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Analysis of In-cab Noise of Passenger Car Using Taguchi Method

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ABSTRACT

In-cab noise is an vital and useful factor in the passenger car analysis. The present work consists of three diverse passenger cars used for the transportation in Indian context. The parameters such as the car speed (CS), pay load (PL) and road profile (RP) are considered as independent parameters. The parameter linked with in-cab noise level is considered as the dependent parameter. The Taguchi method is intended to predict and analyze the in- cab noise level. The experiments are conducted based on three factors, three-level, and central composite face centered design with full replications technique, and mathematical model is developed. The conclusion is drawn from the results. The proposed method is an simple and efficient tool for modelling and analyzing the performance of any mechanical system. The optimization technique will be used to find out the best set of parameters for minimizing the In-cab noise effect. The project is focused on the optimization of the in-cab noise level for human comfort. Taguchi is used for analyze the performance.The parameter related with the noise level measure in DB and the vibration amplitude. The experiments are conducted based on four factors, three-level, and central composite face centered design with full replications technique, and mathematical model is developed. The results show that the Taguchi is an easy and effective tool for modelling and analyzing the performance of any mechanical system. The Taguchi will be used to predict and analyze the performance of passenger car for the human comfort against in-cab noise level.

Keywords—Car Speed, Noise, Payload, Taguchi, Vibration.

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I. INTRODUCTION

In recent years, there has been a desire by vehicle manufacturers to lessen the in-cab noise of vehicles, in order to look up driver comfort and boost the satisfaction of in-vehicle entertainment systems. This reduction of in-cab noise is accompanied by policy initiatives to trim down transport related noise by implementing low noise road surfaces. However, it is not known how such reductions in the ease of use of auditory cues affect drivers' ability to judge speed, and there is a danger that drivers will increase their speed, to balance for the absence of auditory cues. Internal combustion engines are generating the acoustic pulse by the Combustion process. This noise is controlled through the use of silencers and mufflers. A silencer has been the conventional name for noise attenuation devices, while a muffler is smaller, mass-produced device designed to reduce engine exhaust noise. Continuous development has been made in improving performance of the silencers used for automotive exhaust systems. In order to maintain a desired noise and comfortable ride, the modes of a muffler need to be analysed. Environmental noise induced by traffic is known to have a serious impact on our health, contributing to stress, annoyance and hearing loss. Indeed, according to a report by the World Health Organisation, between 1 and 2% of the total world disease burden is thought to be attributable to traffic noise, which can be a major cause of sleep deprivation, raised blood pressure and heart disease (WHO, 2000). It is not surprising then that substantial efforts have been made in recent years to condense traffic related noise through measures such as infrastructure improvement. Examples include investing in low height barriers and introducing low noise road surfaces. In parallel to such implementations, there have also been considerable advances in vehicle engine technologies, with "quietness" one of the major selling points of high end and luxury cars. This is chiefly because vehicle manufacturers are ready to increase driver comfort and pleasure, by creating vehicle cabs which convey little or no noise, thus allowing better utilize and enjoyment of in-car entertainment and communication systems.

The study reported here used a Taguchi by allowing drivers to make both absolute and relative judgments of their speed of travel, in a driving experiment. Drivers will first ask to drive the car at different speeds, with access to the speedometer and accompanied by normal in-car acoustics. They were then asked to judge their speed of travel in the absence of the speedometer and their accuracy in speed perception was compared with and without normal in-cab acoustics.

I. LITERATURE REVIEW

Kerr [1] has reported on the "accident proneness" of factory departments, or the tendency of certain factory departments to have more accidents than other departments. He has attempted to determine the factors that could be contributing to this increased accident incidence. Forty variables had been investigated, and only a few of these correlated significantly with accident rate. One significant factor has mean noise level, which has been found to correlate significantly with accident frequency, though not with accident severity. Kerr has unable to determine from the results of this study whether the noise level caused the higher number of accidents, or whether the more hazardous operations also tended to be the more noisy operations.

Foley, Wallace, and Eberhard [2] also have performed a well-designed study of risk factors for vehicle accidents among older drivers. This study has used drivers in rural Iowa, and part of a large-scale longitudinal health survey. Participants self-reported on the three hearing measures, which have included "wears a hearing aid" "cannot hear normal voice," and "has ringing in the ears." There has no increased risk for drivers self-reporting any of these hearing problems. The only increased risks were for drivers who were men, had back pain in the preceding twelve months, used non-steroidal anti-inflammatory drugs, or could recall less than three words on a delayed-recall memory test. The lack of significance for a relationship between hearing and driving could be attributed to the use of self-report, or to the fact that the question about the use of a hearing aid while driving was not asked.

Morrison and Clarke [3] have performed several different types of interior truck-cab noise measurements in order to specify the correction factors for converting standardized stationary measurements into real-world figures. Several makes and models of trucks have been tested. In all cases, the noise level measured at the left ear was about 1 dB higher than the noise at the right ear. For the over-the-road tests, the readings were about 85-88 dBA. They concluded that the over the road tests showed significantly lower readings than the stationary tests. The work was said to be incomplete, but Morrison and Clarke predicted that the correction factor would be in the range of 3-5 dB (to be subtracted from the stationary test results to obtain the over the road values). Although the years of the trucks tested in these two studies were not specified, they were probably late 1960's models, based on the dates of publication of the two reports (1970 and 1972).

Reif, Moore, and Steevensz [4] have tested the noise levels of 58 commercial vehicles during normal long-distance operations. Model years ranged from 1968-1978 with 42 of the trucks in the 1974-1978 model year range. A wide range of makes and models were represented, and the trucks and drivers were obtained from a variety of long-haul trucking companies. For freeway driving, the Leq averaged 88 dBA, for highway driving the Leq averaged 86 dBA, and for city driving the Leq averaged 84 dBA. In a follow-up analysis, Reif and Moore (1983) found that 40% of trucks were capable of exceeding the OSHA 90 dBA criterion level over a 10-hour shift, and 90% of trucks were capable of exceeding the 85 dBA action level. Worst case driving conditions were assumed (freeway driving, windows open, normal use of radio and CB radio, and 10-hour driving shift).

Hessel, Heck, and McJilton [5] have measured the noise levels in eight tractors under actual driving conditions. Model years ranged from 1973-1977, with three truck makes and two engine types represented. The measurements have been made with a sound level meter with an attached octave-filter set, and for the first time, the truck-cab noise was analysed by frequency, showing that the noise levels have been considerably higher in the lower frequencies (below 125 Hz). As discussed earlier, A-weighted measurements (dBA) tend to underrepresent the lower frequencies, and Hessel et al. presented both the dBA and dBC levels. The dBA measurements averaged 83.4 and the dBC values averaged 102.2. They noted that the higher dosimeter levels probably occurred because the dosimeter was turned on during the entire driving time, while the sound level meter was only turned on when the standardized driving conditions had been reached.

Morrison [6] has measured the noise levels of four new truck cabs under ideal driving conditions (clear weather, constant speed, windows closed, and accessories off). Five minute A-weighted Leq measurements were taken, and the results have showed that sound levels varied from 74.3 dBA to 78.8 dBA. Spectral analysis has also been performed, and showed that sound energy below 250 Hz was considerably greater than the higher frequency components. This was a substantial overall noise reduction compared to previous reports. The reduction may have been partly due to the idealized conditions, and to the fact that the trucks were new, but Morrison attributed most of the reduction as compared to 1970's era trucks to improved cab design, drive-train design, and passive noise control. The calculated OSHA noise dose was 0%, since all freeway measurements were below 80 dBA, and measurements below 80 dBA are not included in OSHA noise dose calculations. Dosimeters typically produce higher noise dose measurements than do sound level meters by about 2-3 dB, in addition to being more accurate (Royster, Berger, and Royster, 1986). Had a dosimeter been used for an entire work shift of driving these same vehicles, it is likely that the noise dose would have been greater than 0%.

Two constant speed measurements were taken under both the realistic and ideal (window up, radio off) conditions. Under ideal conditions, the noise level was 74.9 dBA, and for realistic conditions the level was 79.7 dBA. Micheal (1995a) also calculated a 0% OSHA noise dose for drivers of these trucks, even under the realistic conditions not tested in the Morrison (1993) study. He has concluded that drivers' hearing was not threatened by the level of noise produced in currently manufactured trucks. The fact that the trucks were new could have contributed to the quiet levels measured in these two studies, but the increase (if any) in noise as trucks get older has not been studied.The main factor for the low noise dose reported here may be that the noise was measured via real-time analyzer rather than with a dosimeter. A dosimeter measures the sound level over an entire work shift, and calculates the noise dose accordingly, but the dose reported was based on a five- minute measurement under constant speed conditions. Another difference between the readings reported in these studies and dosimetry is in the microphone placement (for Morrison and Michael, in the center of the cab, and for a dosimeter, on one shoulder of the driver, with the left shoulder probably providing a higher reading than the right shoulder). Therefore, the true noise dose for drivers of these vehicles under real-world conditions would probably be greater than 0%.

II. TAGUCHI METHOD

Taguchi Method is a statistical approach to optimize the process parameters The orthogonal array, signal-to-noise ratio, and the analysis of variance are employed to study the in cab noise. In this analysis, three factors namely speed; pay load and the road profile are considered. Accordingly, a suitable orthogonal array is selected and experiments are conducted. After conducting the experiments the in-cab sound level and the vibration level are measured and Signal to Noise ratio is calculated. With the help of graphs, optimum parameter values are obtained.

Taguchi method is a statistical method developed by Taguchi and Konishi. Initially it was developed for improving the quality of goods manufactured (manufacturing process development), later its application is expanded to many other fields in Engineering, such as Biotechnology etc. Professional statisticians have acknowledged Taguchi's efforts especially in the development of designs for studying variation. Success in achieving the desired results involves a careful selection of process parameters and bifurcating them into control and noise factors. Selection of control factors must be made such that it nullifies the effect of noise factors. Taguchi Method involves identification of proper control factors to obtain the optimum results of the process. Orthogonal Arrays (OA) are used to conduct a set of experiments. Results of these experiments are used to analyze the data. Here, an attempt has been made to demonstrate the application of Taguchi's Method to analyze the In-cab noise and vibration level and its optimization.

The Full Factorial Design requires a large number of experiments to be carried out as stated above. It becomes laborious and complex, if the number of factors increase. To overcome this problem Taguchi suggested a specially designed method called the use of orthogonal array to study the entire parameter space with lesser number of experiments to be conducted. Taguchi thus, recommends the use of the loss function to measure the performance characteristics that are deviating from the desired target value. The value of this loss function is further transformed into signal-to-noise (S/N) ratio. Usually, there are three categories of the performance characteristics to analyze the S/N ratio. They are: nominal-the-best, larger-the-better, and smaller-the-better.

The use of Taguchi's parameter design involves the following steps:

a) Identify the main function and its side effects.
b) Identify the noise factors, testing condition and quality characteristics.
c) Identify the objective function to be optimized.
d) Identify the control factors and their levels.
e) Select a suitable Orthogonal Array and construct the Matrix.
f) Conduct the Matrix experiment.
g) Examine the data; predict the optimum control factor levels and its performance.

In accordance with the steps that are involved in Taguchi's Method, a series of experiments are to be conducted. Experimental Set up is shown in Fig 1. Here, the procedure is given below.

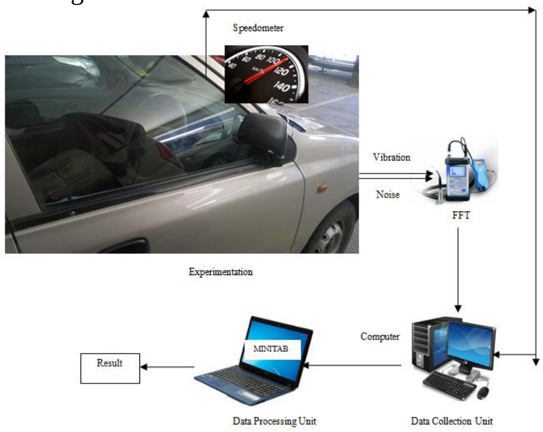

Fig. 1 Experimental Set up

1. Identification of Main Function and its Side Effects

The function needs to be identified through the different parameters. Speed, Payload, and Road surface are the main functions. In-cab noise and vibration are the side effects.Before proceeding on to further steps, it is necessary to list down all the factors that are going to affect or influence the In-cab noise and the vibration and from those factors one has to identify the control and noise factors. The "Factors" that affect while vehicle in motion are listed in the Table 1.

TABLE 1

Parameters\Factors	Control Factor	Noise Factor
1	Speed	Noise Level
2	Pay load	Vibration Level
3	Road Surface	

After listing the control and the noise factors, decisions on the factors that significantly affect the performance will have to be ascertained and only those factors must be taken into consideration in constructing the matrix for experimentation. All other factors are considered as Noise Factors.

Identify the Testing Conditions and Quality Characteristics to be Observed For in-cab testing the quality characteristics are Noise and Vibration. The instruments used for measuring parameters are shown in Table 2.

Sr No.	Process parameters	Instrument Used
1	Noise Level	FFT Analyzer
2	Car Speed	Speedometer
3	Vibration Level	FFT/Vibrometer

TABLE 2

Car Model: Maruti Alto K10/2012 model

1. Identify the Objective Function

For in-cab testing the objective function is to minimize the vibration and noise. Smaller the noise and vibration better will be for human beings sitting in-cab.

S/N Ratio for this function: $\eta = -10 \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y^2{}_i\right)$

Where n is a sample size and the y is noise and the vibration level observed.

2. Identify the Control Factors and Their Level

The factors and their levels were decided for conducting the experiment, based on a "brain storming session" that was held with a group of the factors and their levels are shown in table 3.

Level	Car Speed Km/hr	Pay Load	Road Profile
1	60	FFT Analyzer	Smooth
2	80	Speedometer	Medium
3	100	FFT/Vibrometer	Rough

1. Selection of Orthogonal Array

To select an appropriate orthogonal array for conducting the experiments, the degrees of freedom are to be computed. The same is given below:

The most suitable orthogonal array for experimentation is L27 array as shown in following table. Therefore, a total 27 experiments are to be carried out.

1. Conducting the Matrix Experiment

In accordance with the above OA, experiments were conducted with their factors and their levels as mentioned each of the above 27 experiments were conducted taccount for the variations that may occur due to the noise factors. Noise and vibration level were measure. The table 4 shows the measured values of noise and vibration obtained from different experiments.

TABLE 4

Exp No	A	B	C	SOUND LEVEL	VIBRATION LEVEL
1	1	1	1	52.36	2.23
2	1	1	1	55.36	2.69
3	1	1	1	54.36	2.58
4	1	2	2	68.36	3.25
5	1	2	2	70.36	3.56
6	1	2	2	74.32	3.86
7	1	3	3	85.32	4.02
8	1	3	3	86.32	4.21
9	1	3	3	88.32	4.36
10	2	1	1	54.48	3.46
11	2	1	1	57.48	3.92
12	2	1	1	56.48	3.81
13	2	2	2	70.48	4.48
14	2	2	2	72.48	4.79
15	2	2	2	76.44	5.09
16	2	3	3	87.44	5.25
17	2	3	3	88.44	5.44
18	2	3	3	90.44	5.59
19	3	1	1	56.51	4.48
20	3	1	1	59.51	4.94
21	3	1	1	58.51	4.83
22	3	2	2	72.51	5.5
23	3	2	2	74.51	5.81
24	3	2	2	78.47	6.11
25	3	3	3	89.47	6.27
26	3	3	3	90.47	6.46
27	3	3	3	92.47	6.61

1. Experimental details

Since the objective function (noise and vibration) is smaller-the-better type of control function, was used in calculating the S/N ratio. The S/N ratios of all the experiments were calculated and tabulated as shown in Table5.

TABLE 5

Exp No	S/N Ratio for Sound Level	S/N Ratio for Vibration	A	B	C
1	-34.37999276	-6.966097261	1	1	1
2	-34.62869416	-7.856500981	1	1	1
3	-34.65447733	-7.985447632	1	1	1
4	-35.26158232	-8.666992803	1	2	2
5	-35.65491929	-9.253275649	1	2	2
6	-36.00399088	-9.777319863	1	2	2
7	-36.48887993	-10.19184561	1	3	3
8	-36.83936287	-10.55405092	1	3	3
9	-37.12644629	-10.86736214	1	3	3
10	-36.93793125	-10.85885407	2	1	1
11	-36.80512512	-10.96066505	2	1	1
12	-36.68241973	-11.0194545	2	1	1
13	-36.70452095	-11.21129604	2	2	2
14	-36.74219585	-11.43380204	2	2	2
15	-36.81032021	-11.67655775	2	2	2
16	-36.96853515	-11.90741983	2	3	3
17	-37.1122502	-12.13327091	2	3	3
18	-37.2524037	-12.34792918	2	3	3
19	-37.16027449	-12.3863564	3	1	1
20	-37.090448	-12.47420969	3	1	1
21	-37.02144623	-12.53982644	3	1	1
22	-37.0301001	-12.67309358	3	2	2
23	-37.27248819	-13.17897356	3	2	2
24	-37.08765414	-12.99413951	3	2	2
25	-37.18475801	-13.15995605	3	3	3
26	-37.27813395	-13.32641731	3	3	3
27	-37.37362675	-13.48920272	3	3	3

Here are the Average S/N Ratios for each factor as shown in Table 6.

TABLE 6

Level	Speed		Pay Load		Road Profile	
	Sum S/N	Average S/N	Sum S/N	Average S/N	Sum S/N	Average S/N
1	-321.1	-107.0	-332.0	-110.7	-334.5	-111.5
2	-325.4	-108.5	-328.6	-109.5	-333.6	-111.2
3	-325.4	-108.5	-328.6	-109.5	-333.6	-111.2

- Linear Model Analysis: SN ratios versus SPD, PL, RF

Model Coefficients for SN ratios are estimated as shown in following Table 7.

TABLE 7

Term	Coeff	SE coeff	T	F
Constant	-34.082	0.0206	-1654.2	0.0
SPD1	0.267	0.0291	9.192	0.012
SPD2	-0.006	0.0291	-0.221	0.846
PL1	2.093	0.0291	71.84	0.0
PL2	-0.207	0.0291	-7.12	0.019
RF1	0.027	0.0291	0.91	0.457
	0.014	0.0291	0.48	0.861

S = 0.06181 R-Sq = 100.0% R-Sq(adj) = 99.9%

Analysis of variance for SN ratios is estimated as shown in following Table 8.

TABLE 8

Source	DF	Seq SS	Adj SS	Adj MS	F	P
SPD	2	0.4203	0.4203	0.2101	55.0	0.018
PL	2	23.941	23.941	11.971	3133.13	0.00
RF	2	0.008	0.0076	0.0038	1.0	0.501
Residual Error	2	0.008	0.0076	0.0038		
Total	8	24.377				

- Linear Model Analysis: Standard Deviations versus SPD, PL, RF

Model Coefficients for Standard Deviations is estimated as following Table 9.

TABLE 9

Term	Coeff	SE coeff	T	P
Constant	37.313	0.000097	383942.5	0.000
SPD1	-0.509	0.000137	-3703.6	0.000
SPD2	-0.022	0.000137	-159.32	0.000
PL1	-8.564	0.000137	-62314.3	0.000
PL2	0.194	0.000137	1410.6	0.000
RF1	-0.0001	0.000137	-0.966	0.436
RF2	0.0002	0.000137	1.372	0.304

S = 0.0002915   R-Sq = 100.0%   R-Sq(adj) = 100.0%

Analysis of variance for Standard Deviation is calculated as shown in following Table 10.

TABLE 10

Source	DF	Seq SS	Adj SS	Adj MS	F	P
SPD	2	1.62	1.624	0.812	9554955.5	0.0
PL	2	430.3	430.4	215.2	2.5314E+09	0.0
RF	2	0.000	0.000	0.000	0.99	0.50
Residual Error	2	0.000	0.000	0.000		
Total	8	431.9				

Following Table 11. shows the Response Table for Signal to Noise Ratios. Smaller is better

TABLE 11

Level	SPD	PL	RF
1	-33.81	-31.99	-34.06
2	-34.09	-34.29	-34.07
3	-34.34	-35.97	-34.12
Delta	0.53	3.98	0.07
Rank	2	1	3

Following Table12 shows the Response Table for Means

TAB LE 12

Level	SPD	PL	RF
1	36.99	29.89	38.62
2	38.67	38.91	38.62
3	40.19	47.05	38.62
Delta	3.2	17.16	0
Rank	2	1	3

Following Table 13 shows the Response Table for Standard Deviations

TABLE 13

Level	SPD	PL	RF
1	36.8	28.75	37.31
2	37.29	37.51	37.31
3	37.84	45.68	37.31
Delta	1.04	16.93	0
Rank	2	1	3

- Graphical Plots for S/N ratio

The S/N ratio response table and response graphs are shown for S/N ratio for Speed, Payload, and Road profile in following graphs.

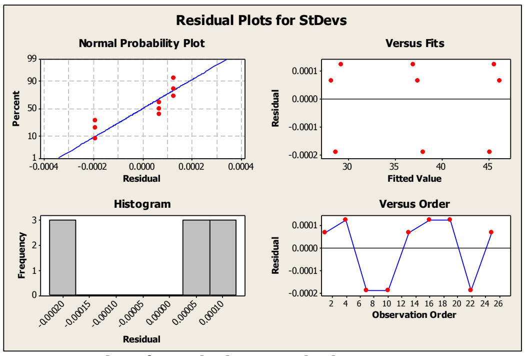

Fig. 2 Plot of Residual vs Standard Deviation

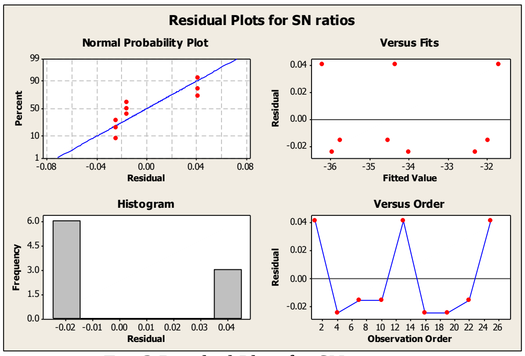

Fig. 3 Residual Plots for SN ratios

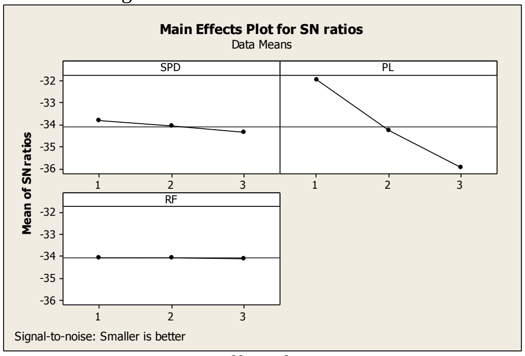

Fig. 4 Main Effects for SN ratios

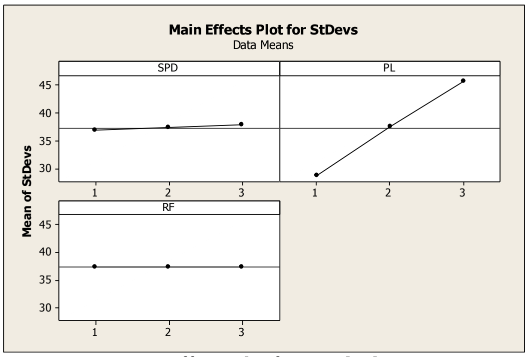

Fig. 5 Main Effects Plot for Standard Deviation

III. Conclusions

A smaller S/N value corresponds to a better performance. Therefore, the optimal level of the parameters is the level with the smallest S/N value. Based on the Figure 4,5 and Table 11,12,13. It is observed that Payload is contributing more weightage as compared to car speed and road profile.

The percentage contributions of the parameters have revealed that the influence of the Pay load is significantly larger than that of Road Profile and Speed. Traditional optimization techniques have very limited scope because of the complexity of the problems since they require a very large number of experiments. But Taguchi Technique requires very less number of experiments to optimize quality characteristics.

It is observed that noise from tires, engine rpm, and wind impacting the cab at higher road speed contributed to the elevated noise levels measured during travel. In order to look up driver comfort it has been a desire by vehicle manufacturers to lessen the in-cab noise of vehicles.Taguchi method will help to optimize such process parameters in future.

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