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Estimating the noise dose range of the NASA X-59 aircraft in supersonic cruise using PCBoom propagation simulations

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Abstract: PCBoom propagation simulations of the NASA X-59 low-boom in supersonic cruise were conducted using near-field CFD pressure waveforms as inputs to estimate the noise dose range. Low-booms were propagated through realistic atmospheric profiles from the Climate Forecast System Version 2 across the USA, and loudness statistics of the low-booms are presented. The near-field waveforms correspond to aircraft configurations expected to produce minimum- and maximum-loudness levels on the ground. The simulations show that the practical Perceived Level noise dose range is 72 to 86.7 dB. Dose ranges for other single event and cumulative sonic boom metrics of interest are also provided.

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1. Introduction

NASA plans to fly its X-59 aircraft in supersonic cruise over several communities across the USA in support of its Quesst Mission.[1] Members of the communities will be recruited to respond to surveys collecting their perceptual response to the X-59 low-boom from a single flyover as well as their end-of-day perceptual response to the cumulative daily flyovers. A range of noise levels is needed to quantify the perceptual response vs the noise dose to enable estimates of the functional form of the dose-response relationship to assist regulators in determining a noise limit. The goal of this work is to estimate a practical dose range for the X-59, defined as the range of levels that can be achieved across the inner portion of its cruise carpet (described in Sec. 2.3) for a set of realistic atmospheric profiles. This practical dose range will be useful for X-59 community test planning.

Recent adjoint-based simulation optimizations identified the flight conditions and control surface deflections within the X-59 cruise flight envelope that achieve the minimum and maximum undertrack loudness level.[2] The optimizations used the NASA Cart3D[3] inviscid computational fluid dynamics (CFD) code to generate the near-field pressure signatures, which were subsequently propagated to the ground through a standard atmosphere without winds. Throughout the current work, this pair of optimized conditions will be referred to as the minimum and maximum loudness cruise conditions. Note that different maxima and minima would be observed if maneuvering flight and focusing were considered. For this paper, only the steady, level cruise condition is considered because this is how the X-59 will overfly the community noise survey areas. To provide increased confidence in the dose range results presented in this work, an additional pair of near-field pressure data were generated for the same aircraft configurations using a second CFD code, the NASA Fully Unstructured Navier-Stokes 3D code (FUN3D).[4] A primary difference between the two codes is that FUN3D solves the viscous Reynolds-averaged Navier-Stokes equations, and Cart3D solves the inviscid Euler equations. The results in this work for both CFD codes are in reasonable agreement, which is shown in Secs. 2.1 and 3.

As stated above, to aid in test planning, it is of interest to quantify the practical dose range of the X-59 that is expected after propagation through realistic atmospheres. Here, the X-59 near-field pressure corresponding to its minimum and maximum loudness supersonic cruise conditions were propagated from the aircraft to the ground through one year of realistic atmospheric profile data from the Climate Forecast System Reanalysis Version 2.[5] The atmospheric profiles were obtained once per day at 19 locations across the USA to capture a range of climate and seasonal conditions. Propagation was conducted for four cardinal aircraft headings to capture the effects of winds. The 19 propagation locations are typical of locations where the X-59 may be flown. However, the exact locations are not disclosed in this work because the final test sites have not been chosen. The Stevens Mark VII Perceived Level (PL),[6,7] as well as five additional metrics described in Sec. 4, was computed for ground waveforms in the primary boom carpet, which is defined as the region exposed to

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noise that is initially directed downward toward the ground from the aircraft. The edges of the primary boom carpet are defined by the lateral cutoff rays, which are the outermost rays that reach the ground without being refracted back upward.

In the community tests, the survey respondents will be recruited from an area within the 40 km-wide (24.85 statute mile-wide) inner portion of the X-59 primary boom carpet. This width was chosen because the majority of X-59 carpets are at least this wide. The mean PL value of the booms within this 40 km region of each carpet was computed in this work, which is referred to as the inner carpet mean PL. At each location, the median value of the one year of inner carpet mean PLs was computed, as well as the interquartile range of the inner carpet mean PLs. Ultimately, the difference between the average of the 19 medians for the maximum loudness configuration and the average of the 19 medians for the minimum loudness configuration is used as the practical "single event" dose range. "Single event" refers to the loudness of a single X-59 supersonic flyover.

The practical daily cumulative dose range of the X-59 is also of interest for test planning. The X-59 operational tempo enables up to six supersonic flyovers per day. The cumulative dose range is given in Day-Night-Average Perceived Level (PLDNL), as well as five other metrics, with the low end of the range achieved with one supersonic flyover during the day at its minimum loudness configuration and the high end of the range achieved with six supersonic flyovers during the day at its maximum loudness configuration.

The current work differs from a previous X-59 low-boom propagation study in several ways.[8] The previous study utilized an earlier design iteration of the X-59, "C609," while this work uses the latest design iteration, "C612A." Compared to C609, the C612A design adjustments include lengthening the nose by about 0.6 m (2 ft) and a variety of outer mold line refinements to include additional systems such airdata probes, environment control, external vision system camera,[9] antennas, and updated control surface geometry. CFD grid refinement also improved. The propagation analyses in this work use PCBoom version 7 instead of 6.7.1. Although the computational implementation of the propagation physics between these versions did not change, the precision in the ray landing locations and the sonic boom perception metrics computation improved. Additionally, much of the previous work focused on the loudness of the undertrack ray of the X-59 in its minimum loudness configuration, but this work computes the mean PL in the inner portion of the carpet for the minimum and maximum loudness configurations. The inner carpet mean PL is likely to be more representative of the exposure experienced by survey participants during community testing than using the undertrack level alone, for example.

2. Propagation information

The NASA PCBoom 7 code[10] was used to propagate the X-59 low-boom from the aircraft near-field to the ground at 19 locations across the USA, which span the country and its climate zones.[11] PCBoom takes as inputs the near-field pressure, the atmospheric profile, and the aircraft trajectory. In this work, the X-59 data were propagated at four cardinal headings at each location.

The PCBoom Enhanced Burgers module[12] was used to perform the propagation simulations in its footprint mode, which outputs the ray landing positions and sonic boom metrics at the ground. The Burgers propagation step size was set to 1, or 60.96 m (200 ft) along the ray, which is the smallest step size allowed. The sampling frequency was set to 100 kHz. The free-field pressure waveforms at the ground are multiplied by 1.9 to approximate the ground reflection factor. More details are on page 39 of Ref. 10. A flat ground is assumed using the local ground elevation at each location.

PCBoom requires specification of the aircraft trajectory, which was set to perfect cruise, i.e., steady and level, for the corresponding min or max loudness flight condition. The min loudness condition has the X-59 at 16.215 km (53 200 ft) mean sea level (MSL) at Mach 1.4. The max loudness condition has the X-59 at 13.106 km (43 000 ft) MSL and at Mach 1.3. Four cardinal headings were tested, resulting in a total of 8 trajectories (2 for min/max times 4 headings).

Finally, near-field pressure data and an atmospheric profile are needed, which are described in more detail in Secs. 2.1 and 2.2. The propagation simulations were performed using Intel Gold 6148 Skylake nodes on the NASA K-cluster midrange supercomputer. A summary of the propagation items that were varied is in Table 1 with more detail on each in the remainder of Sec. 2.

2.1 Near-field pressure and standard atmosphere predictions

The near-field pressure data were obtained using Cart3D and FUN3D for the X-59 in its minimum and maximum loudness flight conditions. As noted in Sec. 1, the designation for this iteration of the X-59 design is "C612A." The min and max loudness conditions were identified using the method outlined in Ref. 2. The method provides the Mach number, altitude, angle of attack, and control surface deflection angles to achieve the min and max loudness of the undertrack ray at the ground after propagation through a standard atmosphere. These near-field data were provided in a cylindrical format with axial pressure along the aircraft given every 2.5° azimuth at a cylinder radius to aircraft length ratio of 3 (i.e., $R/L = 3$), with the length L taken to be 27.4 m (90 ft). The data were transcribed into the PCBoom CYLINDERVARYX format, details of which are outlined in Sec. 3.1.12.9 of the PCBoom 7.1 User's Guide.[10]

Figure 1 shows several interesting quantities for the X-59 in its min and max loudness condition assuming a standard atmosphere.[13] The standard atmosphere uses the ICAO 7488/3[14] for temperature and pressure with no wind.

Table 1. Description of the factors varied to estimate the practical dose range of the X-59.

Factor varied	Description	Factor levels
Aircraft Configuration	Min (Mach 1.4 at 53 200 ft) and Max (Mach 1.3 at 43 000 ft)	2
Near-field CFD Code	Cart3D and FUN3D	2
Aircraft Heading	North, East, South, and West	4
Location	19 locations; ground elevation varies from 0 to 4900 ft MSL	19
Time period	18:00 UTC daily over 1 year (2017)	365
Total number of simulated carpets		110 960

The humidity profile is taken from Table 1 of ISO 5878 Addendum 2 at 50° N latitude, annual median[15] from 0 to 8 km and ISO 9613-1 Annex C otherwise.[16] In each subplot, the black curve and triangles correspond to the Cart3D min loudness data, the blue curve and circles correspond to the FUN3D min loudness data, the magenta curve and triangles correspond to the Cart3D max loudness data, and the red curve and circles correspond to the FUN3D max loudness data. Figure 1(a) shows the near-field pressure at 16.215 km (53 200 ft) for the min loudness or 13.106 km (43 000 ft) for the max loudness condition. The front portion [0 to about 15.24 m (50 ft)] of the near-field pressures are fairly similar between the four cases; however, the rear portion of the waveforms differ with the max loudness conditions having sizeable spikes

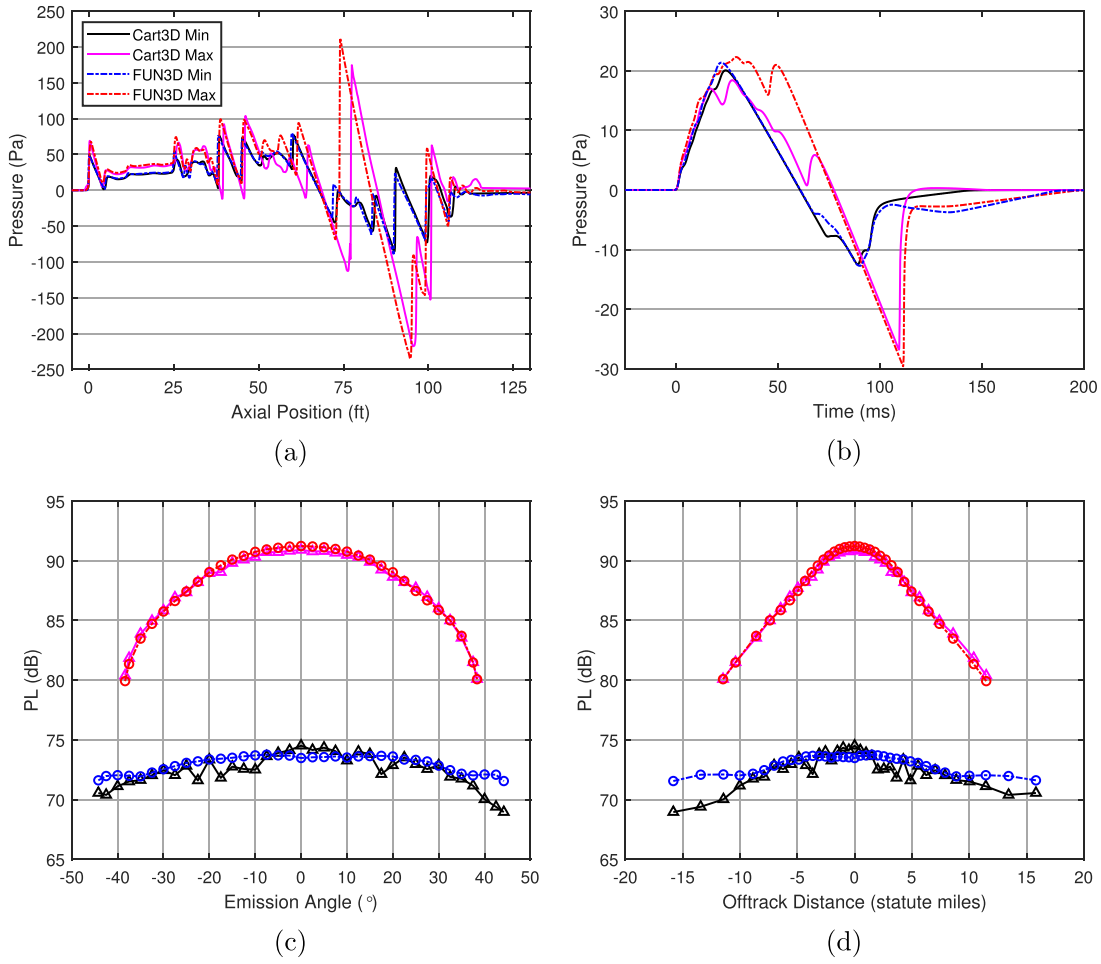


Fig. 1. Waveforms and PL for Cart3D Min (black, triangles), Cart3D Max (magenta, triangles), FUN3D Min (blue, circles), FUN3D Max (red, circles). (a) The near-field pressure undertrack. (b) Undertrack ground waveforms after propagating through a standard atmosphere. (c) PL of the ground waveforms as a function of azimuthal emission angle. (d) PL as a function of lateral distance from the undertrack ray.

due to changes in the control surface deflections from the max-loudness optimization procedure. On the ground, these result in a shock at the rear of the waveform as shown in Fig. 1(b). Figures 1(c) and 1(d) show the PL of the off-track booms on the ground as a function of azimuthal emission angle or distance from the undertrack ray. The figure illustrates why the inner carpet mean PL is more representative of what survey participants will experience rather than the undertrack PL. The PL for the max loudness configurations match almost exactly, while the carpet PL for the FUN3D min loudness case is slightly flatter than for the Cart3D solution.

2.2 Climate Forecast System Version 2 Reanalysis

Atmospheric profiles were taken from the NOAA Climate Forecast System Version 2 Reanalysis (CFSv2) database.[5] One profile per day per location was selected for the year 2017 at 18:00 UTC. This corresponds to around midday, 10:00 to 14:00 local time depending on the USA time zone and daylight/standard time. CFSv2 has 0.5° by 0.5° spatial resolution with data available every 6 h on 37 isobaric pressure levels from 1000 mbar to 1 mbar. Occasionally the 1000 mbar isobar of the atmospheric profile, which is the isobar at the lowest elevation provided by CFSv2, is above the local ground. In this case, the profile is supplemented with near-ground forecast data from the CFSv2 18:00 UTC +1 h forecast following Ref. 8. The pressure, temperature, winds, humidity, and ground elevation data of the atmospheric profiles were transcribed to the PCBoom ATT input file format (see Ref. 10, Sec. 3.1.8.1 for more details).

2.3 Inner carpet definition

For perfect cruise trajectories and unvarying terrain, the 2 D primary boom carpet of an overflight can be described by a 1 D curve lateral to the flight path because the loudness does not change with distance along the flight track. This 1 D curve is shown in Fig. 2 and is known as an "isopemp." Low-booms generated by the aircraft at the same instant in time but at different azimuthal emission angles arrive at the ground along the isopemp line. This is the "ray viewpoint" as described in Fig. 6.1.4 of Ref. 17.

As discussed in Sec. 1, understanding the inner portion of the carpet is of interest for X-59 community tests. Three options were explored for defining the inner carpet: undertrack-centered inner carpet, center-anchored inner carpet, and edge-anchored inner carpet. The undertrack-centered inner carpet captures the rays that land within ±20 km from the undertrack ray. The center-anchored inner carpet first finds the midpoint of the carpet between the two lateral cutoff rays, then the inner carpet contains those rays that land within ±20 km of the midpoint. The three definitions resulted in nearly identical inner carpet statistics, so only the edge-anchored carpet results are shown here for brevity.

The edge-anchored carpet definition has three cases, which are shown in Fig. 2. Case 1 is when both lateral cutoff rays are greater than 20 km from the undertrack ray. In this case, the inner carpet includes all rays that land within 20 km of the undertrack ray. Case 2 is when the geometric carpet width is less than 40 km. In this case, all rays that reach the ground comprise the inner carpet. Finally, case 3 is when one side of the carpet is less than 20 km from the undertrack ray, but the other side of the carpet is greater than 20 km from the undertrack ray. In this case, the shorter edge of the carpet is used as an "anchor," and all rays that land within 40 km of this ray are included in the inner carpet. After the inner carpet is identified for each carpet, the mean PL of the inner carpet is computed. On average, 32 rays land within the inner carpet.

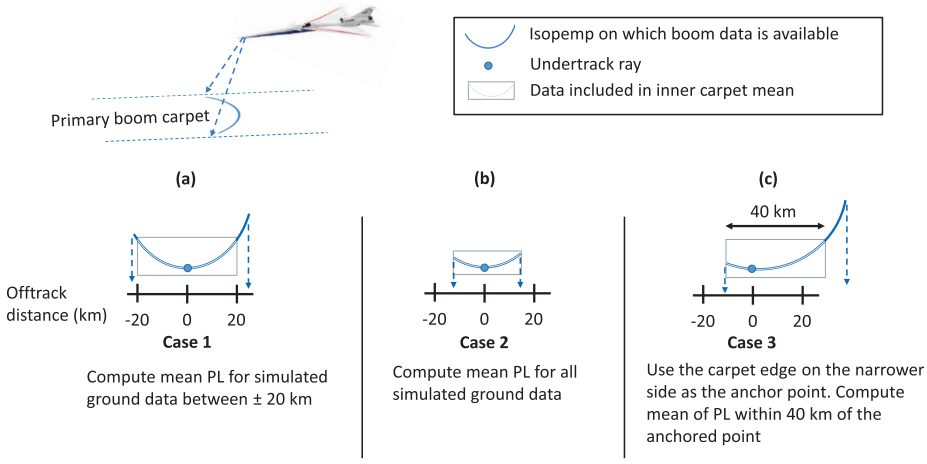


Fig. 2. Three cases defining the 40 km edge-anchored inner carpet. The cases are shown as a top-down view along an isopemp. (a) Both lateral cutoff distances are greater than 20 km from undertrack. (b) The carpet is less than 40 km wide. (c) One side of the carpet is less than 20 km from undertrack while the other is greater than 20 km from undertrack.

3. Dose range results

At each location, the median and interquartile of mean PL of the inner carpet were computed grouping the 1-year carpet results from each heading. These results are grouped together for each location, resulting in $365 \times 4 = 1460$ inner carpet mean PL per group, and are shown in Fig. 3. The medians are shown by the markers, and the interquartile is given by the whiskers. The Cart3D results are shown by the triangle markers, and the FUN3D results are shown by the circle markers. The colors group locations within similar geographic regions. The interquartiles of the Cart3D and FUN3D max condition results are nearly identical, with FUN3D less than 0.5 dB greater than Cart3D. The interquartiles of the Cart3D and FUN3D min loudness condition results are also in fairly good agreement, with FUN3D about 1 dB greater than Cart3D. In the rest of this work, the FUN3D results are used to compute the dose ranges as its dose range is more conservative, and as stated in Sec. 1, the FUN3D code includes additional physical effects that are neglected in Cart3D. It is also notable that location A1 has the lowest PL values. Location A1 is Edwards, CA, where the dry desert climate reduces the X-59 low-boom loudness due to increased atmospheric absorption. The other locations are not disclosed as noted in Sec. 1.

The practical single event PL dose range of the X-59 was determined by computing the difference in the average of the 19 medians of the maximum loudness and the average of the 19 medians of the minimum loudness configuration of the inner carpet mean PL for the FUN3D results (i.e., the 19 min/max dots in Fig. 3). The resulting dose range is 72.0 to 86.7 dB.

The cumulative daily dose range of the PLDNL metric was also computed, utilizing the operational tempo of the aircraft. The X-59 can deliver up to six low-booms per day to the test community. The cumulative daily dose PL_{dn} of i low-booms, each with a PL dose of S_i in dB is given by

$$PL_{dn} = 10 \log_{10}\left(\sum_i 10^{S_i/10}\right) - 49.4. \tag{1}$$

Details of Eq. (1) are available in Ref. 18 on page 85. The low end of the cumulative dose range is set by the PL_{dn} of one supersonic flyover event at its minimum loudness of 72.0 dB. This results in a PLDNL of 22.6 dB. The top end of the cumulative dose range is set by the PL_{dn} of six supersonic flyovers at its maximum loudness of 86.7 dB. This results in a PLDNL of 45.1 dB. Thus, the PLDNL dose range is 22.6 to 45.1 dB.

4. Dose ranges of additional perception metrics

In addition to PL, five other single event perception metrics are of interest to the ICAO for potential future supersonic aircraft noise certification standards, and dose-response data for all of these metrics will be collected during X-59 community tests. These are the Indoor Sonic Boom Annoyance Predictor (ISBAP), and A-, B-, D-, and E-weighted sound exposure level (SEL). A dose range for each metric is also of interest. Dose ranges for these other metrics, computed using the procedure described in Sec. 3, are given in Table 2 along with PL. These six single event metrics also have cumulative dose counterparts computed as in Eq. (1). The cumulative dose ranges are also in Table 2.

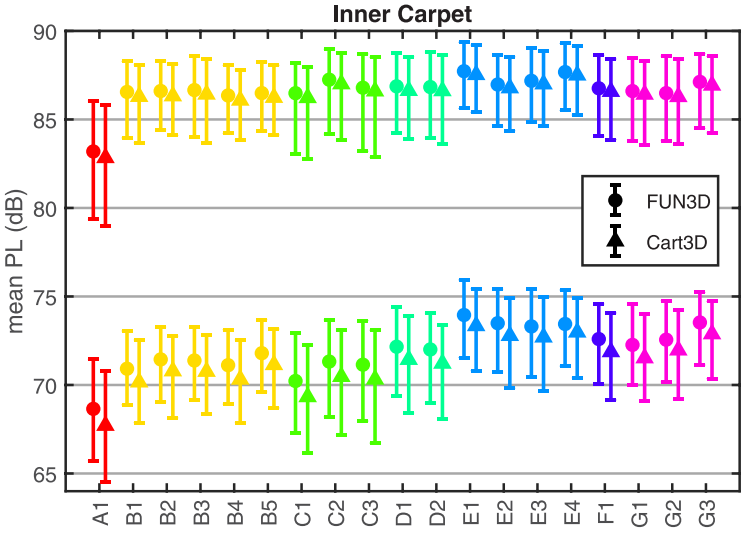


Fig. 3. Median (marker) and interquartile range (whiskers) of inner carpet mean PL for 19 locations across the USA, grouped by similar geographic regions. The Cart3D results correspond to the triangle markers, and the FUN3D results correspond to the circle markers. Results are shown for both the maximum and minimum loudness configuration for each location.

Table 2. X-59 single event (left) and cumulative (right) dose ranges for six perception metrics.

Single event				Cumulative			
Metric	Low (dB)	High (dB)	Range (dB)	Metric	Low (dB)	High (dB)	Range (dB)
PL	72.0	86.7	14.7	PLDNL	22.6	45.1	22.5
ASEL	57.6	72.5	14.9	ASELDNL	8.2	30.9	22.7
BSEL	74.1	83.8	9.7	BSELDNL	24.7	42.2	17.5
DSEL	77.6	84.2	6.6	DSELDNL	28.2	42.6	14.4
ESEL	68.9	80.4	11.5	ESELDNL	19.5	38.8	19.3
ISBAP	85.5	95.9	10.4	ISBAPDNL	36.1	54.3	18.2

It is interesting to note that DSEL and BSEL have smaller single event dose ranges, and that PL has one of the largest dose ranges. The same trend is found for the cumulative dose ranges, but the values are somewhat larger because up to six supersonic overflights can be conducted per day. In X-59 community testing, the survey responses are the same regardless of the metric chosen for the dose. The implications of this for modeling dose-response data are not immediately obvious as the metrics with smaller dose ranges are typically affected less by ambient noise and turbulence.

5. Limitations

It is important to note the limitations of this study. Only one year of atmospheric model data is used at each location and for four cardinal headings to compute the dose range. Using a single number such as the inner carpet mean PL for the dose range obscures the fact that participants will experience doses around and beyond this value. Additionally, the effects of atmospheric turbulence are neglected. On average, turbulence reduces the loudness of sonic booms, but it can result in higher levels.[19,20] Steady, level cruise flight is assumed, while the effects of real piloting would introduce additional perturbations on the loudness. Finally, the near-field is propagated assuming constant altitude above MSL regardless of the atmospheric pressure, even though the CFD data is generated at a specific Reynolds number. Finally, the X-59 has not been flown, so these predictions represent the current best estimate of the dose range until the predictions can be validated with real low-boom data.

6. Summary

An estimate of the X-59 noise dose range is needed to create a noise exposure test design for the X-59 Community Response Tests across the USA. To estimate the range, near-field pressure waveforms of the X-59 during steady level supersonic cruise flight was propagated using PCBoom through realistic atmospheric profiles at 19 locations across the USA over one year and for four cardinal headings. The mean PL of the inner 40 km of each X-59 carpet was computed at each location, and these results were summarized by the mean of their median inner carpet mean PL. The single event PL dose range estimate is 72 to 86.7 dB, and the cumulative PLDNL dose range estimate is 22.6 to 45.1 dB. The achievable range of doses will be confirmed during X-59 acoustic validation test flights.

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