# OPTIMIZATION OF A DIESEL ENGINE SOFTWARE CONTROL STRATEGY

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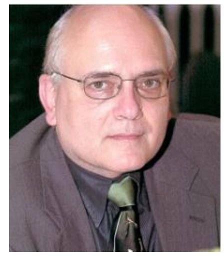

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## ABSTRACT

This paper discusses optimization of software control strategy for eliminating "hitching" and "ringing" in a diesel engine powertrain. Slow- and high-amplitude oscillation of the entire vehicle powertrain under steady pedal position at idle is called "ringing," and similar behavior under cruise-control conditions is called "hitching." The intermittent nature of these conditions posed a particular challenge in arriving at proper design alternatives.

Zero-point-proportional dynamic S/N ratio was used to quantify vibration and tracking accuracy under six driving conditions, which represented noise factors. An L18 orthogonal array explored combinations of six software strategy control factors associated with controlling fuel delivery to the engine. The result was between 4 and 10 dB improvement in vibration reduction, resulting in virtual elimination of the hitching condition. As a result of this effort, a 12 repair per thousand vehicle reliability (eight million dollar warranty) problem was eliminated.

The Robust Design methodology developed in this application may be used for a variety of applications to optimize similar feedback control strategies.

## INTRODUCTION

What makes a problem difficult? Suppose you are assigned to work on a situation where:

- the phenomenon is relatively rare;
- the phenomenon involves not only the entire drivetrain hardware and software of a vehicle, but specific road conditions are required to initiate the phenomenon;
- even if all conditions are present, the phenomenon is difficult to reproduce;
- and if a vehicle is disassembled and then reassembled with the same parts, the phenomenon may completely disappear!

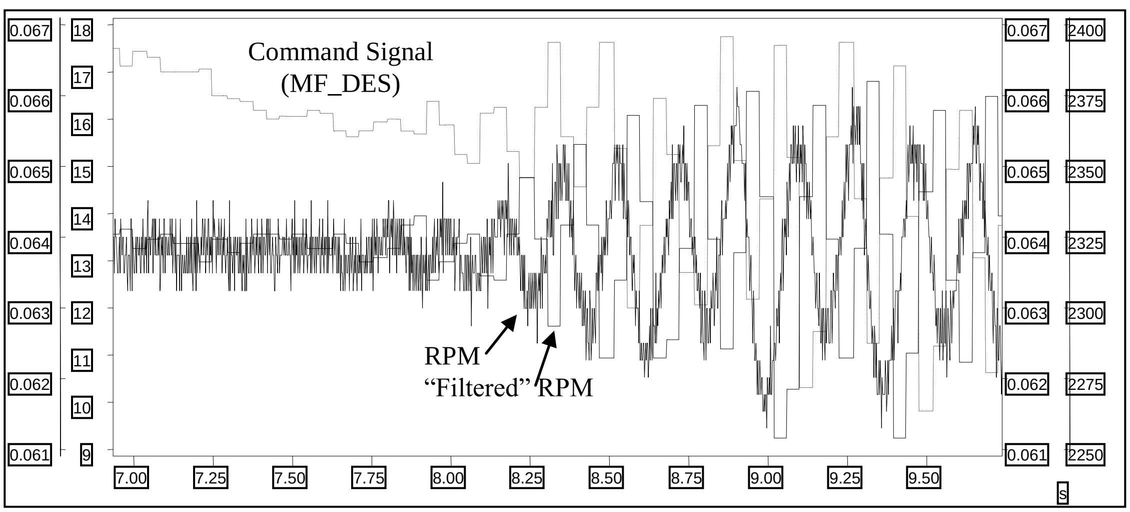
For many years, various automobile manufacturers have occasionally experienced a phenomenon like this associated with slow oscillation of vehicle rpm under steady pedal position (ringing) or cruise control conditions (hitching). Someone driving a vehicle would describe hitching as an unexpected bucking or surging of the vehicle with the cruise control engaged, especially under load (as in towing). Engineers define hitching as a vehicle in speed-control mode with engine speed variation of more than fifty rpm (peak-to-peak) at a frequency less than sixteen Hertz.

A multi-function team with representatives from several areas of three different companies was brought together to address this issue. Their approaches were more numerous than the team members and included strategies ranging from studies of hardware variation to process FMEAs and dynamic system modeling. The situation was resolved using TRIZ and Robust Design. The fact that these methods worked effectively and efficiently in a complex and difficult situation is a testament to their power, especially when used in tandem.

TRIZ, a methodology for systemic innovation, is named for a Russian acronym meaning "Theory of Inventive Problem Solving." Anticipatory Failure Determination (AFD), created by Boris Zlotin and Alla Zusman of Ideation, is the use of TRIZ to anticipate failures and determine root cause. Working with Vladimir Proseanic and Svetlana Visnepolschi of Ideation, Dr. Dmitry Tananko of Ford applied TRIZ AFD to the hitching problem. Their results, published in a case study presented at the Second Annual Altshuller Institute for TRIZ Studies Conference (Proseanic, 2000), found that resources existed in the system to support seven possible hypotheses associated with hitching. By focusing on system conditions and circumstances associated with the phenomenon, they narrowed the possibilities to one probable hypothesis, instability in the controlling system.

By instrumenting a vehicle displaying the hitching phenomenon, Tananko was able to produce the plot shown in Figure 1. This plot of the three main signals of the control system (actual RPM, filtered RPM, and MF_DES, a command signal) verified the AFD hypothesis by showing the command signal out-of-phase with filtered RPM when the vehicle was kept at constant speed in cruise-control mode.

**Figure 1: The Hitching Phenomena**




Actual RPM is out-of-phase with the command signal because of delays associated with mass inertia. In addition, the filtered RPM is delayed from the actual RPM because of the time it takes for the filtering calculation. The specific combination of these delays, a characteristic of the unified control system coupled with individual characteristics of the drivetrain hardware, produces the hitching phenomena. The solution lies in using Dr. Taguchi's techniques to make the software/hardware system robust.

## ROBUST ENGINEERING

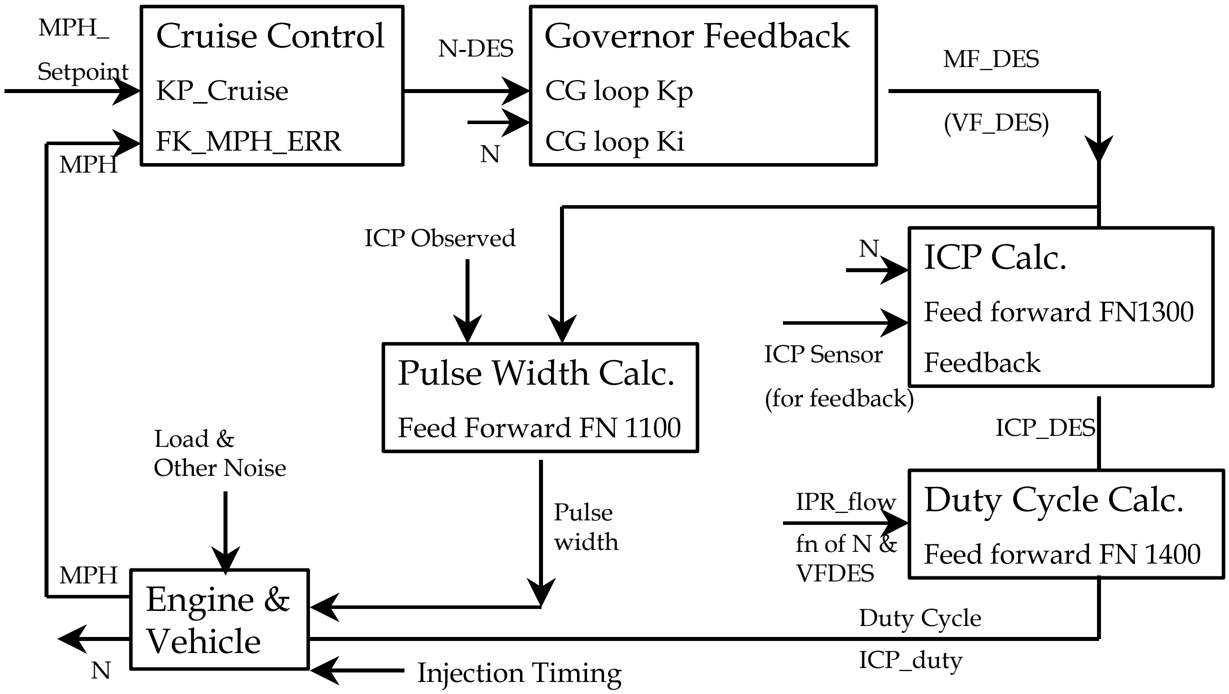
One of the most significant achievements associated with designing quality and reliability into a product or process is Dr. Taguchi's concept of Robust Engineering using Parameter Design [Phadke, 1989]. Parameter Design involves the use of designed experiments to systematically find a combination of factors that can be adjusted in the design (called "control factors") to make the functional performance insensitive to "noise." Here "noise" is defined as variation the engineer cannot control (or choose not to control), but may affect product performance. For example, environmental and system conditions are "noises." An automotive engineer cannot control whether the vehicle will be required to start in cold or warm weather, but the vehicle must start and perform in both conditions. The humidity may be dry or moist, the driver may be conservative or extremely aggressive, and system temperatures may not be friendly; nevertheless the vehicle must function as intended. Variation in material and/or part characteristics are also "noises." So is functional deterioration over time (reliability). Parameter or P-Diagrams are frequently used to document a system's ideal function in terms of initial setting or signal and resultant response, control factors, and noise factors (for an example, see the P-Diagram from this case study shown in Figure 3).

Prior to the creation of Parameter Design, the best an engineer could do to improve reliability was to understand what is important to reliability in terms of product and process characteristics. Find the targets or set points, and tighten tolerances (achieve six sigma). Dr. Taguchi calls this NASA quality or quality at high cost. With Parameter Design, an engineer can find combinations of factors that may be easily adjusted in the design in order to make the above characteristics insensitive to quality and reliability performance. In fact, tolerances may be opened up to achieve high quality at low cost. In this case study, quality and reliability are improved by finding a combination of software factors to make the cruise control software and hardware system insensitive to vehicle driving conditions.

## SYSTEM DESCRIPTION

A simple schematic of the controlling system is shown in Figure 2. The MPH set point is determined by the accelerator pedal position or cruise-control setting. Depending upon a number of parameters, such as vehicle load, road grade, and ambient temperature, the control system calculates the amount of fuel to be delivered for each engine cycle, as well as other fuel delivery parameters. Accordingly, the engine generates a certain amount of torque resulting in acceleration/deceleration of the vehicle. The feedback loop parameters and the speed sensor parameters must be set at appropriate values to achieve smooth vehicle behavior with no hitching/ringing.

**Figure 2: Simplified Functional Flow**




## P-DIAGRAM

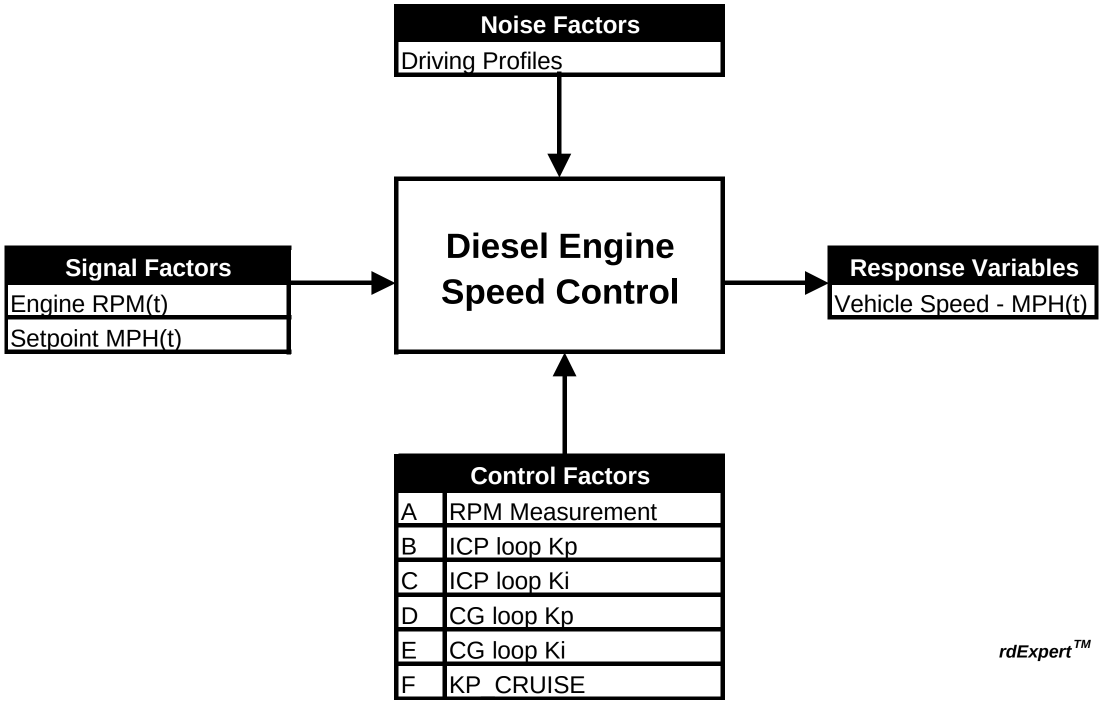
The parameters studied in this project are given in the P-diagram shown in Figure 3.

## NOISE FACTORS

Different driving profiles constitute important noise factors because they cause major changes to the load on the engine. The following six noise levels were used in this experiment:

1. accelerating in 1 mph increments from 47-56 mph
2. accelerating in 1 mph increments from 57-65 mph
3. decelerating in 1 mph increments from 65-57 mph
4. decelerating in 1 mph increments from 56-47 mph
5. rolling hill at 65 mph
6. rolling hill 57 mph

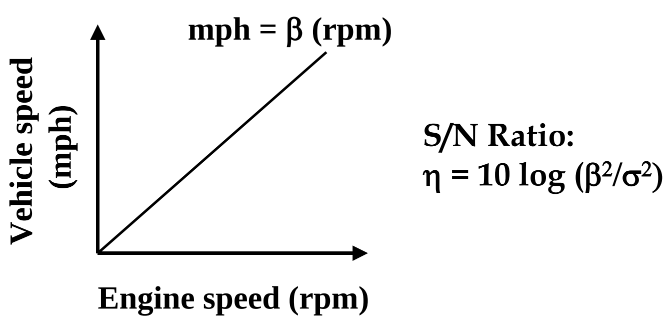
**Figure 3: P-Diagram**




## SIGNAL FACTOR, RESPONSE, AND IDEAL FUNCTION

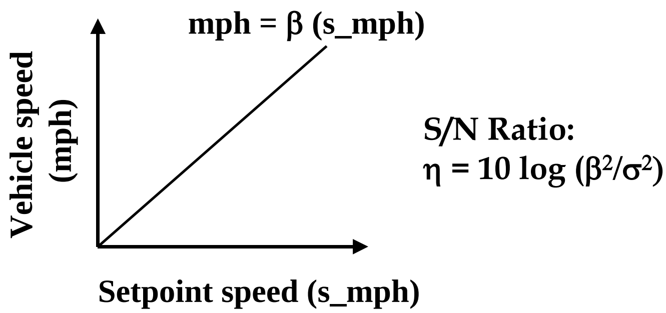
There would be no vibration or hitching or ringing if the vehicle speed (mph) were directly proportional to the engine speed (rpm) at every instant of time. Of course, the gear ratio was constant over the time period considered. Thus, the selected ideal function was zero-point-proportional with scaled engine rpm as the signal and vehicle speed (mph) as the response (see Figure 4). The scale depends on the gear ratio and the tire type.

**Figure 4: Ideal Function 1, Hitching**




While eliminating hitching, it is also important to have a good tracking between the set-point mph and the actual mph. We need another ideal function and corresponding S/N ratio as shown in Figure 5.

**Figure 5: Ideal Function 2, Tracking**




## CONTROL FACTORS

Six control factors listed in Table 1 were selected for the study. These factors, various software speed control strategy parameters, are described below:

**Table 1: Control Factors and Levels**

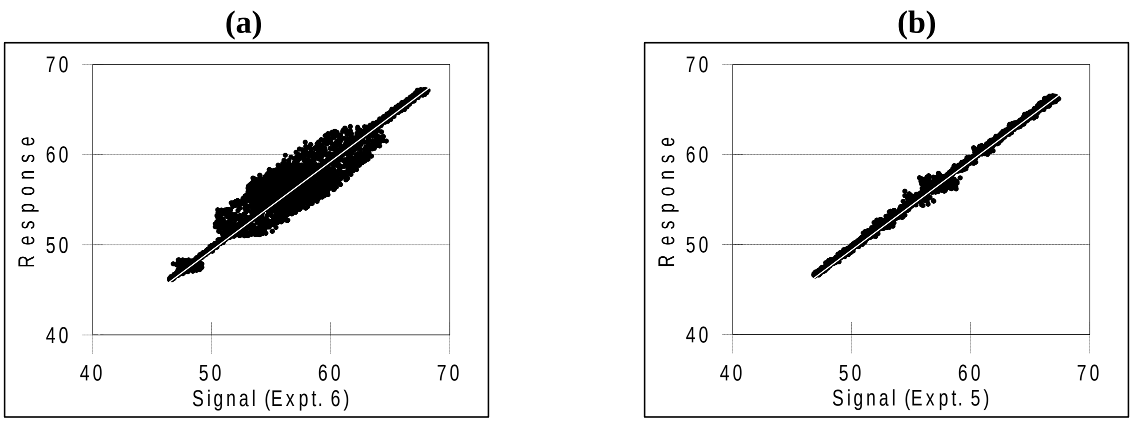
| Label | Factor Name | No. of Levels | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|---|
| **A** | **RPM Measurement** | **2** | 6 teeth | 12 teeth | |
| **B** | **ICP loop Kp** | **3** | 0.0005 | 0.0010 | 0.0015 |
| **C** | **ICP loop Ki** | **3** | 0.0002 | 0.0007 | 00012 |
| **D** | **CG loop Kp** | **3** | 0.8*(current) | Current fn | 1.2 (Current) |
| **E** | **CG loop Ki** | **3** | 0.027 | 0.032 | 0.037 |
| **F** | **KP_CRUISE** | **3** | 0 | 0.5 (Current) | Current |

A) RPM Measurement is the number of consecutive measurements over which the rotational speed is averaged for estimating rpm.
B) ICP loop Kp is the proportional constant for the ICP loop
C) ICP loop Ki is the integral constant for the ICP loop
D) CG loop Kp is the proportional constant for the Governor Feedback
E) CG loop Ki is the integral constant for the Governor Feedback
F) KP_CRUISE is the proportional constant for the Cruise Control feedback loop.

# EXPERIMENT PLAN AND DATA

An L18 orthogonal array was used for conducting the experiments. For each experiment, the vehicle was driven under the six noise conditions. Data for rpm, mph set point, and actual mph were collected using Tananko's vehicle instrumentation.  About 1 minute's worth of data were collected for each noise condition. Plots of scaled RPM (signal factor) versus actual mph (response) were used for calculation of the zero-point-proportional dynamic S/N ratios. Plots for two experiments, showing low and high values for the S/N ratio in the L18 experiment [corresponding to pronounced hitching (Expt 6) and minimal hitching (Expt 5)], are shown in Figures 6a and 6b, respectively. The corresponding S/N ratios were:  –1.8 and 11.8.  This is an empirical validation that the S/N ratio is capable of quantifying hitching.

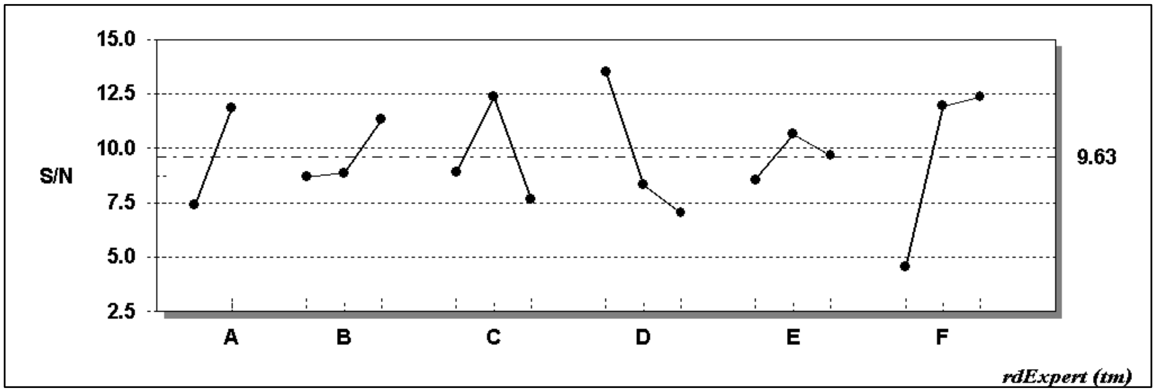
**Figure 6:  Data Plots for Hitching Ideal Function**




# FACTOR EFFECTS

Data from the L18 experiment were analyzed using ***rdExpert***™ software developed by Phadke Associates, Inc.  The control factor orthogonal array is given in the Appendix. The Signal/Noise (S/N) Ratio for each factor level is shown in Figure 7. From the analysis shown in Figure 7, the most important factors are A, D, and F.

**Figure 7:  Factor Effects for Ideal Function 1 (Hitching)**




| F Value | 5.9 | 0.8 | 2.3 | 4.6 | 0.4 | 7.5 |
|---|---|---|---|---|---|---|
| %SS | 13.6 | 3.9 | 10.7 | 21.3 | 2.0 | 34.6 |

1) Factor A is the number of teeth in the flywheel associated with rpm calculations. The more teeth used in the calculation, the longer the time associated with an rpm measurement and the greater the smoothing of the rpm measure. Level 2, or more teeth, gives a higher S/N ratio, leading to reduced hitching.

2) Factor D is CG loop Kp, a software constant associated with gain in the governor loop. Here Level 1, representing a decrease in the current function, is better.

3) Factor F is KP_Cruise, a software constant in the cruise control strategy associated with gain. Level 3, maintaining the current value for this function, is best, although Level 2 would also be acceptable.

Confirmation experiments using these factors were then conducted. Predicted values and observed values were computed for the best levels of factors, the worst levels of factors, and the vehicle baseline (original) levels of factors.

1) Best: A2, B3, C2, D1, E2, F3

2) Worst: A1, B1, C3, D3, E1, F1

3) Baseline: A1, B2, C1, D2, E2, F3

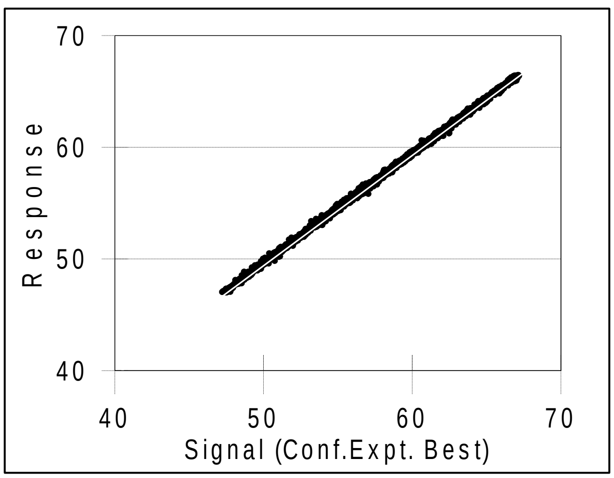
The results are shown in Table 2. We have shown the S/N ratios separately for noise conditions 1-4 and 5-6 to be able to ascertain that the hitching problem is resolved under the two very different driving conditions. As can be seen in this table, there was very good agreement between the predicted and observed S/N ratios under the above conditions.

**Table 2: Confirmation Experiment Results**

| | Ideal Function 1 (Hitching) | | Ideal Function 2 (Tracking) | |
|---|---|---|---|---|
| | Noise Conditions 1 - 4 | Noise Conditions 5 , 6 | Noise Conditions 1 - 4 | Noise Conditions 5 , 6 |
| **Best** | | | | |
| **Observed** | 18.44 | 19.01 | 11.80 | 15.39 |
| **Predicted** | 21.25 | 17.85 | 12.31 | 12.37 |
| **Worst** | | | | |
| **Observed** | -0.04 | 6.45 | 4.04 | -1.56 |
| **Predicted** | -2.26 | 3.28 | 2.74 | -2.89 |
| **Baseline** | | | | |
| **Observed** | 14.88 | 9.56 | 12.86 | 10.31 |
| **Predicted** | 8.08 | 5.66 | 11.55 | 10.8 |

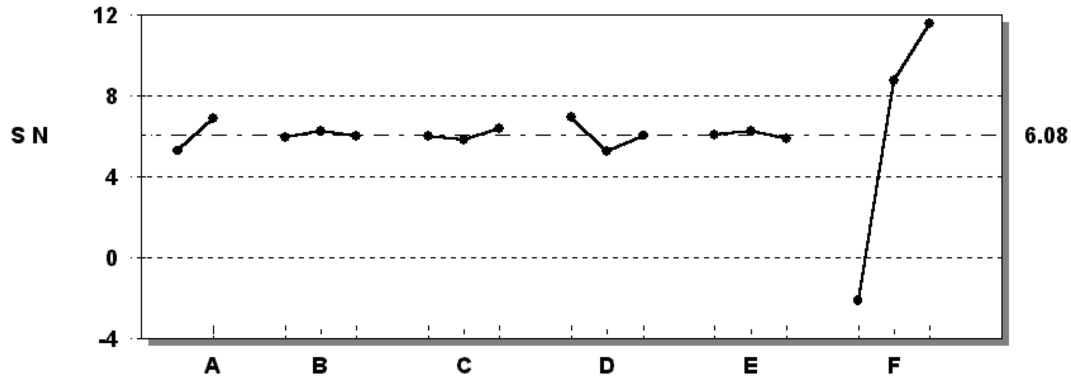
The confirmation experiment plot of rpm vs mph for the best factor combination is shown in Figure 8. This plot clearly supports the conclusions reached by the S/N ratio analysis.

**Figure 8: Plot of Ideal Function 1 (Hitching) with Best Factor Combination**




An additional S/N ratio analysis of the mph set point vs. vehicle speed (mph) was done to evaluate ability of the speed control software to accurately track the set-point speed. The factor effects for the tracking ideal function are shown in Figure 9. Only factor F, KP_CRUISE, is important for tracking. Furthermore, the direction of improvement for the tracking ideal function is the same as that for the hitching ideal function. Thus a compromise is not needed. The confirmation results for the tracking ideal function are also given in Table 2.

**Figure 9: Factor Effects for the Tracking Ideal Function**




| F Value | 4.2 | 0.1 | 0.2 | 1.6 | 0.1 | 118.3 |
|---|---|---|---|---|---|---|
| % SOS | 1.7 | 0.0 | 0.2 | 1.3 | 0.1 | 94.4 |

## FURTHER IMPROVEMENTS

The factor effect plots of Figures 7 and 9 indicate that improvements beyond the confirmation experiment can be achieved by exploring beyond Level A2 for Factor A, below Level D1 for Factor D, and beyond Level F3 for Factor F. These extrapolations were subsequently tested and validated.

## CONCLUSIONS

The team now knew how to completely eliminate hitching. Many members of this team had been working on this problem for quite some time. They believed it to be a very difficult problem that most likely would never be solved. The results of this study surprised some team members and made them believers in the Robust Design approach. In the words of one of the team members, "When we ran that confirmation experiment and there was no hitching, my jaw just dropped. I couldn't believe it. I thought for sure this would not work. But now I am telling all my friends about it and I intend to use this approach again in future situations."

After conducting only one L18 experiment, the team gained tremendous insights into the hitching phenomenon and how to avoid it. They understood on a root-cause level what was happening, made adjustments, and conducted a complete prove-out program that eliminated hitching without causing other undesirable vehicle side effects. As a result of this effort, a 12 R/1000 reliability problem with associated warranty costs of over eight million dollars, was eliminated.

## ACKNOWLEDGEMENTS

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The data were analyzed by using the ***rdExpert*** software developed by Phadke Associates, Inc. ***rdExpert*** is a trademark of Phadke Associates, Inc.

# APPENDIX

## Control Factor Orthogonal Array (L18)

| Expt No. | A : Col. 1 RPM Measurement | B : Col. 2 ICP loop Kp | C : Col. 3 ICP loop Ki | D : Col. 4 CG loop Kp | E : Col. 5 CG loop Ki | F : Col. 6 KP_CRUISE |
|---|---|---|---|---|---|---|
| **1** | 1) 6 teeth | 1) 0.0005 | 1) 0.0002 | 1) 0.8*(current) | 1) 0.027 | 1) 0 |
| **2** | 1) 6 teeth | 1) 0.0005 | 2) 0.0007 | 2) Current fn | 2) 0.032 | 2) 0.5 (Current) |
| **3** | 1) 6 teeth | 1) 0.0005 | 3) 00012 | 3) 1.2 ( Current) | 3) 0.037 | 3) Current |
| **4** | 1) 6 teeth | 2) 0.0010 | 1) 0.0002 | 1) 0.8*(current) | 2) 0.032 | 2) 0.5 (Current) |
| **5** | 1) 6 teeth | 2) 0.0010 | 2) 0.0007 | 2) Current fn | 3) 0.037 | 3) Current |
| **6** | 1) 6 teeth | 2) 0.0010 | 3) 00012 | 3) 1.2 ( Current) | 1) 0.027 | 1) 0 |
| **7** | 1) 6 teeth | 3) 0.0015 | 1) 0.0002 | 2) Current fn | 1) 0.027 | 3) Current |
| **8** | 1) 6 teeth | 3) 0.0015 | 2) 0.0007 | 3) 1.2 ( Current) | 2) 0.032 | 1) 0 |
| **9** | 1) 6 teeth | 3) 0.0015 | 3) 00012 | 1) 0.8*(current) | 3) 0.037 | 2) 0.5 (Current) |
| **10** | 2) 12 teeth | 1) 0.0005 | 1) 0.0002 | 3) 1.2 ( Current) | 3) 0.037 | 2) 0.5 (Current) |
| **11** | 2) 12 teeth | 1) 0.0005 | 2) 0.0007 | 1) 0.8*(current) | 1) 0.027 | 3) Current |
| **12** | 2) 12 teeth | 1) 0.0005 | 3) 00012 | 2) Current fn | 2) 0.032 | 1) 0 |
| **13** | 2) 12 teeth | 2) 0.0010 | 1) 0.0002 | 2) Current fn | 3) 0.037 | 1) 0 |
| **14** | 2) 12 teeth | 2) 0.0010 | 2) 0.0007 | 3) 1.2 ( Current) | 1) 0.027 | 2) 0.5 (Current) |
| **15** | 2) 12 teeth | 2) 0.0010 | 3) 00012 | 1) 0.8*(current) | 2) 0.032 | 3) Current |
| **16** | 2) 12 teeth | 3) 0.0015 | 1) 0.0002 | 3) 1.2 ( Current) | 2) 0.032 | 3) Current |
| **17** | 2) 12 teeth | 3) 0.0015 | 2) 0.0007 | 1) 0.8*(current) | 3) 0.037 | 1) 0 |
| **18** | 2) 12 teeth | 3) 0.0015 | 3) 00012 | 2) Current fn | 1) 0.027 | 2) 0.5 (Current) |

# S/N Ratios

| Exp No. | Hitching S/N | | Tracking S/N | |
|---|---|---|---|---|
| | Noise 1-4 | Noise 5-6 | Noise 1-4 | Noise 5-6 |
| **1** | 2.035 | 9.821 | 3.631 | -2.996 |
| **2** | 11.078 | 4.569 | 11.091 | 7.800 |
| **3** | 4.188 | 4.126 | 9.332 | 9.701 |
| **4** | 15.077 | 7.766 | 11.545 | 8.256 |
| **5** | 11.799 | 3.908 | 12.429 | 9.233 |
| **6** | -1.793 | 3.001 | 3.415 | -1.390 |
| **7** | 9.798 | 4.484 | 11.841 | 9.793 |
| **8** | 5.309 | 6.212 | 4.392 | -2.053 |
| **9** | 8.987 | 8.640 | 9.618 | 9.324 |
| **10** | 13.763 | 12.885 | 10.569 | 10.267 |
| **11** | 18.550 | 18.680 | 12.036 | 14.106 |
| **12** | 2.538 | 15.337 | 1.826 | -3.128 |
| **13** | 0.929 | 16.065 | 1.492 | -1.200 |
| **14** | 9.022 | 9.501 | 8.688 | 7.856 |
| **15** | 18.171 | 18.008 | 11.260 | 14.804 |
| **16** | 11.734 | 11.823 | 12.031 | 11.852 |
| **17** | 18.394 | 16.338 | 7.000 | -1.881 |
| **18** | 13.774 | 17.485 | 9.943 | 9.142 |
| **Average** | 9.631 | 10.480 | 8.452 | 6.083 |