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Rumble strips noise emission effects on urban road traffic

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ABSTRACT
Road traffic has become a prominent feature of many urban areas and one of the dominant sources of community noise exposure. For this reason, a great deal of attention should be paid to reduce noise as urban planning activities are performed. In the last decade, traffic-regulation devices have been widely used on city roads. Rumble strips have been over-employed within urban and residential areas. Their function in successfully reducing traffic speed is extremely controversial because they are responsible for noise pollution as vehicles transit over them. In this study, a determination of the effects rumble strips have on the acoustic climate is achieved by evaluating the Sound Pressure Levels (SPLs) produced as different-weight vehicles transit over them at various speeds. The recorded SPLs are compared with those produced by the same vehicles operating in an undisturbed condition. An analysis of the measured equivalent continuous A-weighted sound pressure level quantifies the noise impact these devices have on the urban area. Furthermore, as more complex parameters are used (e.g. A-weighted sound exposure level, percentile levels, spectral composition, impulse events, etc.), the results demonstrate that rumble strips aggravate the already noisy urban road traffic output without producing any improvements on vehicles circulation and road safety.

1 INTRODUCTION
Traffic is one of the main noise sources in urban areas due to the increasing number of vehicles. Many studies have demonstrated that road traffic noise is of serious concern for those who are exposed to it[1], and it can result in number of problems ranging from annoyance[2] to serious health diseases[3]. As a consequence, noise reduction is a desirable feature when urban planning activities are scheduled. Nevertheless, municipal staffs and local authorities are mainly focused on reducing the traffic speed and, oftentimes, some of the performed activities cause an increase in noise. An example is the widespread use of traffic-regulation devices placed on urban roads in the last decade. They consist of different physical designs put in place for slowing down vehicles, keeping drivers attention, and improving pedestrians and cyclists' safety[4].

In this study the problem of the noise emitted by vehicles crossing the Transverse Rumble Strips (TRSs) in urban areas is addressed. The research consists of an experimental analysis of the Sound Pressure Levels (SPLs) generated by the transit of several passenger-vehicles over the strips at different speed and in a comparison with the noise produced by the same vehicle in undisturbed conditions (i.e. flat pavement surface). The study proves that many acoustic parameters have to be taken into account to characterize TRSs' noise pollution. The analysis of the continuous equivalent A-weighted sound pressure level (L_{Aeq}) shows an increase of nearly 4 dB(A), but when more complex descriptors are considered it is shown that TRSs are responsible for increases in the SPL's peak value up to 14 dB.

This research may lay the foundation for improving the urban planning decision-making process. It introduces the noise intake standpoint and tries to highlight some aspects that local authorities often neglect during the design stages. This paper is organized as follows: Section II describes the investigated rumble strips features, then an overview of related works is provided in Section III. The test setup is presented in Section IV together with the experimental data analysis. Finally, conclusions are drawn and future work is briefly anticipated in Section V.

2 RUMBLE STRIPS TYPOLOGIES AND FEATURES

Rumble strips (also known as sleeper lines or audible lines) are not vehicle traffic-regulation devices as they do not produce an actual decrease in the speed; rather they are mainly used to alert inattentive drivers of a potential danger by causing a tactile vibration and audible rumbling in specific audio frequencies. Their use varies according to the position where they are placed on the lane (i.e. centerline, shoulder or transverse) as well as the profile (i.e. shape, spacing and depth) depending on the levels of both noise and vibration, which wants to be activated[5, 6].

Centerline rumble strips are an effective countermeasure to reduce head-on collisions and are primarily used to warn drivers whose vehicles are crossing centerlines of two-way roads. Shoulder rumble strips are primarily used to warn road users when they have drifted from their lane and are an effective means of reducing run-off-the-road crashes[7]. These types of rumble strips are extremely common on highways and rural roadways. Transverse rumble strips are installed in a series, across the travel direction while approaching danger spots (e.g. toll plazas, horizontal curves, work zones, urban road intersections, etc.) and their efficiency in successfully reducing traffic speed is extremely controversial[8]. At the same time, their use is responsible for increasing the SPL of the area they are installed in due to the modification they induce in the traffic flow speed (e.g. acceleration/brake phases), and because of their interaction with the vehicles. This study focuses on the latter typology, as they are mainly used on urban roadways.

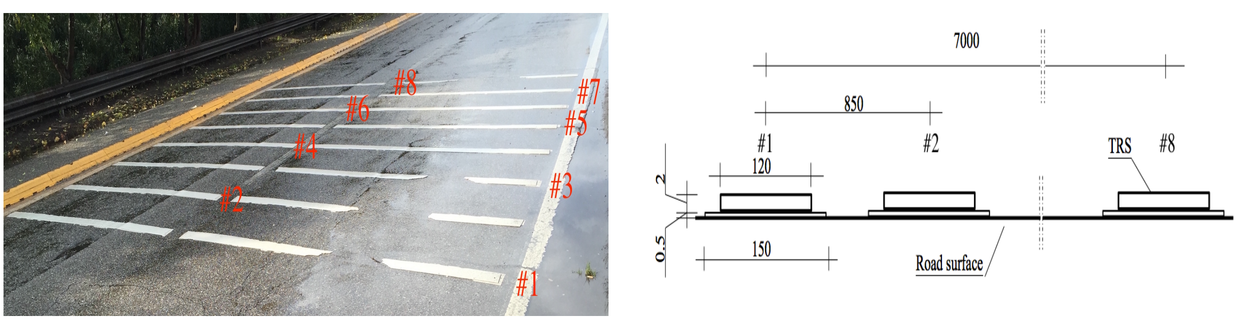


Figure 1: *Transverse Rumble Strips and road side view with TRS dimensions in millimeters (not in scale).*

In particular, the TRSs investigated in this research occupy the whole width of the roadway and consist of eight 0.002 meter high bands of an elastoplastic laminate anchored to the asphalt using 0.0005 meter fixing foils placed 0.85 meter one from the other. The TRSs shown in Figure 1 are located in one of the main roadways in the city center of Rende, Italy. The road, with a posted speed limit of 40kmh^{-1}, connects this town with the Provincial Capital city of Cosenza. Together these cities have nearly 105,000 inhabitants and belong to a wider metropolitan area of nearly 250,000 inhabitants. Considering that the motorization rate (i.e. number of motor vehicles for every 1,000 inhabitants) of the two cities is nearly 640 (+16.30% compared to the European average) it is easy to imagine how the road considered possesses heavy traffic.

3 RELATED WORKS

The determination of the SPLs generated by rumble strips was the subject of several studies. A significant amount of research is focused on determining the most efficient profile, type, number, and spacing for increasing strips efficiency[6, 9]. Research made by Gupta studied the noise level generated by a car and a truck three meters away from the strips and measured increases of 5 dB and 7 dB [10]. Sutton and Wray proved that increases in SPLs, measured at different distance from the pavement's edge, vary from 12 to 7 dB(A) with the distance[11]. Miles and Finley measured the SPLs produced by two types of vehicles traveling over five types of rumble strips at two different speeds[12]. Kragh et al. compared the noise generated by five different types of milled centerline rumble strips with baseline conditions when three types of vehicles were driven at 80 kmh^{-1} [13]. Cynecki et al. reported problems with noise when raised transverse rumble strips were employed in residential areas, but no experimental data were provided in the study[14]. Finally, Haron et al. investigated the annoyance caused by the installation of typical TRS in rural roadways, showing an increase of 14 dB(A) in the hourly $L_{Aeq,\,1h}$ [15]. Despite the relevant number of studies performed, all of them investigate only a few cases at a time (e.g. two typologies of vehicles, a specific speed, effect of different strips, etc.) or suburban scenarios. The traffic flow's SPLs evaluation in urban areas is still missing and is the focus of this work.

4 MEASUREMENT DETAILS

This research aims to provide an estimation of the increase of traffic noise on a road in which rumble strips were installed. In order to do that, extensive measures were performed by positioning two class-1 microphones connected to a real-time analyzer. Microphones were placed one meter outside the roadway's edge, nearly three meters from the road's central axis.

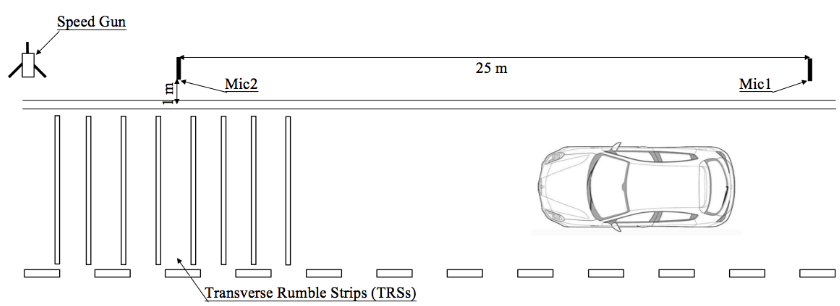


Figure 2: *Experiment setup for the determination of the SPLs (not in scale).*

As shown in Figure 2, one microphone (Mic2) was positioned in alignment with the TRSs' middle point, while the other (Mic1) was located 25 meter before the TRSs in a part of the street that had a flat road surface. Mic1 was used for recording the SPLs generated in undisturbed condition, while Mic2 was used to record the SPLs produced by the vehicle passing over the strips. Measurements were performed for one-hour according to the recommendation provided by ISO standards measuring the noise level generated by the vehicles[16]. A distinction between light vehicles (LVs) and heavy vehicles (HVs) was considered as well as the vehicles' speed using a laser gun placed right after the TRS.

4.1 Analysis of the results

During the one-hour measurement, nearly 700 vehicles traveled over the portion of the road being analyzed. Of those, only 500 were considered in this analysis, as they were clear transits (i.e. no vehicles passing together or in group). An example of the time history (TH) recorded using the A-weighted Fast time constant is plotted in Figure 3. The SPLs measured with Mic1 (blue line) and Mic2 (red line) refer to three different-weight vehicles traveling at different speed: a single-decker 12 meter long bus traveling at 29 kmh^{-1}, a hatchback car at 40 kmh^{-1}, and another hatchback car passing-by at 37 kmh^{-1}. An increase in the SPL values can be easily observed for each vehicle as it passes by the respective microphone. Moreover, it is interesting to note that the SPL for Mic1 increases even after the vehicles are 25 m away and have reached the TRS test section (i.e. the second smaller peak in the blue curve after instance of maximum vehicle sound radiation as shown in in Figure 3). These results provide evidence that the TRS devices significantly increase a vehicle's sound radiation contributing to noise pollution.

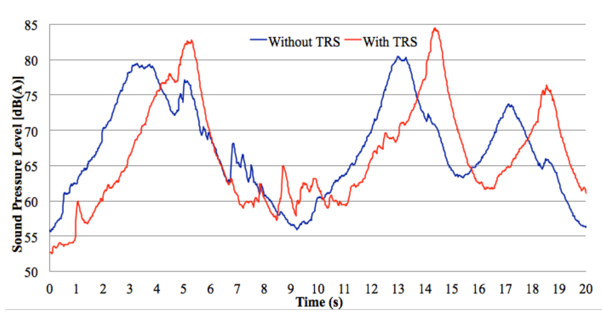


Figure 3: *Sound radiation TH of three separate vehicles traveling over the test section (Mic1 = blue; Mic2 = red).*

To determine the difference between the two transiting conditions, the values of some acoustic parameters (i.e. L_{Aeq}, Sound Exposure Level *SEL*, maximum A-weighted SPLs determined using the Fast time constant $L_{AF,\,max}$, and the Peak sound pressure level p_{peak}) were studied. The values related to the data plotted in the figure above are listed in Table I as an example.

Table 1: Investigated acoustic parameters' values for the three vehicles in Figure 3.

		Without TRS				With TRS			
	Speed [km h^{-1}]	L_{Aeq} [dB(A)]	SEL [dB(A)]	$L_{AF,max}$ [dB(A)]	p_{peak} [dB]	L_{Aeq} [dB(A)]	SEL [dB(A)]	$L_{AF,max}$ [dB(A)]	p_{peak} [dB]
Transit#1	29	78.1	80.4	79.3	99.6	79.6	81.6	82.5	104.5
Transit#2	40	78.6	79.9	80.5	98.4	80.9	81.6	84.1	103.1
Transit#3	37	71.8	72.9	73.7	89.7	73.2	74.4	76.1	94.4

As observed, the passages over the TRSs are characterized by an increase in the values of all parameters. The L_{Aeq} rises from nearly 1.5 dB(A) for the first and the third transit to 2.4 dB(A) for the second one. On average, it corresponds to an increase more than 2% in the emitted acoustic energy. A similar trend is recorded for the SEL, while the increases in the $L_{AF,max}$ and p_{peak} values are even more noticeable. In particular, an increase ranging from 2.4 to 3.6 dB(A) is measured for the first parameter (+3.77%) and one ranging from 4.7 to 4.9 dB(A) for the latter (+4.74%). The same trend was observed for all the 500 studied transits. Average increases of 2.4 dB(A), 1.7 dB(A), 1.2 dB(A), and 3.7 dB are recorded for the L_{Aeq}, SEL, $L_{AF,max}$, and p_{peak} respectively. Those increases are as high as 6.7 dB(A), 6.0 dB(A), 8.3 dB(A), and 13.8 dB when the maximum overall values are considered. To finish, when an evaluation on hourly basis is performed, vehicles produce a $L_{Aeq,1h}$ of 76.9 dB(A) when they transit under undisturbed conditions and a $L_{Aeq,1h}$ of 80.9 dB(A) as they pass over the TRSs. An $L_{Aeq,1h}$ increase of 4 dB(A) corresponds to more than doubling the acoustic energy emitted by the vehicles in the environment. Practically, the TRSs' installation effect is equivalent to that produced by doubling the number of vehicles transiting in that area in one hour (from nearly 700 to more than 1,400).

In addition to the simple evaluation performed on the L_{Aeq}, other considerations, which may help better characterize how TRSs affect the acoustic climate of the area, should be accomplished. These factors include the possible presence of impulsive sound events and tonal components. A detail of the TH recorded with Mic2 is plotted using the maximum A-weighted SPLs determined using the Fast time constant $L_{AF,max}$, the Slow time constant $L_{AS,max}$, and the Impulse time constant $L_{AI,max}$ highlights the impulsivity of the sound.

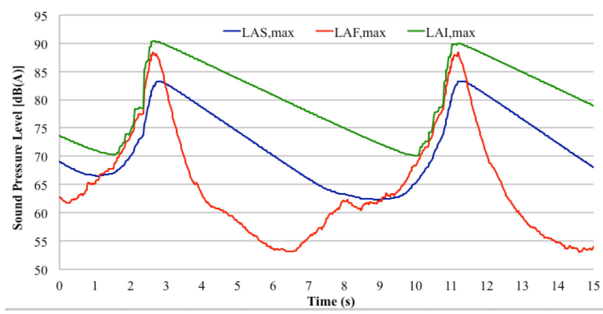


Figure 4: *Impulsive sound events individuation for two vehicles traveling through the test section.*

The TH in Figure 4 refers to the transit of two vehicles at 48 and 40 km h^{-1} respectively. Both produce impulsive sound events (i.e. $L_{AI,max}$ - $L_{AS,max}$ > 6 dB(A); $L_{AF,max}$ decays of more than 10 dB(A) in less than one second) as the wheels impact the first strip. Impulsive sound events can be dangerous and contribute to the annoyance expressed by people living in the surrounding areas. Figure 4 shows an example of impulsive sound events, but the same trend was found in almost all the investigated transits. In addition, results show that the impulsive sound is independent from the speed and it also occurs for vehicles traveling below the speed limit.

The TRSs also effects the spectral composition of the emitted noise. As shown in Figure 5, where a 1/3-octave-band frequency analysis of the recorded signals is performed by means of Fast Fourier Transform (FFT), a change in frequency response is highlighted.

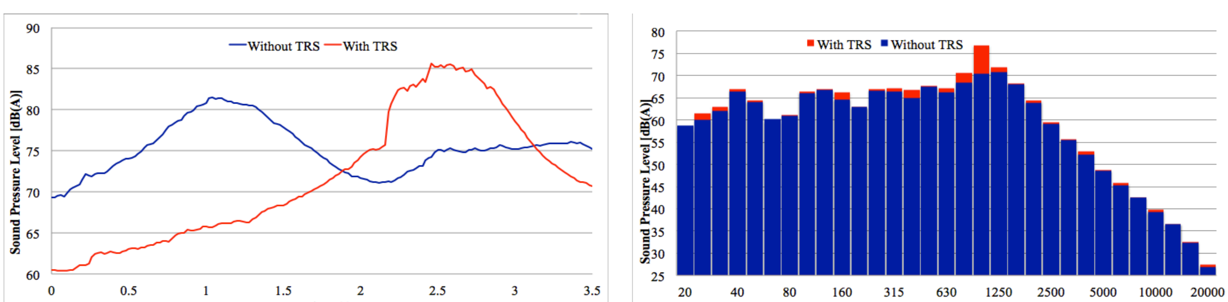


Figure 5: *TH (left) and 1/3-octave band FFT (right) of a vehicle traveling at 36 km h^{-1}.*

Data plotted in Figure 5 refers to a vehicle traveling at 36 km h^{-1}, which is characterized by a L_{Aeq} increase of 3.3 dB(A) and equal to 4.2 dB(A) for $L_{AF,max}$ when a comparison with the baseline conditions is made. In particular, the transit over the TRSs produces a sound characterized by a higher contribution at the middle-frequencies (i.e. between 1000 and 1600 Hz). Due to the interaction between the wheels and the strip's elastoplastic laminate, a sound having different spectral characteristics is produced. The particular emitted frequencies, for a determined speed range, depends on strips pattern and mutual distance[9]. Also, from an analysis of Figure 5, it is observed that the signal recorded during the passage over the strips has a tonal component at the center frequency of 1250 Hz. The presence of this component further increases the annoyance produced by the TRSs.

The contribution to noise provided by impulsive sound and tonal components has to be taken into account when the environmental noise produced by the TRSs is evaluated. In this case, the value of the hourly continuous equivalent A-weighted sound pressure level needs to be corrected to consider the annoyance of the two above-described effects. Based on the legislation of the country in which the measurement was performed, the correction factor is equal to + 3 dB(A) for each of the two effects (other authors suggest a correction of + 5 dB(A)[15]). Thus, the effective $L_{Aeq,1h}$ is equal to 86.9dB(A). As a result, the installation of TRSs is responsible for a total increase of 10 dB(A) in the $L_{Aeq,1h}$ value compared to undisturbed conditions.

4.2 Further considerations

Important information regarding the influence of the TRSs can also be deducted from analyses of the percentile levels L_n (i. e. the noise level exceeded for n% of the measurement time). In particular, the trend of the percentile levels L_1, L_{10}, and L_{50} is considered in this study. When the above-mentioned levels are evaluated with sampling time equal to one minute, the results for both undisturbed conditions and transit over TRSs are those plotted in Figure 6.

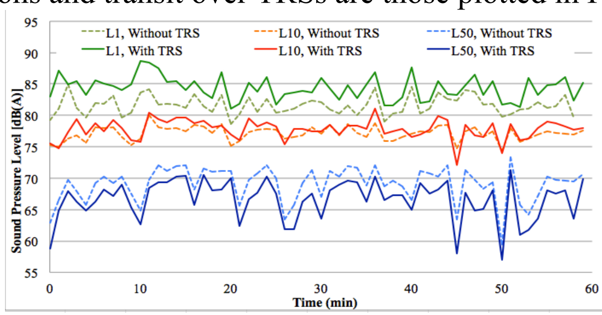


Figure 6: *Percentile levels evaluated for undisturbed conditions and transit over the TRSs.*

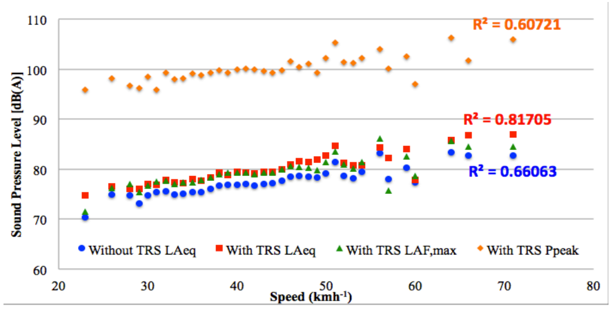
Comparing the L_{50} trends, it is observed that the values related to the undisturbed conditions are higher than those related to the TRSs. This means that the strips modify the traffic flow lowering its speed. As a result vehicles' noise emissions increase as they transit over the strips. By analyzing the percentile levels L_{10}, it is clear that TRSs are characterized by higher SPLs values. This consideration is even more evident as L_1 trends are studied. For the one-hour measurement described in this research, the difference is as high as 4 dB(A).

As observed from the recorded data, predicting the effect TRSs have on noise increase is not easy because it depends on the typical factors used in urban traffic noise analyses (i.e. vehicles' speed and mass).

Table 2: Comparison of the evaluated parameters' increase for two different mass and speed vehicles.

	Level increase				Percentage increase			
	L_{Aeq} [dB(A)]	SEL [dB(A)]	$L_{AF,max}$ [dB(A)]	p_{peak} [dB]	L_{Aeq} (%)	SEL (%)	$L_{AF,max}$ (%)	p_{peak} (%)
Transit#1	1.5	1.2	3.2	4.9	1.88	1.47	3.88	4.69
Transit#3	1.4	1.5	2.4	4.7	1.91	2.02	3.15	4.98

For instance, when Transit#1 and Transit#3 reported in Table 1 are considered, some interesting considerations can be drawn. Transit#1 is a bus traveling at 29 kmh^{-1}, while the latter is a hatchback car traveling 8 kmh^{-1} faster. The values measured for the heavy vehicle (L_{Aeq} = 79.6 dB(A); SEL = 81.6 dB(A); $L_{AF,max}$ = 82.5 dB(A); p_{peak} = 104.5 dB) are higher than those measured for the light vehicle (L_{Aeq} = 73.2 dB(A); SEL = 74.4 dB(A); $L_{AF,max}$ = 76.1 dB(A); p_{peak} = 94.4 dB) which is normal, but when the percentage increase is considered the results are similar despite the difference in the mass of the vehicle as summarized in Table 2. Also, the vehicles' speed plays a key role in the emitted noise as proved when the acoustic parameters analyzed in this study are plotted against the speed for both LVs and HVs.



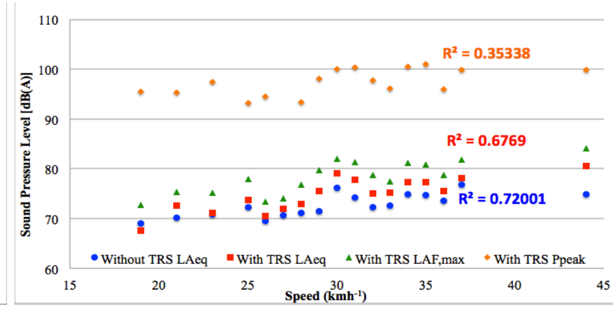


Figure 7: *Trend of the principal acoustic parameters with speed for LVs (left) and HVs (right).*

Results shown in Figure 7 were obtained by averaging the values of the acoustic parameters recorded for each vehicle traveling at a certain speed. Again, data confirm that there is a L_{Aeq} increase of nearly 4 dB(A) as the noise produced by the transits over the TRSs (red dots) are compared to the undisturbed conditions (blue dots). Also, it is noticed that the produced noise increases as the transit speed increases and this relation is almost linear as shown by the correlation coefficient R^2. On one side, the deviation from the perfect linearity depends on several factors such as the limited statistical population of the sampled data, as shown by the case in which HVs are considered. Due to the number of samples (only 35 transits in one hour), it has not always been possible to average the results. On the other hand, the non-perfect linearity may suggest that speed is not the only parameter to be taken into account as the problem of the TRSs noise is addressed. It is highlighted when the SPLs produced by two similar vehicles transiting at the same speed are analyzed. In the examples summarized in Table 3, the acoustic parameters recorded for two sedan cars traveling at 40 kmh^{-1} are considered. As it is observed, the two cars have similar values in the acoustic parameters as they travel in undisturbed conditions, but the same values significantly diverge as the transit over the TRS is considered.

Table 3: Comparison of two sedan cars' acoustic parameters (at 40 kmh^{-1}).

	Without TRS				With TRS				Variation			
	L_{Aeq} [dB(A)]	SEL [dB(A)]	$L_{AF,max}$ [dB(A)]	p_{peak} [dB]	L_{Aeq} [dB(A)]	SEL [dB(A)]	$L_{AF,max}$ [dB(A)]	p_{peak} [dB]	L_{Aeq} (%)	SEL (%)	$L_{AF,max}$ (%)	p_{peak} (%)
Transit#4	72.5	74.3	73.8	97.1	75.5	75.6	77.3	100.2	3.97	1.72	4.53	3.10
Transit#5	73.0	75.0	74.7	92.0	74.8	76.1	78.1	93.5	2.40	1.44	4.35	1.60

It may indicate that noise also depends on other several mechanical parameters (e.g. suspensions type, tires status, wheel drive characteristics, driving style, etc.), which should ideally be considered to perform accurate analyses of the acoustic phenomenon.

4 CONCLUSIONS

In this study, the effect Transverse Rumble Strips (TRSs) have on urban road traffic noise in analyzed. These traffic-regulation devices, initially used for alerting drivers of potential dangers by causing a tactile vibration and audible sound, are now used also within the urban fabric. The devices result in a considerable increase of the already noisy SPLs produced by vehicular road traffic. This research shows that the effect of installing TRSs are characterized by a $L_{Aeq,1h}$ of the area equal to 80.9 dB(A), which corresponds to an increase of nearly 4 dB(A) when a comparison with the noise produced by vehicles on flat road surfaces is performed. The annoyance effect produced is worsened by the presence of impulsive sounds events and tonal components, which are responsible of a further increase equal to 6 dB(A). In terms of overall trend, it has been observed that the noise increases with speed, but the variation compared to the undisturbed conditions is independent from that factor and is constant for all the investigated speeds. The non-perfect linearity observed in the trend may suggest that noise also depends on other external factors such as suspensions type, tires status, wheel drive characteristics, and driving style. Thus, it is evident that the commonly used provisional models, which use to consider the vehicles' speed and the mass only, may be poorly representative for the investigated phenomenon. For this reason further analyses are required in order to have a more statistically significant sample of data and to investigate the importance of each factor on the emitted SPLs.

5 AKNOWLEDGEMENT

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