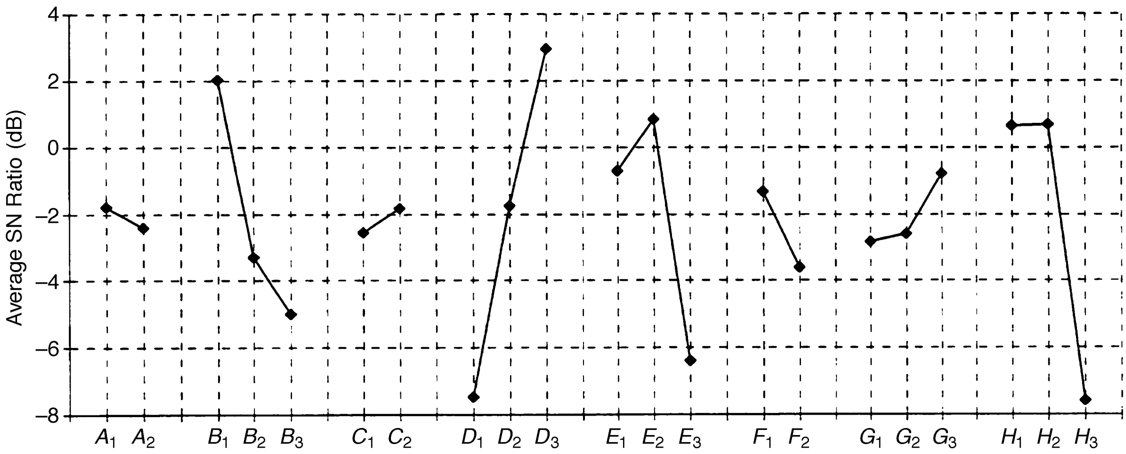

Figure 6
SN response plot

$$V_e = \frac{S_e}{f_e}$$

$$V'_N = \frac{S_e + S_N}{f_e + f_N}$$

Sample Calculations

We have $m = 2$, $n = 2$, $r_0 = 2$, and $M_{\text{ref}} = M_1$.

$$M_1 = M_1 - M_1 = 0$$

$$M_2 = M_2 - M_1 = 15$$

$$\begin{aligned} Y_{\text{ref}} &= \text{average response at } M_1 \\ &= \tfrac{1}{4}[(-28) + (-5.9) + (-73) + (-5.1)] \\ &= -5.275 \end{aligned}$$

$$Y_{11} = (-2.8 + 5.275) + (-5.9 + 5.275) = 1.85$$

$$Y_{12} = (10.70 + 5.275) + (9.20 + 5.275) = 30.75$$

$$Y_{21} = (-7.30 + 5.275) + (-5.10 + 5.275) = -18.5$$

$$Y_{22} = (11.10 + 5.275) + (9.40 + 5.275) = 31.05$$

$$L_1 = 0(1.85) + 15(30.45) = 456.75$$

$$L_2 = 0(-1.85) + 15(31.05) = 465.75$$

$$r = (2)(2)(0^2 + 15^2) = 900$$

$$S_\beta = \tfrac{1}{900}\,(456.75 + 465.75)^2 = 945.5625 \quad (f_{\beta=1})$$

$$\begin{aligned} S_N &= \frac{(456.75)^2}{(\frac{1}{2})(900)} + \frac{(465.75)^2}{(\frac{1}{2})(900)} - 945.5625 \\ &= 0.09 \qquad (f_N = 1) \end{aligned}$$

$$\begin{aligned} S_T &= (-2.8 + 5.275)^2 + (-5.9 + 5.275)^2 + \cdots \\ &\quad + (9.4 + 5.275)^2 = 958.87 \qquad (f_T = 8) \end{aligned}$$

$$\begin{aligned} S_e &= 958.87 - 0.09 - 945.5625 = 13.2175 \\ &\quad (f_e = 6) \end{aligned}$$

$$V_e = \frac{13.2175}{6} = 2.202916667$$

$$V_N = \frac{13.2175 + 0.09}{7} = 1.901071429$$

$$\begin{aligned} \beta &= \sqrt{\tfrac{1}{900}\,(945.5625 - 2.202916667)} \\ &= 1.023805311 \end{aligned}$$

$$\begin{aligned} \text{SN} &= 10 \log \frac{(1.023805311)^2}{1.901071429} = -2.585636787 \\ &= -2.59 \end{aligned}$$

Appendix

The original analysis sets the value for M_1 at -1 and M_2 at $+1$. See Figures 1 to 5 and Tables 1 and 2. Note C_2 and C_3 had similar levels and were grouped in analysis. The same is true for F_1 and F_3.

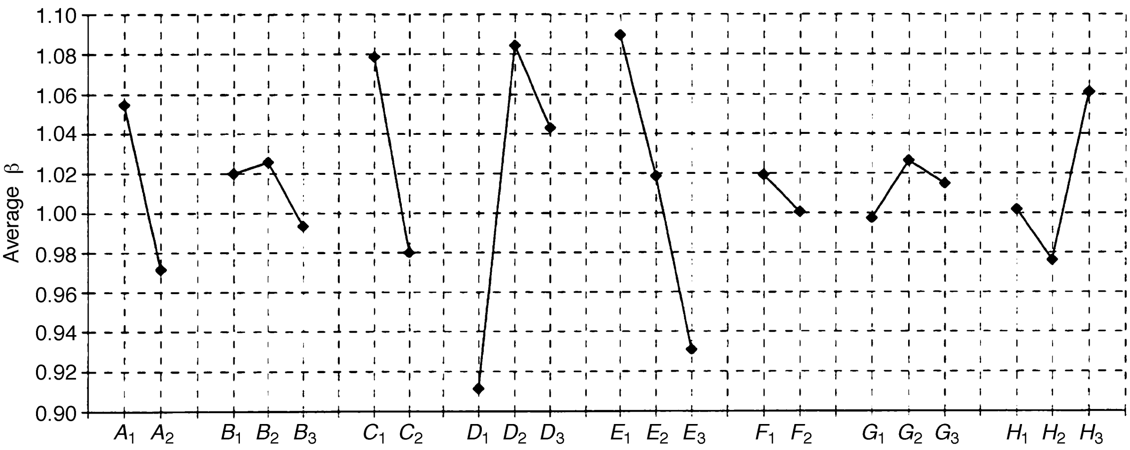

Figure 7
Beta response plot

The current process (baseline configuration) was $A_1B_1C_2D_3E_1F_2G_3H_1$. The optimum configuration selected was $A_1B_1C_1D_3E_2F_1G_3H_1$. Although the optimum configuration for level A is A_1 (smooth), A_2 (rough) is acceptable. Allowing a facility to use its current condition (either smooth or rough) will result in a cost savings.

The optimum combination has an SN ratio of 34.54 dB; the baseline method yielded a 24.19 dB ratio. The improvement predicted was 10.35 dB, which corresponds to a 70% reduction in variability. Time constraints did not allow a confirmation run at both signal levels. Instead, a gauge repeatability and reproducability study, which measures standard deviation at one signal level, was conducted using the optimum configuration. Results (Table A1) indicated that measurement error was reduced to 39%, versus the predicted error of 30% (based on a 70% reduction in variability).

Derivation of SN and β

$$\text{SN} = 10 \log_{10} \frac{\frac{1}{4}(S_\beta - V_e)}{V_N} = 10 \log_{10} \frac{\beta^2}{\sigma^2}$$

$$\beta = \sqrt{\frac{S_\beta}{2}}$$

$$S_\beta = \frac{Y_1^2}{4} + \frac{Y_2^2}{4} - \frac{7'^2}{8} \qquad V_N = \frac{S_N}{f_N}$$

$$Y_1 = \sum_{i=1}^{4} Y_i \qquad Y_2 = \sum_{i=5}^{8} Y_i$$

Table 3
Values predicted and confirmed

		Std. Dev. Relative to Spec. (%)	
	SN	**Predicted**	**Confirmed**
Baseline	−16.42	100	100
Optimum	−6.06	30	39
Gain	10.36	70	61

Table A1
Values predicted and confirmed (at one signal level only)

	Std. Dev. Relative to Spec. (%)		
	SN	Predicted	Confirmed
Baseline	24.19	100	100
Optimum	34.54	30	39
Gain	10.35	70	61

$$T_2 = (Y_1 + Y_2)^2$$

$$S_T = \sum_{i=1}^{8} Y_i^2 - \frac{T^2}{8} \qquad S_N = S_T - S_\beta$$

Sample Calculations

$Y_1 = (-2.8 - 5.9 - 7.3 - 5.1) = -21.1$

$Y_2 = (10.7 + 9.2 + 11.1 + 9.4) = 40.4$

$$T^2 = (-21.1 + 40.4)^2 = 372.49$$

$$S_T = [-2.8^2 + (-5.9^2) + (-7.3^2) + (-5.1^2) + 10.7^2 + 9.2^2 + 11.1^2 + 9.4^2] - \frac{372.49}{8} = 486.09$$

$$S_\beta = \frac{(-21.2)^2}{4} + \frac{40.4^2}{4} - \frac{372.49}{8} = 472.78$$

$$S_N = 486.09 - 472.78 = 13.31$$

$$V_N = \frac{13.31}{6} = 2.22$$

$$\text{S/N} = 10 \log_{10} \frac{\frac{1}{4}(472.78 - 2.45)}{2.22} = 17.24$$

$$\beta = \sqrt{\frac{472.78}{2}} = 15.38$$

This case study is contributed by Ellen Barnes, Eric W. Crowley, L. Dean Ho, Lori L. Pugh, and Brian C. Shepard.