Traffic-induced vibration in buildings - use of site cut-off frequency as a remedial measure

M.O. Al-Hunaidi^a, J.H. Rainer^a, G. Pernica^a, M. Tremblay^b ^aInstitute for Research in Construction, National Research Council of Canada, Ottawa K1A 0R6, Canada ^bVille de Montréal, 999 rue de Louvain Est, Montréal, Quebec H2M 1B3, Canada

ABSTRACT

Various corrective measures are usually suggested to reduce the levels of traffic-induced vibrations in buildings, e.g. road rehabilitation, speed control, soil improvement, the use of building isolation systems, etc. Although some of these measures are effective, they are in most cases difficult to implement and (or) expensive. In view of recent measurements of vibration levels at several sites in Montréal, it appears feasible and economical to significantly reduce vibration induced by transit buses, the cause of the majority of traffic vibration complaints in the City, by modifying the characteristics of their suspension systems. Modifications would be either to achieve a small axle hop amplitude or an axle hop frequency that is below the lowest site cutoff frequency in the City. In addition to these results, a description of test vehicles, field tests, and measurement and analysis procedures are presented.

INTRODUCTION

Building vibration induced by road traffic, in particular trucks and buses, is becoming an important environmental problem due to increasing vehicle loads and traffic volume, and diminishing road maintenance budgets. Vibration induced in buildings adjacent to roads may under some conditions reach levels that cause human annoyance, possible damage to historical as well as modern buildings, and interruption of sensitive instrumentation and processes. Consequently, road administrators and transit system operators are confronted with complaints and in some cases litigation.

The presence of discrete, periodic, and random irregularities in road surfaces and imperfections in vehicles themselves lead to dynamic interaction forces between vehicles and roads. These forces generate stress waves in the

Transactions on the Built Environment vol 14, © 1995 WIT Press, www.witpress.com, ISSN 1743-3509

558 Soil Dynamics and Earthquake Engineering

supporting soil which in turn induce vibration in adjacent buildings. The predominant frequencies and magnitude of ground vibration depend to a significant degree on the characteristics of vehicle suspension systems and the properties of the site.

The load imposed on the road as a result of a vehicle encountering a surface irregularity may be broken into two parts: (i) initial impact load, and (ii) periodic load in the form of 'axle hop' as a result of the initial impact. The initial impact load induces ground vibrations that are predominant at the natural frequencies of the stratified soil site. On the other hand, the load resulting from the axle hop induces ground vibrations at the hop frequency which is determined by the characteristics of the vehicle's suspension system. If any of the natural frequencies of the vehicle, including the hop frequency of the axle, coincides with or is close to one of the natural frequencies of the soil, the resulting vibration will be substantially greater than vibrations where no such coincidence occurs. Furthermore, if the predominant frequencies of ground vibration coincide with any of the resonance frequencies of the building structure or its components, vibrations will be further amplified. It should be mentioned, however, that the predominant frequencies of building vibration may not be necessarily the same as those of the soil or the vehicle. For example, if there is sufficient ground-borne vibration energy at the resonance frequencies of the building or its components (although not predominant in the ground motion), the building or its structural components may have predominant vibrations at their resonance frequencies rather than at. or in addition to, predominant frequencies of the ground vibration.

In contrast to discrete irregularities, small amplitude random or periodic surface roughness induces continuous dynamic interaction forces between the vehicle and the road. If the surface profile includes wave-number components that at posted vehicle speeds lead to forcing frequencies which coincide with the natural frequencies of the vehicle¹ and (or) those of the soil profile, substantial ground vibration, and in turn building vibration, may be induced.

Some of the above phenomena were observed in a recent study of building vibration induced by road traffic in Montréal. For example, transit buses induced ground vibrations that were much higher than those induced by trucks of the same weight category. The frequency content of vibrations induced by these two types of vehicles was not the same. In addition, there was a frequency at each site below which vibration levels were extremely small. Consequently, it appears feasible to significantly reduce bus-induced vibration in buildings, which are the cause of the majority of traffic vibration complaints in Montréal, by modifying the characteristics of their suspension systems. Modifications, if possible, would be either to achieve a small axle hop amplitude or an axle hop frequency that is below the lowest site cutoff frequency in the City.



DESCRIPTION OF FIELD TESTS

Vibration levels induced by test vehicles and a falling weight device were measured at several sites in Montréal. Results presented in this paper are for test vehicles driven on the traffic lane nearest to buildings at a speed of 50 km/h, which is the posted speed limit at most residential roads in Montréal. Actual test vehicle speeds, measured using a hand-held radar gun, varied by approximately \pm 5 km/h. The falling weight device was located in the parking lane in front of test buildings. Roads remained open to traffic during the measurements, except for site 9.

Measurement sites

A total of 9 buildings (referred to here as buildings or sites 1 to 9) were selected in different parts of Montréal where in the past complaints about traffic vibration had been received by the City. Buildings were selected so that they are representative of several combinations of building types and site conditions in a list of 220 complaint sites in the City (consisting mostly of residential homes). Top soil type at 7 of the 9 selected sites was silty-clay and sand at the other 2 sites.

Test vehicles

The following two types of test vehicles were used: (i) a typical transit bus, and (ii) a mid-size flat-bed / 2-axle truck. The same truck (International model SE-1800/1974) and the same type of bus (GMC model T6H53/1981) were used at sites 1 to 8. At site number 9, the bus (MCI model TC401/1990) was of the same category as that used at sites 1 to 8 and the truck (International model S-1900/1985) was flat-bed / single-axle vehicle. Buses were used empty; the front and rear axle loads were, respectively, about 2900 kg and 7100 kg for the type used at sites 1 to 8 and 3750 kg and 7600 kg for the type used at site 9. The trucks were loaded either with sand bags or steel plates; the front and rear axle loads were, respectively, about 3895 kg and 9050 kg (combined load for the two rear axles) for the type used at sites 1 to 8 and 4070 kg and 8470 kg for the type used at site 9. Test buses or trucks were not available on the scheduled test day of some sites.

Falling weight device

The falling weight device consists of a 125 kg weight and an impact target instrumented with a load cell. The weight was dropped from a height of about 1.2 m. The peak impact force generated was about 100 kN. This load is believed to be close to the dynamic force generated by a typical transit bus traveling over a discrete irregularity in the road surface. The falling weight device did not have a rebound/catch mechanism after the first impact; thus only the vibration signals induced by the first impact of the falling weight were analysed. Force amplitudes generated by the falling weight were significant up to about 100 Hz. At 50 Hz, the amplitude was down by only 3 dB.

MEASUREMENT & ANALYSIS PROCEDURES

Measurement locations

Vibration levels were measured on the ground at approximately 1 m from the front of test buildings, at corners of basement floor slabs, and at corners and mid-points of floors of above-ground storeys. On the ground and at corners of floors, vibrations were measured in both the vertical and transverse (perpendicular to the road) directions. At mid-points of floors, vibrations were measured in the vertical direction only. For measurements on the ground, accelerometers were mounted using 300 mm long aluminum stakes². On rough concrete surfaces in basements, accelerometers were mounted using small aluminum plates which were attached to the surface using 5-minute epoxy glue. And for measurements on smooth surfaces, e.g. wood flooring, accelerometers were directly attached using double-sided adhesive tape.

Instrumentation & data acquisition

Vibration measurements were made using servo electro-mechanical acceleration transducers having a sensitivity of 10 volts/g (g is the unit of gravitational acceleration) and a linear frequency response $(\pm 5\%)$ in the range Vibration signals from the accelerometers were amplified if DC-300 Hz. necessary, low-pass filtered at 125 Hz, and then acquired directly in digital form at a sampling frequency of 500 samples/s using a 16-channels PC-based data acquisition system³. At the onset of a test vehicle pass-by, data acquisition was initiated for a period of about 20 seconds. If vehicles other than the test vehicle passed in front of the building during this period, data was discarded and the test repeated. After each vehicle pass-by, vibration signals were displayed to check if the voltage range of the data acquisition system was exceeded. If overloaded channels were detected, necessary adjustments were made to channel gains and the test was repeated.

Data processing

Narrow-band frequency analysis using the Fast Fourier Transform (FFT) was performed in order to resolve the frequency content of recorded signals in detail. An appropriate FFT size was used so that the major part of vibration signals (including the rise and fall parts) was included. No smoothing windows were used. Results are presented in terms of Fourier spectra. In addition, 1/3-octave band frequency spectra^{4,5} and overall frequency weighted levels⁵ were calculated to evaluate human response to the measured vibration levels.

OBSERVATIONS & DISCUSSION OF RESULTS

Vibration Levels

In general, vibration levels induced by the buses were at least two times those induced by the trucks although the latter were slightly heavier than buses. An explanation for this large difference could be the fact that the test truck used at sites 1 to 8 had 2 rear axles while the buses had only one. However, the same

trend was observed for tests at site 9 where a truck with only one rear axle was used. The same trend was also observed in an earlier study⁶ (in a different city) in which a single-axle test truck and bus of the same weight category were used. The cause for this phenomenon is attributed to the different types of suspension systems of the two vehicles, air-bag spring for the bus and steel multi-leaf spring for the truck. Different suspension systems induce different dynamic loads on roads^{1,7}, e.g. amplitude and frequency content.

The trend observed in this study, however, is the opposite of that observed in a study of dynamic loads induced by different suspension systems⁷. Results of tests reported in reference 7 reveal that for roads in fair condition and at a speed of 80 km/h, the dynamic load induced by a test truck fitted with air-bag suspension is about 60% of the dynamic load induced by the same truck but fitted with steel multi-leaf suspension. The difference between the dynamic loads induced by the two types of suspension decreased for better road conditions and (or) lower vehicle speeds⁷. The contradiction between the trend observed in this study and that observed in reference 7 can be explained in simple terms as follows. The dynamic load induced by a road vehicle is concentrated at two frequencies. The first frequency corresponds to the vertical vibration of the sprung mass of the vehicle while the second frequency reflects the vertical vibration of the unsprung mass (i.e. axle, rims, tires, etc.). The majority of the dynamic load on the road is caused by the vibration of the sprung mass which for commercial vehicles occurs in the frequency range from 1.5 to 3.5 Hz^{1.7}. As shown below, the soils at sites considered in this study impede the propagation of vibrations at these frequencies. On the other hand, the dynamic load at the second frequency component is mainly due to the unsprung mass. This frequency should be much higher than that due to vibration of the sprung mass since the latter is much larger than the unsprung mass. In view of the results obtained in this study, it appears that the dynamic load at the second frequency (i.e. axle hop frequency), although it is not the dominant component of the dynamic load, is the main cause of ground vibrations.

At most sites considered in this study, 1/3-octave band as well as overall frequency weighted levels of vibrations induced by the test trucks did not exceed recommended levels⁵ above which adverse comment may arise in residential buildings. This, however, was not the case for buses. Consequently, it appears feasible to alleviate most traffic vibrations in Montréal by modifying the suspension systems of transit buses used in the City.

Predominant frequencies

Narrow-band frequency spectra of vertical vibration signals induced by test buses and trucks are shown for ground measurement points in Figures 1 and 2, respectively. It can be seen that the frequency content of bus-induced vibrations is generally concentrated in a narrow frequency range while the frequency content of truck-induced vibrations is spread over a wider range.

The predominant frequencies of bus-induced vibrations at most sites fall in the narrow range from 10 to 12.5 Hz, while those of vibration induced by trucks sometimes occur at higher frequencies. Further inspection of the spectra in Figures 1 and 2 reveals that outside the predominant frequency range of bus-induced vibrations, the amplitudes of bus and truck-induced vibrations are not significantly different. The difference in frequency content between bus and truck-induced vibrations is again attributed to the different types of suspension systems of the two types of vehicles.

Narrow-band frequency spectra of vertical ground vibrations induced by the falling weight device are shown in Figure 3. From these spectra, it can be seen that most sites have at least one natural frequency in the range from 10 to 12.5 Hz, which is the predominant frequency range of bus-induced vibrations. In view of remarks made in the introduction, it might be said that the axle hop frequency of buses used in this study is close to or coincides with the above mentioned natural frequency at most sites. Furthermore, it seems that vibrations induced by the axle hop of the bus overshadow vibrations induced by the initial impact with irregularities in the road surface. For the truck, on the other hand, either the axle hop frequency is outside the 10 to 12.5 Hz range, or more likely, the truck's axle does not hop as much as that of the bus, and therefore, its initial impact with irregularities in the road surface is the main mechanism for vibration generation. An impact usually produces vibration energy with a wide frequency content which induces vibrations at several natural frequencies of a site. This would explain the wide frequency content of truck-induced vibrations.

Cutoff frequency

Finally, it can be observed from the narrow-band spectra in Figures 1 to 3 for the bus, truck, and falling weight, respectively, that there is a "cutoff frequency" for each site below which vibrations are extremely small. A soil site with soft upper layers underlain by a much stiffer layer does not propagate vibrations at frequencies below a certain cutoff frequency; vibrations below the cutoff frequency decay exponentially with distance from the vibration source⁸. In other words, the site behaves like a high-pass filter which blocks the transmission of vibrations at frequencies lower than its cutoff.

From the spectra in Figures 1 to 3 it can be said that 7 out of the 9 sites considered in this study have a cutoff frequency higher than 7.5 Hz. The cutoff frequency phenomenon has a practical significance. Vibration levels in Montréal would be reduced drastically if suspension systems of existing transit buses used in the City could be modified, or those of future ones designed, so that the axle hop frequency is below the cutoff frequency of most complaint sites in the City. Recently, stiff horizontal barriers buried under the vibration source (or the receiver) were explored as a way of altering the cutoff frequency to impede the transmission of vibrations⁹. At this time, however, the authors' were not aware of any studies that investigated vehicle suspension systems in



view of the cutoff frequency phenomenon or as a means of reducing ground vibration in general. Modification of suspension systems, if possible, appears to be effective and economical for this purpose, in addition to perhaps increasing passenger comfort as the suspension would probably be softer. It would also be beneficial in terms of reducing pavement damage caused by dynamic vehicle/pavement interaction forces, and hence, indirectly lead to less ground vibration.

ACKNOWLEDGMENTS

This study is part of a joint project between IRC/NRC and the City of Montréal. Messrs. L. Wang, R. Glazer, T. Hoogeveen and A. Laberge of IRC/NRC and Mr. C. Sanfaçon of the City of Montréal participated in field experiments and data processing. The cooperation of the regional Public Works Departments of the City of Montréal in arranging the tests and STCUM for providing test buses is gratefully acknowledged. Also, the cooperation of tenants and owners of buildings used in the study is greatly appreciated.

REFERENCES

- 1. Woodrooffe, J.H.F., LeBlanc, P.A., & Papagiannakis, A.T. Suspension Dynamicsexperimental findings and regulatory implications. *Vehicle/Pavement Interaction-Where the Truck Meets the Road*, SP-765, Society of Automotive Engineers, Inc., Warrendale, PA, 1988, 69-77.
- 2. Al-Hunaidi, M.O., & Rainer, J.H. Evaluation of measurement limits of transducer mountings in the ground. Canadian Acoustics, 1990, **18** (3), 15-27.
- Al-Hunaidi, M.O., Rainer, J.H., & Pernica G. Measurement and analysis of traffic-induced vibrations. Proceedings 2nd International Symposium - Transport Noise and Vibration, St. Petersburg, Russia, 1994, 103-108.
- 4. Al-Hunaidi, M.O., Hofmeister, M., & Halliwell, R.E. A program for 1/3 octave analysis of traffic vibrations using digital filtering on PCs. *Inter-Noise 92 (Noise Control and the Public)*, Toronto, Canada, 1992, **2**, 1153-1156.
- ISO 2631/2. Evaluation of human exposure to whole-body vibration Part 2: Continuous vibration and shock-induced vibration in buildings (1 to 80 Hz). International Organization for Standardization, Geneva, Switzerland, 1989.
- Al-Hunaidi, M.O. & Rainer J.H. Remedial measures for traffic-induced vibrations at a residential site Part 1: Field tests. Canadian Acoustics, 1991, 19 (1), 3-13.
- Woodrooffe, J.H.F., LeBlanc, P.A., & LePiane, K.R. Effects of Suspension Variations on the Dynamic Wheel Loads of a Heavy Articulated Highway Vehicle. Vehicle Weights and Dimensions Study, Transportation Association of Canada, 1986, Technical Report Volume 11 (ISBN 0-919098-88-6).
- 8. Wolf, J.P. Foundation Vibration Analysis Using Simple Physical Models. Prentice-Hall, Inc., Englewood Cliffs, N.J., 1994.
- Chouw, N., Le, R., & Schmid, G. Source depth effects on impediment of waves in Soil. Proc. 2nd European Conference on Structural Dynamics - Eurodyn'93, Trondheim, Norway, 1993, 1, 419-426.

©Government of Canada



迹





Transactions on the Built Environment vol 14. © 1995 WT Press, www.withers.com ISSN 1743-35965



迹

