

A new approach of accelerated life testing for metallic catalytic converters

Thomas Nagel, Jan Kramer, Manuel Presti, Axel Schatz, Juergen Breuer
Emitec

Ron Salzman, John A. Scaparo, Andrew J. Montalbano
Ford Motor Company

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ABSTRACT

The Environmental Protection Agency (EPA) and California Air Resources Board (CARB) requirements for high mileage durability of emission components make it necessary to ensure the mechanical robustness of metallic catalytic converters. In addition, the robustness of design features must be assessed in the early design development phase without resorting to vehicle fleet testing.

By following established reliability methods, a new approach for time and cost efficient accelerated durability testing was developed, which can account for the combined effects of critical stressors of a metallic catalytic converter.

This paper describes the methodology used to determine the critical stressors and their levels in actual operating conditions which were determined by analyzing a broad range of vehicle test information. This information was used to develop a temperature profile and a high vibration load profile for the new life test method. Finally, this paper describes the combination and superimposed introduction of all stressors in a hot vibration/ thermal cycling component bench test.

The new time and cost efficient highly accelerated test method can reproduce metallic converter failure modes and can be used to develop the robustness of mechanical designs for metallic catalytic converters.

INTRODUCTION

The purpose of this new life test method is to reproduce typical metallic converter failure modes under accelerated mechanical conditions. The new test was developed so that robust design features for metallic catalytic converters can be developed without resorting to vehicle fleet testing.

A metallic catalytic converter typically consists of a matrix, a mantle and its retaining brazing system. Figure 1 depicts a typical metallic catalytic converter assembly with heat shield.

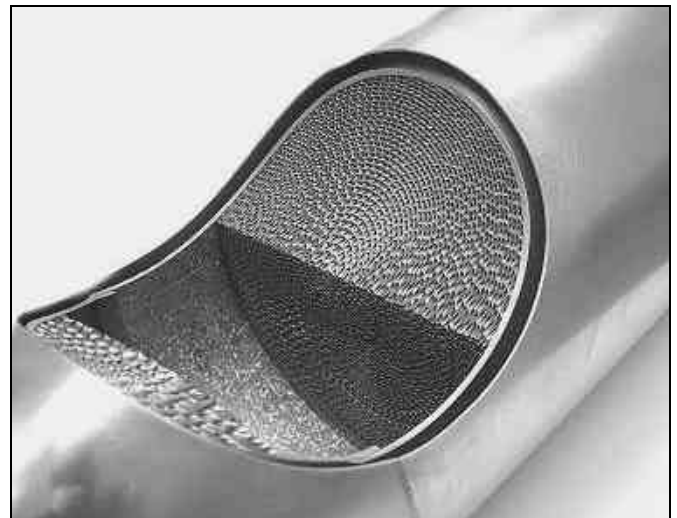


Figure 1: Typical metallic converter with heat shield

The new life test is an accelerated bench test under combined thermal and mechanical designed loads [1].

This test does not include degradation of the washcoat catalytic function necessary to assess feedgas to tailpipe emissions reduction efficiency. This efficiency measure is established in certification protocols, and calibration sign-off for tailpipe emissions through the in-use assessment procedures.

TEST BOUNDARIES DEVELOPMENT

REVIEW OF EXISTING TESTS FOR REDUNDANCY

The review of the established bench test method for ceramic catalytic converters, such as extended Hot Vibration Test showed, this test is normally conducted at

- **steady state** temperature
- **fixed** vibration load (sine frequency, const. acceleration)
- **constant** exhaust gas flow rate

The test procedures for ceramic converters are specifically designed to detect failures of the ceramic substrate mounting and retention system (mat, wire). For Metallic catalyst, these tests did not lead to a loss of matrix integrity or a loss of matrix-mantle retention, which are the characteristic mechanical failures [2].

Figure 2 shows a metallic converter after 200 hours of Hot Vibration Test at 1050 deg. C (1922 deg. F) and 185Hz at 28g peak acceleration. The tested part shows that the matrix is intact and fully attached to the mantle. None of the described failures occurred.

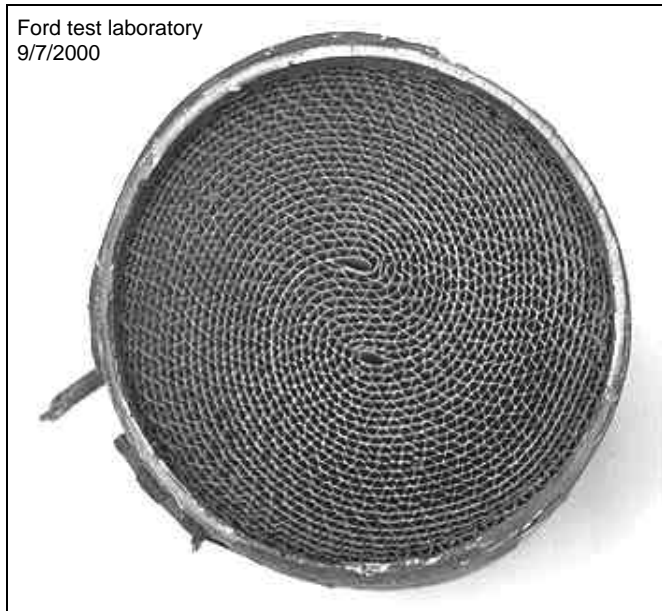


Figure 2: Metallic catalytic converter after 200 hours of Ceramic Converter Hot Vibration Test

The new bench test was developed specifically for the detection of characteristic failure mechanisms, which are unique due to the brazing/foil design of metallic catalyst converter assemblies.

BOUNDARY DIAGRAM

Figure 3 depicts the generic metallic converter sub-system boundary diagram and illustrates the relationship between the metallic catalytic converter and interfacing sub-systems and components of the exhaust system. The new life test method was developed for the catalytic converter system shown in the figure.

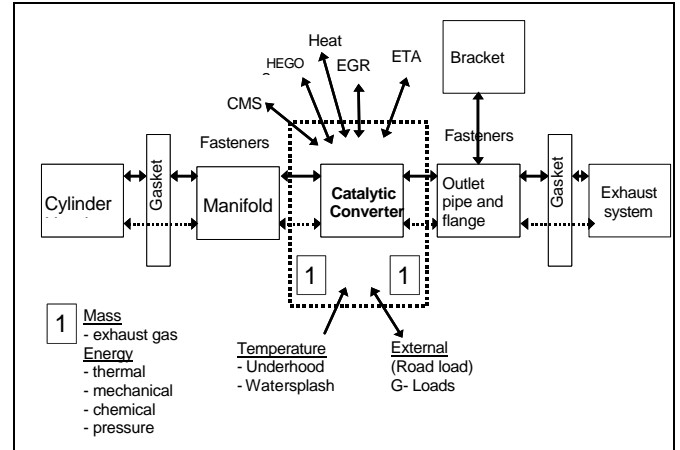


Figure 3: Generic catalytic converter system boundary diagram

REAL WORLD USAGE PROFILE

The new accelerated life test method was developed using vehicle test information following standard reliability methods. First, the typical real world environment of a metallic catalytic converter was surveyed and the critical stressors shown in Figure 4 were characterized.

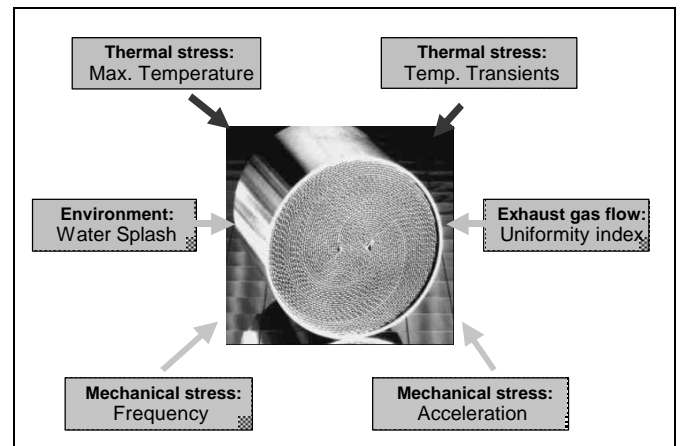


Figure 4: Real world environment of a metallic catalytic converter

BASIC MECHANICAL FUNCTION

The basic mechanical function of the metallic catalytic converter is to retain the catalytic coated metal foil matrix (substrate) and to direct unrestricted flow of the exhaust gas from the exhaust manifold and/or down pipe through the catalytic coated substrate matrix to the vehicles exhaust system for the useful life of the vehicle as required by its emission certification.

Additionally, the chemical function of metallic catalytic converter is to convert HC / CO / NOX in the engine exhaust to primarily water vapor, carbon dioxide and nitrogen while conveying the exhaust gases to the muffler and pipe system.

This chemical function is not covered in this life test.

FAILURE MODES, ERROR STATES

The development of the functional relationship (Y=F (X) diagram) was used to identify and characterize two high level loss functions (error states) from a sub-system level, leading to noncompliance of regulatory requirements or customer dissatisfaction.

These error states at the mechanical life test level are:

Y_A: **Loss of matrix integrity:** mechanical change in matrix foil structure causing higher flow restriction or foil separation leading to untreated exhaust gas flow (pass by).

Y_B: **Loss of matrix/mantle retention:** mechanical loss of matrix-mantle interface joint causing partial or complete matrix detachment.

CRITICAL STRESSORS

To detect the critical stressors that cause the error states, a Pareto Analysis of the Design Failure Mode and Effects Analysis (DFMEA) of metallic catalytic converters was conducted and is shown in Figure 5. In this chart, the product of severity and occurrence is shown for the most probable failure modes.

The level of occurrence for all failure modes was determined from Emitec design development and vehicle test data, and the severity of each failure mode was defined following established DFMEA guidelines [3].

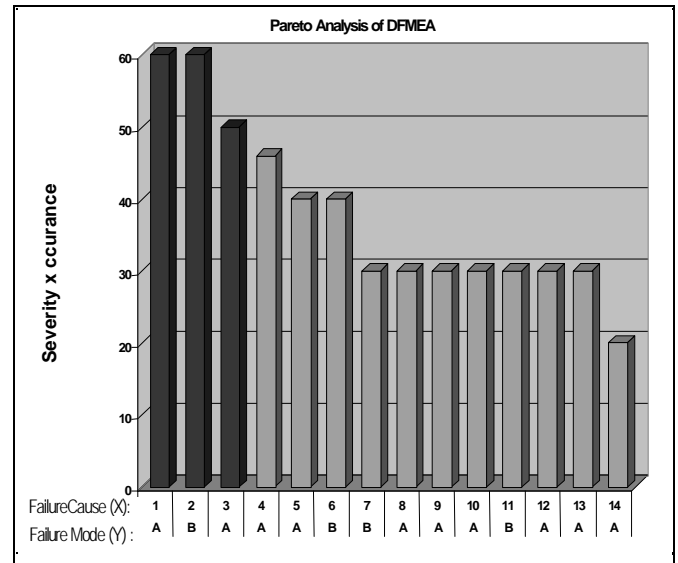


Figure 5: Metallic converter DFMEA failure mode/cause chart

The DFMEA failure mode/cause chart in Figure 5 shows, that the most severe and critical environmental stressors (noise, X1..X3) that can cause the mechanical function losses (Y_A, Y_B) of metallic catalytic converters are prioritized in the following order:

- X(1) Temperature/Temperature change rates (transients) too high
This can lead to exceeding the mantle/matrix attachment capability to maintain dimensional and physical properties when exposed to severe thermal stresses.
- X(2) Mechanical loads / frequency too high
High g-forces can exceed the design capability of the matrix and matrix/mantle attachment to hold the substrate in place. These g-loads provide the energy necessary for forcing the matrix out of the assembly when applied at high magnitude. The combination of high g-loads at the high frequency can even increase this effect.
- X(3) Poor uniformity index for exhaust gas flow (mass and distribution)
Impinging forces acting on the portion of the substrate with high localized flow concentration can lead to possible foil damage. High localized flow concentration at the matrix/mantle interface can result in possible failure of matrix/mantle retention.

VEHICLE CHARACTERIZATION AND DATA ANALYSIS

To define the level of the critical environmental stressors (temperature, vibration and flow) a series of vehicle characterization tests was conducted at Emitec. These tests are listed in Figure 6.

The chosen vehicle characterization tests represent severe thermal and mechanical stresses on the brazing system and foil structure of metallic catalytic converters such as high temperature, rapid temperature transients and high vibration loads.

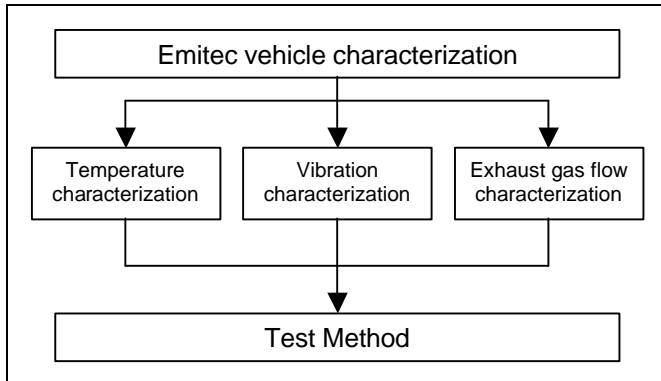


Figure 6: Test definition process

TEMPERATURE CHARACTERIZATION

Exhaust gas and catalyst matrix temperatures were measured during a severe vehicle operation cycle.

This cycle consists of a steady phase with high temperature conditions followed by a number of Wide Open Throttle (WOT) accelerations. Each acceleration phase is followed by a downshift sequence for vehicle deceleration.

A vehicle test cycle was used by Emitec to characterize the maximum thermal loads on the catalytic converter during severe operating conditions [4,5]. The measured temperature data are shown in Figure 7.

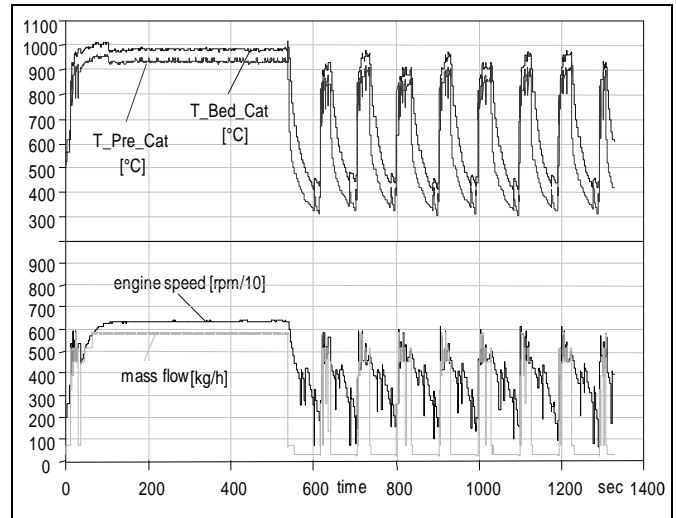


Figure 7: In-Vehicle Temperature / mass flow data

From these data, the maximum temperatures and maximum temperature change rates (positive and negative transients) have been determined as shown in table 1.

	Vehicle temperature characterization	New Accelerated life test
Max. temp. 2mm behind matrix front [deg. C]	930	930
Min. temp. 2mm behind matrix front [deg. C]	300	300
max. positive temperature transient 2mm beh. matrix front face [C/min]	5014	6000
max. negative temperature transient 2mm beh. matrix front face [C/min]	-2201	-2500

Table 1: Boundaries of temperature and temperature transients

VIBRATION CHARACTERIZATION

For reproducible analysis of vibration loads and frequency distribution, a number of vehicles were tested through an engine sweep test under wide open throttle (WOT) condition. The result of this test with having a 4-cylinder engine vehicle is shown in Figure 8.

In this test, the vehicle is accelerated in third gear (second gear for automatic) from minimum drivable engine speed to maximum engine speed with WOT. This operation represents the highest mechanical load to an engine and its attached components over the full engine speed range.

It represents the maximum vibration load (acceleration and frequency) for the close coupled mounted metallic catalytic converter.

The vibration load data from this characterization test, which consists of low and high frequency data, was then used to develop a vibration load profile that can be applied to the vibration shaker table during the bench test as described under section VIBRATION LOAD PROFILE.

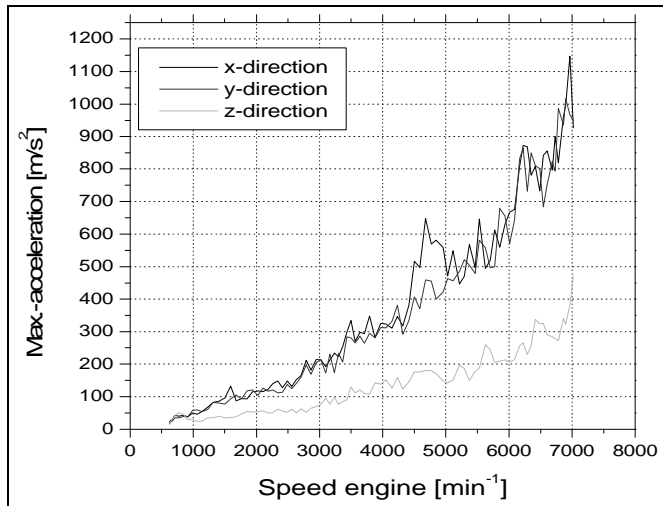


Figure 8: In-Vehicle vibration load

EXHAUST GAS FLOW CHARACTERIZATION

The DFMEA analysis identified exhaust flow mal-distribution (Bias Flow) as a significant causal factor when combined with temperature and mechanical loads. Bias flow could result in high backpressure and high thermal gradients resulting in high thermal and mechanical stresses to the brazing system / foil structure.

Optimizing a uniform flow distribution (Uniformity Index, Gamma close to 1.0) and centered peak velocity location (Velocity Index close to 0) ensures robustness against bias flow [6]. To eliminate this noise factor, most car manufacturers have developed an exhaust specification for flow distribution that all catalytic converters must meet for engineering sign-off.

For the new bench test, a high exhaust gas mass flow was chosen, which represents the upper range of all surveyed vehicle applications at WOT operation. In the bench test, this high mass flow is combined with an uneven flow distribution to introduce accelerated flow conditions.

BENCH TEST STRATEGY

The environmental critical thermal and mechanical stresses that were defined in the vehicle characterization tests were then applied in a test laboratory through a combination of equipment (gas burner, shaker table, test fixture) and instrumentation (data acquisition system, analysis software).

In the new accelerated test method, the specimen is installed in a new fixture (patent pending) on a shaker table, and the environmental loads for temperature, vibration and mass flow are introduced in a combined cycle. Figure 9 describes this new method.

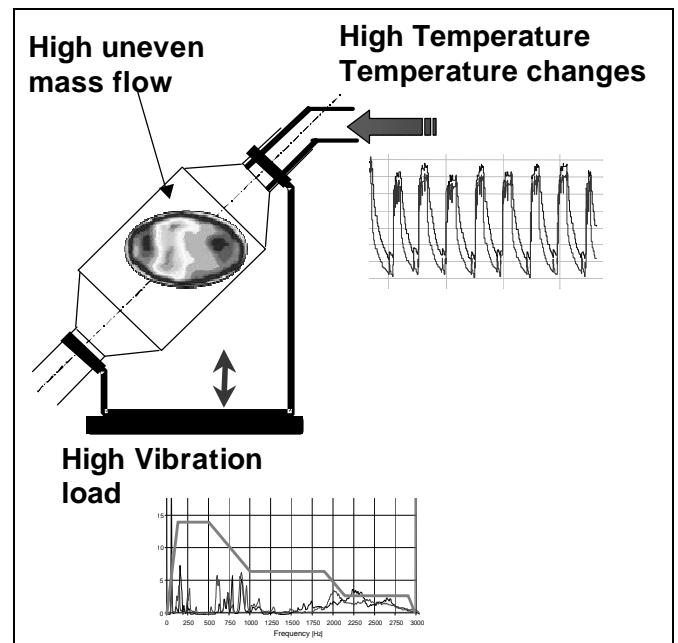


Figure 9: New accelerated test method

The definition of the load cycles of the three stressors was conducted using the vehicle characterization data and is described below:

TEMPERATURE CYCLE PROFILE

With the temperature data measured during the vehicle characterization, the most significant load cycles were localized. The maximum and minimum temperature levels were determined and temperature transients were calculated. The transients describe the rate of temperature change in positive and negative direction in the matrix in [degree C / minute].

The Ordered Overall Range Method [7,8] describes, that only the most severe temperature cycles lead to cumulative failure. From a temperature profile measured in a vehicle, the highest and lowest temperature peaks of a sequence were defined. Small peaks between the selected events were discarded [9].

The Method of High Usage Rate or Time Compression Method [7,8] was used to reduce off-time during the temperature cycle and therefore stressing the tested parts at a greater fraction of the time. Instead of a stochastic occurrence of high load phases in normal operation, the test part is tested with much more frequent high-load events.

These methods lead to a significant test time reduction of the new accelerated life test. Figure 10 shows an example for a temperature sub-cycle during the accelerated bench test. This temperature cycle was derived from the vehicle temperature characterization data (Figure 7) by eliminating minor temperature cycles caused by gearshift events (Ordered Overall Range Method) and shortening the non-damaging phase of steady high temperature (Time Compression Method).

The bench test temperature cycle focuses only on a time-compressed occurrence of maximum and minimum temperatures and severe positive and negative temperature transients.

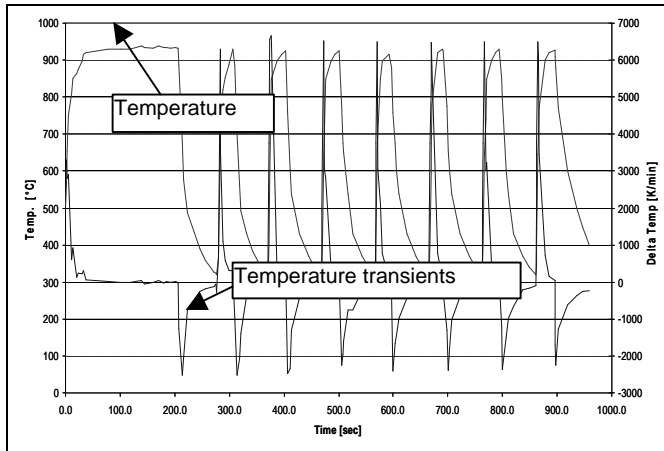


Figure 10: Example of temperature sub-cycle during the bench test

VIBRATION LOAD PROFILE

To simulate worst-case vibration in the accelerated life test, the same time compression test strategy was chosen. The acquired data from the vehicle tests have been analyzed, the vibration level and frequency were evaluated, and all events were then classified in order to identify the most severe vibration condition.

Figure 11 shows an example of measured RMS (Root Mean Square) acceleration level of all three converter main axis in a 4-cylinder vehicle. The maximum acceleration level for all directions was determined at an engine speed of 6500 rpm.

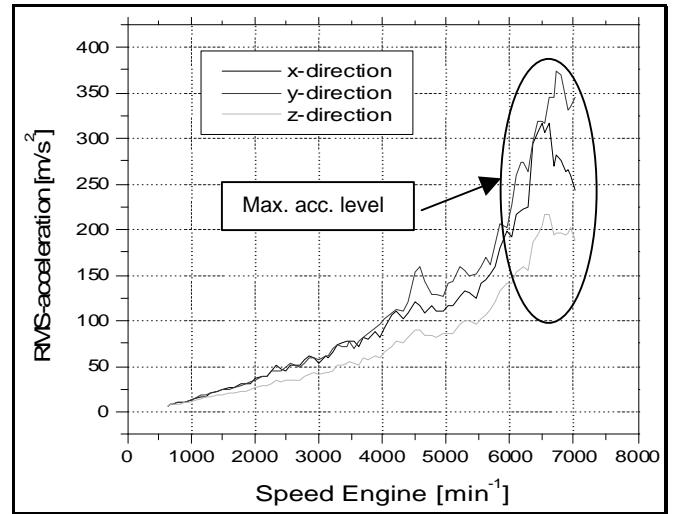


Figure 11: RMS acceleration during an engine sweep

To accelerate the bench test and reduce test time, only the maximum vibration load from this vehicle data at an engine speed of 6300 rpm – 6700 rpm was used to calculate the vehicle PSD (Power Spectral Density) curve of this test (Method of Time Compression).

By calculating the PSD of a vibration signal, the data are transformed from a time-based domain into a frequency-based domain. The PSD curve is an envelope curve, and the area under this envelope represents the square of the average vibration level (RMS).

To introduce a vibration load in the bench test that is representative for most vehicle applications and to avoid resorting to expensive vehicle testing for every new application, it was necessary to define a generic PSD envelope curve, which has a greater area under the envelope and therefore a greater average vibration load (RMS) than the vehicle PSD.

Assuming that higher accelerations occur at lower frequency and lower accelerations occur at a higher frequency, the generic bench test PSD curve was developed as shown in Figure 12. This PSD envelope curve covers the complete frequency range as measured in the vehicle characterization test.

Because it is a generic envelope curve, it cannot account for every single acceleration peak for each vehicle application; however, its average vibration load level (RMS) was defined to being representative for all surveyed vehicle applications.

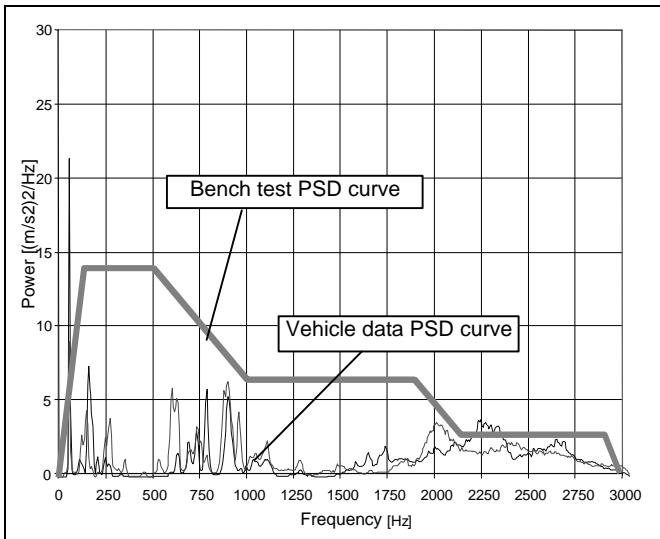


Figure 12: Generic bench test PSD and vehicle PSD

EXHAUST GAS MASS FLOW PROFILE

Most cases current vehicle applications do not provide optimum flow distribution due to packaging or NVH restrictions. The influence however on the thermal-mechanical robustness of a converter system should not be underestimated. Therefore, it is important to account for severe uneven flow distribution when testing the durability of catalytic converters.

In any case a flow concentration located to the edge of the matrix has a negative influence on the mechanical durability of the converter. To simulate accelerated bias flow conditions during the bench test, the actual exhaust gas pipe and inlet cones directing the gas flow into the tested converter was used.

Figure 13 shows high localized bias flow measured on the bench test during the baseline tests. The measured uniformity index, $\Gamma = 0,83$, is representing a worse-case environment.

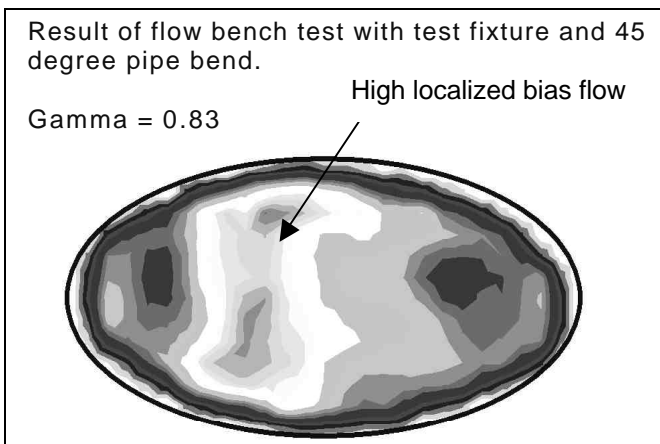


Figure 13: Flow distribution during bench test

The superposition of these severe levels of each single load type -temperature, vibration and flow- lead to a very high test acceleration factor.

To ensure a reproducible simulation of these high load levels, it was necessary to develop special test equipment.

TEST EQUIPMENT

EXHAUST GAS SOURCE

To simulate the thermal loads in the accelerated life test and to ensure that all current vehicle applications in the field can be covered, a new type of heat source was used.

This new burner system allows an independent control of exhaust gas mass flow and exhaust gas temperature and can provide rapid gas temperature transients of +15000 C/min and -8000 C/min and an exhaust gas mass flow change rate (dynamics) of +/- 200 kg/h per second can be achieved. Figure 14 shows the temperature/mass flow map of a burner, which is typically used for the test.

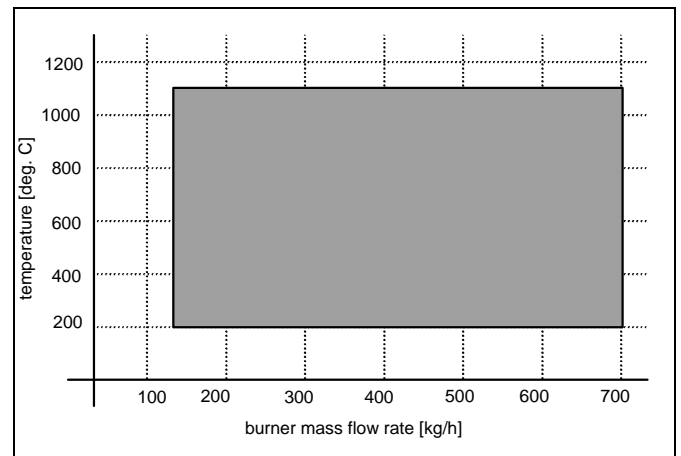


Figure 14: Temperature/ mass flow map of a gas burner used for the accelerated life test

VIBRATION SOURCE

The vibration of a vehicle application is typically a multi-axis load. To account for this effect, a two-axis excitation was required for the bench test. This was achieved by mounting the converter in an angle of 45° to the shaker vibration axis. The vector of force introduction is divided into two directions: axial (X) and radial (Y). For Vibration control, accelerometers on water-cooled adaptors were used, which are directly mounted by welding to the converter mantle.

To ensure an introduction of vibration loads of 500 Hz and beyond to the test converter, a new very rigid and stiff fixture (patent pending) was developed which allows frequencies up to 3000 Hz. A schematic showing the principle of the vibration introduction into the test converter and the accelerometer setup is shown in Figure 15.

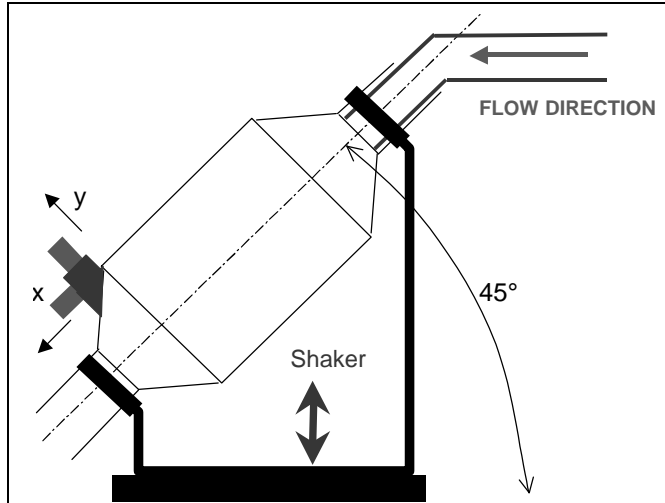


Figure 15: Schematic principle for load introduction.

TEST FIXTURE

To compensate for thermal elongations during temperature cycling, thermal expansion elements have been welded between the mounting brackets. The temperature control is done by thermocouples installed directly into the matrix. The flow distribution can be adapted by changing the angle of the welded inlet cone and adjusting the exhaust gas flow into the converter.

Figure 16 shows an example for mounting a round shaped converter to the shaker armature (moving element of the shaker). A patent pending slip joint is used to connect the exhaust gas pipes to decouple the gas burner outlet from the vibrating test part.



Figure 16: Example for a test converter mounting (patent pending)

ACCEPTANCE CRITERIA, ERROR STATE DETECTION

The basic mechanical function of the metallic catalytic converter is to retain the catalytic coated metal foil matrix (substrate) and to direct exhaust gas from the exhaust manifold and/or down pipe through the catalytic coated substrate matrix to the vehicle's exhaust system. To identify the onset of an error state or complete loss of this mechanical function, a monitor system was developed, which allows continuous monitoring of the matrix retention.

It is assumed that any spring-mass system has a characteristic signature. This means, that, for a metallic catalytic converter test setup configuration, any discrete frequency requires a defined input drive signal into the shaker to achieve the required PSD vibration level.

When failure in matrix retention occurs, the mechanical and modal properties of the test system (shaker table, fixture, converter) will change and cause a change of the specific drive signal (characteristic signature). To detect a function loss of the tested converter in the early stage (onset of failure) this shaker drive signal is monitored. Figure 17 shows how this signal (power or current) was used to detect a loss of retention (fracture) of the substrate during the baseline test.

The graph displays the inverted transfer function (ITF) between shaker drive signal and vibration output level vs. frequency.

$$1/H(f) = \text{Output}(f) / \text{Input}(f) \quad (1)$$

When an onset of fracture occurs, the input level for the low frequency significantly decreases. If the input signal reduction exceeds a predefined abortion limit, a matrix detachment is indicated.

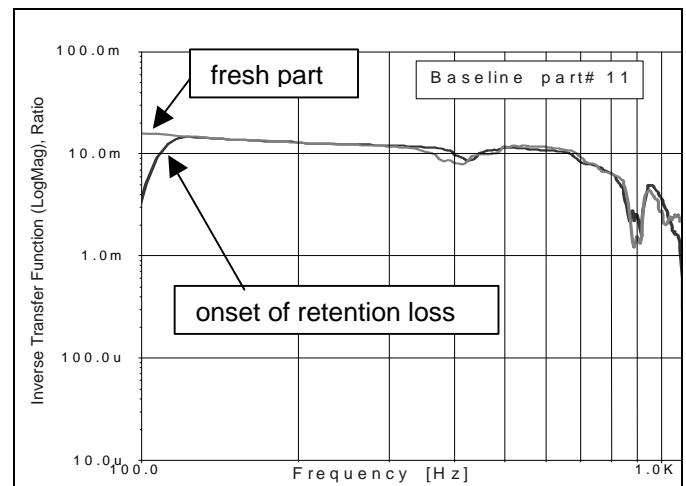


Figure 17: Example for matrix detachment monitored with ITF evaluation.

TEST RESULTS

BENCHMARK SYSTEM RESULTS

This test was performed with 6 samples of a current production vehicle catalytic converter as baseline system. Each sample was tested until complete matrix detachment occurred. This error state was detected by using drive signal monitoring. The data was analyzed and plotted in a Weibull chart. The result of this baseline test is shown in Table 2.

Part #	1	2	3	4	5	6
Vibration level [g RMS]	13	13	13	13	13	13
Max. temperature [deg. C]	930	930	930	930	930	930
Min. temperature [deg. C]	330	330	330	330	330	330
Max. positive transient [C/min]	6000	6000	6000	6000	6000	6000
Max. negative transient [C/min]	-2500	-2500	-2500	-2500	-2500	-2500
Test time to failure [hours]	30	18	14	10.15	15.45	15

Table 2: Test results from baseline system showing hours to test failure.

Figure 18 shows the Weibull distribution curve for the test times of the baseline system. The failure probability for 10% (B_{10}) and the 90% confidence bands are also shown in the plot.

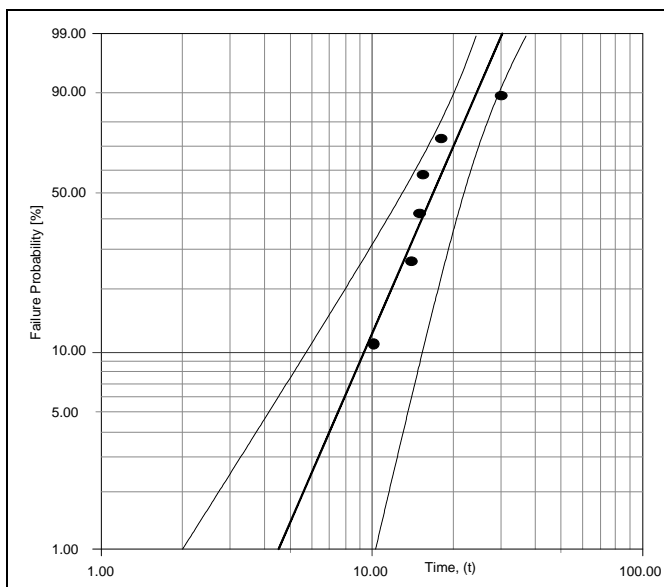


Figure 18: Weibull plot of test results [6]

It was found that the methods used to accelerate the test were very effective. The achieved test times with the new test are much shorter than with single stressor tests.

DESIGN DISCRIMINATION CAPABILITY

The above described test methodology provides a capable tool to evaluate the durability of metallic converter designs and to discriminate between their design features.

In particular, different matrix retention systems (matrix/mantle brazing designs) can be compared and evaluated. Thus, the new accelerated life test can enable the design engineer to predict and determine the useful life of metallic catalytic converters in the customer fleet and assess the robustness of design features in the early design phase without resorting to vehicle fleet testing.

This design assessment capability can be used early during the test development phase. Two additional metallic catalytic converter designs with different mantle matrix retention technologies were tested in the accelerated bench test. The test data was analyzed and compared to the data from the baseline system. The same Weibull analysis method as for the baseline system was used to determine the B_{10} life probability of these metallic converter designs.

Figure 19 shows the B_{10} life in the bench test for all three tested metallic converter systems. Design A & B both demonstrated durability performance that was superior to the baseline.

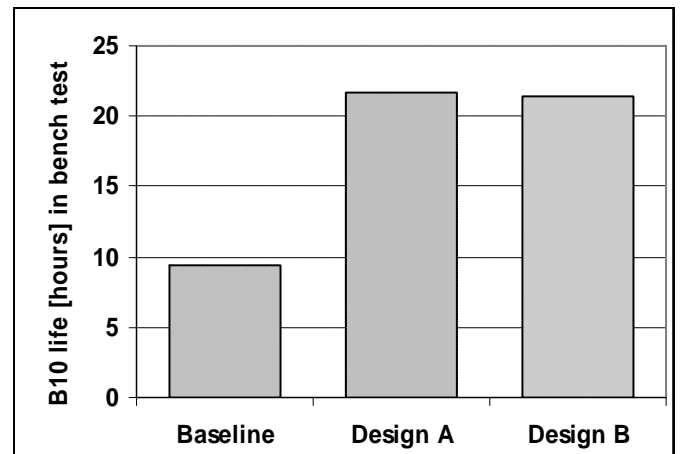


Figure 19: Result of design discrimination tests with the new accelerated bench test

PREDICTION OF FIELD PERFORMANCE

METHOD: WEIBAYES TECHNIQUE

Since the new test method is an accelerated life test that simulates thermo mechanical fatigue failures of metallic catalytic converters, the same failure mode would occur in both the accelerated bench test and in the field under real world operating conditions. The shape factor for the predicted field performance will then be the same as in the test.

If no field failure data are available, then data with no failure (suspension data) can be used to estimate the potential limits of the predicted failure rates for field performance from accelerated bench test results.

The shape factor and characteristic life from a test life distribution are then used to predict the expected life of the part under real world operating conditions. This method is known as the Weibayes method. It is widely used i.e. in the aircraft industry where it is difficult to test large and expensive products under real life environmental conditions until end of life.

Based on this method, available field data (high mileage data) from both Emitec and Ford fleet vehicles that used similar metallic catalytic converter components have been collected and analyzed. Similar designs of metallic catalytic converters were assumed to have the same failure mode.

All vehicle data consisted of suspension data, because none of the inspected metallic catalytic converters showed fractures of the matrix/mantle brazing system after high mileage usage. This vehicle data is shown in Table 3, where m_i is the actual vehicle miles at the time the metallic converter was removed from the vehicle.

From this suspension data in Table 3, the characteristic life of the predicted field Weibull q was determined using the Weibayes method:

$$q = \frac{\alpha}{\beta} \cdot \frac{m_i^b}{k} \cdot \frac{1}{\theta} \quad (2)$$

where m_i are the suspension data (miles), k is the number of failures assumed as 1 (failure is imminent) and $b=3.23$ is the shape parameter from the test life Weibull distribution [10].

Vehicle	m_i	m_i^b
Vehicle 1 - LH	100000	1.42889E+16
Vehicle 1 - RH	100000	1.42889E+16
Vehicle 2 - LH	100000	1.42889E+16
Vehicle 2 - RH	100000	1.42889E+16
Vehicle 3 - LH	100000	1.42889E+16
Vehicle 3 - RH	100000	1.42889E+16
Vehicle 4	100000	1.42889E+16
Vehicle 5 - LH	103000	1.57209E+16
Vehicle 5 - RH	103000	1.57209E+16
Vehicle 6 - LH	112000	2.06074E+16
Vehicle 6 - RH	112000	2.06074E+16
Vehicle 7 - LH	118000	2.43922E+16
Vehicle 7 - RH	118000	2.43922E+16
Vehicle 8 - LH	120000	2.57534E+16
Vehicle 8 - RH	120000	2.57534E+16
Vehicle 9 - LH	150000	5.29604E+16
Vehicle 9 - RH	150000	5.29604E+16
Vehicle 10 - LH	156000	6.01154E+16
Vehicle 10 - RH	156000	6.01154E+16
Vehicle 11 - LH	174000	8.55489E+16
Vehicle 11 - RH	174000	8.55489E+16
Vehicle 12	156739	6.10408E+16
Vehicle 13	147506	5.01674E+16
Vehicle 14	157075	6.1464E+16
Vehicle 15	154030	5.76971E+16
Vehicle 16	161044	6.66249E+16
Vehicle 17	145522	4.80201E+16
Vehicle 18	187183	1.08317E+17
Vehicle 19	155343	5.93009E+16
Vehicle 20	250000	2.75895E+17
Vehicle 21	202028	1.38606E+17

Table 3: Vehicle fleet field suspension data

Using the characteristic life from the accelerated bench test $h=18.9$, the predicted field Weibull distribution can be plotted by multiplying the test times by the following conversion factor

$$CF = \frac{q}{h} \quad (3)$$

This factor is computed as $CF = 22,818$ miles/test hour.

The Weibull distribution for the potential limits of the predicted field failure region is shown in Figure 20.

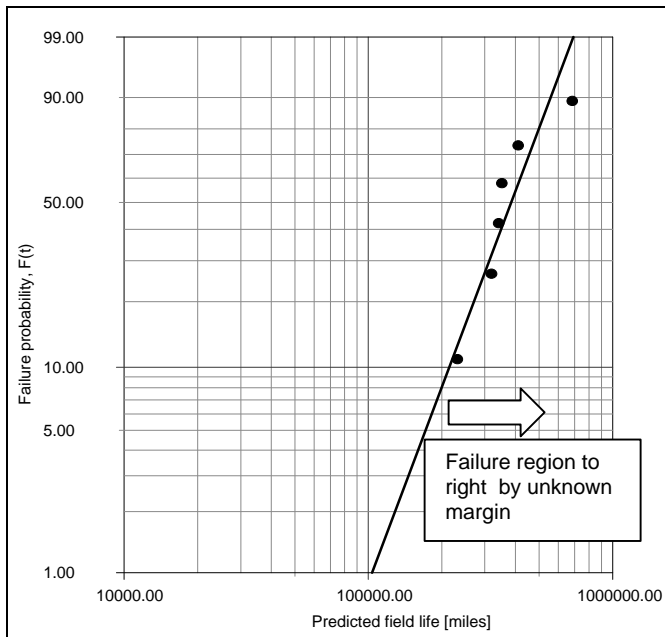


Figure 20: Weibull plot of predicted field life miles

Since only a limited amount of high mileage vehicle data was available, and no failures were found, the failure region will be to the right of the plotted curve shown in Figure 6 by an unknown margin. More vehicle data will be required to improve, this estimate of field performance.

TEST ACCELERATION FACTOR

Assuming a typical average speed of 37 mph as indicated from Ford fleet data, the conversion factor (CF) of 22,818 miles/test hours can be computed to actual field hours per test hour using the characteristic life $h = 18.9$ hours of the metallic converter from the accelerated bench test.

Thus, the average test acceleration factor for this new bench test method is computed as $AF = 615.6$ field hours per accelerated bench test hour.

PARAMETRIC BOGEY TEST METHOD

When a test life distribution (Weibull, Normal or LogNormal) is determined from accelerated testing during the design development phase, the information from this distribution can be used in the future to define a bogey test time and a required sample size to qualify the metallic converters for production validation (PV) testing.

The bogey test time T for the metallic converters for PV testing may be determined using the cumulative binomial distribution [11] with a system of N identical items in the test where K out of N items are allowed to fail with the

reliability R and the test confidence level C specific for the test life time distribution.

This is computed from an algorithm based on the following:

$$C = 1 - \sum_{i=0}^K \binom{N}{i} R^i (1-R)^{N-i} \quad (4)$$

From the baseline testing with 6 samples that were tested until end of life, a Weibull distribution was determined as

$$R = \text{EXP} \left(- (T/h)^b \right) \quad (5)$$

where $b = 3.23$ and $h = 18.9$ were calculated.

A flow diagram for the algorithm used to compute these values is shown in Figure 21.

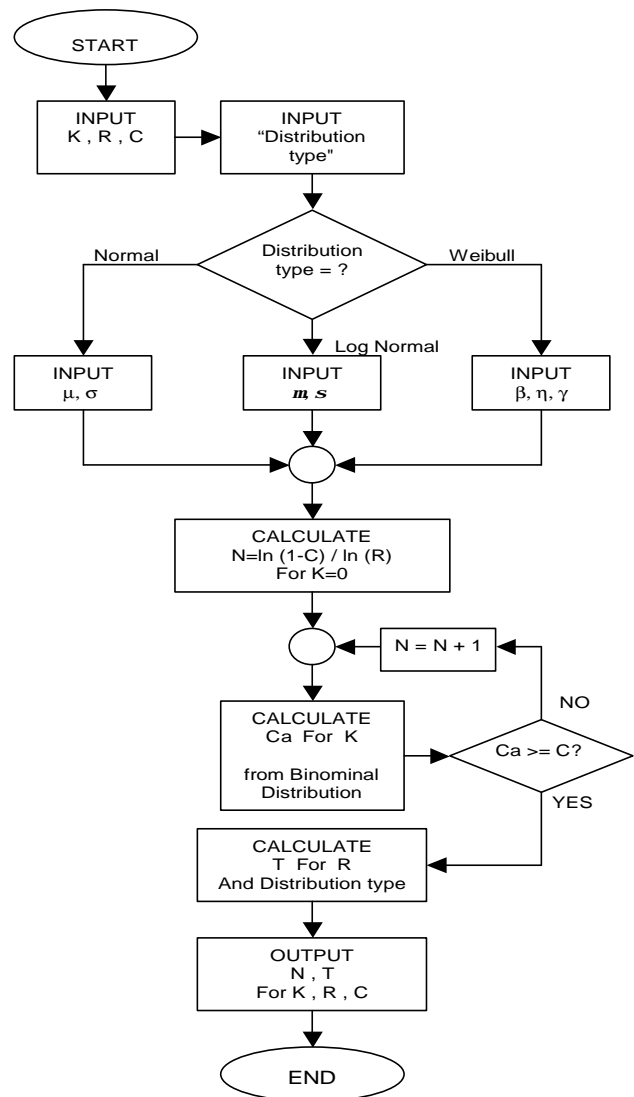


Figure 21: Algorithm for calculation of test bogey and sample size

With this algorithm, the test time and sample size (for $K=0$ failures) was computed as shown in Table 4.

Confidence C	Reliability R	Bogey sample size (N) (K=0 failures)	Test bogey time T [h] (K=0 failures)
50%	0.9 (B ₁₀)	7	9.22
70%	0.9 (B ₁₀)	12	9.26
80%	0.9 (B ₁₀)	16	9.27
90%	0.9 (B ₁₀)	22	9.38

Table 4: Test bogey and sample size

EXTENDED BOGEY TEST METHOD

To reduce testing cost, these large sample sizes may be reduced by extending the bogey test time based on the following equations from a test strategy that provide the basis for a trade-off between sample size and test time

$$T_e = T_c \left(\frac{N}{N_e} \right)^{1/b} \quad (6)$$

where

$$N = \frac{a \log(1 - C)}{c \log(R)} \quad (7)$$

With these equations and a Weibull slope of $b = 3.23$ as determined from the accelerated life test, the extended bogey time can be calculated as shown for specified sample sizes in the Table 5.

Confidence C	Reliability R	Sample size N _e	Extended Bogey time T _e [h] (K=0 failures)
50%	0.9 (B ₁₀)	4	10.96
50%	0.9 (B ₁₀)	5	10.23
50%	0.9 (B ₁₀)	6	9.67
70%	0.9 (B ₁₀)	4	13.01
70%	0.9 (B ₁₀)	5	12.14
70%	0.9 (B ₁₀)	6	11.47
80%	0.9 (B ₁₀)	4	14.23
80%	0.9 (B ₁₀)	5	13.28
80%	0.9 (B ₁₀)	6	12.55
90%	0.9 (B ₁₀)	4	15.89
90%	0.9 (B ₁₀)	5	14.83
90%	0.9 (B ₁₀)	6	14.02

Table 5: Extended Bogey time and sample size

Depending on the required reliability R and confidence level C , the data in Table 4 can be used to determine how many samples N must be tested for T_e hours each with no failure allowed. This verifies the mechanical reliability of the metallic catalytic converter as determined from the accelerated bench test and qualifies this component for production.

It should be noted that for $K > 0$ the bogey test algorithm must be used to determine the test time and sample size for a given test life distribution that may be Normal, LogNormal or Weibull distribution.

SUMMARY AND CONCLUSION

1.) A new time and cost efficient accelerated component durability test was developed, which can account for the combined effects of critical stressors at a metallic catalytic converter.

2.) The accelerated component test was first performed under independent loads (Inner thermal cycling test / hot vibration test) and the resulting time to failure of each test was evaluated. The combined effects of the critical loads have been determined and validated as the optimized accelerated testing strategy. The combination of all loads in the new accelerated life test resulted in a decreased test time until loss of substrate retention.

3.) An ongoing drive signal monitoring is performed to indicate the deterioration of the structural integrity of the substrate and its retention. This first indication is used to define further more frequent detailed inspections (i.e. optical) so that step-by-step details of the mechanism of function loss can be recorded for engineering analysis towards corrective actions.

4.) A post mortem analysis, including macroscopically and microscopically documentation, was performed on tested parts to analyze and verify the function loss mechanism. This Analysis can be used for design improvements or other corrective actions.

5.) The results from this test can be used to perform a Weibull analysis to predict the durability of the converter design.

6.) It could be demonstrated that the new accelerated bench test can be used as a tool to discriminate between different matrix/mantle retention designs of metallic catalytic converters and to help the design engineer choosing the design that best fits the vehicle application requirements.

7.) Using the Weibayes method, the Weibull distribution of the test data and available field suspension data were used to estimate a prediction of reliability and useful life of the metallic catalytic converter under real world conditions in the field.

8.) An algorithm was developed to be used during the PV phase of the product development cycle to qualify the production components. This algorithm determined the sample size and test time with a specified number of failures (bogey testing) that was needed to demonstrate a specific reliability at a given confidence level for the production design using the life distribution parameters from the accelerated life test that may be Normal, LogNormal or Weibull distribution.

9.) Finally, the new accelerated life test has the potential to be used for validating future metallic catalytic converter designs to meet or exceed EPA and CARB reliability and durability requirements for exhaust after treatment systems of 120000 miles under Tier II/LEVII or 150000 miles under CARB PZEV requirements.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

PZEV	Partial Zero Emission Vehicle
EPA	Environmental Protection Agency
Suspension data	Data with no failures
B₁₀ life	Life at 10% failure probability
Characteristic life	Life at 63.2% failure probability
PV	Product validation
NVH	Noise, Vibration & Harshness
CARB	California Air Resources Board
HC	Hydrocarbons
CO	Carbon Monoxide
NOX	Nitrogen Oxide
PV	Product Validation
ITF	Inverted Transfer Function
PSD	Power Spectral Density
Uniformity Index, Gamma	Industry standard for velocity distribution in a catalyst. Gamma = 1.0 indicates totally uniform flow.
Velocity Index	Peak velocity location in the normalized coordinate system (-1 to 1). Velocity index Zero indicates centered flow.
PZEV	Partial Zero Emission Vehicle
EPA	Environmental Protection Agency