Software Test and Calibration Using Virtual Manufacturing

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Abstract

This paper describes how distributive computing along with statistical subsystem simulation can be applied to produce near production ready embedded vehicle software and calibrations. Coupling distributive computing and statistical simulation was first employed over a decade ago at General Motors to design and analyze propulsion subsystem hardware. Recently this method of simulation has been enhanced extending its capabilities to both test embedded vehicle code as well as develop calibrations. A primary advantage of this simulation technique is its ability to generate data from a statistically significant population of subsystems. The result is the acquisition of an optimal data set enabling the development of a robust design now including both embedded code and calibrations. Additionally it has been shown that there are significant economic advantages in terms of time and cost associated with this type of development when compared to traditional method. The following section will describe in detail using examples and data the advantages of this innovative approach to software testing and calibration.

Introduction

The development of automotive embedded software and calibrations presently involves an expensive development cycle in terms of both time and cost. A primary reason is the associated expense and time required to apply the various technologies needed for software testing and calibration development. Early in the design cycle software-inthe-loop (SIL) and Hardware-in-the-Loop (HIL) systems are typically employed. Later stages use costly engine and vehicle hardware as part of the software test and calibration development process. During this phase propulsions systems may initially utilize dynamometers and eventually migrate to vehicle level testing. All these technologies contribute to large budgets and design times for embedded software and calibration development.

Extending the capability of General Motors Virtual Manufacturing **(SAE 2008-01-0288)** vehicle level software testing and calibration development can now be accomplished using an enhanced statistical simulation and analysis process. This has been accomplished through the integration of embedded software and calibration into the virtual high fidelity subsystems being analyzed. The accuracy of these high fidelity subsystems coupled with statistical analysis provides an optimal method to test embedded code and develop production ready calibrations. Additionally, due to Virtual Manufacturing's comparatively low budgetary requirements significant cost savings are realized compared to current design methodologies. Data presented in the following sections will show the advantage in terms of cost, the ability to test software, and produce a production ready calibration using this enhanced Virtual Manufacturing process.

Virtual Manufacturing Review

It has been determined that effects due to component variation and aging within an automotive subsystem are a major cause of quality and warranty related problems. Prior to Virtual Manufacturing, identifying the effects of all known sources of variation has been impossible. The technical problem has been that the application of statistical analysis to determine the effects of component variation within a subsystem can require hundreds or even thousands of samples to be statistically significant. Building and testing this many subsystem prototypes is economically impractical. GM Propulsion Systems solved this problem by combining the subsystem virtual prototype with statistical simulation to economically determine performance effects associated with all known sources of variation. This has been accomplished by developing Virtual Manufacturing that allows engineering to effectively build and test thousands of simulated subsystems at a small fraction of the expense of physical prototyping. GM uses a tool from Synopsys called Saber to do this. By using Saber, engineers are able to use Monte Carlo techniques to simulate a subsystem. The Saber Monte Carlo analysis randomly varies specified parameters within user-defined tolerance ranges and executes the specified Saber analysis at each parameter value.

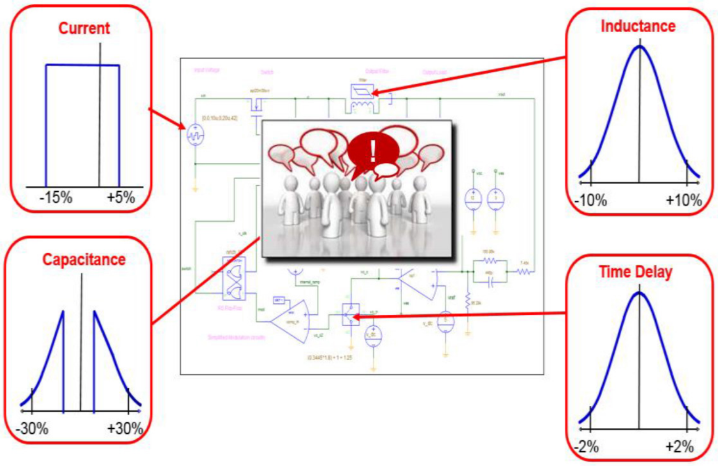

Figure 1. Saber Monte Carlo analysis randomly varies parameters within pre-defined tolerance ranges

This technique allows the engineer to simulate hundreds or thousands of virtual prototypes. By specifying the tolerance ranges on the parts in the design of concern, Saber will randomly vary specified parts allowing the engineer to evaluate how the variance of part values, in the production environment, affect the performance of the design. Upon completion, the engineer is able to perform statistical measurements to determine mean, standard deviation, median, and other data. Additionally, the Saber Pareto Analysis is used to rank the importance of parameter variation in affecting system performance. An example is shown below. In this example, a simple voltage divider is simulated in Saber using Monte Carlo analysis, and the results are analyzed using Pareto analysis. The Pareto result bar graph, shown on the right, ranks the parameters by how much their variation affects the measured output, in this case voltage - this is the bottom bar graph. The Pareto result also shows the sensitivity of the output to the parameters in the top bar graph. For even a simple circuit, the Pareto analysis shows the importance of tolerance stack-up.

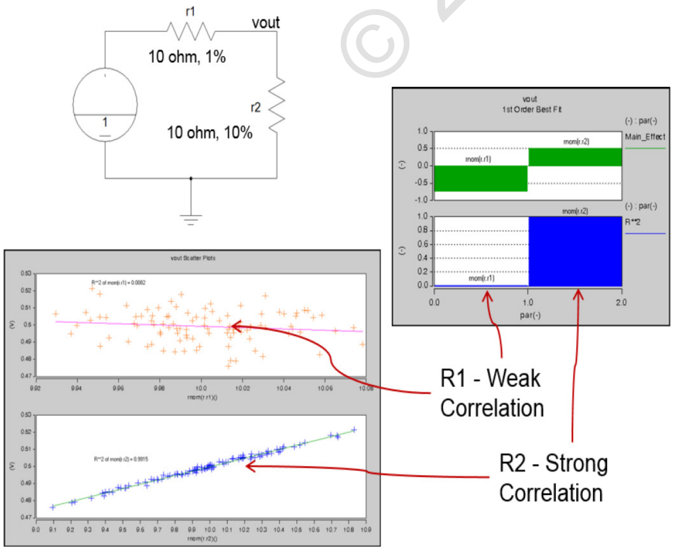

Figure 2. Pareto Analysis Voltage Divider Example

Scatter plots are another way to view the data generated by the Pareto Analysis. Each scatter plot is a parameter value vs measured output from the Monte Carlo analysis. The Pareto Analysis calculates a Least-Squares fit line, the slope of which is the sensitivity of the measured output to that parameter value, and the "tightness" around the least-squares fit line is the correlation to the change in output. This is what determines the ranking identified by Pareto.

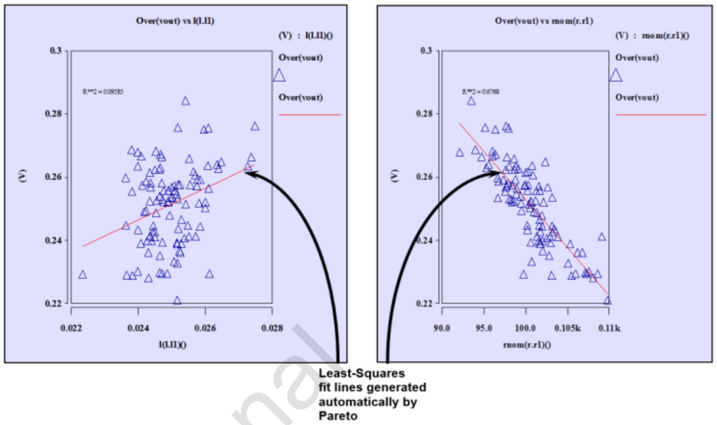

Figure 3. Pareto scatter plots

Data generated using this capability provides the ability to accurately characterize the effect on performance due to component variation.

GM Propulsion Subsystem in partnership with Synopsys have developed Virtual Manufacturing through the use of distributed computing technology. Distributed computing uses cluster of computers to statistically build and test subsystems in parallel. This system at GM is called the High Performance Computing (HPC) system. This assembly line can therefore manufacture and test hundreds of subsystem prototypes in hours. By employing various automation techniques, statistical simulation, analysis, and report generation activities can take place unmanned 24 hours a day, 7 days a week.

Statistical results generated from these thousands of virtual build and test cycles can be used to quantify the effects of variation. Design changes or other modifications can then be made to these subsystems to improve performance and product quality while simultaneously reducing development costs.

Software Test and Calibration

GMPT and Synopsys have recently enhanced Virtual Manufacturing to including the capability to perform software test and calibration development. At the core of this enhancement is the integration of embedded software and calibration into high-fidelity subsystem level models. Referred to as CAL-SIL the objective of this enhancement is to provide a virtual platform to test software and develop calibrations.

As with the original Virtual Manufacturing concept, the CAL-SIL enhancement was achieved through the integration of a number of existing technologies. A primary technology included is software-in-the-loop (SIL), which is the integration of embedded software into the subsystem level model. Integration of the software into subsystem hardware models provides the ability to develop, test, and analyze embedded code.

CAL-SIL, like Virtual Manufacturing, uses subsystem level models as opposed to an entire plant simulation. This technology models sections of an engine, transmission, or vehicle by function (electronic throttle control, fuel, ignition, etc…). These subsystem functions are constructed using accurate, high-fidelity models. Required inputs from outside the subsystem level models are simplified, yet maintain a high level of accuracy relative to the testing required. Use of this subsystem level modeling concept for software development has been successfully implemented on past projects, with the current implementation greatly automated.

Calibration utilities have also been included into the enhancements mentioned earlier. These utilities allow the calibrations to be uploaded and downloaded. This allows calibrations within the embedded software to be modified based on statistical data generated by build and test analysis. Capabilities also exist to compile the embedded software with updated calibrations, thus preparing it for execution.

Software and Calibration Process

As mentioned in the previous section, CAL-SIL provides the capability to both develop and calibrate embedded software on a statistically representative sample size of products in a virtual environment. The diagram below is the design flow for the CAL-SIL technology. CAL-SIL begins with the selection of the appropriate embedded software. The required embedded subsystem software is then modified to include inputs & outputs for subsystem integration. The inputs included are provided by the subsystem simulated hardware and any other simplified subsystem inputs needed for execution. The outputs included are only those required for the subsystem under test. A task scheduler is also added to ensure proper timing and execution. Subsystem timing is provided by the system simulator.

Calibration utilities are also integrated into the embedded software. These utilities provide a number of functional capabilities. As an example, routines within the embedded software enable calibrations to be read from a data file, allowing the calibration to be accessible by the embedded software. The calibration file can also be written to by external routines. This provides the flexibility to update calibrations as required. The embedded code is also virtually instrumented to acquire data on selective “internal” variables. The data stored can later be used to modify calibrations for improved controllability.

The modified software is then compiled and tested to verify proper execution. If these tests pass they are repeated within the Synopsys Saber simulator. The embedded software will then be integrated into the Subsystem Under Test (SUT) within Saber. Testing will, once again, be performed to ensure the embedded software provides the expected control logic to the SUT.

The subsystem level model will next be executed within the previously mentioned distributed computing technology, the HPC system. The HPC environment performs simulations, as mentioned earlier, on large subsystem models using parallel computing. Parallel computing is employed to generate statistical system data required for the robust development of software and calibrations.

Statistical simulation data acquired from the variables of interest will then be provided to Calibration Evaluation Tool(s). The Calibration Evaluation Tool(s) will use the simulation data to evaluate whether the current calibration set, in conjunction with the embedded code, has been optimized for controllability of the SUT. If it is determined that further calibration changes are needed, the next set of calibrations are then generated by the Calibration Evaluation Tool(s). These updated calibrations, along with the embedded software, are used to repeat the testing process. If the calibration set is found to be optimized per GM requirements then the code is ready for production hardware testing.

Calibrations generated from this CAL-SIL process are expected to behave better than calibrations developed with traditional methods. In fact, testing a representative sample size of subsystems is a major reason for the expected quality of the calibrations produced using this method. Traditional calibration methods are limited due to cost constraints, and limit testing to only a small sample size. Consequently, traditionally generated calibrations are produced using a statistical insignificant sample size, which will negatively affect quality.

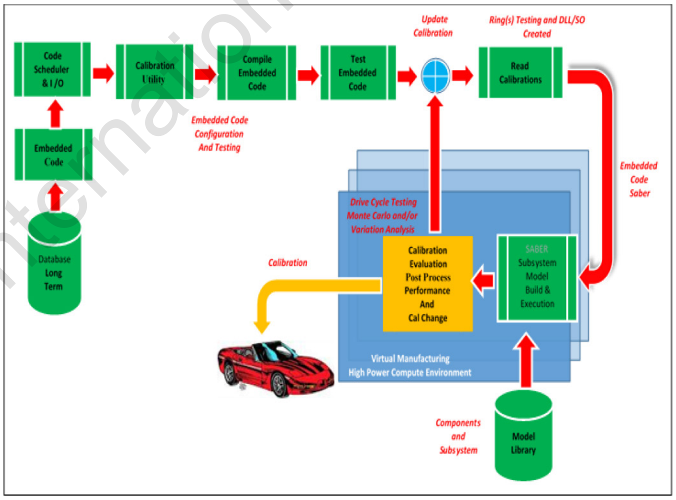

Figure 4. CAL-SIL Process Flow Diagram

Diesel Hydrocarbon Injector Example

To better understand the benefits of software and calibration enhancements to virtual manufacturing, consider the example of a hydrocarbon fuel injector subsystem in a diesel engine. A significant problem with diesel emissions is the particulate matter (a.k.a. soot) generated as part of the combustion process. General Motors addresses this issue by placing a fuel injector in the exhaust system. The objective of this hydrocarbon injector and its control subsystem is to precisely pump the correct amount of fuel for a given set of condition into the exhaust system. The combustion result of the fuel entering the hot exhaust system helps to increase the exhaust temperature leading the combustion of the soot and dramatically reducing its contents from the emissions. Injecting more than expected can cause temperature overshoot while less than expected can cause inability of reaching DPF (Diesel Particulate Filter) regeneration.

An example of a hydrocarbon subsystem model is found in Figure 5. Inputs to this subsystem are gathered from a number of engine sensors that define the current operating conditions. These sensors are inputs to the embedded software code ("HCINJ Ring") within the subsystem. The HCINJ software and associated calibrations will then determine the appropriate fuel required for injection into the exhaust based on these inputs. The amount of fuel required is the output from the HCINJ code. The high side driver embedded in the ECU acts as enabling condition providing a low impedance path from the main automotive battery to the injector while the low side driver regulates the frequency and duty cycle; this modulation of the battery voltage will in turn be translated into the appropriate amount of fuel injected into the exhaust system.

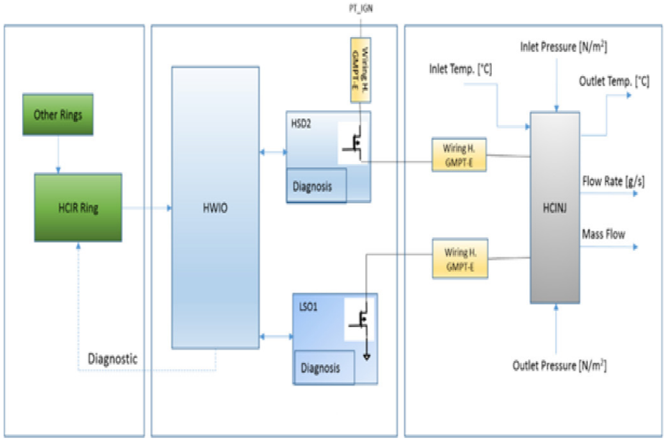

Figure 5. Hydrocarbon Injector Subsystem

As mentioned earlier, simulation subsystems like the hydrocarbon injection include all known sources of variation. Monte Carlo analysis was performed on the HCINJ model (including software) using distributed computing to obtain a statistically representative sample size of data. The analysis performed also simulated numerous drive cycle tests (DOE Points).

Performance measurements gathered included both results associated with hardware variation as well as data from specific "internal" embedded software variables. Post-processing was performed on the simulation results using various calibration utilities. These utilities, as discussed earlier, produce updated calibrations based on the statistical information provided by the Monte Carlo drive cycle testing. This process was repeated until the software testing indicated the hydrocarbon injector subsystem with the generated calibration had been optimized per GM requirements.

A comparison in terms of relative error was made at the completion of this process (Appendix A).

The calibration currently employed in a vehicle in-production software was compared with that generated using the CAL-SIL process. Both sets were also compared with General Motors requirements.

The graph in Figure 6 of the Appendix A shows this comparison: the Y axis represents the relative error while in the X axis there are the DOE (Design of experiment) points tested during the Validation phase of the project.

DOE set-points (frequency, battery voltage, pressure and desired mass flow) used to validate the two set of calibrations can be found in Figure 7 of the Appendix A. The column labeled "Error%" is the relative error of the quantity injected mean value to the desired mass flow defined in the DOE Test Matrix proper column.

The columns labeled as 'HCINJ CAL-SIL Calibration' found with the CAL-SIL calibration and 'L5P (DMAX) Production Calibration' found with the in-production calibration (traditional method) represents the results of 500 runs Monte Carlo analysis.

Examination of the results indicates that the CAL-SIL results were able to easily meet the GM requirements for production intent calibrations being within the limits, while instead the production calibrations produce points outside the limits (Figure 5 and 6). Moreover, the CAL-SIL calibration when compared with the production calibration is found to behave significantly better.

It can be seen by comparing these results that by using the CAL-SIL process, GM Propulsion Subsystems is able to simulate and test both hardware and software accurately and use the data generated to produce production ready calibrations. These are calibrations developed without the need for expensive prototypes or extensive testing.

CAL-SIL Virtual Manufacturing Advantage

CAL-SIL and Virtual Manufacturing provide a number of significant technological and budgetary improvements over current design processes. As an example, the hydrocarbon injection subsystem was presented. In it a comparison was made between actual production calibration and one generated using the CAL-SIL Virtual Manufacturing simulation and analysis process. Evaluation of these two calibration sets clearly showed the ability of CAL-SIL to produce superior results.

Cost savings associated with CAL-SIL and Virtual Manufacturing are also significant. It is estimated that current, or traditional, software testing and calibration costs conservatively $325 million a year in staff and equipment. This compares with CAL-SIL costs that are less than 5% of the $325 million presently required annually.

An additional benefit of this simulation and analysis process is that hardware problems are identified on approximately 60% of all subsystems tested using Saber and Virtual Manufacturing. These are problems that are not discovered using traditional hardware testing methods. As with calibration, the sample sizes used for hardware testing are limited due cost constraints. Virtual Manufacturing does not have this limitation and can therefore build and test a statistically representative sample size of subsystems. Therefore, outliers in a population that result in quality issues can be identified prior to prototyping or production. It is also known that quality issues of an unknown origin (a.k.a No Trouble Found, NTF) accounts for two-thirds of General Motors warrant. These are exactly the problems being uncovered using Virtual Manufacturing. This is also the reason for the near matching percentage between problems identified using Virtual Manufacturing and NTF warranty. It is conservatively estimated by quality engineering that having the capability to detect NTF would result in an additional cost savings of $100 million a year.

To further validate the benefits of distributed computing in a virtual manufacturing methodology, a single engineer at GM Propulsion Systems performed a backlog of 60,000 simulation runs in 2.5 weeks. These simulations completed analysis on four subsystems of comparable complexity to the hydrocarbon injector subsystem described earlier.

Conclusion

General Motors' enhancement to Virtual Manufacturing, CAL-SIL, allows for vehicle level software testing and production quality calibration to now be performed using simulation and analysis. Embedded software tests and calibration development have now been included into this process, which builds on the existing Virtual Manufacturing concepts of performing statistical analysis of high fidelity subsystems. The accuracy of the high fidelity subsystems used, coupled with statistical analysis, provides the optimal platform to develop robust, production ready, embedded software and calibrations. Due to the use of distributed computing, results can be generated on a statistically significant sample size of subsystems in hours, dramatically increasing productivity and reducing development time. The calibration generated using CAL-SIL enhancement were shown by example in this publication to better than those using traditional methods. The cost saving outlined in the paper associated with CAL-SIL software testing and calibration development were determined to be substantial. Additionally, reduced hardware quality costs were also discovered to be significant. It can therefore be argued that the data in presented in this paper demonstrates the superiority of this development capability.

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APPENDIX

APPENDIX A

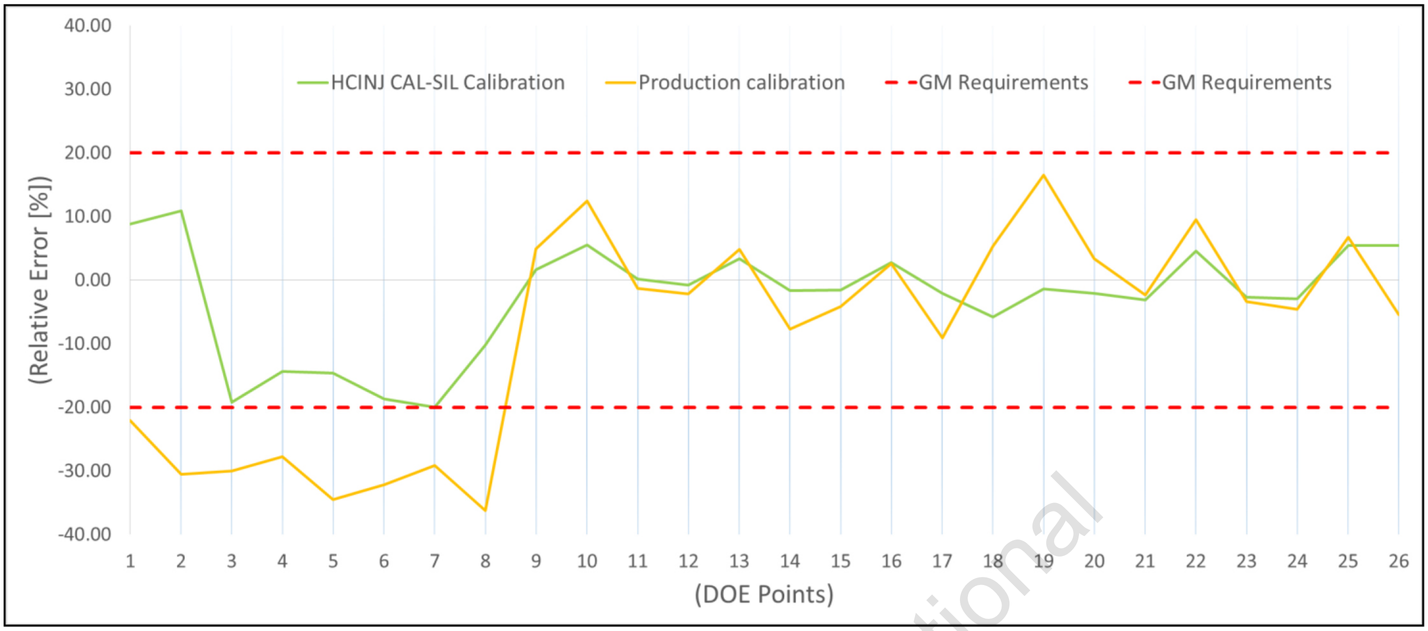

Figure 5. Calibration results graph comparison

DOE Test Matrix					HCINJ CAL-SIL Calibration					L5P (DMAX) Production Calibration				
					Collected Mass Flow Calsyn Project Cals [500 runs]					Collected Mass Flow Calsyn Project Cals [500 runs]				
DOE Point	Freq	Vbatt	Pressure	Desired Mass	Min	Mean	Max	Error [%]	Sigma	Min	Mean	Max	Error [%]	Sigma
1	10	9	525	0.5	0.44	0.54	0.67	8.78	0.006	0.31	0.39	0.49	-22.06	0.003
2	10	9	675	0.5	0.47	0.55	0.69	10.86	0.006	0.29	0.35	0.45	-30.53	0.003
3	10	9	375	1.25	0.80	1.01	1.23	-19.25	0.007	0.71	0.87	1.13	-30.00	0.007
4	10	9	525	1.25	0.88	1.07	1.35	-14.40	0.008	0.71	0.90	1.15	-27.81	0.007
5	10	9	675	1.25	0.87	1.07	1.30	-14.63	0.008	0.65	0.82	1.03	-34.48	0.007
6	10	9	375	2	1.24	1.63	2.01	-18.73	0.012	1.08	1.36	1.62	-32.19	0.010
7	10	9	525	2	1.30	1.60	2.00	-19.97	0.013	1.13	1.42	1.73	-29.15	0.011
8	10	9	675	2	1.28	1.80	1.89	-10.21	0.012	1.03	1.27	1.61	-36.28	0.010
9	10	12	375	0.5	0.40	0.51	0.62	1.66	0.006	0.41	0.52	0.66	4.91	0.004
10	10	12	525	0.5	0.42	0.53	0.71	5.50	0.007	0.44	0.56	0.68	12.42	0.004
11	10	12	675	0.5	0.40	0.50	0.62	0.19	0.007	0.42	0.49	0.58	-1.32	0.004
12	10	12	375	1.25	0.98	1.24	1.55	-0.75	0.010	0.98	1.22	1.52	-2.15	0.009
13	10	12	525	1.25	1.02	1.29	1.02	3.32	0.010	1.03	1.31	1.60	4.83	0.010
14	10	12	675	1.25	1.03	1.23	1.53	-1.67	0.009	0.90	1.15	1.40	-7.75	0.009
15	10	12	375	2	1.62	1.97	2.41	-1.56	0.015	1.57	1.92	2.34	-4.18	0.015
16	10	12	525	2	1.71	2.06	2.65	2.75	0.016	1.69	2.05	2.57	2.54	0.016
17	10	12	675	2	1.62	1.96	2.40	-2.13	0.015	1.41	1.82	2.17	-9.11	0.014
18	10	15	375	0.5	0.38	0.47	0.59	-5.80	0.005	0.42	0.53	0.69	5.31	0.004
19	10	15	525	0.5	0.40	0.49	0.60	-1.40	0.007	0.47	0.58	0.69	16.53	0.005
20	10	15	675	0.5	0.60	0.49	0.57	-2.08	0.007	0.41	0.52	0.65	3.35	0.004
21	10	15	375	1.25	0.99	1.21	1.68	-3.13	0.009	0.96	1.22	1.53	-2.34	0.010
22	10	15	525	1.25	1.07	1.31	1.66	4.54	0.010	1.10	1.37	1.70	9.53	0.011
23	10	15	675	1.25	0.96	1.22	1.56	-2.73	0.010	0.90	1.21	1.44	-3.41	0.009
24	10	15	375	2	1.47	1.94	2.42	-2.96	0.015	1.57	1.91	2.38	-4.60	0.014
25	10	15	525	2	1.70	2.11	2.59	5.46	0.016	1.74	2.13	2.62	6.70	0.017
26	10	15	675	2	1.70	2.11	2.59	5.46	0.016	1.55	1.89	2.39	-5.50	0.014

🟩 = error lower than GM Requirements
🟥 = error greater than GM Requirements

Figure 6. Calibration results table comparison

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