Journal of Sound and Vibration (2001) **246**(2), 319–335
doi:10.1006/jsvi.2001.3648, available online at http://www.idealibrary.com on IDEAL®

MEASUREMENT AND PREDICTION OF TRAFFIC-INDUCED VIBRATIONS IN A HERITAGE BUILDING

M. CRISPINO

Department of Structural Engineering (*D.I.S.*), *Politecnico di Milano*, *P.zza Leonardo da Vinci*, 32, 20133 *Milano*, *Italy*. *E-mail*: *crispino@mail.dstm.polimi.it*

AND

M. D'APUZZO

Department of Transportation Engineering (*D.I.T.*), *University of Naples "Federico II" Via Claudio*, 21, 80125 *Naples*, *Italy*. *E-mail*: *mardapuz@cds.unina.it*

(*Received* 19 *June* 2000, *and in final form* 5 *February* 2001)

The paper describes measurements of road traffic-induced vibrations in a heritage building in Naples. The measurements have been related to vehicle type and speed and have been compared with values obtained by a "modified" prediction model. Analysis of results showed that the ISO 2631 [1] perception threshold for peak particle velocity (PPV) (0·14 mm/s) was exceeded for all acquired data, and in some cases the vibration level exceeded the lowest damage PPV threshold found in literature (1 mm/s) [2]. In some cases the Swiss Standard threshold [3] (1·5 mm/s) for particularly sensitive buildings was also exceeded. The prediction model was developed by modifying an existing model initially developed to predict vibrations due only to localized surface irregularities (bumps). The novel feature in this study is that the road roughness parameter in the model has been characterized by the root mean square (r.m.s.) value of the surface wavelengths that drive the natural frequencies of wheel hop and body bounce of heavy vehicle suspensions. This also allows vibration of longitudinally distributed irregularities (roughness) typical of stone block road pavements to be predicted and should potentially be of practical use in identifying high-exposure sites in sensitive heritage areas.

1. INTRODUCTION

The environmental impact of vibrations induced by road traffic is an increasing concern in residential areas. Growing awareness of this phenomenon appears to be also confirmed in a recent study [4]. Within historical city centres, it is possible to identify a series of common elements that tend to highlight such phenomena:

- road surfaces most commonly used in historical centres are often of stone and their use is typically due to aesthetic reasons; poor design or lack of maintenance are often the cause of high levels of roughness;
- municipal policies aimed at discouraging the use of private vehicles in order to reduce air pollution have caused a significant increase in the number of high-capacity, heavy-weight public transport vehicles in city traffic and future trends suggest further increase;

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- the presence of heritage buildings or, more generally, of buildings protected by laws on heritage preservation, require particular care in the evaluation of actions that cause additional stress to the structures and to assess potential damage.

Presently, in spite of the importance of the issue, information on road traffic-induced vibrations and their effects on heritage buildings is still limited.

This study deals with this issue by investigating vibration levels to which heritage buildings are subjected due to vehicle traffic. The need for a straightforward prediction method for the assessment of vibration levels induced by traffic acted as a stimulus for the authors to initiate this study to investigate the possibility of extending the field of validity of a widely used prediction method.

2. PREVIOUS STUDIES ON TRAFFIC INDUCED VIBRATIONS

Considerable analysis on this topic was first carried out over 30–40 years by the *Road Research Laboratory* (now *Transport Research Laboratory*, *TRL*). Initial experience dates back to 1960 [5], when heavy good vehicle (HGV)-induced vibrations were measured experimentally by TRL on a trunk road (A1) at Alconbury Hill in Huntingdonshire. The vehicle moved at a speed of 48 km/h on different types of newly constructed road surfaces (flexible and rigid) and, again, on the same surfaces artificially modified by the presence of a triangular ramp 230 mm long by 21 mm high. Results showed that the peak particle velocity (PPV) measured close to the road side reached higher values (by one order of magnitude) and exceeded the perception threshold when passing from the smooth surface to the irregular one. The influence of the type of surface did not seem to cause appreciable effects on the level of measured vibrations. In general, it was observed that the level of vibrations measured at the roadside increased with the transit speed of the vehicles and with the height/depth of the localized surface irregularity. Moreover, the frequency interval peculiar to this phenomenon was below 30 Hz, with many peaks at 44 Hz when the vehicle passed over an expansion joint of a rigid surface.

Subsequent studies [6] revealed, from measurements of vibrations in four different buildings alongside smooth surface roadways, that the vibration level exceeded the perception threshold defined in the ISO 2631 standard [1] in only two of the buildings and for only 1% of the time. Watts [7] showed that heavy vehicles produce most of the perceptible vibrations, and confirmed that the level of vibration tends to increase with the speed of vehicles and the height or depth of surface irregularity. The length or shape of the localized surface irregularity did not seem to influence the result substantially. In particular, when the irregularity was within 5 m of the building and its height or depth was greater than 20 mm, it was possible to measure perceptible vibrations on building floors due to the passage of HGVs. Watts also found that, during an experiment conducted on a building subjected to artificial vibrations [8], the vibration seemed to be amplified on the upper floors and on walls when compared to those found at foundation level. Finally, in subsequent experiments where measurements were carried out on four different types of buildings [9] the ratio between the maximum level of vertical vibration at the first floor (with the sensor positioned on the main walls) and at foundation level was between 0·79 and 2·07. Analogous ratios with the sensor positioned at the centre of floors and at foundation level were between 2·47 and 3·73 for the first floor while for second and third floor values the ratios were, respectively, 4·16 and 5·10.

In Italy there is little information on the measurement of vibration induced by HGV traffic and only few experiments have been conducted on buildings considered to be heritage sites. It is however relevant to refer to an experiment carried out near Villa Farnesina in Rome [10] as it was aimed at establishing the effectiveness of antivibration pavements, made in the early 1970s, alongside the Tiber river.

Most of the experiments on traffic-induced vibration indicated that the level of measured vibrations did not seem to cause structural damage to building structure [11]. However, according to ISO 4866 [12], vibration could cause cosmetic and minor damage and this is undoubtedly of the utmost concern when considering heritage buildings. It is also important to note that, for this type of building, no in-depth research has yet been carried out on the consequences of continued exposure to micro-stress induced by vibrations due to road traffic. For almost all experiments carried out on buildings, the perception threshold was exceeded; thus the issue also becomes that of the 'quality of life' in buildings adjacent to roads due to the nuisance caused by vibrations.

2.1. WATTS' PREDICTION MODEL

From a theoretical standpoint, there are few mathematical models that address the calculation of traffic-induced vibrations [13, 14]. The reasons may be attributed to the fact that the problem is extremely complex and involves a number of differing disciplines (mechanical, structural, highway engineering and geotechnics). Literature, however, shows that TRL [11, 15] formulated a prediction model that was developed experimentally from data extracted from simulations and measurements of vibrations induced by traffic for various types of soil, vehicle speeds and different heights or depths of localized irregularities (bumps). The model suggests using an expression for the vertical peak particle velocity as a means of assessing the vibration induced at the foundation level of a building caused by a heavy vehicle passing over a localized irregularity.

The formula takes into account the maximum height or depth of the localized surface irregularity over which the heavy vehicle passes, the speed of the vehicle, and the distance between the irregularity and the building. The expression is:

$$PPV\ (\mathrm{mm/s}) = 0{\cdot}028\ a\ (v/48)\, tp\, (r/6)^{x} \tag{1}$$

where PPV is the Vertical peak particle Velocity (mm/s); a the maximum height or depth of a localized surface irregularity (mm); v the maximum expected speed of heavy vehicle (km/h); t the ground scaling factor; p the wheel track index for the heavy vehicle equal to 0·75 if the irregularity only involves one wheel path (left or right wheels), otherwise equal to 1; r the distance between the irregularity and building foundation (m); x the exponent of the power that defines the damping of the vibration with the distance.

The values for t and x are shown in Table 1 according to the type of soil involved.

In this paper, the possibility of extending the field of validity of such a prediction method to the case of real longitudinally distributed irregularities (roughness) is investigated.

3. DESCRIPTION OF THE EXPERIMENT

3.1. MEASUREMENT SITE

The site of the experiment is Riviera di Chiaia, a major road in the city of Naples (Italy). The same site was recently the subject of a survey of surface profile and the degree of nuisance to people caused by traffic-induced vibrations. The results were described by Crispino *et al.* in reference [4].

Table 1

Values for coefficients x and t in Watt's formula for different soils (after [11])

Soil type	Number of sites researched	x Interval	x Average	t
Peat	1	—	– 1·19	3·84
Alluvium	2	– 0·79– – 0·80	– 0·79	7.07
London clay	3	– 0·99– – 1·13	– 1·06	3·10
Sand/Gravel	3	– 0·69– – 0·82	– 0·74	0·94
Boulder clay	3	– 0·71– – 1·18	– 0·93	0·43
Chalk rock	1	—	– 1·08	0·10

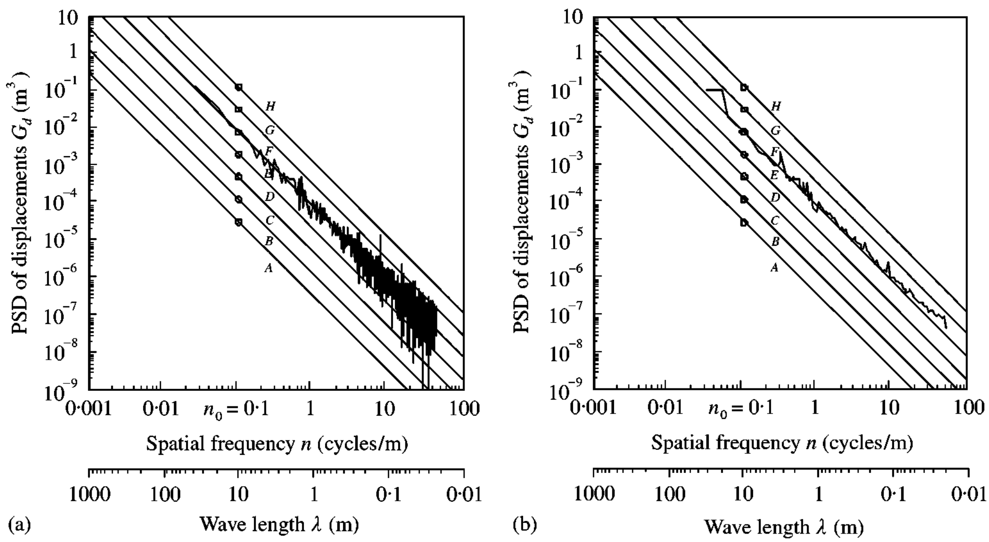

Figure 1. (a) PSD of the measured road profile; (b) Smoothed PSD and regression line of the measured road profile, according to ISO 8608 [4].

Riviera di Chiaia is important for the traffic in Naples as it is a link between the eastern and the western metropolitan area. For this reason, it is subject to very high volumes of traffic, with a significant percentage of heavy vehicles (buses and trucks). On the basis of a recent study [16] it seems reasonable to assume that the road surface, consisting of small cubes of porphyry, is laid on a sandbed which is, in turn, laid directly on to the subgrade or perhaps on to a granular material layer. The surface is characterized by a high degree of roughness that can even be detected visually. The road surface profile, measured by a straightedge profiler with a rolling wheel, according to the ISO 8608 standard [17] was found to belong to class E (for $n < n_o$) and to class F (for $n > n_o$) (where n is the space frequency (cycles/m) and $n_o = 0{\cdot}1$ cycles/m). In Figure 1a and 1b the power spectral density (PSD) of the road profile and the smoothed PSD (with its regression line according to ISO 8608), respectively, are shown.

A line of buildings lies adjacent to the road (Riviera di Chiaia) and many of these can be classified as historical heritage buildings. Palazzo S. Teodoro, built in 1826 and designed by Architect Guglielmo Bechi, was chosen from several important buildings since it was vacant

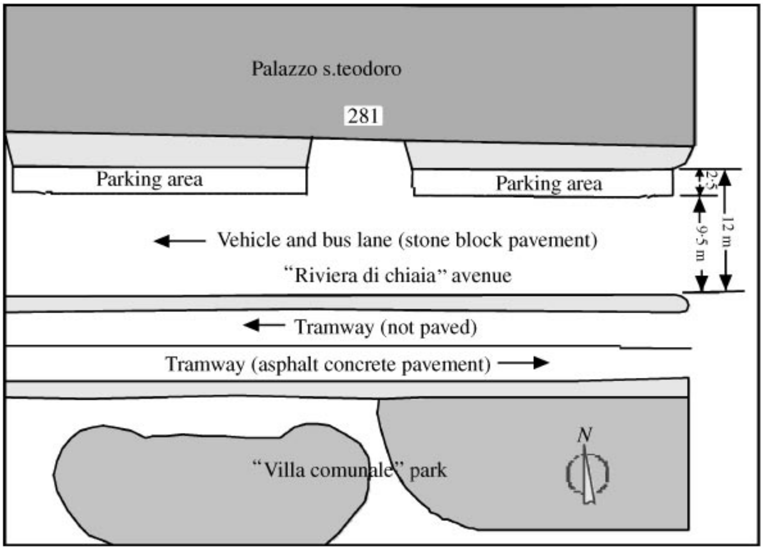

Figure 2. A scheme of the site of the experiment: Palazzo S. Teodoro and the road "Riviera di Chiaia"

due to some restoration works. It was thus possible to carry out measurements with greater freedom because of the unrestricted access to all the rooms facing the road and instrumentation could be installed without affecting residents. A plan of Palazzo S. Teodoro and of Riviera di Chiaia is shown in Figure 2. The building structure is a masonry made of yellow Neapolitan tuff. The ground floor and the second floor plan, with measurement locations, are shown in Figure 3. Some ceilings are stone vaulted (ground floor and first floor) while others are lapil slabs with wooden beams (second and third floor); most of the floors have recently been strengthened with steel beams, particularly those of the first and second floors.

3.2. MEASUREMENT INSTRUMENTATION

Data acquisition system used for the measurement of vibrations at Palazzo San Teodoro was supplied by Tecno In S.r.l. (that also participated in testing activities). The system included the following equipment:

- Vertical and horizontal geophones (by Mark Electronics, model L28B, 395 Ω (Standard Coil Resistance), 4.5 Hz (Standard Frequency));
- data acquisition board;
- PC for data recording and data processing.

The signal is transmitted to a data acquisition card that, after amplifying the signal, scans the input channels at the given sampling frequency f_c chosen for each channel. At this point, the acquired signal is processed as follows (a) Fourier transform, (b) subsequent correction in accordance with instrument calibration curve, (c) integration and derivation in the frequency domain and (d) subsequent inverse transform to obtain a time history of acceleration, velocity and displacement. The processing cycle also uses anti-aliasing and anti-leakage algorithms. Acquired data is finally stored on PC hard drive.

Simultaneously, a video recording of the transit of heavy vehicles involved was also carried out.

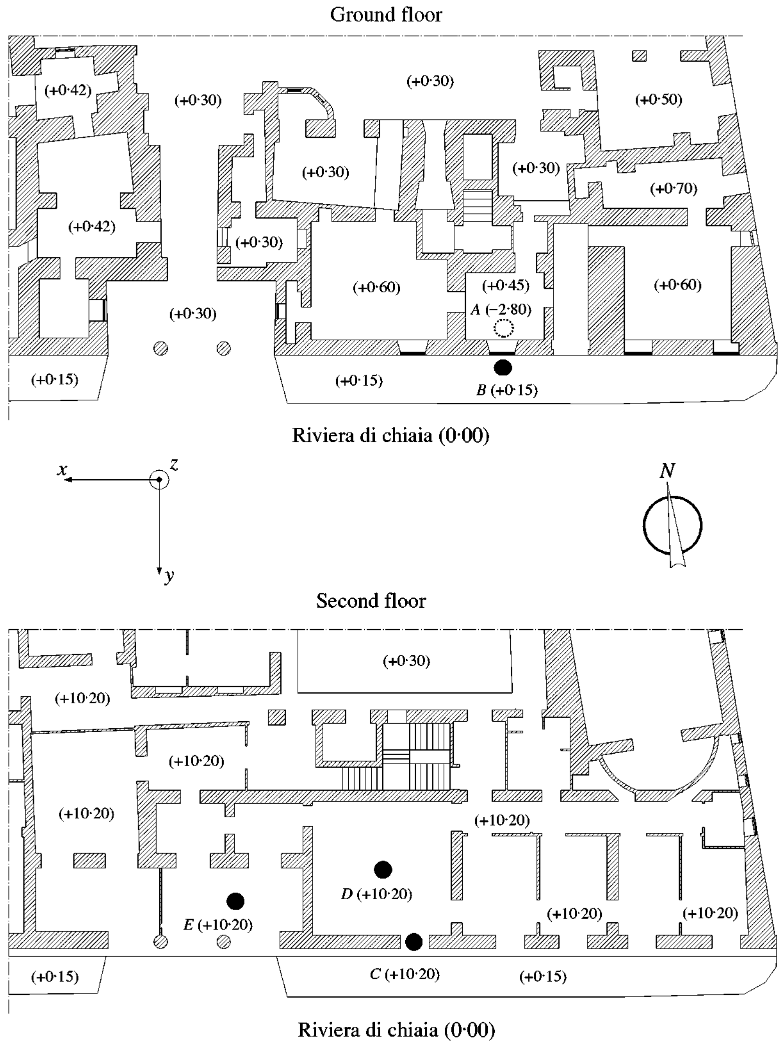

Figure 3. Plan of the building and of the measurement stations: Points A and B (Ground floor), Points C, D and E (second floor).

3.3. SENSOR PLACEMENT

Three geophones were used for each measurement location: one for vertical displacements (z direction) and two for horizontal displacements (x and y directions); these two sensors were positioned along two orthogonal directions, one of which was parallel to the road (x direction).

After a survey, it was decided to position geophones at five measurement locations. A total of 15 geophones were thus positioned as follows (as shown in Figure 3):

- at foundation level (point A), close to the building external wall;
- on the sidewalk (point B), corresponding with the same wall mentioned for point A;
- at the second floor (point C), on the ledge of the balcony of the room adjacent to the one above points A and B;
- at the second floor (point D), at the centre of the room floor mentioned for point C;

TABLE 2

Speed and length of heavy vehicles passed during measurement period

Name*	Model	Length (m)	Speed (km/h)	Name*	Model	Length (m)	Speed (km/h)
2	Tram	11·0‡	?	29	Iveco 490 (U-R)	10·79†	37
3	BredaMenariniBus	8·97†	25	30	Iveco 490 (U-R)	10·79†	31
5	Autodromo	12·0†	30	31	Iveco 480 (U)	10·715†	42
7	BredaMenariniBus	8·97‡	26	33	Autodromo	12.0†	34
8	Autodromo	12·0†	27	34	BredaMenariniBus	8·97†	28
9	Iveco 490 (U-R)	10·79†	29	35	InBus U-150	8·62†	25
11	Iveco 480 (U)	10·715†	23	36	Autodromo	12·0†	33
12	Autodromo	12·0†	27	37	Truck	12·0‡	32
13	Iveco 490 (U-R)	10·79†	30	38	Truck	4·8‡	25
14	BredaMenariniBus	8·97†	28	39	BredaMenariniBus	8·97†	28
16	Autodromo	12·0†	29	40	Iveco 490 (U-R)	10·79†	43
17	Truck	11·2‡	44	41	Iveco 480 (U)	10·715†	28
18	Iveco 470 (U)	10·715†	32	42	Iveco 480 (U)	10·715†	32
19	Iveco 490 (U-R)	10·79†	32	43	Autodromo	12·0†	26
20	BredaMenariniBus	8·97†	31	44	Truck	12·0‡	21
21	Autodromo	12.0†	33	45	InBus U-150	8·62†	17
22	Iveco 480 (U)	10·715†	33	46	Truck	7.4‡	22
23	Iveco (Bus milit·)	8·8‡	30	47	BredaMenariniBus	8·97†	22
24	Autodromo	12·0†	24	48	Autodromo	12·0†	24
25	Turistic Bus	12·0‡	45	49	Truck	5·3‡	20
27	Autodromo	12·0†	27	50	Iveco 480 (U)	10·715†	25
28	BredaMenariniBus	8·97†	21	—	—	—	—

* Recordings were identified using cardinal numbers from 1 to 50 excluding numbers 1, 4, 6, 10, 15, 26, 32 (due to incorrect data acquisition).
† *Source*: Manufacturer.
‡ *Source*: Length estimated from video recording.

- at the second floor (point E), at the centre of the room floor adjacent (west) to the one mentioned for points C and D.

Geophones at points A, B and C were fixed at the measurement location via perforation and application of mortar, while geophones at points D and E were fixed to a 10×10 cm steel plate, 1 cm thick. Steel plates were secured to the floor using three small screws: this choice was dictated by the need to avoid any damage to the valuable flooring.

3.4. ACQUIRED DATA

Vibration velocities induced by the transit of heavy vehicles (mainly buses and trucks) were recorded at each measurement location. During vibration measurements, care was taken in recording each vehicle passage separately; the vehicles selected were moving freely and far enough away from other vehicles, so that only the passing vehicle produced the vibration recorded.

A video tape from a fixed camera recording vehicle traffic, provided a reliable estimate of the heavy traffic flow, of the average speed of the vehicles and of their respective size. In particular, the hourly traffic volume of bus and heavy good vehicles was respectively 35 and 10 vehicles/h. Table 2 shows a synoptic chart of the recordings carried out.

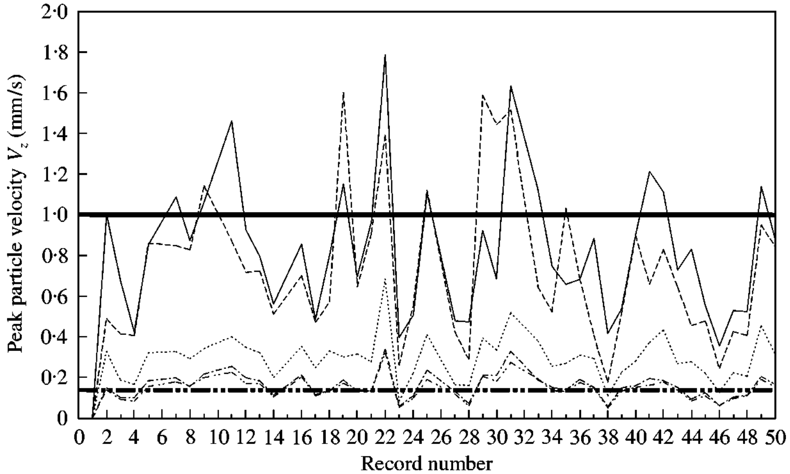

Figure 4. Peak particle velocity in vertical (z) direction, v_z, for each vehicle passage and comparison with vibration magnitude thresholds. —··—, Point A; —·—·, Point B; ·········, Point C; - - - - -, Point D; ——, Point E; ▬▬, Lower value of damage threshold from [2, 19]; ▬··▬··, Lower value of perception threshold according to ISO 2631 [1].

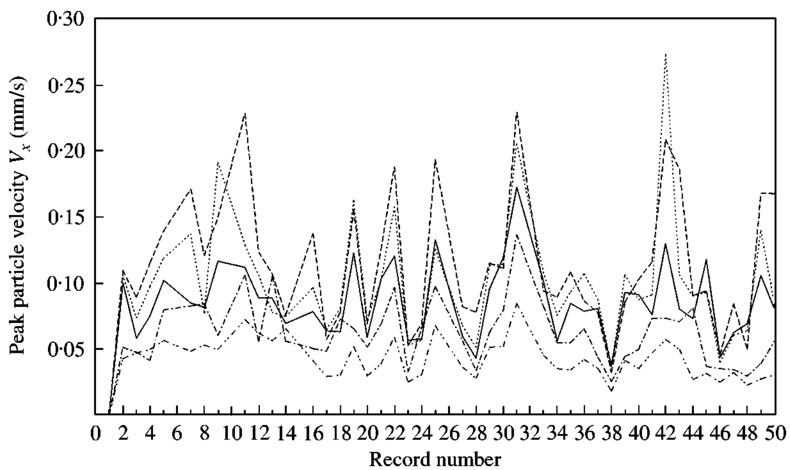

Figure 5. Peak particle velocity in horizontal x direction, v_x, for each vehicle passage. —··—, Point A; —·—·, Point B; ·········, Point C; - - - - -, Point D; ——, Point E.

4. ANALYSIS OF RESULTS

4.1. ANALYSIS OF VIBRATION LEVELS

Figures 4–6 show the peak particle velocity evaluated from each recorded interval (average length 15 s) respectively along vertical (z-axis) and horizontal (x- and y-axes) directions, for each measurement station. In abscissa the identification number, according to Table 2, is reported.

For vibrations along z-axis (vertical axis) Figure 4 shows a meaningful difference between peak values at floor centres (points D and E) with respect to other points (A, B, C). This could be ascribed to the greater vertical flexibility of the floors when compared to the wall (point C) that may also induce local resonance phenomena. On the other hand peaks for

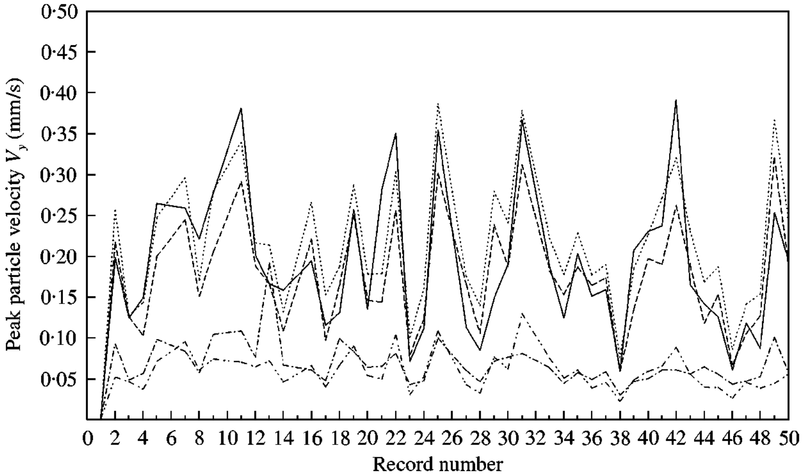

Figure 6. Peak particle velocity in horizontal y direction, v_y, for each vehicle passage. —··—, Point A; —·—·, Point B; ·········, Point C; - - - - -, Point D; ——, Point E.

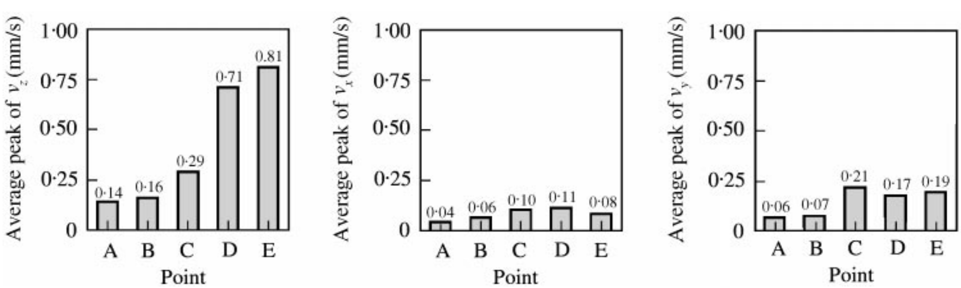

Figure 7. Average peak of velocity for each measurement station (along z, x and y axes).

point A and B are rather similar and this may be due to the closeness of main external walls that induce, through friction, an oscillatory motion that is similar for both measurement stations, as found also by other authors [8].

In Figures 5 and 6, it can be clearly seen that for the horizontal directions x and y there is a meaningful reduction of the vibration levels with respect to the z direction. This is mainly due to the fact that the vibration propagates predominantly as a Rayleigh wave (surface wave) and its principal component is thus vertical. It should also be noted that floors have greater rigidity in the x and y directions when compared to z and, therefore, the reduction of vibration levels is more pronounced. To display this aspect better, Figure 7 shows the average peak of the vertical and horizontal velocities evaluated over the entire data recordings for each measurement station. It is interesting to observe in Table 3 that PPV amplification factors at upper floors with respect to foundation level are rather close to those provided by the other researchers previously mentioned [9].

Power spectral density (PSD) functions were extracted for each velocity component and for each measurement station from recorded data. Analysis of these functions showed that the signal frequency content was almost entirely localized around a frequency corresponding to the peak value of PSD, as can be easily detected by examining Figure 8 which shows a typical vertical velocity PSD diagram, for measurement station C. For the same measurement station, the peak values extracted from each vertical velocity

TABLE 3

Comparison between PPV amplification factors for upper floors (respect to foundation level) reported in [9] with those measured

Position	Amplification factor	
	After [9]	Measured data
First Floor (at floor centre)	2·4–3·73	—
Second Floor (at floor centre)	4·16	5·07–5·78

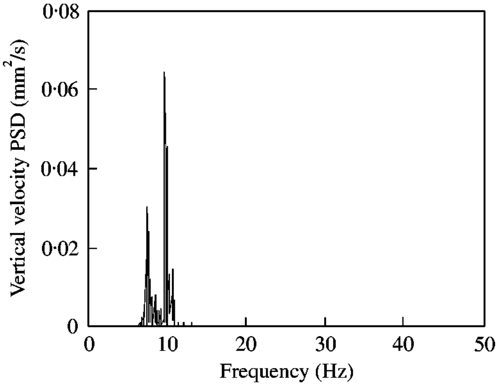

Figure 8. Typical vertical velocity PSD at measurement station C.

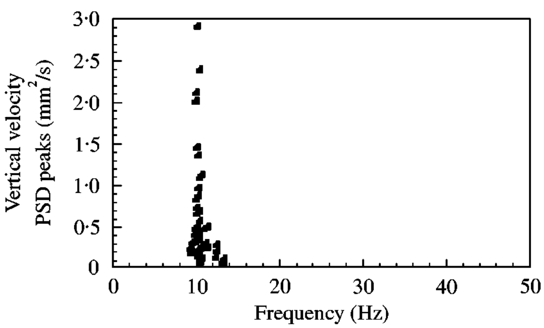

Figure 9. Peak values extracted from Vertical Velocity PSD vs frequency, for station C.

PSD, against frequencies are shown in Figure 9. It can be clearly seen that the distribution of peak frequencies for most of the acquired data falls within the 8–12 Hz interval, with highest peaks at 10 Hz frequency.

The measured vibrations were then compared with acceptable levels of the effects on residents and the risk of possible damage for the building or its parts. In both cases peak velocities were used for the comparison. With respect to the risk of building damage, it has to be emphasized that the adoption of PPV as reference value for the acceptability criterion has raised some doubts since recent evidence has suggested that constant root-mean-square velocities would provide more realistic band—boundaries to assess allowable/unacceptable

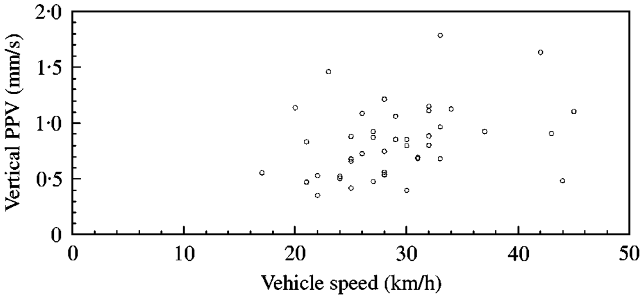

Figure 10. Vertical peak particle velocity measured at station D vs vehicle speed.

vibration levels [18]. This subject is currently under review by the ISO (ISO/TC108/SC/Wg3-9) [18]. However, at present, most current national and international standards and studies on vibration damage still refer to PPV thresholds and so it was decided to use this parameter as a reference in this study.

On the basis of the results obtained (shown in Figure 4) it was seen that the vertical PPV at floor centres exceeded the perception threshold that, according to studies and standards, is between 0·14 [1] and 0·5 mm/s [2, 19] for frequencies around 8–12 Hz, such as those measured.

However, with regard to cosmetic damage, among the standards examined there is a great disparity in the value assigned to the damage threshold for heritage buildings or for buildings of historical and architectural interest. For example, Italian standards (UNI 9916) [20] report a threshold value of 3 mm/s at foundations and 8 mm/s at upper floors for frequencies below 10 Hz. German standards DIN 4150/3 [21] refer to the same threshold values but consider for a reference measure the instantaneous velocity calculated as the square root of the sum of the squares of the velocities in the three directions. Swiss standards [3] set the threshold at 1·5 mm/s, in terms of instantaneous velocity, if the stress is of the permanent type; other authors [2, 19] even report a threshold value equal to 1 mm/s.

This last value, along with the one that places the perception threshold at 0·14 mm/s [1] (for frequencies above 8 Hz, as in the present case), is, for convenience, shown in Figure 4 for immediate comparison with measured values.

4.2. INFLUENCE OF VEHICLE TRANSIT SPEED ON VIBRATION VELOCITY

The analysis of recorded measurements has shown that for each type of vehicle there exist different recordings at different transit speed. An attempt was therefore made to verify the existence of a relationship between the vertical PPV (PPV_z), in mm/s, in the building and the speed of transit of the vehicle v, in km/h. Figure 10 shows paired values (v, PPV_z), for all types of vehicles, relative to measurement station D.

As can be observed, even though there is a trend for the level of vibration to increase as a function of increasing vehicle speed, the range seems too scattered to draw an acceptable relationship. It was thus attempted to extract a relationship characterized by a greater correlation, by reporting the pairs of measured points for each type of vehicle. Figures 11 and 12 show, for measurement stations A and D, the curves that best approximate (v, PPV_z) according to vehicle type. Correlation coefficients are also reported in the figures. It must be recognized that, for these cases, the correlation coefficients (calculated with the assumption of a linear behaviour) are rather low. It is also important to mention that the choice for

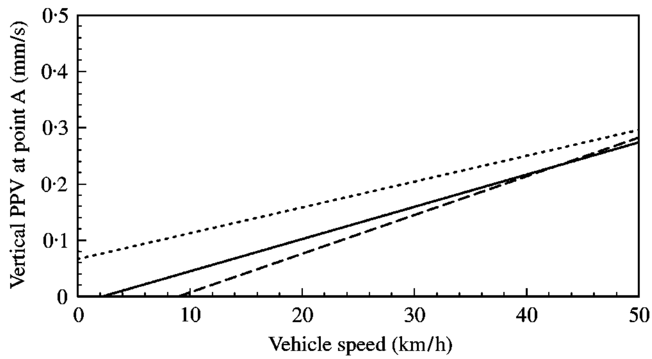

Figure 11. Regression lines (and correlation coefficients), for each vehicle type, of vertical peak particle velocity vs vehicle speed, for station A; ——, Autodromo Bassotto, $\rho = 0{\cdot}623$; - - - - -, BredaMenariniBus, $\rho = 0{\cdot}646$; ·········, Iveco 480(U), $\rho = 0{\cdot}442$.

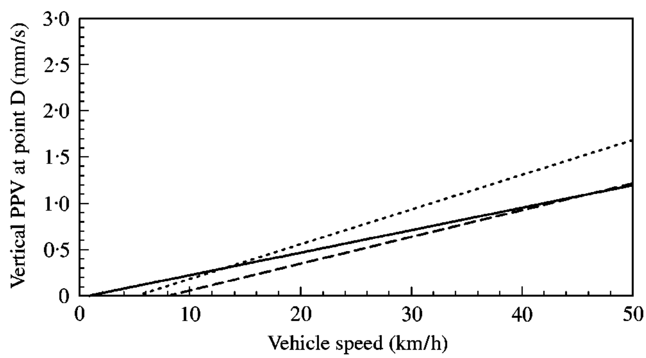

Figure 12. Regression lines (and correlation coefficients), for each vehicle type, of vertical peak particle velocity vs vehicle speed, for station D; ——, Autodromo Bassotto, $\rho = 0{\cdot}541$; - - - - -, BredaMenariniBus, $\rho = 0{\cdot}570$; ·········, Iveco 480(U), $\rho = 0{\cdot}649$.

a linear relationship of the type $PPV_z = av + b$ is dictated exclusively by the need to highlight qualitatively the trend for PPV to increase. Nevertheless, it is interesting to observe that:

- the different vehicle types have quite different regression lines, therefore, the influence of vehicle type on vibration levels is not negligible;
- Iveco 480 is the vehicle that often makes a major contribution to vibration; this is mainly due to the fact that this is the oldest model within the vehicle fleet.

The difficulty in finding a distinct relationship between vibration velocity and vehicle speed can be ascribed to different factors:

- transit speed modifies the way the road surface is "interpreted" by the vehicle thus changing the frequency content of the motion at the vehicle base. For certain speed values, it is in fact possible for the signal to be biased by resonance conditions due to dynamic interaction between vehicle and road profile as was evidenced also by other authors [5, 22, 23]; it follows that a monotonic growth law may not always describe adequately the relationship between vibration and vehicle speed;
- given a specific vehicle type and speed, some inertial and mechanical parameters may vary (such as the increase of the mass as a consequence of the payload or the stiffness of the

suspension system), influencing the dynamic response of the vehicle and therefore the level of vibrations generated;

- finally, even when characteristic parameters are equal, the wheel track on pavement and therefore the roughness "read" by the vehicle may differ, influencing the dynamic interaction phenomenon between vehicle and road profile.

4.3. EXTENSION OF WATTS' FORMULA TO THE CASE OF NON-LOCALIZED IRREGULARITIES

The empirical model developed by Watts [11], previously described (see section 2), seems, among the different models developed, the easiest to use and this was considered an important attribute in view of the wider attention paid by road administration technicians to traffic-induced vibration problems.

It is important to mention, though, that this model only addresses a localized irregularity (bump). The present study was, therefore, also aimed at investigating whether it was possible to extend its field of application to the case of longitudinally distributed irregularities as occur for the road surface in the site examined.

To this end, a comparison was made between measured values of velocities (at station A) and those found through the application of Watts' prediction formula. Station A was chosen for comparison as it was close to the foundation of the building and therefore measured values could be compared directly with predicted values. Watts' formula was calculated for each vehicle passage using different values of parameters for the vehicle speed v and the amplitude of the road roughness parameter, a.

The speed of each vehicle passage was assessed on the basis of the video recordings. Speeds were in the range 20–35 km/h.

The value of the road roughness amplitude a (see expression (1)) was based on the calculation of the r.m.s. between the wavelengths of the road profile PSD [see Figure 1(b)] that were fundamental for the generation of the vibrations. Several studies [23] have shown that heavy vehicles have similar mechanical and inertial characteristics. It follows that principal modes of vibration have characteristic frequencies within a rather limited bandwidth. In particular, various authors agree that it is possible to identify a frequency field between 1.5 and 4 Hz where oscillatory modes of sprung masses can be found and another interval, between 8 and 12 Hz, for unsprung mass modes. By making use of the relationship that ties the vehicle speed v with the frequency f and with the characteristic wavelength of the road profile λ, $\lambda = v/f$, and based on previous characteristic vehicle frequency ranges, it was possible to obtain, for a given vehicle speed, two fields of wavelengths of the road profile, named $\Delta_1\lambda(v)$ and $\Delta_2\lambda(v)$, relevant for the generation of vibrations (for example, for $v = 27$ km/h the following two intervals are obtained: $\Delta_1\lambda$ (27 km/h) = 1·875–5·0 m and $\Delta_2\lambda$ (27 km/h) = 0·625–0.9375 m). By integrating the road profile PSD diagram (Figure 1b) along these two wavelength intervals and calculating the square root, an r.m.s. value was obtained for each vehicle speed, which was therefore assumed as the "size" of the road roughness parameter in Watts' formula. Summarizing, the following expression is suggested by the authors for the calculation of a:

$$a = a(v) = \sqrt{\int_{\Delta_1\lambda(v)} PSD_{profile}\,\mathrm{d}\lambda + \int_{\Delta_2\lambda(v)} PSD_{profile}\,\mathrm{d}\lambda} \qquad (2)$$

where, besides the symbols already defined, the $PSD_{profile}$ is the PSD of the measured profile (its plot is shown in Figure 1b).

The values $a = a(v)$, for each vehicle speed v, to be used in the formula, are reported in Table 4.

TABLE 4

Measured vehicle (*) speeds v and calculated values of the road roughness parameter $a = a(v)$

v (Km/h)	$a = a(v)$ (m)	v (Km/h)	$a = a(v)$ (m)
17	0·014183	28	0·017902
21	0·015653	29	0·018198
22	0·015996	31	0·018773
24	0·016659	32	0·019053
25	0·016980	33	0·019329
26	0·017294	42	0·021631
27	0·017601	43	0·021870

(*) Among all recorded data, only vehicles passing on the road profile track measured, at about 9 m from the building foundation (point A), were considered for the comparison between measured and estimated PPV values.

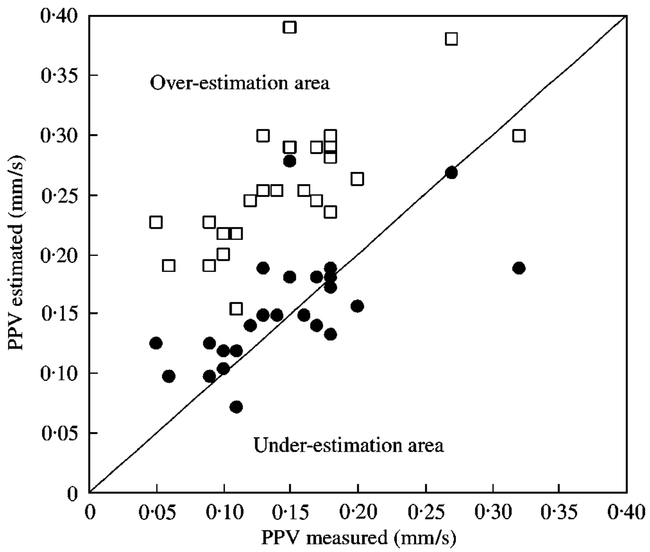

Figure 13. Comparison between measured and estimated values of PPV (station A). ●, $p = 0·75$; □, $p = 1$.

The assumptions pertaining to the other parameters in Watts' formula are:

- it was assumed that $p = 0·75$, because, according to Watts' experience, the wheel track index p being equal to 1 means that left as well as right wheels pass, at the same instant, over the same road surface singular irregularity (bump); this clearly implies the assumption of a transversally cylindrical surface, which is not true as in the transverse direction roughness is also a random phenomenon (i.e., road roughness is homogeneous and isotropic [24, 25]). In other words, assuming that $p = 0·75$ appears to better represent the fact that left and right wheels do not simultaneously pass over the same irregularity. A further confirmation of this assumption seems to come from the analysis of the diagrams where estimated PPV ($PPV_{estimated}$) is reported against measured PPV ($PPV_{measured}$) as shown in Figure 13: it can be observed that assuming $p = 0·75$ considerably reduces data scatter, therefore improving PPV prediction.
- Among soil types mentioned by Watts, "sand/gravel" was chosen as it was the closest to the type of soil found at Riviera di Chiaia, t and x values were found correspondingly from Table 1.

- Finally, as far as the distance from the vibration source is concerned, a mean value of 9 m was assumed, equal to the distance between the reference measurement station (point A) and the track followed by vehicles, measured by the straightedge profiler (only 25 vehicles were therefore considered).

$PPV_{estimated}$ vs $PPV_{measured}$ is shown in Figure 13, for both cases $p = 0{\cdot}75$ and 1. From Figure 13 it is interesting to note the following:

- data were rather close to the equivalence curve when $p = 0{\cdot}75$, whereas for $p = 1$ greater differences existed between measured and estimated values. To quantify such an aspect, the following parameter s was calculated in both cases ($p = 0{\cdot}75$ and 1), over the n points considered ($n = 25$; note that in Figure 13 only 24 points are visible as 2 are overlapped):

$$s^2 = \frac{1}{n} \sum_{n} {}_i (PPV^i_{estimated} - PPV^i_{measured})^2 \quad [\mathrm{mm}^2/\mathrm{s}^2]. \tag{3}$$

  The parameter s^2 equalled $0{\cdot}002254\,\mathrm{mm}^2/\mathrm{s}^2$ for $p = 0{\cdot}75$ while it equalled $0{\cdot}01398\ \mathrm{mm}^2/\mathrm{s}^2$ for $p = 1$ (more than six times the former value). This result confirmed the previous hypothesis that $p = 0{\cdot}75$. On the basis of this result, the following further remarks are referred only to the results obtained for $p = 0{\cdot}75$.
- For only a reduced number of measurements the offset between measured and estimated values seemed to reach higher values. For this purpose, the mean percentage difference D between such values was calculated by the following expression:

$$D = \frac{1}{n} \sum_{n} {}_i \frac{|PPV^i_{estimated} - PPV^i_{measured}|}{PPV^i_{measured}}. \tag{4}$$

  D equalled 26%, which is not exceeded in most cases (72% of all points).

- Vibration velocities were overestimated in most cases, but approximations were more than acceptable, while in a few cases vibration velocities were underestimated.
- Taking all vehicles and their speeds into account, Watts' formula allows the maximum expected PPV to be predicted at a site which can be compared with the maximum measured PPV. In this case the maximum predicted PPV equalled 0·28 mm/s, very close to the maximum measured value of 0·32 mm/s (obtained from Figure 13).

Considering all approximations in the vibration phenomenon and, in particular, the uncertainties concerning the type of soil, profile and wheel path, vehicle speed, variety of vehicles, type of road surface, etc., it is possible to conclude that Watts' formula, appropriately modified as presented here also represents a valid prediction model for distributed irregularities.

5. CONCLUSIONS

An experimental survey was carried out to determine the level of traffic-induced vibrations in heritage buildings. An old masonry building from the early 19th century adjacent to a major road in the city of Naples and protected by laws for the preservation of heritage buildings was chosen as the site for the experiment. Instrumentation was placed in its premises and vibration levels induced by the transit of heavy vehicles (buses and trucks) were recorded. The measurements were correlated with vehicle type and speed and to values obtained by a modified prediction model.

The analysis of measurements revealed that:

- For all data recorded, the perception threshold defined by ISO 2631 [1] for peak particle velocity (0·14 mm/sec) was exceeded. This indicates that traffic-induced vibrations, just as noise, impact significantly on the quality of life in urban centres;
- Several measurements showed that the lowest threshold for damage found in literature (1 mm/s) [2] was exceeded and in some cases the Swiss Standard threshold [3] (1·5 mm/s) for particularly sensitive buildings was also exceeded; while there is still uncertainty about a unique threshold value, this result should stimulate consideration on the actions to be undertaken in order to limit the risk of damage to buildings of historical or architectural importance.
- It is not generally possible to find a strong correlation between the vibration level and the speed of transit of the vehicles in a real traffic flow. This may be due to the fact that the dynamic overload does not always increase with vehicle speed as this modifies the way the road profile is "read" by the vehicle i.e. the frequency content of the vehicle base motion; in addition, the relationship is rather scattered since the inertial and mechanical parameters of the vehicles may vary, as well as the path followed by the wheels. Notwithstanding this, a trend increasing with vehicle speed was, however, found.
- Watts' prediction formula was extended to estimate peak particle velocity of vertical vibrations at building foundations from the typical case of a localized road irregularity (bump) to the case of longitudinally distributed irregularities. The novel feature is that the road roughness parameter in the model has been characterized by the r.m.s. value of the road surface wavelengths that, for a given vehicle speed, drive the natural frequencies of wheel hop and body bounce of a heavy vehicle suspension. This will allow vibration predictions for longitudinally distributed irregularities typical of stone block road surfaces and should potentially be of practical use in identifying high-exposure sites in sensitive heritage areas.

Further measurements at other sites (if possible on different soils) would help to confirm the validity, and therefore the usefulness, of the modified prediction formula.

ACKNOWLEDGMENTS

The authors wish to thank Tecno In of Naples, and in particular Dr. Gianni Antonucci, for the loan of measurement instrumentation and for the help in carrying out the measurements. Thanks are also due to Eng. Roberto Costanzo for his valuable help in data processing. Many thanks are also due to the owners of Palazzo S. Teodoro, to the "Sovraintendenza per i Beni Ambientali ed Architettonici" of Naples and to the Municipality of Naples for allowing the survey along Riviera di Chiaia. The authors, finally, are greatly indebted to Prof Renato Lamberti and Prof Giovanni Da Rios for their helpful suggestions during the development of the work.

The report is part of the contribution by the Unità Operativa del Politecnico di Milano chaired by Prof. Giovanni Da Rios to the **IASPIS** (COFIN 98) Research Project on Environment/Safety interaction in the Design of Road Infrastructures. Participating Universities at the projetc are: University of Florence (Coordination), University of Bologna, University of Padova, University of Pisa, University of Roma "La Sapienza", University of Trieste, Politechnic of Bari, Politechnic of Milano.

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