Light-Duty Noise Guidelines for Advanced Combustion Research

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Introduction

The U.S. Department of Energy funds a significant amount of advanced combustion research. The ultimate goal of that research is to reduce petroleum consumption in the United States by developing high efficiency engine technology. To have an impact on petroleum consumption, the technology must not only meet regulatory constraints, but must also be accepted in the marketplace (i.e. purchased by US consumers).

Many of the advanced combustion strategies that are the focus of research activity fall under the broad category of low temperature combustion (LTC). One of the key tradeoffs in LTC is combustion noise. High noise levels can be an impediment to customer acceptance and market penetration in automotive applications where customers demand refinement in terms of both cabin noise and vehicle radiated noise. Those customer expectations go beyond regulatory requirements for pass-by noise. [1, 2]

The USDRIVE Advanced Combustion & Emissions Control (ACEC) Tech Team has recognized the need to increase awareness of the importance of combustion noise in light-duty applications and to provide guidance regarding relevant noise levels. This document presents the team's guidance on recommended noise metrics to use to assess noise during combustion research, including information about data acquisition requirements and post-processing methods for both experimental and analytical studies. Also provided are typical values in modern automotive engines applications for the recommended noise metrics.

The intent of this guideline is to provide combustion researchers with information they can use to guide their own research to automotive relevant regimes. The values provided in this document are not intended as hard targets or limits. If the noise is less than the maximum value for both metrics, then the noise may be acceptable in a future light-duty vehicle application. The authors of this document recognize that future regulatory and customer expectations will be for low noise in light-duty vehicle applications and that there is merit to exploring the tradeoffs between noise, emissions and efficiency both above and below the provided guideline values.

Noise Metrics

To assess combustion NVH and demonstrate relevance to light-duty, it is this team's recommendation that researchers assess both combustion noise (Noise) and ringing intensity (RI). A description of each metric, including recommended data acquisition practices and calculation methods for both experimental and analytical studies are provided below.

Combustion Noise

Combustion Noise (Noise) is an estimate of the magnitude of audible noise or loudness that radiates from an engine, including frequency content. It is important to note that Noise is a measure of loudness but does not provide information about transient sound quality such as knocking. Noise can be calculated using either

- a commercially available combustion noise meter, which uses cylinder pressure data as an input to calculate and output noise level in dBA.
- a cylinder pressure data post-processing script such as that published by Shahlari *et al* [3].

Both of these options use the same algorithm, which involves transforming cylinder pressure data into the frequency domain, filtering the resulting frequency spectrum with two filters representing both engine structural attenuation and human ear frequency perception (A-weighting) and converting the remaining spectrum into a single value representing the loudness (in dB) that would be perceived outside of an engine. Although each engine has a specific noise attenuation function, all engines have similar attenuation function shape. [4-7] Consequently, a generic structural attenuation function is recommended during fundamental research, enabling the comparison across different research projects done on various engines. A full description of the Noise calculation, including a Matlab algorithm that can be used to perform this calculation, can be found in Shahlari, *et.al.* [3].

Data Acquisition and Post-Processing for Noise Calculation

The input signal used to calculate Noise is cylinder pressure data from an engine. That input signal should be individual cylinder pressure traces that have not been subject to ensemble averaging or digital filtering. It is recommended that researchers report the average Noise level calculated from at least 50 individual cylinder pressure traces, more depending on combustion stability and subject to data storage capacity. Both ensemble averaging and digital filtering cylinder pressure data prior to Noise calculation alters the frequency content causing an underestimation of the Noise. This is discussed further in Shahlari *et al* [8].

In order to correctly calculate Noise, the input signal should include the frequency content between 0.1 and 10 kHz. To ensure that the frequencies within this range are fully resolved, cylinder pressure data should be acquired with sufficient resolution such that the highest frequency needed in the calculation is below the Nyquist frequency [9]. The Nyquist sampling theorem states that in order to resolve the frequency spectrum up to frequency F, the sample rate must be at least twice that frequency (2F). Thus, to resolve the frequency content between 0.1 and 10 kHz, a minimum of 20 kHz sampling rate must be used. In addition, it is recommended to use a sampling rate sufficient to minimize aliasing. Aliasing occurs during conversion of data from analog to digital when frequency content exists above the Nyquist frequency. [9] The unresolved frequency content effectively "flips" around the Nyquist frequency and is interpreted as low frequency content, which can influence the Noise calculation. Figure 1 shows the recommended minimum cylinder pressure crank angle resolution as a function of engine speed both to resolve all required frequencies and to minimize aliasing. Since encoder resolution typically does not vary based on operating condition, it is recommended to acquire cylinder pressure data with at least 0.2 CA resolution, which meets the minimum recommendation at engine speeds 1000 rpm or greater. All appropriate frequencies are resolved with 0.2 CA resolution data at engine speeds as low as 600 rpm. At all conditions, but especially at speeds below 1000 rpm, it is a good practice to apply an anti-aliasing filter with a cutoff frequency set at the Nyquist frequency to completely avoid aliasing.

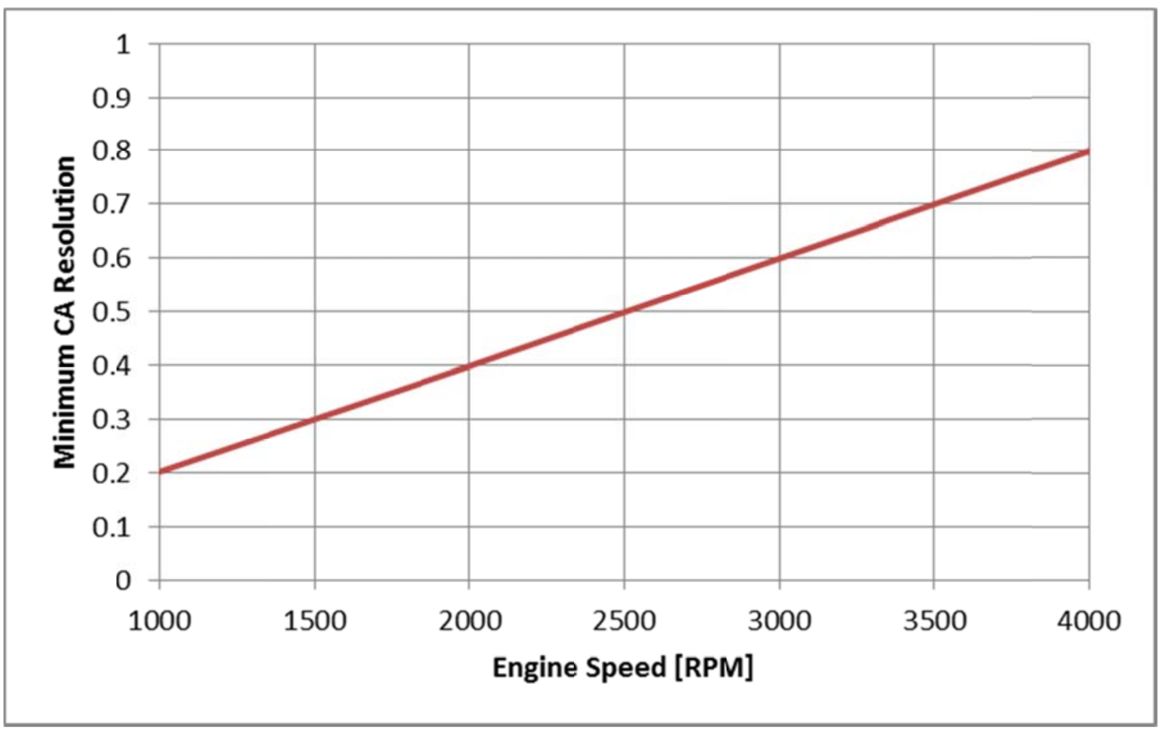

Figure 1. Cylinder pressure resolution required to minimize aliasing and resolve required frequencies for Noise calculation.

Since a commercial stand-alone combustion noise meter uses analog cylinder pressure as an input, it will automatically use individual cycles, which will be free of aliasing with all required frequencies properly resolved. Thus, the minimum sampling rate and other considerations discussed above are only a concern when Noise is calculated during post processing of digitally acquired data.

Closed Cycle Noise Calculation

Typically, the Noise calculation uses the entire 4-stroke cylinder pressure trace to calculate noise; however, modeling results often contain only a portion of the engine cycle, such as the closed engine cycle from IVC to EVO. In order to get the appropriate magnitude of Noise from such data sets, the application of the noise calculation should be modified. Since the Noise is calculated from the root mean square of the pressure, when only the closed portion of the cycle (i.e. the high energy portion of the cycle) is used for the calculation essentially the low energy data points are excluded in the averaging, leading to an overestimation of Noise. A suggested method for applying the noise calculation to data containing only a portion of the cylinder pressure can be found in Shahlari *et al* [8].

Typical Automotive Noise Range

The Noise value on an automotive engine varies based on the engine speed and load. Figure 2 shows the typical range of Noise as a function of IMEP360 (i.e. gross IMEP) at five different engine speeds from modern diesel engines. These ranges were generated using a cross-section of both North American and European automotive diesel engines that meet Tier II, EU5 or EU6 emissions regulations. The data range in Figure 2 represents the extreme limits of Noise values on all of these engines (as calculated with the algorithm described in *Shahlari et al* [3, 8]). While it may be acceptable in some applications to operate at the upper limit of this noise range, operation within the lower half of the range is preferred. The extent to which additional sound package could be applied to allow operation above the upper limit is very limited; however, there is value in understanding the tradeoffs between attributes such as noise and fuel consumption both within and above the range provided in Figure 2.

It is recommended that researchers use the ranges in Figure 2 as follows:

1. Compare Noise values obtained during advanced combustion research to the range from Figure 2 at the same engine speed and IMEP360.
2. If the observed Noise is outside the range in Figure 2, investigate ways to achieve Noise within (or at least toward) that range.
3. Explore the tradeoff between noise and other attributes such as efficiency and emissions, particularly in and around the noise ranges provided in Figure 2.

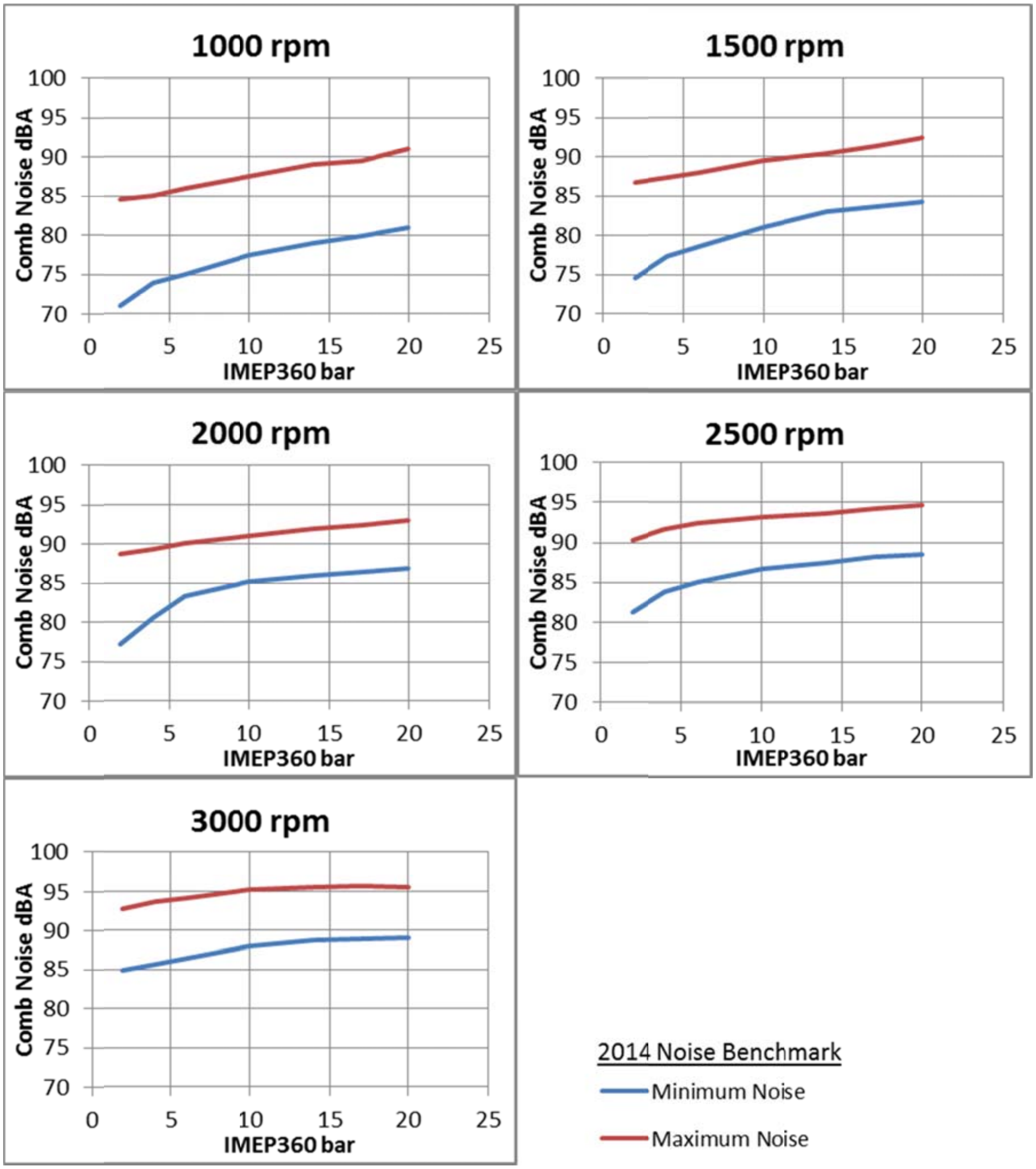

Figure 2. Typical range for combustion noise on modern production diesel engines when operated at 1000, 1500, 2000, 2500 and 3000 rpm.

When conducting research at multiple operating conditions, it is suggested not only to target a noise level within or near the provided range, but also to limit the rate of change of Noise with speed and load. Sudden changes in noise or non-monotonic behavior lead to customer complaints, service requests, product dissatisfaction and ultimately rejection of product technology. As an example, Figure 3 shows two examples plotted against the noise range at 1500 rpm. While the Noise for example #1 is consistently above the maximum noise line, the steady progression at an elevated level may be more acceptable to customers than the Noise shown in example #2, which has a sudden jump and a sudden decline in Noise as load increases.

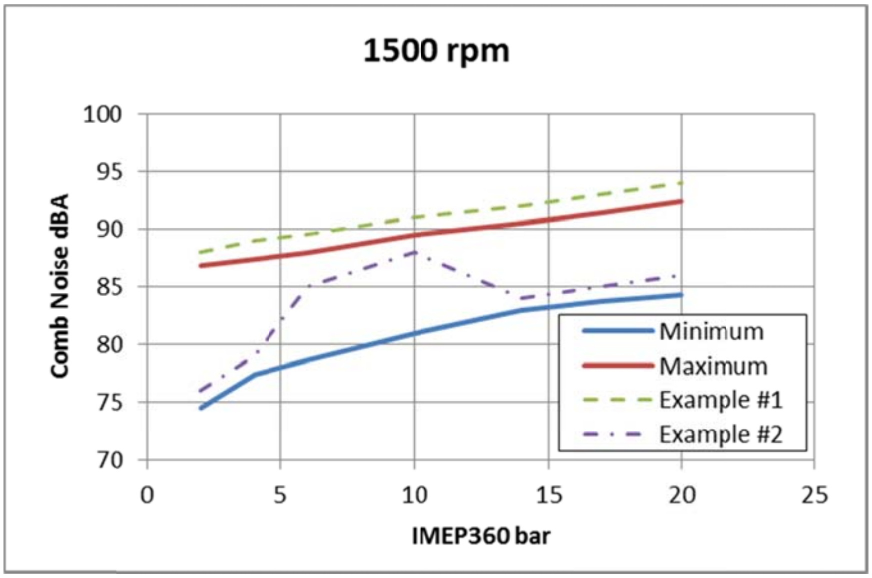

Figure 3. Generic examples of noise progression showing a good (example #1) and poor (example #2) noise progression.

The contours of the minimum and maximum benchmark Noise values represent a typical noise progression with speed and load. Figure 4, which provides the minimum and maximum Noise curves for all engine speeds, shows that Noise steadily and monotonically increases with both speed and load. The rate of increase in Noise with engine speed is typically less than 0.5 dB/100 rpm with some low speed conditions near the minimum noise values that approach 1 dB/100 rpm. The rate of change of Noise with IMEP360 is typically less than 0.6 dB/bar, except at very low loads where the progression is as high as 1.7 dB/bar. Researchers are encouraged to consult with industry partners when it is unclear whether observed rate of change of Noise with either speed or load is acceptable.

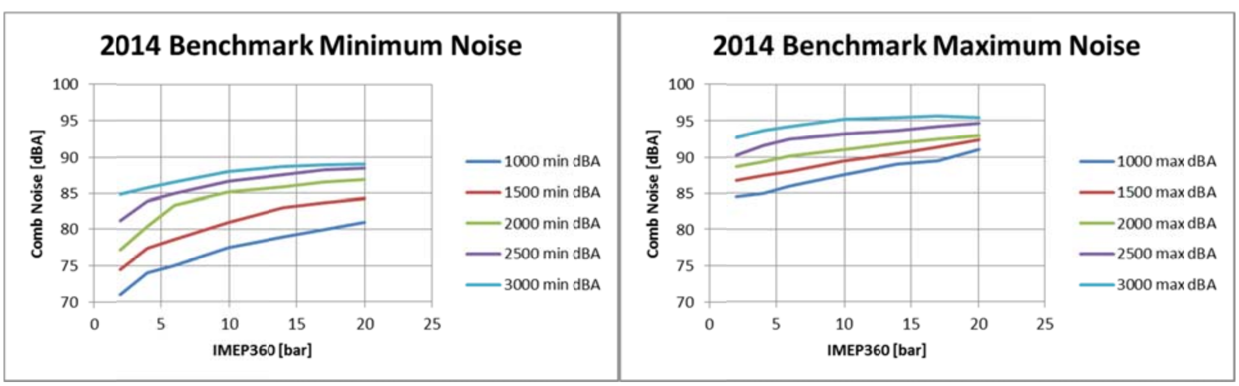

Figure 4. Maximum and minimum Noise curves showing noise progression with engine speed and load.

Ringing Intensity

Description and Calculation Method

The ringing intensity approximates the in-cylinder energy from combustion. The value is calculated with Eq. 1: [10]

$$RI \approx \frac{1}{2\gamma} \frac{\left(\beta \frac{dP}{dt_{max}}\right)^2}{P_{max}} \sqrt{\gamma R T_{max}} \,. \tag{1}$$

where γ is the ratio of the specific heats, β is a scale factor determined from experimental data (assumed to be 0.05 ms), dP/dt_{max} is the maximum derivative of the cylinder pressure (in kPa/ms) as calculated from a gradient of consecutive data points, P_{max} is the maximum cylinder pressure (in kPa), R is the specific gas constant, T_{max} is the maximum bulk gas cylinder temperature (in K) as determined from heat release analysis [11].

The scale factor β represents the ratio of the pressure pulsation amplitude to the maximum rate of pressure rise and may depend on the engine conditions. Eng assigned the parameter a value of 0.05 ms.

Data Acquisition Requirements

Cylinder pressure data is acquired and digitized at a resolution set by the test cell hardware. The recommended increment between data points is 0.2 degrees. A larger crank-angle increment of up to 1 degree is possible for engines not using compression ignition. The small increment is necessary for a good value of the pressure derivative. If the pressure derivative is calculated at the data point increment, a larger crank-angle increment will smooth the pressure curve and reduce the pressure gradient (dP/dt) and thereby reduce the ringing intensity.

Data is collected from 50 or more consecutive engine cycles, depending on the capability of the data acquisition system. The number of engine cycles recorded depends on the hardware installed at the measurement location and the engine variability. 50 engine cycles is suitable for an engine with low variability such as a diesel with low EGR. More cycles are required for higher variability engines such as a gasoline SI with high EGR.

The cylinder pressure data are filtered with a low-pass frequency filter with a cutoff frequency of 4 kHz. The cutoff is set so that the first order frequencies that are the significant contributor to the noise are not attenuated.

Maximum Ringing Intensity

The recommended maximum ringing intensity for combustion development is 5MW/m^2 for all speeds and loads.

This recommendation is based on OEM experience for combustion systems using spark ignition and compression ignition (diesel and gasoline). Sjoberg et al [12] also adopted this criteria for the ringing intensity.

Recommended Actions

The following process is recommended to assess combustion noise and determine relevance to automotive applications.

Step 1: Acquire digitized cylinder pressure data

- Recommended encoder resolution: At least 0.2 CA encoder resolution for 0.2 CA between samples.
- Recommended number of measured cylinder pressure cycles: 50 cycles or more, depending on cycle-to-cycle variability and data capacity. Record cycles individually.
- Recommended low-pass filter: No filtering until post-processing.
- Best practice: Apply an anti-aliasing filter with a cut-off frequency at the Nyquist frequency (if available). Note: When acquiring time-based data, an anti-aliasing filter is required.

Step 2: Calculate <u>BOTH</u> Noise and Ringing Intensity from digitized cylinder pressure data

Noise: (apply the following procedure if a commercial noise meter is not used)

1. Use raw, individual cycle cylinder pressure data (No digital filtering or ensemble averaging of input data prior to calculation)
2. Calculate Noise for each individual pressure trace
    - Full cycle data: Use a commercial noise meter to calculate Noise or the algorithm presented in [3].
    - Partial cycle data: Use method presented in [8].
3. Average Noise from step 2 over all cycles and all cylinders to determine overall Noise

Ringing Intensity:

1. Apply a low-pass filter with a 4 kHz cutoff frequency to the cylinder pressure data
2. Determine the maximum pressure, maximum temperature and maximum pressure gradient for each cycle
3. Average the maximum pressure, maximum temperature and maximum pressure gradient from step 2
4. Use the values from step 3 in Eq. 1 to compute the ringing intensity

Step 3: Compare each metric to its respective guideline value(s)

Noise:

- Typical automotive diesel ranges provided as a function of IMEP360 for 5 engine speeds
- Compare how calculated Noise compares with the range at each test condition (as defined by engine speed (N) and IMEP360)
- If testing at multiple operating conditions, compare the rate of change of Noise with N and/or IMEP360

Ringing Intensity:

- Compare calculate ringing intensity with the maximum recommended value of 5 MW/m^2.

If the value for both Noise <u>and</u> Ringing Intensity is below the maximum recommended value provided, the combustion concept may be acceptable in a light-duty vehicle application.

Step 4: Report results

- Report BOTH combustion noise level and ringing intensity
- Noise should be reported in absolute dBA. Reference to the proximity to the provided range for that operating condition can also be useful.
- Ringing Intensity should be reported in MW/m2, with optional reference to 5 MW/m2 maximum value.

Step 5: Explore the tradeoffs between noise and other attributes

It is highly valuable to understand how thermal efficiency and emissions change with noise. The ACEC Tech Team encourages exploration around the recommended values for both Noise and Ringing Intensity.

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