Musical Pavements

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Currently, considerable research effort is being directed towards reducing tire-pavement noise and designing inherently quieter pavements. This article explores one aspect of the issue . . . and seeks to have a little fun in the process.

Portland cement concrete (PCC) pavements are durable, low maintenance surfaces. The wet weather traction of these pavements can be greatly enhanced by inscribing transverse (i.e., widthwise) grooves in the surface during casting – a process known as tining. Unfortunately, uniformly spaced tining has a highly undesirable side effect of causing a very offensive whine when driven over. Such noise is objectionable not only because it elevates the overall magnitude of the tire-pavement sound levels, but also because of its harsh tonal character.

Examples of narrowband frequency spectra measured alongside roads with tined pavements are shown in Figure 1 for spectra corresponding to the vehicle pass-by maximum overall A-weighted sound levels.[1] The vehicles are traveling at 60 mph on PCC pavements with transverse tining at 25 mm, 19 mm and 13 mm spacing intervals between the grooves. As can be seen in the graphs, the sound levels are characterized by a prominent discrete frequency along with broadband sound. The frequencies of the tones are related to the vehicle speeds and the tining intervals. The broadband component likely contains background sound and the results of other tire-pavement noise mechanisms, as well as the masked overtones or harmonics of the fundamental tire whine frequency.

Let There Be Harmony. As anyone who has driven over transversely tined pavements can attest, the tonal signature of these pavements is quite annoying. However, if some means can be found to divide the noise into two different frequencies, the noise radiated from the tire-pavement interaction can be made less objectionable – provided the frequencies are suitably chosen. If noise is defined as unwanted sound, music might be defined as 'wanted' sound, issues of taste aside. An essential feature of music is the selection of musical notes (i.e., frequencies) that combine in a pleasing way. Frequencies which combine harmoniously are related to each other by ratios of small integers, e.g., 2:1, 3:2 and 4:3. The larger the magnitude of the integers, the less pleasing the sensation produced by the combined tones, as shown in Table 1.

Since the fundamental frequency generated by the tires on the pavement can be controlled by the tining interval selected, distances can be chosen to produce tones combining harmoniously. For example, the ratio 5:4 (known as a "major third" in music and considered by musicians to produce a 'happy' sound) could be obtained with tining spacings of 24 mm and 30 mm in successive sections along a lane of pavement, as shown in Figure 2. A single vehicle on such a stretch of road would create tones alternating between the two frequencies; a stream of vehicles would produce both tones simultaneously.

Table 1. Harmonious frequencies.

Musical Interval	Frequency Ratio	Character
Unison	1:1	Consonant, pleasing
Octave	2:1	↓
Fifth	3:2	
Fourth	4:3	
Major Third*	5:4	
Major Sixth	5:3	
Minor Third	6:5	
Minor Sixth	8:5	
Second	9:8	Dissonant, disagreeable

*'happy' sound

Table 2. Tining frequency vs. speed and spacing.

	Frequency (Hz) at speed (mph)		
Tine Spacing (mm)	30	45	60
38	353	529	706
25	536	805	1073
19	706	1059	1412
13	1032	1547	2063

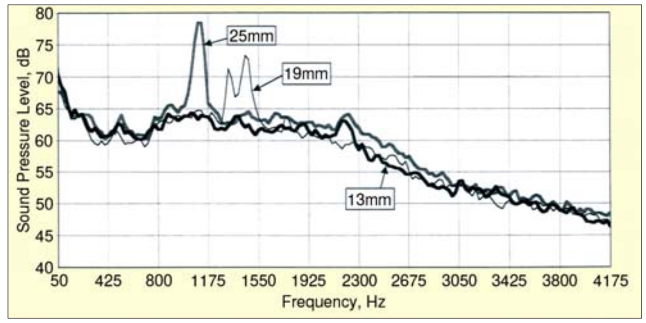

Figure 1. Tined pavement-narrowband spectra. Wayside spectra corresponding to pass-by maximum overall A-weighted sound levels of vehicles traveling at 60 mph on PCC pavements with transverse tining at 25 mm, 19 mm and 13 mm spacing intervals.

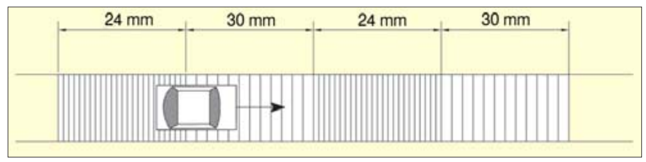

Figure 2. Harmonious tining intervals. A vehicle traveling from left to right over a lane of pavement with tining spacings of 24 mm and 30 mm in successive sections.

Let There Be Music. As noted above, the frequencies generated depend upon vehicle speed and tining intervals. Examples of the tones produced for various typical intervals and traffic speeds are given in Table 2. With imagination, opportunities appear. Figure 3 shows a portion of the musical scale (whose notes are designated by a repeating series: C, D, E, F, G, A, B). [*A common style of musical nomenclature represents "middle C" (approximately 262 Hz) as 'C4,' an octave above middle C (about 523 Hz) as 'C5,' two octaves above middle C as 'C6' and so on. F directly above middle C (about 349 Hz) is represented as 'F4,' and F in the octave above F4 (about 698 Hz) as 'F5,' etc.*] By comparing Table 2 and Figure 3, it can be seen that a vehicle traveling at 30 mph will produce a tone roughly corresponding to F4 with 38 mm tined pavement, C5 with 25 mm pavement, and C6 with 13 mm pavement. Double the speed to 60 mph and tones an octave higher are generated, respectively-F5, C6 and C7. Table 2 is completely translated into the corresponding approximate musical notes in Table 3.

While the tining intervals in Table 3 only yield the approximate musical notes, the exact notes could be obtained (for a given vehicle speed) by computing the necessary tining spacing, as tabulated in Table 4. For a given speed, a two-octave range of frequencies is produced from a practical range of tining intervals – more than enough to make recognizable tunes! Figure 4 is the music to one such tune, four bars of "Mary Had a Little Lamb." Figure 5 is the pavement to "Mary Had a Little

Table 3. Musical notes vs. speed and spacing.

	Approximate musical note at speed (mph)		
Tine Spacing (mm)	30	45	60
38	F4	C5	F5
25	C5	G5	C6
19	F5	C6	F6
13	C6	G6	C7

Notes given in common musical nomenclature, e.g., "middle C" (approximately 262 Hz) is represented as 'C4.'

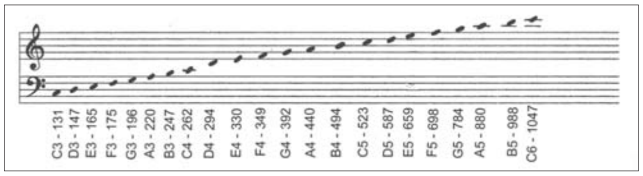

Figure 3. Musical scale.

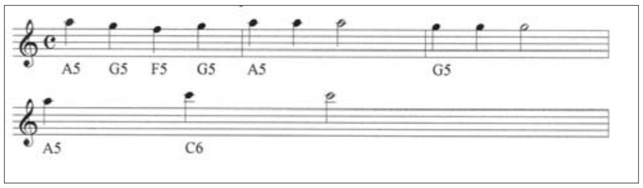

Figure 4. "Mary Had a Lttle Lamb" music.

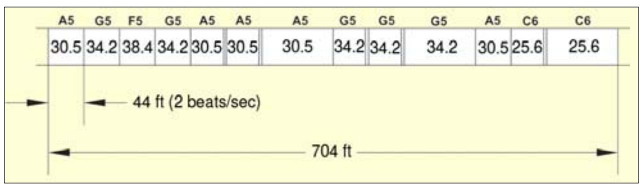

Figure 5. "Mary Had a Little Lamb" pavement. A lane of pavement with the musical notes indicated above the lane and the necessary tining intervals (mm) marked in the pavement sections for a vehicle traveling at 60 mph from left to right.

Lamb" for a vehicle traveling at 60 mph. (Figure 5 illustrates a lane of pavement for vehicles traveling from left to right. The musical note is indicated above the pavement and the necessary tining interval is marked in the pavement section.) Since music consists of time as well as pitch, the lengths of the pavement sections are significant. 60 MPH corresponds to 88 ft/s. Thus, 44 ft long pavement sections will produce 120 beats/minute at that speed, about the tempo of a march. The first six notes are quarter notes, but the seventh section (the third consecutive A5) is a half note and must be 88 ft long. Furthermore, to articulate the individual notes in the succession of three A5 or G5 notes, a short stretch of un-tined pavement is necessary (represented in the figure by the doubled line separating the pavement sections). Otherwise, the continuous pavement would sound as a whole note. The four bars are repeated every 704 ft.

More is Better. Working under the theory: "Anything worth doing is worth doing to excess" and recognizing the opportunities provided by multi-lane roadways, the possibilities become virtually unlimited. Figure 6 is the music to "When the Saints Come Marching In," eight bars of both the melody and harmony. Figure 7 is the pavement in three lanes, including a rhythm section of expansion strips 22 ft apart ("dadum-dadum-dadum")! This scheme requires three vehicles side-by-side at 60 MPH. The eight bars are repeated every 1408 ft and include not only quarter, half, whole notes, but also 44 ft lengths of un-tined pavement corresponding to quarter rests.

The repertoire is limitless. Rap would be an endless succession of at-grade railroad crossings. Beethoven's "Fifth?" The "1812 Overture?" Imagine.

Back to Reality. Practically speaking, the reproduction of a recognizable tune for a bystander along a road would be difficult even for a single lane since closely spaced vehicles in the lane would tend to blur the notes. Multiple lanes with separate music parts would be even more difficult. (For the passengers inside a vehicle, this problem does not exist.)

Another problem also presents itself. Although tire-pavement interaction noise is much less prominent at low speeds, the musical character is maintained for any vehicle speed – the key and tempo merely are shifted. However, if there are speed differences between vehicles within a traffic flow, then those vehicles will produce slightly different tones, which may combine harmoniously or discordantly in accordance with their speeds.

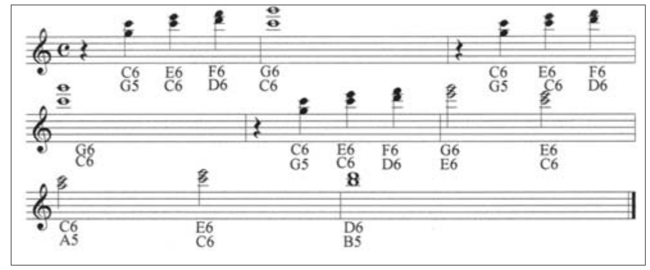

Figure 6. "When the Saints Come Marching In" music.

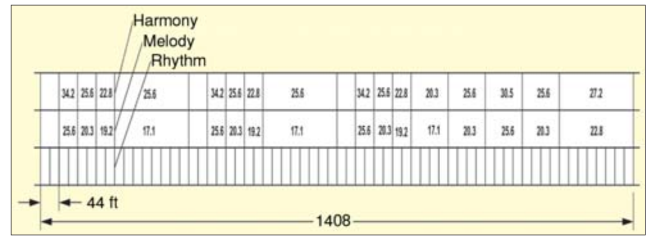

Figure 7. "When the Saints Come Marching In" music. Three lanes of pavement with the necessary tining intervals (mm) marked in the pavement sections for vehicles traveling from left to right.

The Beat Generation. If two sounds of nearly the same amplitude but different frequency occur simultaneously, they will combine in such a way that the amplitude of the resultant sound will vary in time. The variations in loudness are called beats. The beats themselves are periodic with a frequency, f_B, corresponding to the difference between the two original tones:

$$f_B = f_1 - f_2.$$

If the beat frequency is very small, the resultant sound is harmonious. However, as the beat frequency increases, the result becomes unpleasant. Beat frequencies between about 10 Hz and 50 Hz are discordant.

To evaluate the likelihood of such discord, the scenario of 38 mm tined pavement and a 60 mph vehicle is considered. The vehicle speed and tining spacing would generate a fundamental frequency of 706 Hz. A second vehicle would be discordant if it produced a frequency between 656 and 696 Hz, or between 716 and 756 Hz. On that pavement, those tones would occur at 56-59 mph or 61-64 mph – a highly probable event on a road with a posted 55 mph limit, for example. For a 13 mm tined pavement and a 60 mph vehicle, a second vehicle at 59 or 61 mph would be discordant.

Clearly, speed variations between vehicles are likely to cause

Table 4. Tining spacing for musical notes.

		Required spacing (mm) at speed (mph)		
Note	**Frequency (Hz)**	**30**	**45**	**60**
C4*	262	51.3	76.9	102.5
D4	294	45.7	68.5	91.3
E4	330	40.7	61.0	81.4
F4	349	38.4	57.6	76.8
G4	392	34.2	51.3	68.4
A4	440	30.5	45.7	61.0
B4	494	27.2	40.7	54.3
C5	523	25.6	38.4	51.3
D5	587	22.8	34.3	45.7
E5	659	20.3	30.5	40.7
F5	698	19.2	28.8	38.4
G5	784	17.1	25.7	34.2
A5	880	15.2	22.9	30.5
B5	998	13.6	20.4	27.2
C6	1047	12.8	19.2	25.6
D6	1175	11.4	17.1	22.8
E6	1319	10.2	15.3	20.3
F6	1397	9.6	14.4	19.2
G6	1568	8.6	12.8	17.1
A6	1760	7.6	11.4	15.2
B6	1976	6.8	10.2	13.6
C7	2093	6.4	9.6	12.8

**Middle C*

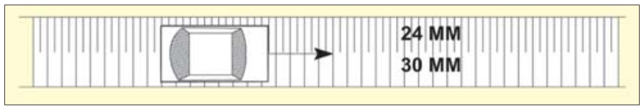

Figure 8. Laterally differentiated tining. A vehicle traveling from left to right over a lane of pavement with tining spacings of 24 mm and 30 mm on the left and right sides of the lane, respectively.

discord. This is true for any regularly tined pavement, whether designed for musical qualities or not.

Mitigation Options. Realistically, the production of music for the benefit of a wayside listener is not practical for busy roadways because of the smearing of the tune by the successive vehicles. Alternate-pitch tining (illustrated by Figure 2) would alleviate the tire whine harshness, although not address the discordant effects due to speed variations between vehicles. Other options in this same vein are "two-tone lanes," which generate the two desired frequencies simultaneously. One two-tone lane configuration could have laterally differentiated tining in which one side of the lane is tined at one interval and the other side at a different interval, as illustrated in Figure 8. With this scheme, the tires on the opposite sides of a vehicle originate the different tones; however, vehicle speed variations are still problematic and the design would be difficult to implement. Another two-tone lane approach is dual-pitch tining in which the tining spacing contains two periodic intervals, as shown in Figure 9. (Note that Figure 9 shows the actual grooves in a section of pavement traversed from left to right in the sketch with the double lines denoting the grooves.)

With dual-pitch tining, all tires of a single vehicle produce both desired frequencies simultaneously. In the illustration, 24 mm and 30 mm intervals are shown. The combined pattern itself is repetitive every 120 mm. The time histories of each of these intervals alone would be sinusoidal with frequencies of 1118 Hz and 894 Hz, respectively, for a 60 mph vehicle. Since the Fourier transform of the sum of two functions is the sum of their Fourier transforms, the inscription of both intervals will produce both frequencies. This design could be readily implemented, but still does not solve the vehicle speed variation problem.

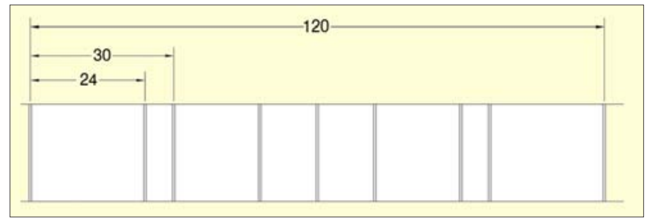

Figure 9. Dual-pitch tining. A 120 mm segment of lane showing tining grooves in the pavement at 24 mm and 30 mm intervals.

Ultimately, the best mitigation is to reduce or eliminate tining-induced whine entirely.[2] This can be accomplished by longitudinal tining or randomization of the spacing for transverse tining, or, better yet, porous pavements that do not need tining for acceptable traction performance and are inherently quieter.

Acknowledgement. I would like to recognize my daughter, Ms. Andrea Staiano, who is an accomplished jazz trombonist. Andrea provided the music, music insights (immediately comprehending the vehicle speed variation problem), and first suggested the mitigation concept of laterally differentiated tining.

References

1. Jaeckel, J. R., et.al., "Noise Issues of Concrete-Pavement Texturing," Paper No. 00-1257, Transportation Research Record – Journal of the Transportation Research Board – No. 1702, National Academy Press, Washington, DC, 2000.
2. Wayson, R. L., "Relationship Between Pavement Surface Texture and Highway Traffic Noise," NCHRP Synthesis 268, 1998.

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