Control of parking garage vibrations in research and healthcare facilities

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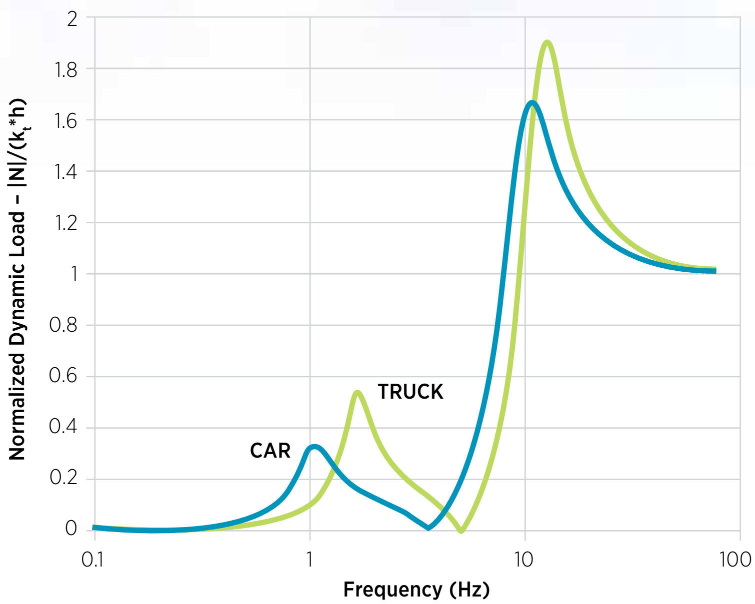
The densification of urban education and healthcare campuses is driving the development of taller buildings that house continuously evolving technologies and treatments. A by-product of 'building up' is challenges with co-location of incompatible spaces from a noise and vibration perspective. Some increasingly common examples include mid-level mechanical floors stacked above/below acoustically-sensitive areas; vibration-sensitive research and medical tools above ambulance or loading bays; and parking garages that share structure with low-noise and low-vibration environments. These challenges are creating a paradigm shift in the vibration design of structures, whereby the structural scheme that satisfies ultimate limit states may no longer be sufficient to meet serviceability requirements.

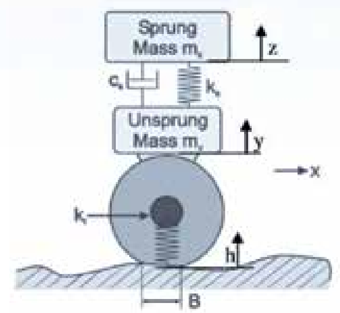
In this paper we discuss the co-location of parking structures with vibration-sensitive spaces, and share some of the approaches to control that we have applied during the design of research labs and hospitals. First we provide an overview of the nature of vehicle vibrations, which is important to understanding some of the approaches to source control. This is followed by a discussion on serviceability criteria. Finally, we provide some practical guidelines for control of vehicle vibrations in sensitive spaces.

Characterizing Vehicle-induced Vibrations

Vehicle-induced vibrations in parking garages are the result of the dynamic interaction that occurs between the tires, suspension system and sprung mass, and irregularities in the roadway surface. The magnitude of the forces are a function of the stiffness and damping of the suspension system, the speed of travel, and the roughness of the roadway surface. A stiffer, more heavily damped vehicle suspension will generally create higher dynamic forces than a soft suspension on the same surface. Additionally, fast moving vehicles on rough surfaces will generally create higher dynamic forces than slow-moving vehicles on smooth surfaces.

The dynamic loads are associated with two classes of vibration modes: 'body bounce' or cabin motion typically occurs at frequencies between 0 Hz – 2 Hz, and 'axle hop' or wheel motions typically occurs at frequencies between 10 Hz – 20Hz. The axle hop modes are the primary concern for vibration-sensitive building structures (both ground-borne from roadways and structure-borne from parking garages and connected ramps), since floor modal frequencies are normally well above 2 Hz and are not excited by the vehicle body bounce. The axle hop forces are characterized by a transient temporal signature, having a peak at the first point of tire impact followed by a train of reduced amplitude forces (wheel hops) that decay quickly. In parking garages these transient forces are generated by vehicles traversing irregularities such as speed bumps, expansion joints and drainage grates. Examples of vehicles forces generated using a numerical model are shown in Figure 1.





	Car	Truck	
m_s	1014	9921	lb
m_u	99	1433	lb
k_s	1439	39057	lb/ft
c_s	103	1439	lb*s/ft
k_t	10278	205565	lb/ft

Fig. 1: Forces from vehicles are generated by body bounce motions at frequencies between 1 Hz – 2 Hz and axel hop motions at frequencies between 10 Hz and 20 Hz. The amplitude of these forces are a function of the physical characteristics of the vehicle (mass, stiffness of the suspension and energy dissipation from the shock absorbers), the speed of travel, and the smoothness of the surface. The plot shows the dynamic forces generated by a car and truck, computed using the quarter-car model and normalized by the product of the tire stiffness and road displacement profile.

Performance Criteria

Vibration criteria are specified based on the use and occupancy of the spaces of concern. In research and healthcare environments there are typically three levels of sensitivity to be considered:

Low sensitivity – tactile or perceptible motions that can result in physical discomfort to occupants;
Moderate sensitivity – motions at or just below human perceptibility that can create audible structure-borne noise; and,
Ultra-sensitive – motions well-below the threshold of human perception, which can impact performance of sensitive medical and research tools.

Over the past 30 years, researchers and practitioners have developed serviceability criteria for use in design and mitigation assessments. Many of these criteria evolved from the isoperceptibility curve shown in Figure 2, which represents the threshold of vibration perception for humans (foot-to-head or spinal axis vibration direction) over the 1 to 80-Hz frequency range [1].

The y-axis is the root-mean-square (RMS) vibration acceleration level—typically computed based on a one-second sliding window of time across the signal. Floor vibration levels having magnitudes greater than this curve will be perceptible to most people. The flat portion between 4 Hz and 8 Hz represents the frequency range of people's greatest sensitivity to vibration. The isoperceptibility curve is also commonly referred to as the *ISO base curve*, or the *ISO-Operating Theatre* curve as it is the basis for the design of general surgery spaces.

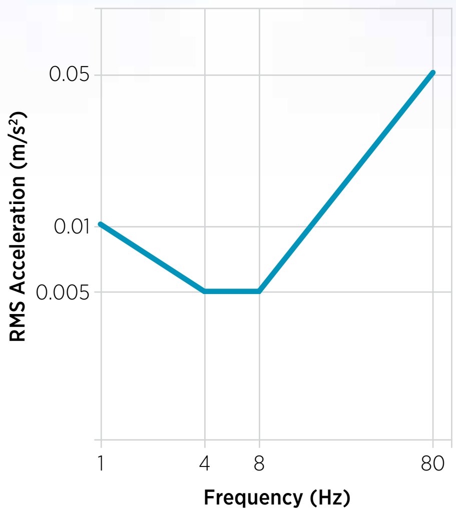


Fig. 2: The ISO Base Curve (isoperceptibility line) for human perception of vibrations along the axis of the spine is the basis for most serviceability criteria.

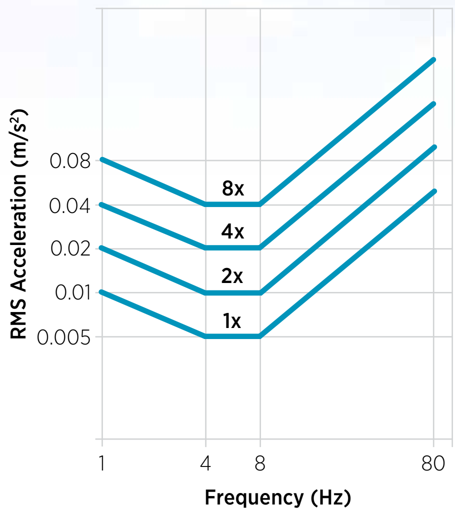


Fig. 3: Multiples of the ISO Base Curve (e.g., 2x, 4x, etc.) are specified for occupied spaces where human comfort is a concern. Increasing multiples indicate reduced sensitivity to structural motions.

Serviceability criteria for occupant comfort

Vibration thresholds related to human comfort are specified as multiples of the base curve. Higher multiples of the curve indicates increasing tolerance to vibrations. For example, workshops or mechanical spaces, where occupants generally expect some level of floor vibrations, have higher vibration specifications than office environments. As shown in Figure 3, the ISO-Workshop criterion is defined as 8x the Base Curve and the ISO-Office criterion is 4x the Base Curve. A multiple of 2x the Base Curve is used for design and evaluation of residential buildings, with a multiple of 1.4x applied to areas where people sleep.

In Europe comfort criteria are specified based on a similar scale, but rather than relying on graphical representations, a single metric known as the Response Factor (R) is used. The R value is equal to the multiplier of the ISO Base Curve. For example, a value of R = 4 (or less) indicates a vibration level that is four times the Base Curve threshold and would be appropriate for an office environment. Similarly, R = 2 is appropriate for a residence, R = 8 is appropriate for a workshop, and so on.

The single-number rating approach greatly simplifies the vibration engineer's data analysis since the values of R can be easily computed during signal processing, and readily compared against comfort criteria without having to consult a graph. This approach is slowly gaining popularity in North America, though it is not currently presented explicitly in design guides or codes.

Serviceability criteria for toolsets and procedures

Generic design criteria for spaces housing sensitive equipment, animal holding spaces, and sensitive procedures are commonly expressed in units of RMS velocity. Although the criterion curves can be shown to originate from the ISO Base Curve, research has indicated that many research tools have velocity sensitivities that are relatively constant with frequency. Similar to the specifications for occupant comfort, these thresholds are specified as fractions of the Base Curve (commonly referred to as the ISO-Operating Theatre curve in this context, as it is commonly specified for surgical suites). These curves are shown in Figure 4.

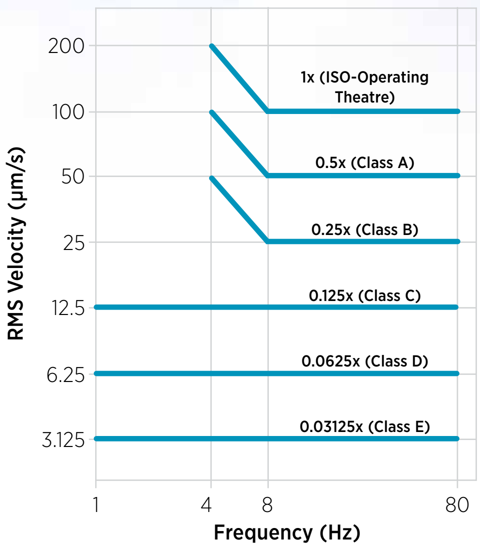


Fig. 4: Fractions of the ISO Base Curve (e.g., 0.5x, 0.25x, etc.) are specified for occupied spaces where sensitive equipment, animals and procedures are a concern. The ISO-Operating Theatre curve is equivalent to the ISO Base Curve (from which generic serviceability specifications are derived). Varying multiples/fractions of the base curve are specified according to the use and occupancy of the space.

Each curve is assigned a 'vibration class,' representing a category of equipment/procedures appropriate for the specified environment — in other words, vibration levels in the environment should not exceed the assigned threshold. Vibration classes C through E are slight modifications of the base curve, with more stringent requirements at frequencies between 1 and 8 Hz, accounting for the heightened sensitivity of high-resolution imaging equipment in this frequency range [2, 3].

A summary of common space uses and equipment associated with the ISO and vibration class criteria is presented in Table 1. For consistency the ISO criteria are expressed in their equivalent metrics in units of RMS vibration velocity. Note that more recently additional vibration classes (F, G, H etc.) have been defined as additional fractions of the Base Curve. These classes currently have limited application other than for site evaluation. We know of only one instrument currently in existence with a vendor requirement of Vibration Cass J, or 0.1 µm/s at frequencies between 2 Hz and 500 Hz — although it is unlikely that commercially available measurement devices would be able to measure such low levels as a basis for assessment.

Table 1: Generic vibration class criteria and associated space usage.

VIBRATION CRITERIA CURVE	MAX RMS VELOCITYLEVEL(1) µM/S	RESPONSE FACTOR R	DESCRIPTION OF USE
Workshop (ISO)	800	8	Distinctly perceptible vibration. Appropriate to workshops, mechanical spaces (in non-sensitive facilities) and other non-sensitive areas.
Office (ISO)	400	4	Perceptible vibration. Appropriate to offices and non-sensitive areas.
Residential (ISO)	200	2	Barely perceptible vibration. Usually adequate for computer equipment, semiconductor probe test equipment, and microscopes with less than 40x magnification.
Operating Theatre (ISO)	100	1	Vibration not perceptible. Suitable in most instances for general surgical suites, microscopes to 100x magnification and for other equipment of low sensitivity. Upper bound for animal spaces (vivaria etc.)

VIBRATION CRITERIA CURVE	MAX RMS VELOCITYLEVEL(1) µM/S	RESPONSE FACTOR R	DESCRIPTION OF USE
Class - A	50	0.5	Adequate in most instances for optical microscopes to 400x magnification, microbalances, mass spectrometers other than MALDI and quadrupole or high-resolution, conventional spectrophotometers, etc. Lower bound of range appropriate for animal spaces (vivaria etc.).
Class - B	25	0.25	Appropriate for microtomes and cryotomes for 5 - 10 micron slices, most tissue and cell culture, except as noted below. Micro-surgery, eye surgery, neurosurgery. Most CT, CAT, PET, fMRI, SPECT, DOT, EROS.
Class - C	12.5	N/A	Appropriate standard for optical microscopes to 1000x magnification; moderately sensitive electron microscopes to 1 mm detail size; digital imaging and/or fluorescence with optical microscope; high precision balances measuring quantities less than 1 mg; MALDI mass spectrometer; nano-drop spectrophotometers, microtomes, and cryotomes for slices less than 5 microns; and tissue and cell culture of slices less than 5 microns; and tissue and cell culture of the following types — hanging drop, unstirred layers, embryonic stem cells, weakly adherent cells, very long-term cultures, chemotaxis, and invasion assays.
Class - D	6.25	N/A	Suitable in most instances for demanding equipment, including many electron microscopes (SEM and TEM), microinjection, micromanipulation, electrophysiology, confocal microscopy, and quadrapole and other high-resolution mass spectrometers. Many nuclear magnetic resonance (NMR) systems require this environment. Low strength MRI (1.5T or less).
Class – E	3.12	N/A	Assumed to be adequate for the most demanding of sensitive systems, including long path, laser-based, small-target systems; systems working at nanometer scales; and other systems requiring extraordinary dynamic stability. Many NMR and MRI (3.0T and higher) systems perform best in this environment.

It is essential that vendor criteria be included in the assessment when available such as those illustrated in Figure 5. These are typically published in site planning guides for the equipment and additional insights on sensitivity can often be obtained from the end user. We have found that circulation of a vibration questionnaire among stakeholders, early in the project, can be an effective way of gathering information relevant to the design. The questionnaire should include queries on space usage, equipment model numbers, published criteria, vendor and end user contact info etc.

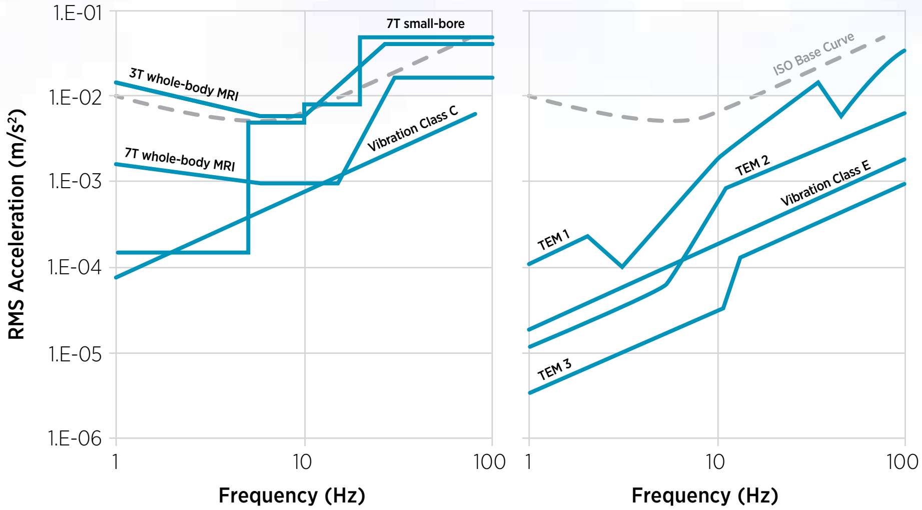


Fig. 5: Examples of vendor criteria for various medical imaging (left) and high resolution microscopy devices (right). Data is shown in units of RMS acceleration for direct comparison of different types of equipment. Also shown are the ISO Base Curve (threshold of human perception, head-to-toe direction), and vibration classes C and E for reference. When available, vendor criteria should always be used as a basis for assessment.

Serviceability criteria for unique conditions

The ISO and vibration class criteria can be used for the design of a broad range of spaces and can be adopted for unique design conditions and spaces that are not listed in Table 1. We recently provided vibration consultation services for the design of an ambulatory surgery clinic located on the ground floor of a six-storey parking structure. The clinic includes patient care rooms and operating suites, and it was necessary to assess all possible vibration transmission paths. Given the stacking conditions multiple design criteria were applied to the assessment to address:

- ground-transmitted tactile motions that could result in discomfort of occupants;
- motions at the supports of medical equipment that could degrade functionality and interrupt surgical procedures; and,
- motions of the superstructure that could result in audible noise or perceptible vibration from equipment such as lighting or screens and monitors.

Comfort criteria were discussed previously, and for patient sleep areas it is appropriate to specify a residential nighttime threshold [4].

In the absence of vendor criteria for medical equipment, Table 1 should be used to determine appropriate thresholds. For equipment supported overhead, an appropriate threshold based on experience and field validation is Vibration Class B [5, 6].

Due to the complex nature of structure-borne noise there are no commonly applied vibration criteria to limit noise disturbances caused by structural motions (noise is not addressed in the descriptions in Table 1). However, one can refer to published guidance related to ground-borne noise disturbances in acoustically sensitive areas, for specification of appropriate criteria [7].

Table 2 lists some of our recommended design criteria for unique conditions.

Table 2: Generic criteria for some unique conditions.

Condition	RECOMMENDED DESIGN CRITERIA	NOTES
Ceiling structure in a surgical space located below parking garage, to which equipment will be mounted (microscopes etc.).	Class B 25 μm/s	Threshold applies to mounting point.
Ceiling structure in a patient room located below parking garage.	Class A – ISO Res Night 50 – 140 μm/s	Control of noise disturbances. Lower bound associated with target background noise rating of 25 dBA. Upper bound associated with target background noise rating of 45 dBA.

In practice these design criteria can be difficult to achieve when the spaces are located below parking without the incorporation of isolation techniques.

Control Strategies

Design strategies to limit vibration impacts from parking garages typically involve a combination of source, path and receiver control measures. Source controls address the vehicle and associated forces on the structure; path controls address the transmission medium (i.e., the building systems); and receiver controls address isolation/decoupling of the vibration receptor.

Source Control

Options which may be considered for controlling forces generated by vehicles include:

- speed restrictions;
- restriction on vehicle types; and,
- managing the roughness of the driveway surface.

Speed limits are usually posted in parking facilities for safety reasons, but can be difficult to enforce. Typically limits are inherently controlled by the geometry of the space (length of open laneways and layout of parking spaces, turning points, ramp placement etc.). While there are no design rules of thumb for speed limits, vibration levels on a parking slab are typically greater in areas of higher speed vehicle movement (all else being equal).

Restrictions on vehicle type are usually limited to buses and transport trucks, and are related more to the height and weight of the vehicles and the ability to navigate the garage, than as a vibration control measure. Nonetheless, the anticipated forces used as a basis for design are important to vehicle modelling studies, which should be based on realistic loads. A plausible recommendation from such studies could include restrictions on the types of vehicles permitted in certain areas.

Controlling the roughness of the driveway surface is an effective means of source control. Expansion joint covers and drainage grates should be specified as smooth as possible, and care taken during construction to avoid large steps in the driveway surface at these locations. Settlement and creep over time can change the surface geometry at these areas and joint/drain coverings should be designed or specified to perform over the long term. Locations and placement of the expansion joints should be determined in coordination with the planned use of the building and fit-out requirements. Speed bumps and other traffic calming obstructions should generally be avoided in parking garages that share structure with or are in close proximity to vibration-sensitive uses.

Fig. 6: Traffic calming measures such as speed bumps can be useful for controlling speeds in some areas However, such obstructions should have broad, shallow slopes to reduce the vehicle forces imparted to the structure.

Path Control
Controls that target the vibration path include space layouts, isolation, and the selected structural scheme.

An effective first line of defense against vibration disturbances is good space planning. Vibration-sensitive spaces that are well-separated from parking will usually be less susceptible to disturbances from vehicles than spaces in close proximity, or spaces that share a floor plate with moving vehicles. While there are no universally applicable guidelines, experience has shown that separations of two or more floors is an effective rule of thumb. There should be a minimum of three structural bays of separation between the driveway surface and sensitive spaces that share the same floor plate. Ultimately the separation will depend on the specifics of the structural scheme and level of sensitivity of the receptor, and greater setbacks may be necessary. Electromagnetic interference from moving vehicles is a critical consideration for many vibration-sensitive research and medical imaging tools, and control of this element may be the controlling factor, warranting greater setbacks than those associated with noise and vibration control.

Decoupling or interrupting the transmission path can be effective for controlling both noise and vibration disturbances. Severing the path using structural breaks is most effective, but may not be feasible. Including resilient isolation elements at connections between architectural, mechanical and plumbing and the base building structure at strategic locations can limit secondary movement that results in noise radiation. Critical areas located below driveway surfaces may require secondary/isolated structural systems that effectively lengthen the travel path of vibration energy and amount of dissipation, prior to arrival at the sensitive receptor. These isolation elements can also control visual and audible vibration cues (i.e. shaking fixtures or services), which exacerbate vibration disruptions.

Reviews of the dynamics of proposed designs during planning can be helpful for identifying areas of the structure that will have limited participation in the vibration modes associated with laneways. Similarly, finite element modelling can be helpful for development of de-tuning strategies, such as modifications to framing to alter and effectively de-couple the dynamic response at laneways and sensitive occupancies. An example is shown in Figure 7.

In practice there may be physical limitations on what can be done with the base parking structure to arrive at the design criteria for the facility. Adding sufficient mass to the system to suppress the impulsive response associated with axle hop may not be possible. Other factors, such as cost, schedule, constructability and space limitations may rule out change to structure such that other strategies must be considered.

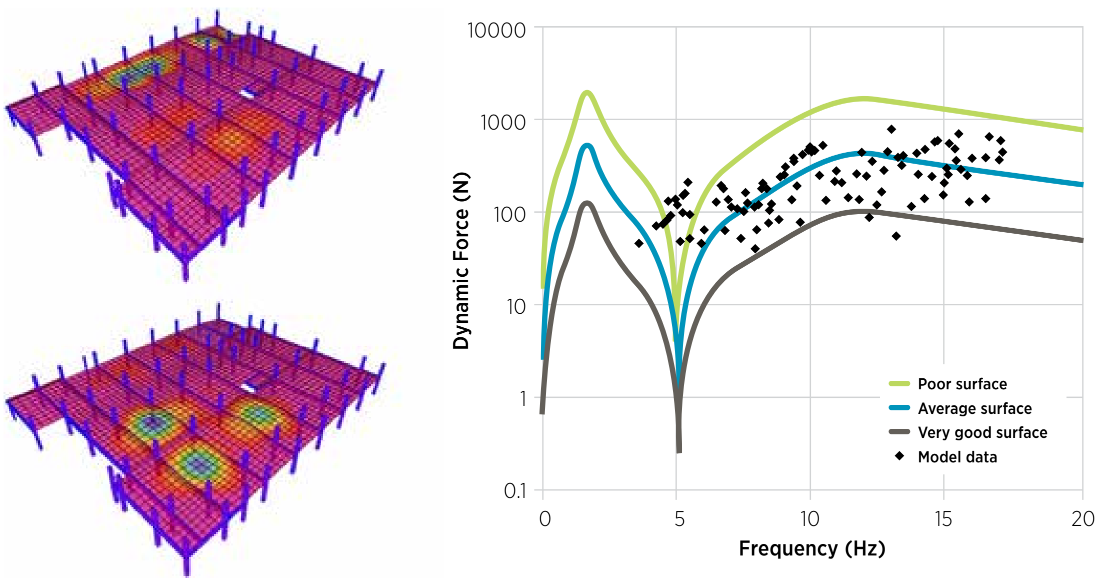


Fig. 7: Finite element modelling and simulations are used during design to evaluate path control strategies, such as optimal placement of sensitive spaces and modifications to the structural system to satisfy serviceability criteria. Computer models, such as that shown on the left, are used in simulations of vehicle responses for various drive surface conditions, speed bump designs etc. A screening level review (example at right), early in design can be used to determine vibration modes that are expected to be problematic. The vehicle forces (curves) are compared with the modal forces (data points) required to excite the structure at amplitudes above design criteria. This type of review can be used to steer the structural design and strategic layout of sensitive spaces

Receiver Control

The third component of controlling vibration within parking structures is application of controls at the receiver space. This might include isolation of equipment within the space and/or isolation of the space itself. There are numerous passive and active vibration control systems commercially available for a wide range of research and medical tools – see for example the links in references [8, 9, 10, 11]. Design or selection of the correct isolation system usually includes measurements of the temporal and spectral characteristics of the parking vibrations (among other sources) at planned equipment locations. An example is shown in Figure 8. Some customization of the isolation system is typically required to accommodate unique toolsets, space constraints etc.

Whole-room isolation may be required for ultra-sensitive spaces located near, or sharing structure with the parking garage. A control concept adopted on a recent project was to build an isolated box around the vibration-sensitive space, which will effectively decouple it from the noisy surroundings. This approach required structural and acoustic treatments to limit incoming vibrations using isolation elements (springs, flex connections etc.), a secondary support structure isolated from the base building, and sound isolation elements (masonry and/or double-stud walls, drywall ceilings etc.), for control of noise.

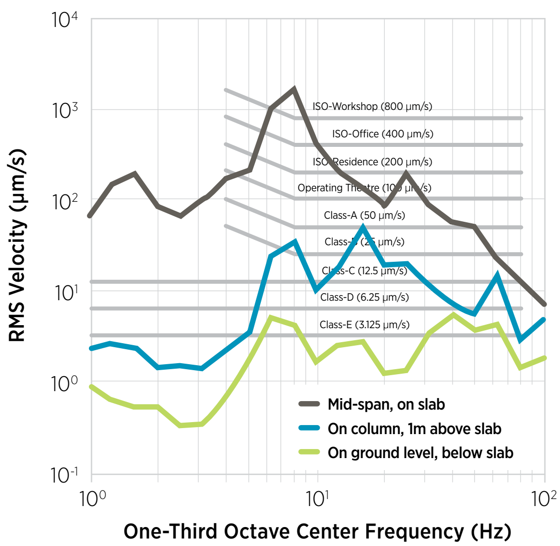


Fig. 8: Vibration responses due to a ½ ton pickup travelling at 15 mph over an expansion joint on the second level of a parking garage. The garage is located above an ambulatory surgical clinic at ground level. Through analysis of concurrent measurements of slab motions, support column motions and vibration levels on ground level below, these data were used to design secondary/isolated structural framework to control vibration transmission to operating rooms and patient care areas.

Which Strategy is best?

The applicability and effectiveness of each control strategy will differ for a new build versus renovation or re-use scenarios.

- **Source** control strategies would generally be applicable to new builds; however, changes to the parking program and retrofit of the driveway surface may also be considerations for renovations and re-use scenarios.
- **Path** control strategies are usually applicable to new build scenarios since they can involve changes to layouts and structure, which can be addressed early in design. In a retrofit or re-use scenario, a vibration survey is required to carefully assess the proposed site(s) of planned spaces, the nature and frequency of disturbances and control measures appropriate to planned occupancy. In a retrofit, controls might include renovations to existing architectural, mechanical and plumbing systems, which can be costly.
- **Receiver** control strategies can be applied to both new builds and renovation/re-use scenarios. In some cases, receiver isolation may be sufficient to satisfy vibration criteria; however, we caution the use of this strategy as the first line of defense since there are no universally applicable solutions.

Summary

Approaches to control of vibrations from parking garages address source, path and receiver elements of the system. Although there is no universally applicable solution, strategies that include control measures for each element are recommended. Control at the source should address the quality of the driveway surface and planned traffic calming measures. Control on the vibration path should address proximity through space planning, opportunities for isolation breaks and secondary structural systems that can effectively lengthen the transmission path. Control at the receiver should address vibration isolation supports for equipment or the space as a whole.

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