Research Article

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Measurements and prediction of road traffic noise along high-rise building façades in Athens

<https://doi.org/10.1515/noise-2020-0001>

Received Sep 10, 2019; accepted Feb 06, 2020

Abstract: Constant exposure to traffic noise pollution can have significant impact on human health and well being. Occupants of high-rise buildings along noisy traffic arteries are severely affected. In an attempt to contribute to noise protection design of prospective high-rise buildings, traffic noise measurements and prediction using the CRTN (calculation of road traffic noise) model, were made along the façade of a high-rise building in central Athens. The aim was to test the accuracy of this model in predicting the vertical distribution (mapping) of traffic noise along such building façades, under the local urban characteristics of the Mediterranean capital. The predicted and measured noise levels were found to be highly coherent with each other, and their vertical distribution pattern, by and large, confirmed findings from earlier studies. Nevertheless, the predicted values had a tendency of underestimation, with a mean difference -2.2 dB(A) with reference to measured values. It is considered that this underestimation is associated mainly with a newly proposed feature of urban morphology, namely (local) geo-morphology. By and large, it can be inferred that the CRTN model is a useful tool, suitable for the prediction of traffic noise along high-rise building façades during their planning and design stage. The results represent a further step towards more general application of this model, as well as a contribution to the use of this model considering a wider number of urban features.

Keywords: road traffic noise, vertical distribution, high-rise buildings, CRTN prediction model

1 Introduction

High-rise buildings in Athens evolved after the 2nd world war as landmarks to express the new spirit of post war modernity in the city. Since then, only recently the interest was grown again for production of such buildings in the Hellenic capital [1]; this was mainly inspired by the necessity to accommodate higher densities of population with relatively improved conveniences and also to create a higher percentage of public open air space, in the congested city.

High-rise buildings are commonly built close to arterial roads for transportation convenience, but this implies also increased traffic volumes with long term noise exposure imposed on the numerous occupiers. Noise induced annoyance can be a cause of adverse effects on public health and well being [2]. Evidence from scientific studies supports the view that annoyance caused by road traffic noise, relates not only to concurrent stress experienced by urban inhabitants [3] but also indirectly this affects self rated health and quality of life [4, 5]. Nevertheless, constant exposure to traffic noise pollution has been shown to relate to several symptoms, ranging from sleep disturbance [6, 7], day-after (morning) tiredness [8], and learning impairment at school [9, 10], to severe health effects such as cardiovascular disease [11, 12], high blood pressure [13], memory problems [14], etc.

In an attempt to mitigate environmental noise, strategic noise maps have been produced by European Member States according to Directive 2002/49/EC (END), and any effort has been made towards enhancing their applicability [15]. Examples from Greece have been reported by Vogiatzis and Remy; in those, there are explored the impact of aircraft noise from the Herakleion city airport in

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Crete island [16], as well as the environmental noise impact and mitigation measures concerning the Athens ring road (Attiki Odos) [17]. At the same time, research continues to move, amongst other goals, towards developing and improving acoustic materials and methods for mitigation of traffic noise in buildings and communities. Examples are, First, the case of sonic crystals as acoustic barriers, which have been proposed in order to avoid typical limitations of conventional noise barriers such as diffraction at the edges, reflections in the opposite direction, etc. [18], Secondly, the development of natural ventilation-enabling façade noise control devices which, particularly, concern high-rise residential buildings of congested cities [19], *etc.*

Amongst recent studies in which it is investigated the question of traffic noise induced annoyance and noise mitigation in high-rise buildings, is the work of Chung *et al.* [20] and Wu *et al.* [21], respectively. Actually, in [20] there are explored through laboratory experiments, both the visual and acoustic aspects of traffic-noise induced annoyance, in an oppressive densely-packed high-rise environment. Results indicate that two environmental variables (namely the ‘spacing’ between tall buildings and the ‘separation distance’ between window viewers and opposite high-rises) are inversely related with the feeling of oppressiveness and perception of traffic noise induced annoyance. The results are capable of providing building designers and urban planners with some insight about strategies for less oppressive views conducive to moderation of noise annoyance.

Furthermore, in [21], Wu *et al.*, amongst other objectives, have investigated the effects of traffic noise in three high-rise residential buildings located 21.0 m apart from an arterial road/bridge in Guangzhou city, China. Short-time noise measurements and questionnaires were employed at the same time on each floor inside the room with windows open. The analysis showed that: on the one hand, 70% of the respondents considered traffic noise having negative effects on people, and on the other hand, 60% and 65% of the respondents considered traffic noise significantly influencing physical and psychological comfort respectively; in both cases, comfort was found to decrease with noise levels increasing. All of the measured noise levels in the test buildings were found to exceed the limit recommended by local authority [22]. In designing for traffic noise protection of prospective high-rise buildings, amongst other data, predictions apparently become important, of the vertical distribution (mapping) of noise along the building façade.

Nevertheless, the British CRTN (Calculation of Road Traffic Noise) prediction model [23, 24], despite being widely recognised, it has also been a lot criticised [25–28]

as to its accuracy and suitability in predicting traffic noise levels in regions of distinct local characteristics. The aim of the present study is to explore the impact of urban characteristics of Athens, on the accuracy of the CRTN model in predicting the vertical distribution of traffic noise along high-rise building façades. This is an experimental study and involves predictions using the CRTN model as well as measurements of traffic noise along the façade of a high-rise building in central Athens.

2 Background

A model for the prediction of traffic noise distribution pattern along the height of high-rise buildings, has been proposed by Wu *et al.* [21] (Section 1 above). The test buildings that were employed in that analysis were of varying height (of 12, 12, and 18 floors respectively for buildings A, B, and C), and the level of noise source (road/bridge) varied in relation to building. A reference floor was employed, *i.e.* a floor co-planar with the road/bridge level; at this floor, a zero noise level (reference noise level) was set. Then, in each test building, for short-time noise measurements in L_{Aeq} , a quadratic polynomial fit curve was created of the noise level transfer function, for each floor in relation to the reference floor (Figures 1, 2, 3). Wu *et al.* acknowledge that, in order to establish a model curve applicable to relatively wide range of high-rise buildings, the proposed model remains to be tested against further practical projects. Nevertheless, an inherent limitation in that method, is that the model curve is bound to predict barely relative noise levels. So, the designer, although he is capable of planning for the relatively less noisy areas in his prospective building, he cannot possibly be aware of the noise levels to be expected.

Figure 1: Transfer function between each floor and 1st floor (building A), (figure taken out of [21])

Figure 2: Transfer function between each floor and 2nd floor (building B), (figure taken out of [21])

Figure 3: Transfer function between each floor and 4th floor (building C), (figure taken out of [21])

Figure 4: Comparison of the measured and predicted L_{A10} values against the height of the assessment point in meters above the source, (figure taken out of [26])

For the prediction of traffic noise levels, classical models have been developed since the mid 20th century. These are useful in the design of highways, as well as in planning and designing for traffic noise protection of the built environment [25]. Amongst those, the CRTN model originated in the mid 1970's thanks to the work of Delany *et al.* [23],

and in year 1988 this method was officially adopted by the UK Dept. of Transport and the Welsh office [24] (Section 3.3 below). The CRTN model also contributed significantly to the development of the relevant International Standard in the mid 1990's [29]. However, as any other mathematical model which has been developed by statistical analysis of experimental data, the CRTN method has been strongly influenced by the characteristics of the measurement location (traffic and site variables) in which this (model) was originated [30]. Therefore it is important to evaluate the prediction accuracy of the CRTN model, whenever this is called for use in regions of distinct local characteristics. Below, reference is made to a number of relevant studies from various countries.

Amongst the fewest studies dealing with the question of prediction accuracy of road traffic noise using the CRTN model along high-rise building façades, is the work of Mak *et al.* [26] in Hong Kong. First, those authors referred to studies which had approached the above question in Hong Kong employing the CRTN model [31–33]. Actually in [31], Lam and Tam attempted to study the validity of the CRTN model by comparing predicted and measured L_{A10} values from a road survey, but they found an average overestimation +1.2 dB(A) with reference to measured values. To *et al.* [32] who conducted a road side survey of traffic noise, found an overprediction of +2 dB(A) to +6 dB(A) when using the CRTN model, with reference to measured noise levels. Furthermore, traffic noise measurements and predictions were conducted by Leung and Mak [33] at the road side and inside buildings; those authors found that measured and predicted results correlated well with each other, with a mean overprediction +0.4 dB(A). Despite differences, a single most distinctive finding common in the above studies is an overprediction in the L_{A10} values with reference to measured noise level.

Secondly, Mak *et al.* evaluated the validity of the CRTN model, through their own experiments; those authors compared the predicted noise levels of L_{A10} with the measured noise at twenty floor levels along the façade of a 20-storey residential building located 8.0 m apart from kerb side of a noisy road. Both the measured and predicted noise levels were found to be coherent with each other (Section 5 below), and decreased with increasing floor level (Figure 4). However a mean overestimation +2.0 dB(A) of the predicted noise levels was identified with reference to measured noise. Mak *et al.* commented: “This overestimation may be due to the fact that the CRTN model was calibrated mainly to suit the urban characteristics of the UK, and the urban characteristics in Hong Kong may be different to that in the UK.. the urban areas in Hong Kong are very complicated and congested with multiple connected

Table 1: Basic details of the test buildings

Building	Location	Date	Storeys (excl. ground)	Height <i>re</i> ground [m]	Façade texture	Use	Occupancy (persons)	Test points
“Apollon”	Panormou st	1970’s	23	80.5	Reflective balconies	Residential /office	~ 900	9
“Tower of Athens”	Mesogeon st.	1970’s	24	88.0	Fixed glazing	Office	~ 1000	1

streets/road.. Mitigation measures for rolling the problem of road traffic noise.. (involve), for example, statutory provisions. (which) require vehicles to be fitted with efficient exhaust silencers, and this would lead to a decrease in overall measured traffic levels.” Based on their findings, Mak *et al.* concluded that the CRTN is a useful tool in predicting traffic noise levels at different floors of prospective high-rise buildings. Further results of that study are reported below in Section 5.

The recognition of the CRTN model as a useful guideline for the prediction of road traffic noise, has been apparent also over the current decade in a number of studies; in these, the above model has been used as a reference for the evaluation of new prediction models tailored to suit local characteristics respectively of distinct localities. Examples are the work, First, of Herni *et al.* [34] in Klang Valley Malaysia which is characterised by relatively increased percentage of motorcycle use, Secondly, of Jadaan and Okasha [28] in Aman, Jordania where traffic involves also interrupted flow, Thirdly, of Osifeco and Odufuwa [27] in Ogun state, Nigeria, etc. A consensus conclusion of those authors was that new prediction models tailored to suit local characteristics respectively of distinct localities, were found to perform better compared with the CRTN model.

The concept of local characteristics of the measurement site, involves also the notion of urban morphology; the latter may contribute to the built-up of traffic noise levels during propagation in the city. This is acknowledged in recent research, with the emphasis being placed on the man made environment and architectural features [35–38]. An example can be seen in the work of Margaritis and Kang [36] from eight UK cities of different settlement forms. Those authors concluded: “...in order to reduce traffic noise levels it is essential to take into consideration different parameters of urban morphology... (such as), green spaces, (and) road and building attributes... combined with the housing types and the local architectural tendencies.” The influence of urban morphology, on the prediction accuracy of the CRTN model in the case of high-rise building façades in Athens, can be a challenge to investigate.

3 Road traffic noise and prediction procedure

3.1 General

“Apollon” is named the high-rise building used in the present experiments (Table 1, Figure 5). According to access feasibility along the “Apollon’s” façade, nine test points, superimposed at nine distinct floor levels, were selected. Measurements were made also at reference point M0 by Panormou st. (Figure 6); the latter is a noisy arterial street, nearby “Apollon”; in-between there is a narrow local street namely L. Riankour st. of light traffic. Along the opposite side of Panormou st. there is the up hill side of Tourkovounia which is occupied by reinforced concrete houses (reflective) (Figure 5). In the vicinity of “Apollon” there are multi-storey buildings of reflective façades with diffusive balconies, -typical of modern architecture in the Mediterranean capital. Panormou street has zero slope and, of course, no sound barriers or screens are at the road site since we are in the city centre. The noise source (effective line of traffic) is taken in the middle of the street’s width [24].

To validate results from “Apollon”, an auxiliary high-rise building in central Athens was also employed, namely

Figure 5: General outlook of “Apollon” towards Tourkovounia hill

Figure 6: (a) Section and (b) plan of "Apollon". S: sound source, M0: reference point, M0': test point on ground floor level, —: direct sound, —: reflected sound

the "Tower of Athens" in Mesogeon st. (Table 1, Figures 7, 8). Access to this building's façade was limited to roof level (test point M25) only, owing to the façade's fixed glazing all the way up. The "Tower of Athens" faces Lycabettus hill, and it is situated at the intersection of two noisy traffic ar-

teries, namely V. Sofias ave. and Mesogeon st. (Figure 9). The noise source (effective line of traffic) is considered in the middle of the width of the two traffic arteries taken together.

Figure 7: External view of the “Tower of Athens”

3.2 Acoustic measurements

For each test building, measurements were made on 14.7.2017 (week day) during rush hour (13:00-15:30 *pm*, i.e. during the busiest / noisiest period of day); these measurements were carried out sequentially for each test point including the reference point (Section 3.3 below), and employing a sampling time of 5' per test point. The assumption was made for each test building that, the traffic noise level at source (reference point) remained steady throughout the measurement session. One sound level meter (B&K 2270 class one) with a transducer type 42189 were used.

The microphone location was chosen flush with the balcony parapet, 1.4 m above floor level (Figure 10). The assumption was made that this location is exposed to façade reflections of the test building in a way equivalent to what the CRTN model considers (Section 3.3, equ. (7)). Of course, the possibility remains that the actual correction for the nearside façade reflections could be different than +2.5 dB(A) provided by the CRTN model. No exact value for the present microphone layout is provided by the CRTN model that can be used for the façade corrections.

Environmental temperature was 34°C and relative humidity 43% according to data from the Hellenic National

Figure 8: General outlook of the “Tower of Athens” towards Lycabettus hill

Meteorological Service (EMY), -Aharnon Weather Station. The mean wind speed was 24 km/h. A 90 mm wind shield type UA 1650 was used to eliminate the influence of the air that was more pronounced on higher floor levels reaching speed up to 60 km/h. This wind screen reduces wind noise by approximately 15 dB for wind speeds up to 120 km/h.

From amongst the noise indices measured, results in L_{10} are presented in this paper. Measurements were carried out in 1/3 oct. frequency bands from 63 Hz to 4000 Hz, as well as in oct. bands and in dB(A). L_{A10} expresses the traffic noise level that is exceeded for 10% of the sampling time. As this index refers to the relatively high noise levels, it has been common practice to use this index in sound insulation applications which, amongst others, are of concern in this study. Also L_{A10} is adopted by the CRTN prediction model in the case of continuous traffic flow, and this model is employed in present study.

3.3 The CRTN prediction model

Traffic noise levels along the test building façade (SPL_{test}) were predicted, by applying appropriate corrections to the noise level measured at reference point M_0 ; the latter is located at the edge of kerb side of the nearby traffic artery (Figure 11). Measurements at reference point, have been made under same conditions and in same way as at the measurement locations along the test building façade (Section 3.2 above); as a result predictions in L_{A10} are suitable for straightforward comparison with measured L_{A10} values. For the predictions, the CRTN model was used [24]. According to this:

$$SPL_{test} = SPL_0 + A_{propagation} \quad (1)$$

SPL_{test} : predicted noise level at a given point M_{test} on the examined building façade, SPL_0 : reference noise level mea-

Figure 9: (a) Section and (b) plan of the “Tower of Athens”. S: sound source, M0:reference point, —: direct sound, —: reflected sound

sured at reference point M0 (the CRTN model offers also the option for prediction of the SPL0 on the basis of traffic and site data in the field), $A_{propagation}$: correction accounting for any attenuation of noise during propagation to the test location.

$$A_{propagation} = A_{div} + A_{gr} + A_{refl} + A_{av} + A_{misc} \quad (2) \quad I.$$

A_{div} : noise attenuation due to geometrical divergence (distance effect) (I. below), A_{gr} : noise attenuation due to ground cover (II. below), A_{refl} : noise modification due to

façade reflections (III. below), A_{av} : noise attenuation due to angle of view (IV. below), A_{misc} : noise attenuation due to miscellaneous effects such as barrier effect etc., which do not apply in present circumstances. The following text refers to Figure 11.

$$A_{div} = -10 \log(d'_{Mtest}/d'_{M0}) \quad (3)$$

Figure 10: Typical balcony of test building façade, with microphone layout.

Figure 11: Typical site layout. MO: reference point, S: sound source (equivalent line of traffic in the middle of road width)

d'_{Mtest} : perpendicular distance of the test point Mtest from the effective line of traffic (noise source), d'_{MO} : perpendicular distance of the reference point MO from the effective line of traffic.

II. Agr depends on the average height of propagation “H”.

$$H = 0.5(h + 1) \quad (4)$$

h : height of test point Mtest above level of noise source.
For $0.75 \leq H \leq (d+5)/6$

$$Agr = -5.21 \log[(6H - 1.5)/(d + 3.5)] \quad (5)$$

For $H \geq (d+5)$

$$Agr = 0 \quad (6)$$

d : horizontal distance of test point Mtest from the effective line of traffic (noise source). The above is valid for $d \geq 4.0$ m. Apparently, this correction mainly affects reception points close to the ground.

III. To account for façade reflections from the test building a correction of +2,5 dB(A) is applied. This, according to the CRTN model, assumes that the test point Mtest is 1.0 m in front of the façade and that the façade is of a hard rigid material (Section 3.2).

$$Arefl_{nearside} = +2.5 \quad (7)$$

Another source of reflections is building façades along the opposite side of the road. The relevant correction is given below, in the case that a reasonably uniform row of buildings exist facing the test point.

$$Arefl_{oppositeside} = +1.5[b/(a + b)] \quad (8)$$

b : average width of row of buildings along the opposite side of the road, a : average width between rows of buildings.

IV. Whenever the angle of view θ° at which the test point subtends the noise source (traffic stream) is less than 180° , a correction must be applied. This accounts for the attenuation owing to the angle of view effect Aav and it is given below:

$$Aav = 10 \log(\theta^\circ / 180^\circ) \quad (9)$$

3.4 Road traffic noise, -Prediction procedure

The test points selected for the acoustic measurements (Figures 6, 9) were used in the predictions of the traffic noise level employing equations (1) to (9) above. The measured noise level at reference point SPL0 is shown in Table 2. Correcting this level to account for the attenuation of noise during propagation to the test point (Apropagation), is summarised in Table 3, and it is outlined below in 3.4.1 and 3.4.2.

Table 2: Difference between measured and predicted traffic noise levels along the test buildings façade

Test building	Test point	Height* re ground [m]	L _{A10} [dB(A)]		Difference [dB(A)]
			Measured	Predicted	
"Apollon"	M0	0.0	71		
	M0'	0.0	63	59.6	−3.4
	M2	+13.5	66	64.6	−1.4
	M5	+22.5	67	65.5	−1.5
	M8	+31.5	68	65.2	−2.8
	M12	+43.5	65	63.4	−1.6
	M14	+49.5	65	63.3	−1.7
	M18	+61.5	65	62.4	−2.6
	M22	+73.5	65	62.4	−2.6
	M24	+80.5	63	60.9	−2.1
					mean: − 2.2
					st. dev.: ± 0.66
"Tower of Athens"	M0	0,0	72		
	M25	+88.0	68	66.2	−1.8

*: excluding microphone height at +1.40 m re floor level, M0: reference point. Measured and predicted noise levels are rounded to the nearest integer and first decimal point, respectively [24]

Table 3: Corrections, applied to the measured sound level at reference point M0 (Table 2). Adiv: correction due to geometrical divergence, Agr: correction due to ground cover effect, Arefl: correction due to façade reflections, Aav: correction due to angle of view effect, Apropagation: total correction

Test building	Test point	Adiv [dB(A)]	Agr [dB(A)]	Arefl [dB(A)]		Aav [dB(A)]	Apropagation [dB(A)]
				Nearside	Opposite side		
"Apollon"	M0'	−7.60	−5.40	+2.50	+1.23	−2.17	−11.44
	M2	−7.78	−0.21	+2.50	+1.23	−2.17	−6.43
	M5	−8.00	0.00	+2.50	+1.23	−1.21	−5.48
	M8	−8.28	0.00	+2.50	+1.23	−1.21	−5.76
	M12	−8.72	0.00	+2.50	0.00	−1.21	−7.43
	M14	−8.95	0.00	+2.50	0.00	−1.21	−7.66
	M18	−9.92	0.00	+2.50	0.00	−1.21	−8.63
	M22	−9.88	0.00	+2.50	0.00	−1.21	−8.59
	M24	−10.13	0.00	0.00	0.00	0.00	−10.13
"Tower of Athens"	M25	−5.80	0.00	0.00	0.00	0.00	−5.80

3.4.1 Attenuation of noise during propagation to "Apollon"

The following text refers to Figure 6.

A correction is applied for the distance effect between the reference point M0 and each of the test points M0' to M24, according to Eq. (3).

A correction is applied for the effect of the absorptive ground cover between the reference point M0 and each of the test points M0' and M2 (equ. (5)). At and above 5th floor

level, the test points are respectively distant from ground level, therefore Eq. (6) predicts zero correction.

A correction for the effect of the nearside façade reflections is applied for each of the test points M0' to M23 according to Eq. (7). Apparently zero correction applies for the test point on the roof. Furthermore, reflections from buildings along the opposite side of Panormou st. reach the "Apollon" façade up to the 10th floor level; it follows that for test points up to this level, namely M0' to M8, a correction is applied respectively according to Eq. (8); the

ratio $b/(a+b)$ is taken equal to 0.82. For the remaining test points relevant correction becomes zero.

The test points M0' up to M5, which are on relatively low floor levels subtend Panormou st. at an angle $\theta^\circ = 109^\circ$ that is defined within $X(M0')X'$. It follows that a correction is applied to account for the angle-of-view effect according to Eq. (9). For relatively high floor levels *i.e.* above the height of surrounding buildings (test points M8 to M23), the angle θ° is defined within $Y(M0')Y'$ and equals 136° . Last, for the test point M24 on the roof, the angle θ is 180° , therefore zero correction is applied.

3.4.2 Attenuation of noise during propagation to the “Tower of Athens”

The following text refers to Figure 9.

A correction is applied for the distance effect between the reference point M0 and the test point M25, according to Eq. (3). Apparently this test point is distant from ground level, therefore Eq. (6) predicts zero correction for any ground cover effect. Similarly, zero correction applies, on the one hand for the nearside façade reflections ($A_{refl_{nearside}}$) according to Eq. (7), and on the other hand for reflections from buildings along the opposite side of the street. Last, the angle at which the test point M25, subtends V. Sofias' ave. is 180° , therefore zero correction applies concerning the angle-of-view effect (Eq. 9).

4 Data processing and results

Results from measurements and predictions of traffic noise levels along the test building façade, are shown in Figures 12, 13 as well as in Tables 2, 3. At the lower and intermediate floors (2^{nd} to 10^{th} floor) of the “Apollon” building façade (Figure 12, Table 2), the measured noise levels were relatively high and varied between 66 and 68 dB(A). Less noisy floor levels (63 dB(A)) were, First, the roof (test point M24), owing to the increased distances from source which are involved, relative to distances of less high floor levels, and Secondly, the ground floor (test point M0'); the latter is separated from Panormou st. by a green zone (Figure 6) which apparently, contributes to local noise abatement.

A measure of the association between measurements and predictions of traffic noise levels, is the square correlation coefficient (R^2); this can be found by applying a linear regression analysis between these two sets of data. Results from this analysis are shown in Figure 14, and suggest that the predicted and measured levels of noise were highly co-

Figure 12: Predicted and measured road traffic noise (L_{A10}) along the façade of “Apollon”. M0: reference point

Figure 13: Frequency spectrum of measured road traffic noise along the façade of “Apollon”. M0: reference point, M0', 2nd, etc.: test points

Figure 14: Predicted vs. measured road traffic noise (L_{A10}) along the façade of “Apollon”. R^2 : correlation coefficient squared, sign.: significance level

Figure 15: Map of central Athens. 1: “Apollon”, 2: “Tower of Athens”, A: Tourkovounia (hill), B: Lycabettus hill, C: Acropolis hill

herent with each other, with a square correlation coefficient $R^2=0.87$ which is significant at the 0.00022 level.

5 Discussion

The traffic noise distribution pattern along the “Apollon” façade (Figure 12) confirms, on the one hand, Wu’s *et al.* [21] proposed model curve (Figure 3) from their 18-floor building (Sections 1, 2 above), and on the other hand, Mak’s *et al.* [26] traffic noise distribution pattern along their 20-floor building façade; exception is Mak’s *et al.* relatively low floor levels in which no sound decay is observed (Figure 4), unlike the present findings (Section 4 above).

Furthermore, it is clear in Figure 12 and Table 2 that the predictions have a tendency to underestimate measured values; the difference is wider at ground floor level (−3.4 dB(A)). In fact, in L. Riankour st. (Figure 6), in addition to local-light-traffic relating noise one must consider also at kerb side ground noise from pedestrians and from commercial activities during the peak hours (test period); this noise apparently is present in the measured levels particularly at test points close to the ground. For the remaining floor levels the difference between measured and predicted noise levels varied between −2.8 dB(A) (test point M8) and −1.4 dB(A) (test point M2). It is considered that some local noise source could possibly have had an effect on the noise measurement at point M8 (see below, comments on Figure 13). Nevertheless, a source of (random) variation of the differences between measured and

predicted data, could have been also a likely violation of the assumption made above (Section 3.2), namely that the traffic noise level at source (reference point M0) remained steady throughout the measurement session. The mean difference over the nine floor levels tested was −2.2 dB(A).

An explanation for the underestimated prediction of traffic noise, can possibly be seen in the (local) geomorphology of Athens; this involves multiple hills such as Tourkovounia, Lycabettus, the Acropolis, *etc.*, (Figure 15) of steep slope (ranging between 25° and 90°) and average height 150 m, *i.e.* higher than the high-rise housing of the city. This mountainous landscape is, mostly, occupied by concrete houses (reflective), therefore it can contribute components of diffuse late sound (reverberant sound levels) to the test building façade; this late sound is capable of increasing the overall measured level of traffic noise. The reflective/diffusive texture of the typical multi-storey building façades in the city (Section 3.1 above) is considered also to enhance the above effect.

A simplified example is given below to illustrate the above argument. Let us consider, First, an area within a distance of about 150 m from Panormou st. (noise source) towards the up hill side of Tourkovounia (Section 3.1 above) (Figures 5, 6) and Secondly, the late sound component, from this area to be reflected to the “Apollon” façade. The late sound path, broadly speaking, does not exceed 350 m ((150+150+50) m). Given that the early sound path is of the order of 50 m, the attenuation of the late sound component with reference to early sound, First, does not exceed 8.4 dB(A) on account of the distance effect (attenu-

ation $\leq 10 \log(350/50)$ dB(A), equ. (3) above), and Secondly, this does not exceed 1.4 dB(A) on account of the atmospheric absorption. The latter is calculated according to the relevant ISO [27], using the measured spectral content at source (Figure 13) and considering ambient temperature 30°C and relative humidity 70%; such weather conditions are common of the local Mediterranean climate. Furthermore, under present circumstances the assumption is made that no other effect accounts significantly for attenuation of the late sound component with reference to the early sound. According to the above, the resulting overall attenuation of the late sound with reference to early sound, does not exceed (8.4+1.4) dB(A), *i.e.* it ranges from above nil to 9.8 dB(A) depending on the path difference between early and late sound. As a result the above said late sound component is capable of contributing significantly to the overall noise level. This example, provides evidence as to the order of magnitude of distances involved in the field, regarding significant contribution of diffuse late sound to the overall measured noise level.

Considering that the notion of geo-morphology, broadly speaking, is part of the concept of urban morphology, the above interpretation is coherent with what is acknowledged in recent research [35–38] (Section 2 above), namely that urban morphology can influence the built-up of traffic noise levels during propagation in the city.

By and large, the above findings were validated in the auxiliary building tests (“Tower of Athens”) (Table 2).

Furthermore, it was found that the spectral content of the vertically distributed measured traffic noise, virtually remained unchanged with reference to the spectrum at source (Figure 13). This finding can be useful in determining construction detailing in prospective high-rise building façades, for improved comfort for the occupier. An exception to this finding, was identified in the 8th floor level (test point M8) at 500 Hz; this suggests that, the measured level in this case was dominated by some local noise source, for instance the exhaust of a local A/C unit.

The present results generally confirm Mak’s *et al.* findings [26]. Firstly, good agreement was identified between measurements and predictions, with a statistically significant square correlation coefficient (R^2) exceeding 0.87. Secondly a mean difference was identified between measured and predicted noise levels, equal to 2.2 dB(A) and 2.0 dB(A), respectively in present study and in Mak’s *et al.* study. However, the two studies clearly differ with each other regarding the polarity of the above mean difference. Apparently (Section 2 above) the polarity of the mean difference between measured and predicted traffic noise levels has been influenced by, amongst others, the local urban character-

istics, and the latter in Hong Kong (Section 2 above) differ to those in Athens (Sections 3.1, 5 above).

6 Conclusions

Traffic noise measurements and predictions in L_{A10} using the CRTN model were made at distinct floor levels, along the façade of a residential/office high-rise building in central Athens; predictions were based on measured noise level at source. The predicted and measured noise levels were found to be highly coherent with each other, and their vertical distribution pattern, by and large, confirmed findings from earlier studies [21, 26]. Nevertheless, the predicted values had a tendency of underestimation, with a mean difference –2.2 dB(A) with reference to measured values. It is considered that this underestimation is associated mainly with a newly proposed feature of urban morphology namely (local) geo-morphology.

By and large, it can be inferred that the CRTN model is a useful tool, suitable for predicting the vertical distribution of traffic noise along prospective high-rise building façades. More experimental work could contribute further to quantifying more precisely the identified underestimation of predicted traffic noise levels. The results represent a contribution to the use of this model considering a wider number of urban features, as well as a further step towards more general application of the model.

Acknowledgement: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. Thanks go to the ex- and present Heads of School Civil Eng. of Tech. Univ. Athens, professors Dimitri Koutsogiannis and Nikos Lagaros respectively, for support in our work.

References

- [1] <http://www.greeknewsagenda.gr/index.php/topics/business-r-d/6997-meet-the-hellinikon-project-greece%E2%80%99s-mega-investment>
- [2] Sotiropoulou A., Karalekas F., Charemis Ch., Subjective evaluation of urban noise in Athens; multi-dimensional description of evaluations, In: Proceedings of the Autumn Conference of The Institute of Acoustics (18-19 Oct. 2005, Oxford, England), 2005, 27(4)
- [3] Wallenius M.A., The interaction of noise stress and personal project stress on subjective health, *J. Environ. Psychol.*, 2004, 24(2), 167-177. <http://doi.org/10.1016/j.jenvp.2003.12.021>
- [4] Pedersen E., City dweller responses to multiple stressors intruding into their homes: noise, light, odour, and vibration,

- Int. J. Environ. Res. Public Health, 2015, 12(3), 3245-3263. <http://doi.org/10.3390/ijerph12030326>
- [5] Shepherd B., Welch D., Dirks K.N., Mathews R., Exploring the relationship between noise sensitivity, annoyance, and health related quality of life in a sample of adults exposed to environmental noise, *Int. J. Environ. Res. Public Health*, 2010, 7(10), 3279-3594. <http://doi.org/10.3390/ijerph>
 - [6] Muzet A., Environmental noise, sleep and health, *Sleep Med. Rev.*, 2007, 11(1), 135-142. <https://doi.org/10.1016/j.smrv.2006.09.001>
 - [7] Douglas O., Murphy E., Source-based subjective responses to sleep disturbance from transportation noise, *Environ. Int.*, 2016, 92, 93, 450-456. <http://dx.doi.org/10.1016/j.envint.2016.04.030>
 - [8] Kluizenaar Y., Van Lenthe F.J., Miedama H.M.E., Mackenbach J.P., Long-term road traffic noise exposure is associated with an increase in morning tiredness, *J. Acoust. Soc. Am.*, 2009, 126(2), 626-633. <http://doi.org/10.1121/1.3158834>
 - [9] Lercher P., Evans G.W., Meis M., Ambient noise and cognitive processes among primary school children, *Environ. Behav.* 2003, 33(6), 725-735 DOI: 10.1177/0013916503256260
 - [10] Minichilli F., Gorini F., Ascari E., Bianchi F., Coi A., Fredianelli L., *et al.*, Annoyance judgment and measurements of environmental noise: A focus on Italian secondary school, *Int. J. Environ. Res. Public Health*, 2018, 15, 208. <http://doi.org/10.3390/ijerph15020208>
 - [11] Babisch W., Beule B., Schust M., Kersten M., Ising H., Traffic noise and risk of myocardial infarction, *Epidemiology*, 2005, 16(1), 33-40. <http://doi.org/10.1097/01.ede.0000147104.84424.24>
 - [12] Van Kempen E., Babisch W., The quantitative relationship between road traffic noise and hypertension: a meta-analysis, *J. Hypertens.*, 2017, 30(6), 1075-1086. doi: 10.1097/HJH.0b013e328352ac54
 - [13] Dratva J., Phulera H.C., Foraster M., Gaspoze J.M., Keidel D., Künzli N., *et al.*, Transportation noise and blood pressure in a population-based sample of adults, *Environ. Health Perspect.*, 2012, 120(1), 50-55. DOI 10.1289/ehp.1103448
 - [14] Matheson M., Clark C., Martin R., Kempen EV., Hanes M., Barrio IL., *et al.*, The effects of road traffic noise and aircraft noise exposure on children's episodic memory: the RANCH project, *Noise Health*, 2010, 12(49), 244-254. <http://doi.org/10.4103/1463-1741.70503>
 - [15] Licitra G., Ascari E., Brambilla G., Comparative analysis of methods to estimate urban noise exposure of inhabitants, *Acta Acust. United Ac.*, 2012, 98(4), 659-666. DOI 10.3813/AAA.918546
 - [16] Vogiatzis K., and Remy N., Strategic noise mapping of Herakleion: the aircraft noise impact as a factor of the Int. Airport relocation, *Noise Mapp.*, 2014, 1, 15-31 DOI: 10.2478/noise-2014-0003
 - [17] Vogiatzis K., Strategic environmental noise mapping & action plans in Athens ring road (Attiki Odos) – Greece, *WSEAS Transactions on environment and development*, 2011, 7(10), 315-324
 - [18] Fredianelli S., Del Pizzo A., Licitra G., Recent developments in sonic crystals as barriers for road traffic noise mitigation, *Environments*, 2019, 6(14). <http://doi.org/10.3390/environments6020014>
 - [19] Tang S.K., A review on natural ventilation-enabling façade noise control devices for congested high-rise cities, *Appl. Sci.*, 2017, 7(7). DOI 10.3390/app7020175
 - [20] Chung W. K., Chau Ch. K., Massulo M., Pascale A., Modelling perceived oppressiveness and noise annoyance responses to window views of densely packed residential high-rise environments, *Build. Environ.*, 2019, 157, 127-138. DOI 10.1016/j.buildenv.2019.04.042
 - [21] Wu J., Zou C., He S., Sun X., Wang X., Yan Q., Traffic noise exposure of high-rise residential buildings in urban area, *Environ. Sci. Pollut. Res.*, 2019, 26, 8502-8515. <http://doi.org/10.1007/s11356-019-04640-1>
 - [22] Ministry of Ecology and Environment (2008) - Environmental quality standard for noise. http://www.mee.gov.cn/2018tz/mep_index.html
 - [23] Delany M.E., Harland D.G., Hood R.A., Scholes W.E., The prediction of noise levels L_{10} due to road traffic, *J. Sound Vib.*, 1976, 25, 305-325
 - [24] UK Dept. of Transport, Welsh Office, Calculation of road traffic noise, HMSO, London, 1988
 - [25] Steele C., A critical review of some traffic noise prediction models, *Appl. Acoust.*, 2001, 62, 271-287
 - [26] Mak C.M., Leung W.K., Jiang C.S., Measurement and prediction of road traffic noise at different building floor levels in Hong Kong, *Building Serv. Eng. Res. Technol.*, 2010, 31(2), 131-139
 - [27] Osifeko MO., Odufuwa B.O., Evaluation of models for predicting highway traffic noise, *J. Exp. Res.*, 2018, 6(1), 55-62
 - [28] Jadaan K.S., Okasha A.A., Developing a traffic noise prediction model for Jordanian conditions, *J. Geotech. Transport. Eng.*, 2016, 2(1), 6-13.
 - [29] ISO 9613-2:1996(E), Acoustics - Attenuation of sound during propagation outdoors. Part 2: General method of calculation, 1996
 - [30] Tomić J., Bogojević N., Pljakić M., Šumarac-Pavlović D., Assessment of traffic noise levels in urban areas using different soft computing techniques, *J. Acoust. Soc. Am.*, 2016, 140(4), 340-345
 - [31] Lam H.K., Tam M., Reliability analysis of traffic noise estimates in Hong Kong, *Transp. Res.*, 1998, D3, 239-248
 - [32] To W.M., Ip R.C.W., Lam G.C.K., Yau C.T.H., A multiple regression model for urban traffic noise in Hong Kong, *J. Acoust. Soc. Am.*, 2002, 112, 551-556
 - [33] Leung B.K.H., Mak C.M., Is the CRTN method reliable and accurate for traffic noise prediction in Hong Kong?, *HKIE Transactions*, 2008, 15, 17-23
 - [34] Herni H., Ramdzani A., Mohd Jallani M.N., Hamidi A.A., Noorhazlinda A.R., Comparison between measured traffic noise in Klang Valley, Malaysia and existing prediction models, *Eng. Herit. J.*, 2017, 1(2), 10-14.
 - [35] Ariza-Villaverde A.B., Jiménez-Hornero F.J., De Ravé E.G., Influence of urban morphology on total noise pollution: Multifractal description, *Sci. Total Environ.*, 2014, 472, 1-8
 - [36] Margaritis E., Kang J., Relationship between urban green spaces and other features of urban morphology with traffic noise distribution, *Urban For. Urban Gree.*, 2016, 15, 174-185
 - [37] Ryu H., Park I.K., Chun B.S., Chang S.I., Spatial statistical analysis of the effects of urban form indicators on road-traffic noise exposure of a city in South Korea, *Appl. Acoust.*, 2017, 115, 93-100
 - [38] Wang B., Kang J., Effects of urban morphology on the traffic noise distribution through noise mapping: A comparative study between UK and China, *Appl. Acoust.*, 2011, 72, 556-568