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How loud is X-59's shaped sonic boom?

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NASA's X-59 Quiet SuperSonic Technology low boom flight demonstrator aircraft is designed to produce a shaped sonic boom or "sonic thump" of 75 dB Perceived Level (PL) at the ground. One communication challenge that NASA's Low Boom Flight Demonstration Mission faces is how to describe the sonic thump to the public, most of whom have never heard a sonic thump or a sonic boom. Furthermore, the public is unfamiliar with the acoustic metrics such as PL used to describe impulsive sounds. One technique to describe unfamiliar sounds using words and graphics only is to put them in the context of more familiar sounds, both in terms of acoustical level and in terms of sound type (continuous vs. impulsive). In this work, a database of recordings of familiar impulsive noise sources at known distances and their associated PL values was assembled and is available online. The comparison of these sounds can be framed as a "thermometer" of acoustic levels. An example acoustic thermometer graphic is presented. Additionally, the impulsive sounds' one-third octave band sound pressure levels and sone spectra are compared to that of a simulated X-59 ground waveform. These show the origin of differences in the PL of each sound.

1. MOTIVATION AND BACKGROUND

Commercial supersonic flight over land has been prohibited since 1973 primarily due to the loudness and startle of sonic booms.[1] NASA has contracted Lockheed Martin to build a demonstration aircraft, the X-59 Quiet SuperSonic Technology aircraft (QueSST),[2] which will produce a low amplitude, quiet sonic boom or "sonic thump." The target loudness for the X-59 is 75 dB on the Stevens Perceived Level (PL) scale.[3,4] The PL metric was previously shown to correlate with human perception of sonic booms.[5] The X-59 will be flown over communities in the USA, and members of the overflown communities will be asked to rate their perception of sonic thumps at various loudness levels. The perceptual response data will help regulators make an informed decision on whether or not to overturn the prohibition on supersonic overland flight, and if so, establish allowable noise standards.

When explaining the X-59 conceptually, a common question received was "how loud is it?" A meaningful answer to this question proved difficult for a few reasons. For the majority of the USA, sonic booms are a very rare event. Many people have never heard a sonic boom. Traditional loudspeakers cannot adequately reproduce the low-frequency-dominated sonic boom waveforms, so it is not practical to play the sonic booms or thumps except in specially designed facilities. It was also shown that common noise metrics, especially those used for continuous sounds, do not correlate well with human perception of impulsive sonic booms. The general public has limited knowledge of the PL metric. Thus, the 75 PLdB level of the X-59 has little explanatory value without context of other sounds. To summarize, it was ineffective to describe an unfamiliar sound that cannot be properly reproduced over typical loudspeakers using a metric with which few are familiar.

The primary output of the current work is a database of recordings of familiar impulsive noise sources at known distances. Another output is a thermometer-type scale that puts the X-59 sonic thump in context with other sounds quantitatively. The thermometer is presented in terms of the PL metric, which is commonly used to describe sonic booms, but the thermometer could easily be converted to other acoustic metrics.

2. IMPULSIVE SOUND DATABASE

The database of common impulsive sounds was populated using a combination of NASA recordings, recordings form external partners, and simulated sounds. The sound recordings were made in the field and not under laboratory conditions, so the precision was not tightly controlled. Because the goal of this work is to aid in general understanding, the precision limitations were deemed acceptable. The description of the recording or simulation techniques and environment for each of the impulsive sounds included in the database is outlined below and in Table 1.

The NASA recording system was made up of a 1/2" GRAS 40AQ microphone and 26CA preamplifier powered by a GRAS 12AX power module and digitized by a Tascam DR-70 recorder. The microphone was calibrated using a B&K Type 4231 single tone calibrator. Hand claps and 1' diameter balloon pops were recorded at 3' in a 15' by 11' by 10' anechoic chamber at NASA Langley. Finishing and lumber nails measuring 1.25" and 2", respectively, being hammered into a wooden two-by-four were recorded at 2' in a 12' by 10' by 10' anechoic chamber also at NASA Langley. The sound of a sedan car door shutting or slamming was recorded outdoors at 3' from the vehicle on a 4' tripod. The interior noise of the door slamming was also recorded at the location of the driver's head. The basketball bounces were recorded in an empty fieldhouse-style gymnasium on a 4' tripod placed 4' from the ball. Thunder was recorded outdoors under a building overhang on a 4' tripod.

Several sounds were provided by external partners. The firework waveform was recorded on a tripod roughly 500' below the firework using a 1/4" B&K microphone. The gunshot recordings were measured at the shooter's head.

Several sounds were produced by simulation. Waveforms of the car door slam recorded across the street and down the block sounds were derived from the pressure signals of the car door slam near the car and with simple spherical spreading applied to the pressure amplitude. Because the X-59 has not been built and flown, its sonic thump waveform was simulated. Finally, the PL of the Concorde boom that is commonly quoted was verified using a simulated signature with overpressure and duration from Fig. 2.1 of Ref. 6.

3. PROCESSING THE SOUNDS TO COMPUTE PL

The PL value of the sounds was computed using the method of Sullivan and Shepherd[4] with a 300 ms window. This window length was chosen to slightly exceed the Concorde boom duration. The Concorde boom had the longest impulsive duration of the sounds in the database. A 5% cosine taper was applied to the ends of the window. For sounds such as the anechoic recordings that were shorter than 300 ms, the cosine taper was applied closer to, but not intersecting the impulse, and the windowed signal was padded with zeros until it was 300 ms long.

Table 1. Impulsive noise sources and measurement description.

Noise Source	Quantification Method	Measurement System	Environment	Location or Distance from source	Mic height
Gunshot	Recorded	External partner	Outdoors	Shooter's head	-
Firework	Recorded	External partner	Outdoors	500'	12'
Balloon pop	Recorded	NASA	15' by 11' by 10' anechoic chamber	3'	Not measured
Concorde sonic boom	Simulated based on recordings	NASA Simulation	Outdoor simulation	60,000'	Ground
Car door slam recorded inside the car	Recorded	NASA	In sedan cabin	Driver's head	-
Nearby thunder	Recorded	NASA	Outdoors	Not measured	4'
Hand clap	Recorded	NASA	15' by 11' by 10' anechoic chamber	3'	Not measured
Nail struck by hammer	Recorded	NASA	12' by 10' by 10' anechoic chamber	2'	2'
Car door slam recorded outside the car	Recorded	NASA	Outdoors	3'	3'
Basketball bounce	Recorded	NASA	Fieldhouse style gym	4'	4'
X-59 sonic thump	Simulated	NASA Simulation	Outdoor simulation	54,000'	Ground
Car door slam recorded across the street	Simulated based on recordings	NASA Simulation	Outdoor simulation	20'	3'
Distant thunder	Recorded	NASA	Outdoors	Not measured	4'
Car door slam recorded down the block	Simulated based on recordings	NASA Simulation	Outdoor simulation	100'	3'

Special considerations were made for determining the PL of the nearby and distant thunder. Instead of a true impulse, thunder can be a fairly long set of impulses or an impulse train. Thunder was recorded throughout a storm over Hampton, Virginia, and the audible events were manually extracted from the long time series. These audible event selections were longer than 300 ms. To compute the PL of each of the thunderclaps, a 300 ms window with 5% cosine tapered ends was slid over each audible signal with 95% overlap and PL was calculated for each segment. The maximum PL of all segments of a thunderclap was assigned as the PL of each of the thunderclaps. The nearby thunder source in the database was chosen to be the loudest thunder signal heard during the storm. Distant thunder describes all the other thunder signals.

Future versions of the database could be expanded to include lower PLdB values using recordings of low-level impulsive sounds such as keyboard clicks.

Table 2 shows the sound sources, the number of waveforms per source, the median, maximum, and minimum PL. The median and range of PL values of the sounds were used to populate the thermometer-type PL scale in Figs. 1 and 2. The pressure waveforms of the sounds in the database are available online.[7]

Table 2. PL statistics of the recorded waveforms in the impulsive noise database.

Noise Source	Number of waveforms	Median PLdB	Max PLdB	Min PLdB
Gunshot	2	131.0	133.9	128.1
Firework	1	113.6	-	-
Balloon pop	4	109.0	110.1	108.1
Concorde sonic boom	1	105	-	-
Car door slam recorded inside the car	6	103.8	105.3	100.4
Nearby thunder	1	102.0	-	-
Hand clap	10	97.2	100.3	89.7
Nail struck by hammer	27	95.9	103.3	79.3
Car door slam recorded outside the car	10	90.3	92.1	85.1
Basketball bounce	8	81.3	91.3	79.8
X-59 sonic thump	1	75	-	-
Car door slam recorded across the street	10	74.5	76.0	70.4
Distant thunder	15	73.8	83.8	70.3
Car door slam recorded down the block	10	61.8	63.5	57.7

4. THE IMPULSIVE NOISE PL THERMOMETER

Two versions of the Impulsive Noise PL thermometer chart are shown in Figs. 1 and 2. The first chart includes the noise sources, the recording distance, and the range of levels of the recorded signals. The simplified version of the chart in Fig. 2 only shows the noise sources and their median recorded levels. The sound levels closest to those of the X-59 sonic thump were the car door slams recorded across the street and distant thunder.

The one-third octave band sound pressure level and sone spectra of the sounds in the database are shown in Fig. 3. The X-59 spectrum is shown in each plot as the blue dash-dotted line. The average spectrum of each type of sound is shown as the black line. Note that the sone axis scale changes amongst noise sources. Looking at both spectra is informative because both are intermediate steps in calculating PL. The pressure band levels determine the sone levels. The maximum sone value and the sum of the sone values at each one-third octave band are two important quantities for calculating PL.

The X-59 sound pressure level spectrum peaks at about 10 Hz and drops off rapidly. However, its sone spectrum peaks at around 100 Hz. The distant thunder sone spectrum matches the X-59's sone spectrum quite well, indicating they will sound similar.

5. SUMMARY

NASA is building the X-59 demonstration aircraft to provide data to regulators about people's perceptions of sonic thumps. The X-59 is designed to have a 75 PLdB sonic thump. In order to more effectively explain this uncommon noise source using the PL metric, several common impulsive noise sources were measured and their PL was computed. The recorded sounds are available online. The measurements have uneven precision due to the conglomeration of different recording systems and techniques, but it is adequate to increase general understanding of sonic thumps. Two thermometer-style Impulsive Noise PL Scale charts were created to put these sounds in context. The first version of the chart has the full ranges of the measured impulsive noise sources and source distances. The simplified version shows only the median PL value of the measured noise sources. Spectra of the sounds are also shown. These graphics will help describe sonic thumps to the general public.

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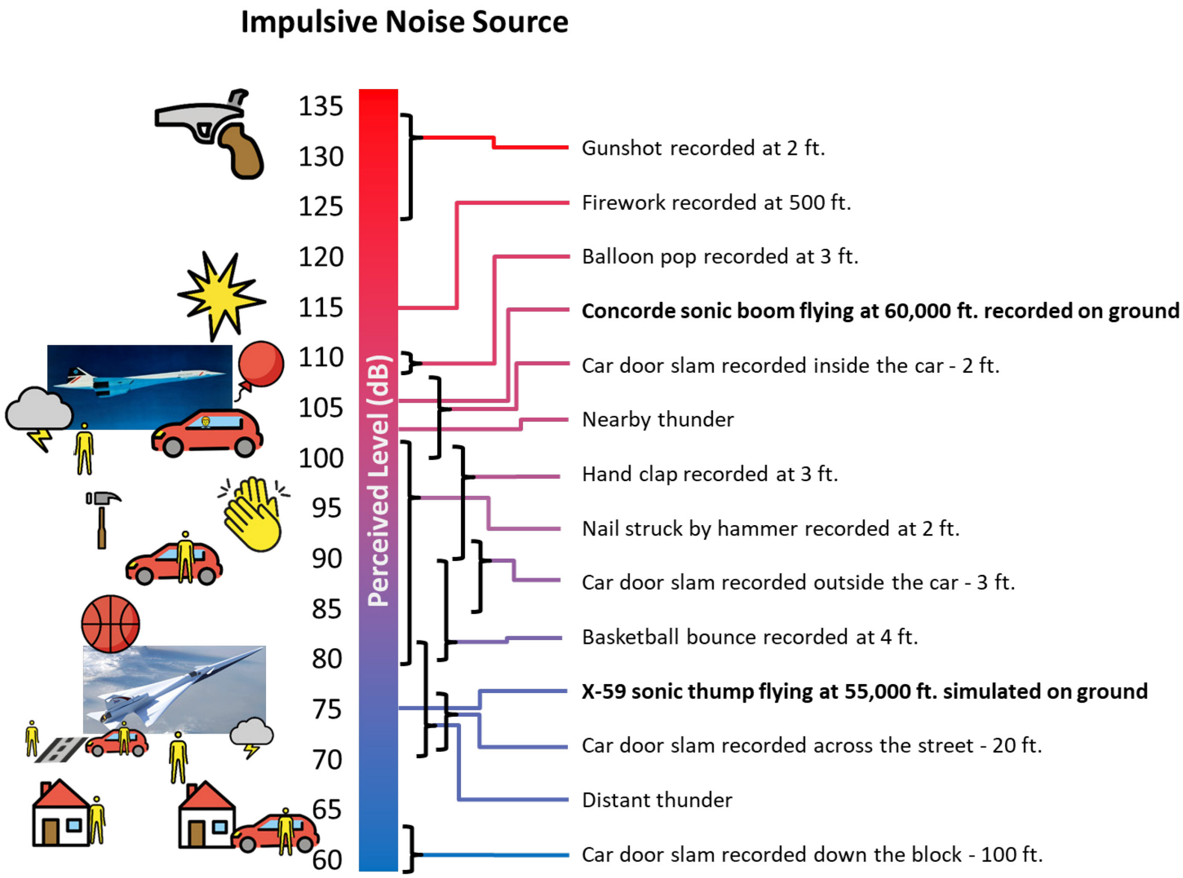

Figure 1. The Impulsive Noise PL Scale with noise source ranges.

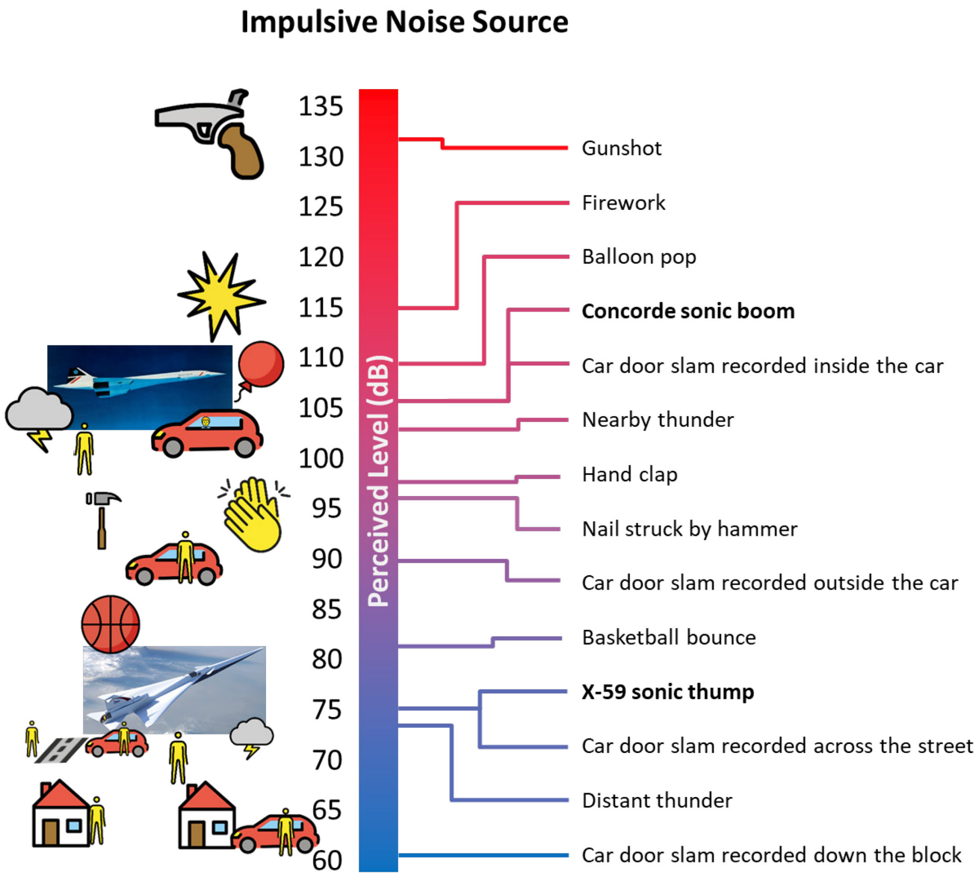

Figure 2. The Simplified Impulsive Noise PL Scale.

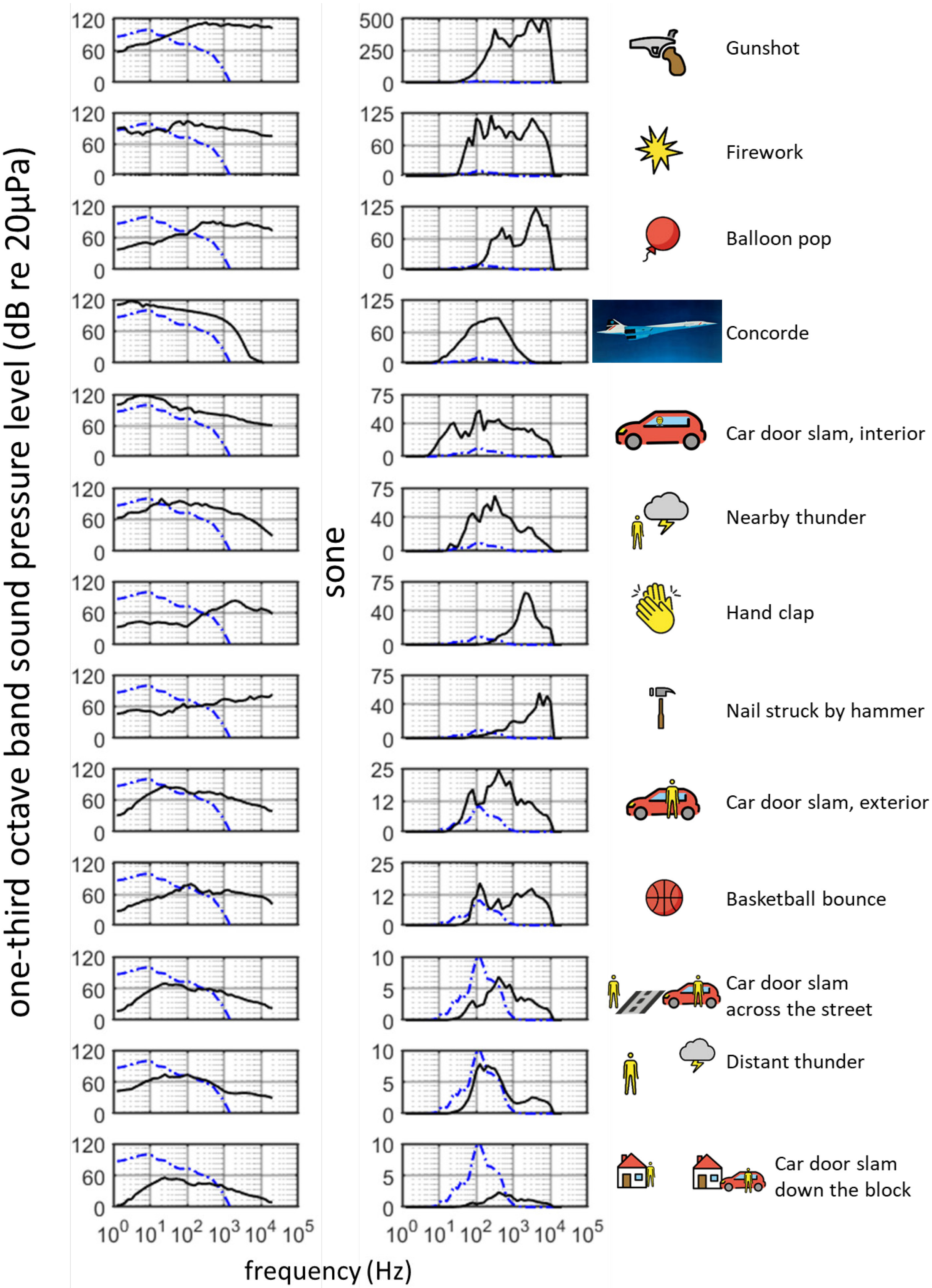

Figure 3. The average one-third octave band SPL and sone levels of the sounds in the PL database. The blue dash-dotted line is the X-59 spectrum.