Vibration Criterion Curves – Part 1: Evolution and Interpretation

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Abstract – The Vibration Criterion (VC) curves were first developed in the US in the early 1980s and are now widely used internationally, including in Australia, to assess and manage the impacts of vibration on sensitive medical and scientific equipment, such as optical and electron microscopes. Several iterations of the VC curves and associated guidance documents have since been published clarifying certain aspects of how the curves should be interpreted and applied. Australian policy and guidance documents refer to different iterations of the VC curves and the subtle differences between these iterations can create confusion regarding their application. This paper, the first of two parts, describes the evolution of the VC curves and aims to collate and summarise the most recent published guidance about how to interpret and apply the curves. A separate paper, part 2, discusses the ongoing challenge of how to apply the curves to transient vibration events.

1 INTRODUCTION

The Vibration Criterion (VC) curves were originally developed in the early 1980s by Eric Ungar and Colin Gordon while working at Bolt, Beranek and Newman and were hence known as the “BBN” criteria.

The VC curves are commonly used in Australia as design criteria for new medical and scientific research facilities containing sensitive equipment such as optical and electron microscopes that require a more stringent vibration criterion than human comfort thresholds, and to assess the vibration impacts from external sources on existing medical and scientific research facilities, such as construction projects and railways; see (AJM Joint Venture, 2016) and (SLR Consulting, 2017) for examples.

The curves have subsequently evolved over the years, culminating in their recent incorporation into the Institute of Environmental Sciences and Technology (IEST) Recommended Practice (RP) 201.1 (WG-NANO201, 2024). A neat summary of this history, up until 2016, is provided in (Ungar, 2016).

This paper describes how the VC curves evolved between the early 1980s and the present day, and notes subtle differences between the various iterations of the VC curves that can lead to different interpretations and outcomes.

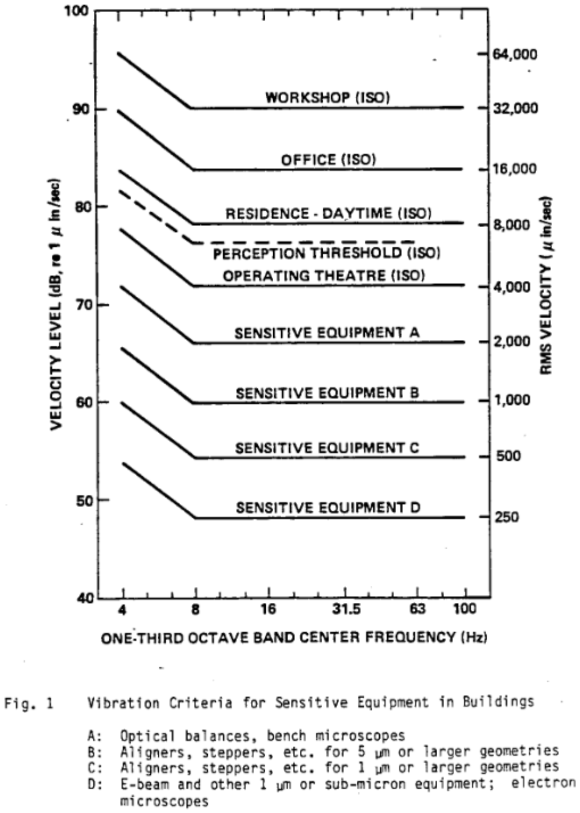
2 EVOLUTION OF THE VC CURVES

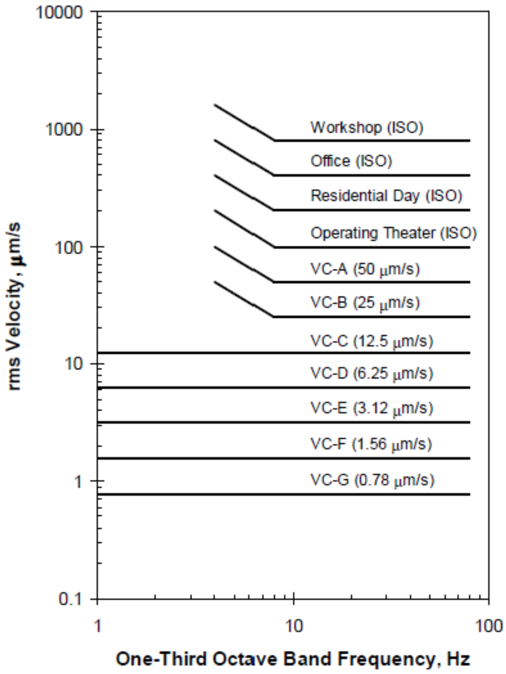
2.1 The beginning

Vibration criterion curves from facility users of microelectronics manufacturing equipment, electron microscopes and optical microscopes, were first presented in terms of root-mean-square (RMS) acceleration in (Ungar & Gordon, May 1983). An abridged version of this paper was also presented at Internoise 83 (Ungar & Gordon, July 1983).

The VC curves were first presented as the now familiar RMS velocity curves in (Ungar & Gordon, 1985). Velocity was chosen as the metric primarily due to the maximum acceptable amplitudes for particular categories of equipment lying on a curve of constant velocity, and because it allows for a vibration criterion to be characterised “essentially by a single number (without a frequency dependence). These are reproduced on the left in Figure 1.

There were four curves for sensitive equipment: Sensitive Equipment A (which is half of the ISO operating theatre curve in linear units (µin/sec) or 6 dB below), and Sensitive Equipment B to D, all of which are half of (or 6 dB below) the preceding letter. The four curves represented different categories of equipment, and were “the requirements for the most vibration-sensitive equipment items in each category”. The curves are constant acceleration between 4 Hz and 8 Hz, and constant velocity from 8 Hz to 100 Hz. The frequency axis is shown in terms of one-third octave bands.





Note that curves VC-B and up remain unchanged graphically, and that units have changed from imperial to metric. A separate detailed table of instruments and their respective categories is also provided in (Amick et al., 2005)

Figure 1 – First presentation of VC curves in terms of RMS velocity, from (Ungar & Gordon, 1985) on left, current presentation of VC curves from (Amick et al., 2005) on right

2.2 Evolution from 1985 to 2005

The evolution of the VC curves is summarised in chronological order below, with each publication shown in **bold**. It is important to note upfront that between 1985 and 2005, the VC curves evolved in a way that is not entirely gradual or linear. There were differences of opinion between different authors and organisations, and these opinions were not necessarily consistent over time. This is discussed further in Section 2.4.

(Gordon, 1987) presents the curves as “BBN Criteria” for the first time and notes that:

- data is typically recorded over a period of 30-minutes and “generally acquired during the day”, “when ambient vibration levels will generally be at their highest”.
- it is usual practice to “examine the data at the 10-percent level—being that level in each band that is exceeded for 10 percent of the total time covered by the recorded data”, corresponding to an L10 level (rather than an L90 level) in common environmental acoustics terminology.

- the frequency axis is in terms of one-third octave bands and extends (as constant velocity) to 125 Hz.
- vertical and horizontal directions should be assessed separately (implied by the statement "Typically, we concentrate our attention on vertical, as opposed to horizontal, vibration.").

(Amick & Gordon, 1989) introduce the 'E' curve "anticipated to be adequate for future fabrication and test equipment for low submicron geometries" and

- include additional descriptions for the other equipment categories.
- state "the curves are generally applied at the energy average level, although in new or green field site studies they are generally applied at the 10% (L10) level.".
- suggest that several periods of 20-30 minutes should be evaluated if conditions vary significantly through the day.
- present data in three orthogonal directions but do not explicitly say that vibration should be assessed in three separate orthogonal axes. The frequency axis shows the curves extend up to 100 Hz.

(Ungar et al., 1990) recommend replacing the constant acceleration component of the curves with constant velocity down to 1 Hz for equipment with low-frequency pneumatic isolation. They also:

- provide a detailed table describing the equipment or use to which each curve applies.
- show curves that extend to 80 Hz only.
- provide commentary on occasional disturbances, noting that more stringent criteria may be applicable in situations where disturbances have more severe consequences. "Where the effect of vibration on productivity is known, the permissible vibration exposure may be specified in terms of exceedance statistics – e.g, in terms of the L_n vibration levels".

(Gordon, 1991) clarifies that "For a floor to comply with a particular equipment category, the measured one-third octave band velocity spectrum must lie below the appropriate criterion curve … at all frequencies.". He also:

- states that "The criteria apply to floor vibration as measured in the vertical and two horizontal directions.".
- shows curves that extend to 80 Hz only, but with supporting text that indicates they apply up to 100 Hz.

Working Group 12 of the IEST **(WG-12, 1993)** promulgates the VC curves described in (Gordon, 1991).

The American Institute of Steel Construction (AISC), in their Design Guide 11 **(Murray et al., 1997)**:

- reproduce the curves and commentary regarding pneumatic isolation from (Ungar et al. 1990), which extend only up to 80 Hz.
- state that the criteria "pertain to the instantaneous maximum or "peak" vibration to which the equipment is exposed" and that "the dominant adverse effect of vibrations on sensitive equipment generally is independent of the time variation". This conflicts with guidance in the preceding papers suggesting evaluation based on L10 and RMS levels.

(Amick, 1997) refers to (WG-12, 1993), (WG-24, 1994) and (Gordon, 1991) and details much of the logic behind the VC curves. He provides answers to frequently asked questions, particularly regarding the respective merits of peak and time-averaged criteria. On this topic in particular, he notes that:

- “Available data are inadequate to develop a general answer, but many believe that rms averaging provides a more appropriate representation of how a tool will respond in most cases, depending upon the averaging time involved.”.
- “It would be too simplistic to suggest that rms amplitude is appropriate for all situations, particularly if the averaging time were long. There can be cases where an instrument could be excited by a single pulse in a support vibration, whereas other systems might require a certain duration of sustained duration.”.
- “Assessment of a vibration should be based on a form of data that can be considered representative of that environment. An environment that can be characterized as continuous, steady-state or stationary should be assessed in terms of rms amplitude with defined averaging time, since that is the repeatable quantity. An environment that cannot be characterized in this manner (such as vibrations caused by footfalls, impacts or certain construction activities) may require special consideration of crest factor or averaging time or the use of actual peak amplitude. Vibrations from transient events, such as train passages, can be considered using time T that is less than or equal to the duration of the event.”

(Gordon, 1999) refers to (Amick, 1997) and recommends that environments that are relatively steady-state in time should be assessed using “energy average” levels, and that “maximum rms” (or peak-hold) measurements should be used when the environment varies with time. He also:

- comments on spatial averaging noting “It is considered reasonable to classify the VC performance based on the “average plus one standard deviation” level at each frequency.”. The curves are shown up to 80 Hz but, like the 1991 version, the supporting text suggests they apply up to 100 Hz.
- acknowledges the suggestion from (Ungar et al., 1990) to extend the constant velocity curve down to 1 Hz for pneumatically isolated equipment.

(Amick et al., 2002) formally extend the constant velocity sections of the VC-D and VC-E curves down to 1 Hz. They also refer to (Amick, 1997) and introduce “NIST-A” and “NIST-A1” as alternative criteria. The NIST criteria are rarely applied in Australia and are not considered further within this paper.

(ASHRAE, 2003) publish VC curves and refer to (Ungar et al., 1990), but:

- label the vertical axis as “Peak RMS Velocity”, which is confusing,
- omit the recommendation in (Ungar et al., 1990) regarding criteria for equipment with pneumatic isolators
- reverse the letter classifications (A being the most stringent, rather than the least)

This version has since been superseded by (ASHRAE, 2011) as described in Section 2.3.

(Amick et al., 2005), promulgated by Working Group 12 of the IEST (WG-12, 2005)**:**

- introduce curves F and G but notes these are not recommended for use as a design criteria
- extend the constant velocity section of curves C through to curve G down to 1 Hz.
- explain that the curves extend up 80 Hz only.
- clarify the amplitude units are in fact RMS velocity (as opposed to zero-to-peak or peak-to-peak), and discourages an overly strict interpretation of the criteria, reflecting the accuracy and repeatability of vibration measurements.
- expand on the commentary on spatial averaging from (Gordon, 1999).

- suggest a linear average for steady-state environments, peak-hold spectra for occasional disturbances, and provide commentary on the importance that should be attributed to occasional events (discussed in Section 3).

2.3 2005 to present

Since 2005, the three different authoritative sources: IEST, ASHRAE and AISC, have broadly converged on how the VC curves are described, albeit in varying levels of detail. This is summarised below.

(ASHRAE, 2011), which remains current in the most recent version (ASHRAE, 2023):

- Supersedes (ASHRAE, 2003) and refers to both (WG-12, 2005) and (Murray et al., 1997). The reference to (Murray et al., 1997) could be interpreted to require assessment of peak (rather than RMS) levels.

- matches the letter classifications in other publications (i.e with A being the least stringent, and following letters being half of the preceding letter), but only presents curves A to E. Curves C, D and E are constant velocity down to 1 Hz, and the curves extend up to 80 Hz only.

(Murray et al., 2016) is an updated Steel Design Guide that refers to (Amick et al., 2005). It

- only presents curves A to E. Curves C, D and E are constant velocity down to 1 Hz, and the curves extend up to 80 Hz only.

- specifies the use of RMS velocity, with the accompanying prediction methods assuming a walking event duration of eight seconds – a noticeable departure from the use of the peak metric in (Murray et al., 1997).

Finally, **(WG-NANO201, 2024)** is a Recommended Practice document that, for the first time, combines both criteria and methodology, and addresses many of the issues faced by practitioners when applying VC curves by consolidating the guidance provided by other publications and providing additional commentary for improved clarification.

2.4 Summary

It is now over 40 years since VC curves (or their precursor) were first described in a technical paper. The curves have been widely adopted and updated several times since then. The practice of interpreting and applying the curves has also evolved significantly. The first 20 years or so of their history (to 2005) saw changing or diverging views on some aspects of interpreting and applying the curves, whereas the subsequent 20 years or so has been a period of consolidation and consensus. Table 1 provides a summary.

It is important to note here that none of the early papers on VC curves were intended to provide comprehensive guidance on how to interpret and apply the curves as design criteria. For example, details such as how to assess different directions of vibration, or time varying vibration, were often not addressed. Despite this, some of these publications were cited in guidelines and adopted as criteria, leading to differences in the way practitioners interpreted and applied the curves.

As the practice of interpreting and applying the curves evolved, greater consideration was given to occasional disturbances, and measurement times. It appears that both AISC (Murray et al., 1997) and IEST (Amick, 1997) considered that the use of peak levels may be appropriate in some circumstances such as assessing the effects of footfalls, but these authors and organisations have since shifted away from this approach in subsequent publications. It is now clear that the curves apply to RMS velocities, even if the integration times are not explicitly stated. This is discussed further in the companion paper. Later publications on VC curves have generally provided more commentary on their application and nuances, compared to earlier versions.

Table 1 – Summary of guidance documents

Publication	Curves described	Table with equipment categories	Table with numerical definition	Applicable directions	Metric[1]	Upper Freq. Limit (Hz)	Occasional Disturbances Commentary	Constant velocity down to 1 Hz
(Ungar & Gordon, 1985)	A to D	Yes	No	No	RMSV	100	No	No
(Gordon, 1987)	A to D	Yes	No	Implied	L10	125	No	No
(Amick & Gordon, 1989)	A to E	Yes	No	Implied	EA or L10	100	No	No
(Ungar, et al., 1990)	A to E	Yes	Yes	No	RMSV	80	Brief	Yes
(Gordon, 1991)	A to E	Yes	Yes	Yes	RMSV	100	No	No
(Murray et al., 1997)	A to E	Yes	Yes	No	Peak V	80	No	Yes, where deemed appropriate
(Amick, 1997)	A to E	Yes	Yes	No	Judgement	100	Detailed	No
(Gordon, 1999)	A to E	Yes	Yes	Yes	EA (SS) P-h (OD)	100	Brief	Acknowledged, but no
(Amick, et al., 2002)	A, B, D, E, NIST-A, NIST-A1	No	Yes	No	RMSV	100	No	D, E
(ASHRAE, 2003)	A to E (reverse order)	Yes	No	No	Peak RMSV	80	No	No
(Amick et al., 2005)	A to G	Yes	Yes	Yes	EA (SS) P-h (OD)	80	Brief	C to G
(ASHRAE, 2011)	A to E	Yes	Yes	No	RMSV from Continuous Vibration	80	No	C to E
(Murray et al., 2016)	A to E	Yes	Yes	No	RMSV	80	Limited to footfalls	C to E
(WG-NANO201, 2024)	A to G	Yes	Yes	Yes	EA (SS) P-h (OD)	80	Detailed	C to G

Note 1: In this column, the following shorthands are used: ‘V’ = velocity, ‘EA’ = energy average, ‘SS’ = steady-state, ‘OD’ = occasional disturbances, ‘P-h’ = peak-hold

3 IMPORTANT ELEMENTS OF THE VC CURVES

The main elements of the criteria in (WG-NANO201, 2024) have only changed with respect to nuance, additional detail and clarity since the publication of (Amick et al., 2005). It is recommended that the reader refer to (WG-NANO201, 2024) for the precise definitions. The following elements from (Amick et al., 2005) that are often the subject of conflict remain broadly correct, including the numerical definition and graphical representation (reproduced in the centre of Figure 1):

- The criteria are expressed in terms of one-third octave bands. For a floor or site to comply with a particular equipment category, the measured one-third octave band velocity spectrum must lie below the corresponding curve. An overly strict interpretation is not encouraged, noting that vibration measurements are only accurate and repeatable to within about 1 or 2 dB.

- The criteria apply to vibration as measured in the vertical and two orthogonal horizontal directions, and are applied to each direction separately.
- The criteria are expressed in terms of RMS velocity:
    - For environments that are continuous and steady-state in time, the criteria apply to the linear average of data samples acquired over an adequate time period, such as a daytime or night-time period. Disturbing events that occur over long enough periods such that it is effectively steady-state during the daytime or night-time should also be evaluated in this way.
    - In instances where the environment is impacted by occasional disturbances such as vehicle movements or passing trains, these should be evaluated using peak-hold spectra. The importance of these occasional events will depend upon the frequency of occurrence and other parameters relating to the vibration-sensitive process.

This last dot point, and what it means in practice, is the focus of the companion paper.

Some important additions from (WG-NANO201, 2024) that are not explicitly stated in (Amick et al., 2005) are:

- If additional VC curves are to be added, each new curve should have an amplitude of one half the one directly above it, and the letter designation incremented by one letter.
- Tonal frequencies at twice AC mains frequencies (100 Hz or 120 Hz, depending on country) should be excluded. This is in accordance with the processing performed originally by Eric Ungar and Colin Gordon (Amick, 2024). If the vibration amplitude at frequencies above 80 Hz exceeds the curve, that can be noted, but it should not be stated that the amplitude exceeds the criterion itself.

4 PRACTICAL CONSEQUENCES IN AUSTRALIA

The VC curves are commonly used in Australia as design criteria for new medical and scientific research facilities and to assess the vibration impacts from external sources, such as construction projects and railways; see (AJM Joint Venture, 2016) and (SLR Consulting, 2017) for examples. However, the cited publications on VC curves are often those published prior to 2005 when the various guidance documents began to converge. This has led to differences in the way practitioners have interpreted and applied the curves in Australia. Some environmental assessments for railways have cited (ASHRAE, 2011) whereas others have cited (Gordon, 1999), which results primarily in differences in the VC-C, VC-D and VC-E curves below 4 Hz. Australian guidance on the application of VC curves for the assessment of construction also varies considerably, as shown in Table 2.

Table 2 – Example NSW and QLD Policy and Guidance documents referring to VC curves

Policy or Guidance Document	Author	VC curve reference(s)
Construction Noise and Vibration Guideline (Roads) (2023)	Transport for NSW	(Gordon, 1991) (ASHRAE, 2003)
Construction Noise and Vibration Guideline – Public Transport Infrastructure (2023)		(Gordon, 1999)
Transport Noise Management Code of Practice: Volume 2 – Construction Noise and Vibration (2023)	QLD Department of Transport and Main Roads	(Ungar et al., 1990)
Assessing Vibration: a technical guideline (2006)	NSW Environment Protection Authority	(Ungar & Gordon, 1985)

The risk of inconsistent interpretation and application of VC curves in Australia is further complicated by differences in authoritative overseas guidance. The ANC “Red Book” (ANC, 2020) for instance, refers to IEST guidance (WG-12, 2015). The 2018 version of the FTA Manual (Federal Transit Administration, 2018) curiously also refers to (WG-12, 2015), but the contents remain unchanged from the 2006 version (Federal Transit Administration, 2006) which refers to (WG-12, 1993). This perhaps reflects an incorrect assumption that the VC curves did not evolve during the intervening period. Both documents are widely used by Australian acousticians particularly in the context of construction and the of operation of railways, but provide conflicting guidance regarding the applicable frequency range, whether the curves below VC-B are constant velocity or constant acceleration below 4 Hz, and how to deal with occasional disturbances. The response-equivalent peak velocity spectrum method described in Parts 1 and 2 of ISO/TS 10811:2000 that provides a connection to VC curves but otherwise employs an alternative methodology is another potential source of confusion, although it is noted that this is not widely applied in Australia.

It is clear from Table 1 that applying VC curves based on different publications can result in different interpretations. Earlier publications were not intended to include all the pertinent details so unintended interpretations are almost inevitable unless practitioners consider the publications in conjunction with other relevant documents. Examples of common misunderstandings or sources of confusion among Australian practitioners, in the author’s experience, include:

- assessing horizontal vibration as the vector sum of the two orthogonal horizontal directions, rather than assessing the orthogonal directions separately.
- confusion on whether the constant velocity sections of the curves extend down to 1 Hz and whether the curves extend up to 80 Hz or 100 Hz.
- Lack of clarity about which assessment metric should be used and the importance that should be attributed to occasional disturbances.

These differences in interpretation, particularly the last dot point, can lead to significant differences in outcomes. For example, for a facility housing sensitive equipment, one possible interpretation is that vibration should never exceed the prescribed curve, even for very short durations (in terms of peak velocity), whereas another possible interpretation is that occasional disturbances should be ignored, and that energy average levels over entire daytime or night-time periods should be used to assess compliance. At sites with quiet background vibrations but significant impacts from occasional disturbances like train passbys or footfalls, these different interpretations can result in either comfortable compliance with the prescribed VC curve, or exceedances of orders of magnitude.

Finally, the risk of inconsistent interpretation and application of VC curves is often compounded by an absence of information from equipment suppliers and/or facility owners, who often prescribe equipment sensitivity in terms of VC curves but with no supporting commentary or guidance with respect to signal processing methods, or the importance that should be attributed to occasional disturbances. This is described in (Stead et al., 2009), who notes that the facility owners were “not able to provide equipment details due to non-disclosure agreements with the microscope manufacturers” and that “limited information was available on the measurement techniques used to obtain the data, which made it difficult to compare measurements with equipment criteria”. (WG-NANO201, 2024) notes that a vibration criterion is meaningless unless the analysis methodology is fully specified.

The publication of (WG-NANO201, 2024), which will eventually be submitted for consideration as an ISO standard[1] (Amick, 2024), provides an excellent basis to apply a more consistent approach, including in Australia.

5 CONCLUSION

The publication of the IEST's Recommended Practice (RP) 201.1 (WG-NANO201, 2024) represents an opportunity for Australian acousticians to "get on the same page" with respect to the implementation of VC curves, for medical and scientific research facilities containing sensitive equipment such as optical and electron microscopes that require a more stringent vibration criterion than human comfort thresholds. This is the first time that the vibration criteria as well as the measurement and reporting methodologies have been published in the same document, and provides an excellent basis for anyone looking to apply VC curves.

Part 2 of this paper elaborates on how to apply the VC curves in environments with occasional disturbances, using guidance from the IEST's Recommended Practice (RP) 201.1 (WG-NANO201, 2024).

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