CORRELATION OF NOISE MEASUREMENT TYPES IN THE ARIZONA QUIET PAVEMENT PILOT PROGRAM

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ABSTRACT

In cooperation with FHWA, the Arizona Department of Transportation (ADOT) initiated a program to reduce highway traffic noise in the Phoenix metropolitan area by overlaying many freeway segments constructed of transversely tined portland cement concrete pavement (PCC) with an asphalt rubber friction course (ARFC). The acoustic performance of this noise mitigation approach was documented with three types of measurements: 1.) tire-pavement noise source levels; 2.) short-term neighborhood noise measurements; and 3.) roadside noise measurements at research sites. Initial comparison of the noise reductions produced by the ARFC indicated good agreement between the Type 1 and Type 3 measurements. The reductions for the Type 2 measurements were about 3 to 4 decibels (dB) lower on average than the other two types. Almost all of the Type 2 locations had features that provided noise reduction prior to the overlay. The effect of these features on the Type 2 noise reductions were examined using a research version of the FHWA Traffic Noise Model (TNM) that accounts for differences in tire-pavement noise source levels. Using Type 1 data and the characteristics of the Type 2 sites, it was found that when the effect of the reduced tire-pavement source strength was added to the already existing noise reducing features, the predicted reductions were consistent with the Type 3 results. In this sense, the Type 2 and Type 1 were found to "correlate" with each other and, by extension, to the Type 3 results.

INTRODUCTION

In the fall of 2003, the Arizona Department of Transportation (ADOT) initiated a Quiet Pavement Pilot Program (QP3) in cooperation with FHWA. Under this program, 115 miles (185 km) of freeway in the Phoenix metropolitan area constructed with portland cement concrete (PCC) pavement received one-inch (25.4 mm) thick ARFC overlays to reduce highway traffic noise. The overlays were applied to existing freeways and to newly built freeways as they were completed. This pilot program represents the first time that a quieter pavement surface type has been allowed as a noise mitigation strategy on federally funded projects. As a condition of using pavement type as a noise mitigation strategy, ADOT developed a 10-year, $3.8 million research program with FHWA to evaluate the efficacy of using quieter pavement solutions. Noise performance is evaluated by means of three testing methods: on-board measurement of tire/pavement noise source levels (Type 1); short-term, time-averaged noise levels measured in neighborhoods surrounding the freeways (Type 2); and time-averaged noise levels measured at five unobstructed “research grade” sites (Type 3).

Consistent throughout the documentation of the first several years after the ARFC overlay, the reductions measured at the Type 2 neighborhood locations were clearly lower than those of both Type 1 and 3. The neighborhood measurements locations were supposed to be representative of where residents would hear the noise in their yards; however, these locations apparently were not experiencing the full benefit of the reduced source level or receiving the reduced levels that were measured in the open settings of the Type 3 sites. With apparent discrepancy between the Type 2 results and those of Types 1 and 3, an investigation of the “correlation” between the three types of measurements was initiated (1). This paper documents the findings of this investigation.

MEASUREMENT PROGRAM

The measurement program, test procedures, and measurement results are fully documented in QP3 progress reports (2), however, the program and procedures are summarized here. The QP3 measurements have continued through 2013 and are planned for 2014. The results used in this analysis concentrate on the first 4 years of the program corresponding to the only period for which the Type 2 measurements were conducted.

Type 1 Tire-Pavement Noise Source Levels

Type 1 on-board tire-pavement noise source level measurements were taken at more than 330 mileposts on freeways in the metropolitan Phoenix area. The intent of the Type 1 measurements was to quantify the influence of the pavement on tire noise in isolation from other vehicle noises. In general, these measurements followed the on-board sound intensity (OBSI) procedures that were developed for Caltrans (3) and later became the AASHTO TP 76 OBSI test procedure (4). These data were acquired in 5-second averages where each average began just as the milepost was passed. In variance with TP 76, only one data sample was collected at each milepost due to the large number of locations. The test tire was a Goodyear Aquatred 3, which was the standard test tire at the beginning of the QP3. The testing was conducted at a constant speed of 60 mph (97 km/h). The use of OBSI for Type 1 measurements began on regular basis only after 2006. Prior to that, the ISO Close Proximity (CPX) method (5) was used by ADOT. As described in

QP3 Progress Report No. 3 (3), a correlation was developed in 2006 to relate the CPX and OBSI results. The Site 1 results used in this report for the years before 2006, are converted to equivalent OBSI levels based on this correlation. These data were adjusted for air temperature using the gradient of 0.04dB/°F specified in TP 76. After 2006, the on-board OBSI measurements were conducted biannually and later, yearly in October. Prior to that, the on-board measurements made by ADOT were sporadic and the data sets are incomplete. In 2004, Illingworth & Rodkin, Inc. (I&R) conducted OBSI measurements at three of the Type 3 site locations.

Type 2 Neighborhood Noise measurements

The Type 2 neighborhood wayside measurements consisted of one-hour average L_{eq} levels acquired before and after the AFRC overlay at a time of day chosen to represent the typical maximum noise hour. The one-hour levels were determined using an average of three 20-minute L_{eq} samples. In addition to the noise data, traffic counts and typical speeds were obtained for the measurement period and meteorological conditions were documented. Eighty-six locations were originally identified for the Type 2 measurements. Of these sites, noise reductions between pre- and post-overlay were measured at 78 locations. A second set of post measurements were taken approximately 18 months afterwards; however, only 24 locations were measured. The intent of the traffic data was to use it to model each site using the FHWA Traffic Noise Model (TNM) to provide a means of normalizing the subsequent post-overlay data to account for traffic differences. Unfortunately, documentation of the Type 2 measurement program is minimal. The results were never presented or reported in a public forum other than a brief presentation in 2005 (6). A report could not be located within ADOT and the personnel within the consulting group that performed the measurements have since left that organization. Aerial locations of some of the measurement sites are available, however, some locations are not known. For the sites included in the first set of post-overlay measurements, the locations of only 52 sites could be determined.

Type 3 CTIM Roadside Noise Measurements

Although the Type 3 noise measurements are similar to those of Type 2, the sites for the measurements were intentionally chosen to be open with a minimum of 150° view of the freeway from each microphone location. The measurements were conducted over longer time periods than the Type 2 measurements, typically including 4 hours of data either measured in two-hour periods in the mornings of consecutive days or in the morning and afternoon of one day. Although the measurements were conducted by different organizations (I&R and the US DOT Volpe Center), the methods were essentially equivalent and follow the practices later defined in the AASHTO TP 99 procedure (7) for measuring continuous flow, time-integrated traffic noise (CTIM). At all five Type 3 locations, common microphone positions of 50 ft from the center of the nearest lane of through traffic and 5 ft above the surface of the roadway were used. The data from these locations are the primary point of comparison with the Type 1 and 3 results, although data at different distances and microphone heights are available from individual sites. Traffic counts and vehicle speeds were determined for all of the measurements. Each site was modeled in TNM to develop adjustment factors to account for differences in traffic over the course of the measurement periods and for comparing measurements made on different days and years.

INITIAL COMPARISON OF RESULTS

The Type 1, 2, and 3 measurements were not coordinated and were made at different times relative to the initial overlay at any one freeway segment making direct comparison somewhat problematic. Many pairs of pre- and post-overlay measurements are missing, especially for the Type 1 and 2 data. Further, there were lag times between the measurement types; Type 3 measurements lag the initial Type 2 measurements by about 3 to 15 months and Type 1 measurements lag Type 2 by 10 to 12 months. Even during these relatively short times, the noise reduction performance of the ARFC has been found to degrade (8). To develop a comparison of averages, Type 1 noise reductions for 71 mileposts from the 2004 time frame were used along with 78 noise reductions from Type 2 sites. For the Type 3 reductions, the initial reductions from all 5 sites are averaged including all microphone locations providing a total of 12 data points. From these data, the average noise reductions were 8.3 dB for the Type 1 measurements, 5.3 dB for the Type 2 neighborhood measurements, and 9.1 dB for the Type 3 roadside measurements.

The noise reductions indicated by the Type 1 and Type 2 results can be more directly compared by pairing the Type 1 data at each milepost with the nearest location of a Type 2 site. This resulted in 63 pairs of data points being identified. In Figure 1, the Type 2 reductions are plotted against the Type 1 results. This plot displays virtually no correlation between the noise

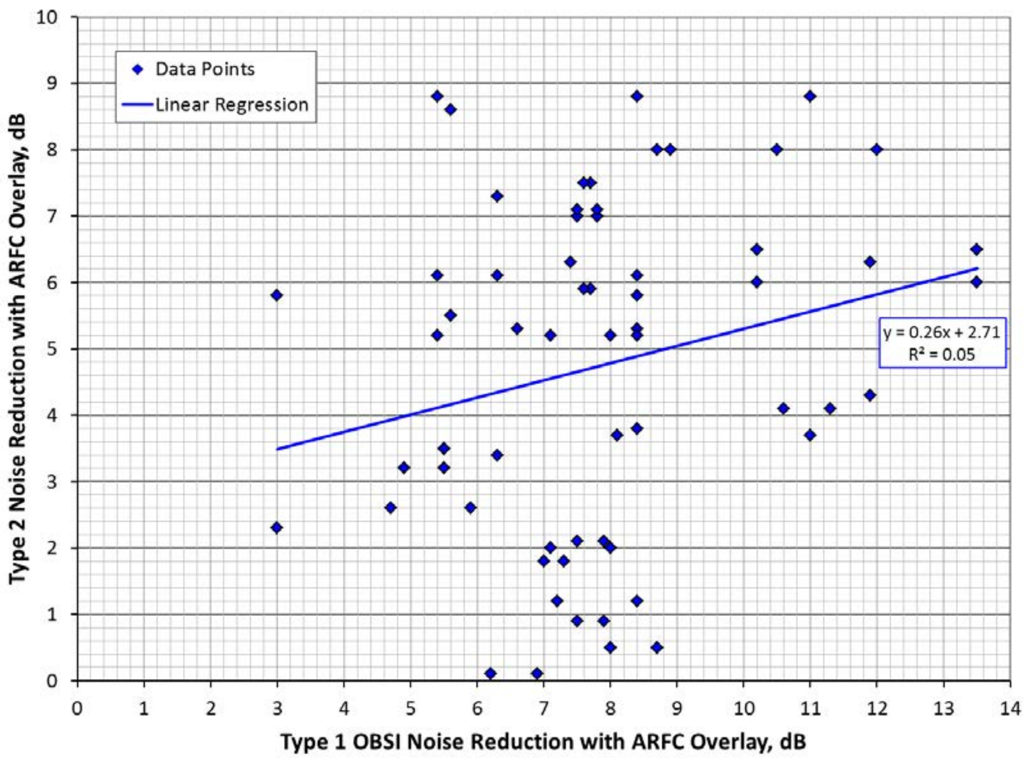

FIGURE 1 Type 2 versus Type 1 noise reductions

reductions with a coefficient of determination (R^2) of 0.05. The average reduction for the Type 1 results is 7.8 dB while the Type 2 is 4.7 dB again giving a difference of about 3 dB. There is a considerable scatter and range in the noise reductions for both the Type 1 and 2 results.

Another means of comparing the results of the different measurement types is to compare the results for the specific locations of the Type 3 measurements. Type 2 measurements were conducted in close proximity to all five sites of the Type 3 measurement locations. For three of the Type 3 sites, true OBSI measurements were completed in the fall of 2004 by I&R. The noise reductions are shown graphically in Figure 2. For the Type 3 measurements, there are some differences in noise reduction at the various distances at each site with the reductions at 50 ft (15

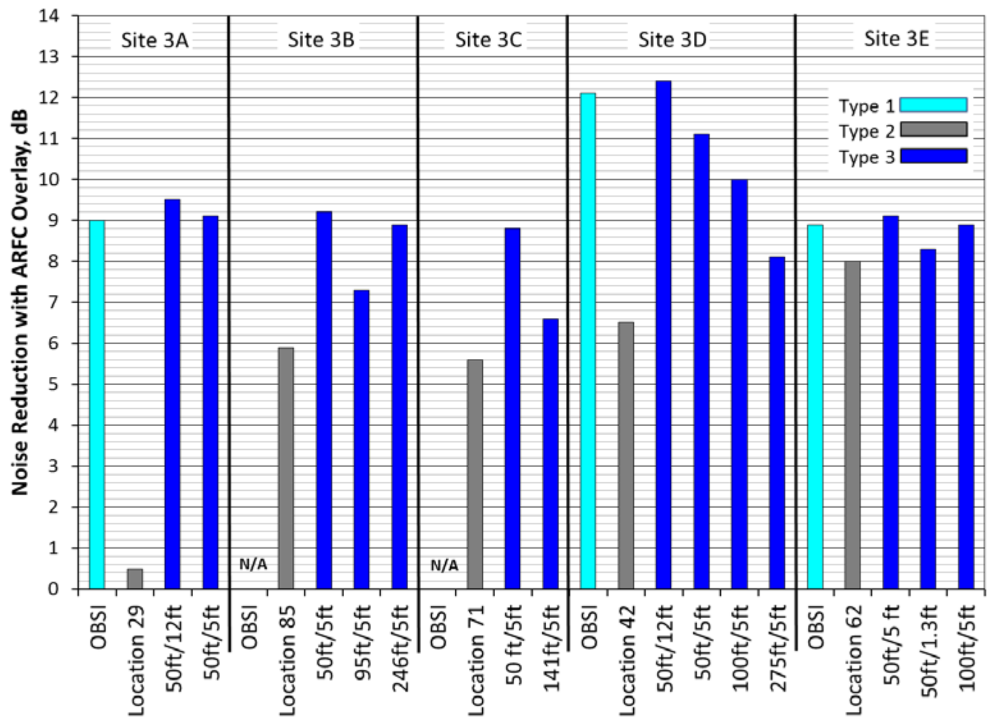

FIGURE 2 Comparison of noise reductions resulting from the ARFC overlay for the Type 1, 2, and 3 measurements

m) being the greatest. For the Type 2 measurements, the distances are unknown except for location 29 at 135 ft. The OBSI results are within about 1 dB or less of the Type 3 at 50 ft (15 m). The rank ordering of the reductions at each location are also consistent between the two data types. For the Type 2 locations, the reductions are always lower than either those of the Type 1 and 3 data even for all microphone distances of the Type 3 results. In some cases, the differences between the Type 2 and 3 noise reductions are quite large. The results of Figure 2 along with the average reductions cited above indicate that the Type 1 and 3 measurements typically show similar noise reductions while the Type 2 noise reduction are regularly less.

EVALUATION OF THE TYPE 2 NEIGHBORHOOD MEASUREMENTS

Examination of Site and Environmental Variables

Using the photographs of 52 documented Type 2 sites, measurement locations were identified using Google Earth™. This tool was used to determine approximate distances to the freeway, the location of structures and existing noise walls, and the elevation of the freeway relative to the measurement location. The sites were examined virtually to determine the approximate height of existing noise walls, freeway recess or elevation, and any other of site geometry nuances that might affect received noise levels. In this manner, the sites were characterized by:

- Open or obstructed view of the freeway
- Flat, elevated, or recessed geometry between the freeway and measurement location,
- Presence of single or multiple barriers and earth berms and approximate height
- Distances from the near lane of vehicle travel to the receiver location and to any intervening barriers or features
- The presence of any nearby potentially high traffic volume streets or other noise sources such intervening frontage roads, and
- General notes about each site.

The average noise reduction for the 52 locations was 5.2 dB compared to 5.3 dB for the complete 78 data points providing some assurance that the analysis of the smaller number of points would be representative of the complete set. Several of the site variables were analyzed to determine if they have a relationship to the reported noise reductions. One hypothesis was that the sites with the higher pre-overlay noise levels would be highly dominated by freeway traffic and hence should record the largest noise reductions with the overlay. Conversely, sites with low initial levels may have other contributing sources and hence would produce only small noise reductions. Regressing noise reduction against pre-overlay levels demonstrated that no such correlation exists. A related hypothesis is that the noise reduction would be less with increasing distance from the highway as indicated by some of the Type 3 measurements. This trend was not found in the Type 2 measurements.

The data from the 52 sites were also used to examine the influence of frontage roads and arterials streets on the noise reductions. Frontage roads between the freeway and the measurement location were found for 21 sites. On average, these sites produced noise reductions of 4.3 dB. The 31 sites without frontage road averaged 5.8 dB. Based on this analysis, there is a possibility that background noise from the frontage roads resulted in lower noise reductions for these locations. Only 3 sites out of the 52 had arterial streets nearby and these sites were actually slightly higher than Type 2 average noise reductions rather than lower.

Another factor that could affect results is the presence of a barrier or a recessed freeway that could diminish the reductions attributable to quieter pavement (9). Using the data from the Type 2 sites, noise reductions were regressed as a function of barrier height and freeway recess. These regressions again show very little correlation between the noise reductions with the overlay and barrier height or recess depth. However, the results are contradicting; increased barrier height shows a slight trend of decreased noise reduction, but increased recess depth shows increased noise reduction with the quieter pavement.

Another aspect of the pre- and post-overlay Type 2 measurements is the range in air temperature under which the data was taken. Most of the pre-overlay measurements were taken in hotter conditions by as much as 30 to 40°F. Noise reduction versus the difference in temperature between the pre- and post-overlay measurements was also regressed and demonstrated poor correlation and only a very slight trend for noise reductions being smaller for greater temperature differences.

Comparison to Type 3 Noise Reductions

Assuming relatively equivalent traffic conditions, the noise reduction from the Type 3 pre- and post-overlay measurements should provide an upper bound of reduction versus distance for comparison to the Type 2 results. The levels from the five Type 3 locations were averaged together for similar distances and results of the pre- and post-overlay data were fitted with logarithmic regressions of level versus distance. The trends for both were quite good with R^2 values of 0.97 and 1.00 for the pre- and post-overlay conditions, respectively. The pre-overlay regressions provided a fall-off rate of about 5.7 dB per doubling of distance (DD) and the post-overlay fall-off is only slightly less at 5.3 dB/DD. Noise reduction versus distance is determined by the difference of these two curves and is shown in Figure 3 along with the individual site reductions from the Type 2 results. The Type 2 results display considerable scatter ranging from

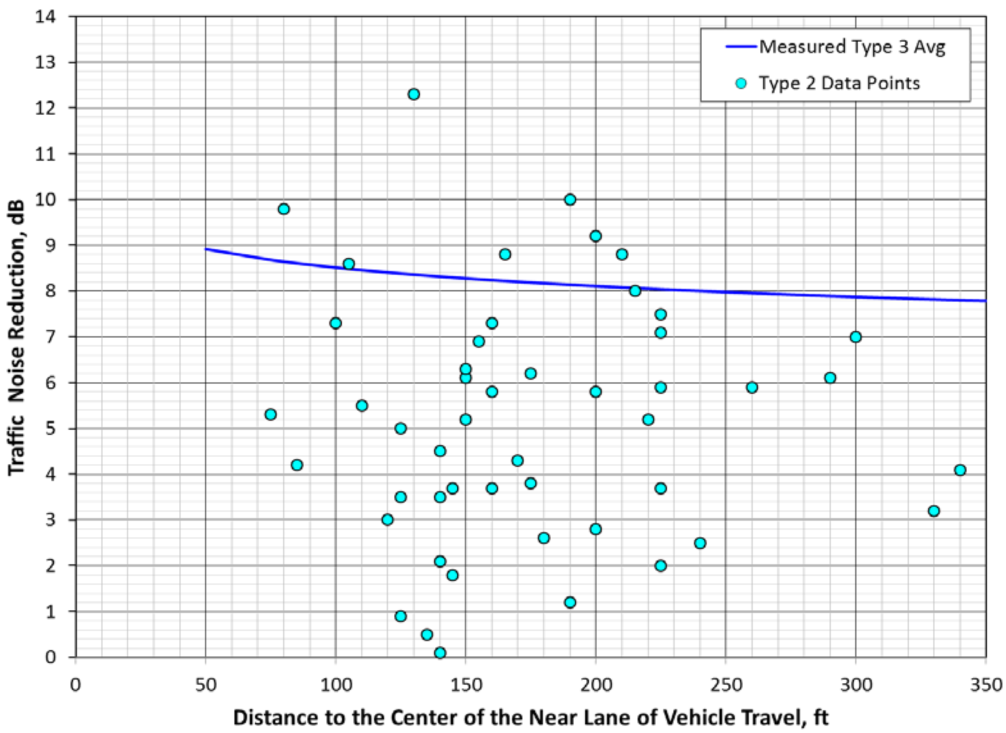

FIGURE 3 Type 2 noise reductions compared to Type 3 average noise reductions as a function of distance from the roadway

3.9 dB higher than the Type 3 curve to about 8 dB below. In principal, the Type 2 reductions should be at or below the noise reduction curve of the Type 3 data, however 6 sites lie above it with 5 being within 1 to 2 dB above the Type 3 curve. Thirty of the data points lay 2 dB or more below the Type 3 curve. The single data point with a reduction slightly greater than 12 dB appears to be errant after closer review.

ANALYSIS USING TNM

Development of Case Models

To assess the effects that site geometries may have had on the reported Type 2 reductions, generic TNM models were constructed to represent different groupings of the sites. Based on the virtual reconnaissance, these fell into three groupings; flat terrain, recessed highway, and elevated highway. Most of the measurement locations were near recessed roadways. Within this grouping, the amount of recess was split into two subgroupings; 6 ft (1.8 m) and 12 ft. In the 12 ft recess grouping, further subgroupings of no barrier, barriers 8 ft (2.4 m) high, or barriers 12 ft high were formed. For each barrier height, several distances between the barrier and the edge of the roadway were selected based on the ranges in the site data. Groupings were also developed for the flat terrain and elevated roadway cases and are presented in Table 1 along with the recessed roadway cases. For each case in Table 1, receiver locations were analyzed at distances of 75 ft (22.9 m) to 425 ft (130 m) from the center of the near lane of travel in 50 ft (15 m)

TABLE 1: Groupings, features, and parameters for TNM analysis of Type 2 results

Site Configuration	Feature Depth/Height	Barrier Geometry	
		Height	Distance from near Lane
Flat	0	0	-
		12 ft	40, 110, & 180 ft
		3 ft K-Rail	20 ft
Recessed	6 ft	0	-
		12 ft	53,100, & 160 ft
	12 ft	0	-
		8 ft	70 & 120 ft
		12 ft	70, 110, & 150 ft
Elevated	4 ft	0	-
		3 ft K-Rail	20 ft

increments. From TNM, each calculation point generates a level with and without a barrier. For the recessed cases, there is also a noise reduction due to the barrier effect of the recess aside from the reduction produced by an installed noise barrier. This site effect noise reduction can be determined by subtracting the flat, open TNM predictions from those for the recessed geometries. At the time of the Site 2 measurements, the freeways were typically 3 lanes in each direction with a large median in between. From aerial photographs, the typical roadway geometry consisted of three 12 ft wide lanes in each direction separated by a 48 ft (14.6 m) wide median and with 20 ft (6.1 m) wide shoulder/clear areas in either direction adjacent to the outside lanes. Based on the traffic data from the Type 2 measurements, a typical traffic condition was developed with 8,000 vehicles per hour at 65 mph, 3% medium truck, and 2% heavy trucks. The intent of this model was not to accurately reproduce the measured levels but rather to evaluate the differences in predicted levels between flat, open sites (Type 3 locations) and groupings of the Type 2 geometries. Since the same roadway geometry, traffic conditions and distributions were used in all cases, the relative differences between the sites were not expected to be very dependent on the traffic parameters.

To evaluate the additional noise reduction produced by the ARFC overlay, a research version of TNM was used that was developed by the US DOT Volpe Center as part of the FHWA Pavement Effects Implementation Study (10). In this version of TNM, the ground level source strength (GLSS) is scaled by using measured OBSI data so that effects of pavement on vehicle emissions can be taken into account in the predicted traffic noise levels. For application to the QP3, representative OBSI spectra were selected for new ARFC and the pre-overlay uniform transverse tine PCC. These data correspond to a reduction of 9.8 dB which is slightly higher than the 9.0 dB average from the Type 1 data (see Figure 2 for Sites 3A and 3E).

Results of Modeling

Using OBSI data and the research version of TNM, traffic noise levels were predicted for the site geometries of Table 1. Predicted noise levels for a 12 ft (3.7 m) recessed freeway with a 12 ft noise barrier located 70 ft (21.3 m) from the roadway are shown in Figure 4 as an example. The highest predicted levels occur for an open site with the pre-overlay PCC corresponding to the

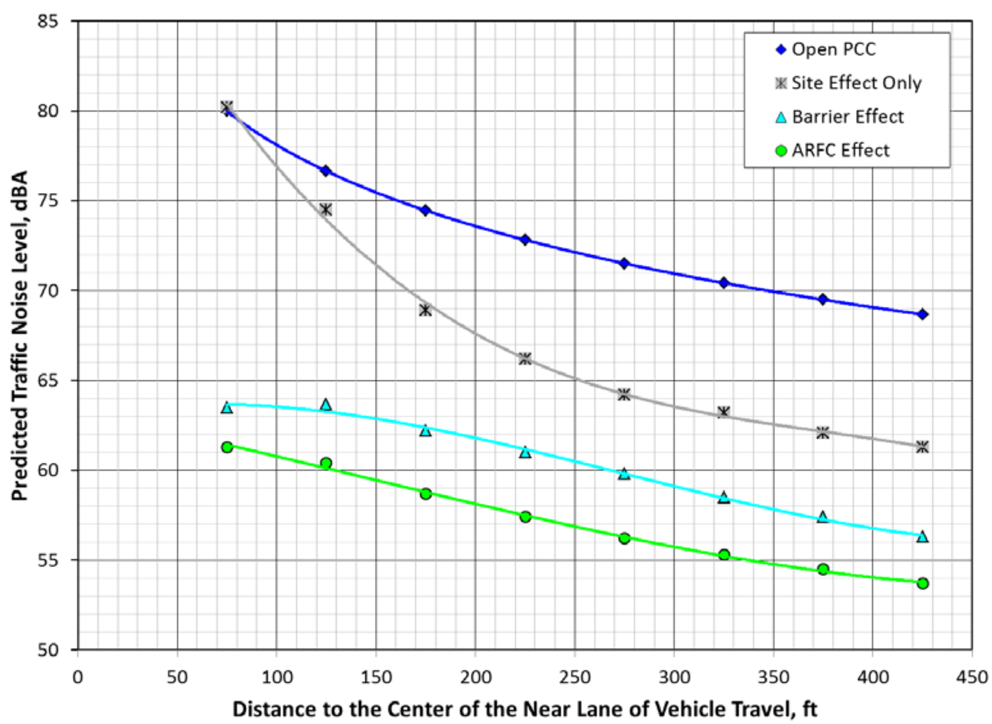

FIGURE 4 Example of TNM predictions for a roadway recessed 12 ft (site effect), with an added 12 ft barrier 70 ft from the roadway (barrier effect) and with ARFC added (ARFC effect)

pre-overlay levels of the Type 3 sites. The next highest levels (still with PCC) show the effects of the recess. The recess provides virtually no reduction near the roadway as there is unobstructed line-of-sight to the traffic. Noise reduction increases at more distant receiver locations as the recess obscures the roadway. When the noise barrier is added to the site, the next lowest levels are produced. In this case, the noise barrier provides substantial reduction near the freeway as the line-of-sight is totally blocked. Finally, the effects of the ARFC overlay are included, and additional noise reductions of about 3 dB are seen with the new pavement. For a Type 2 location corresponding to this recessed geometry with a 12 ft (3.7 m) barrier, the application of ARFC would only provide a 3 dB reduction compared to the original PCC pavement.

The predicted levels for a flat site with a 12 ft (3.7m) high barrier 110 ft (33.5 m) from the roadway are shown in Figure 5. In this case the site effect is small, essentially equal to the open

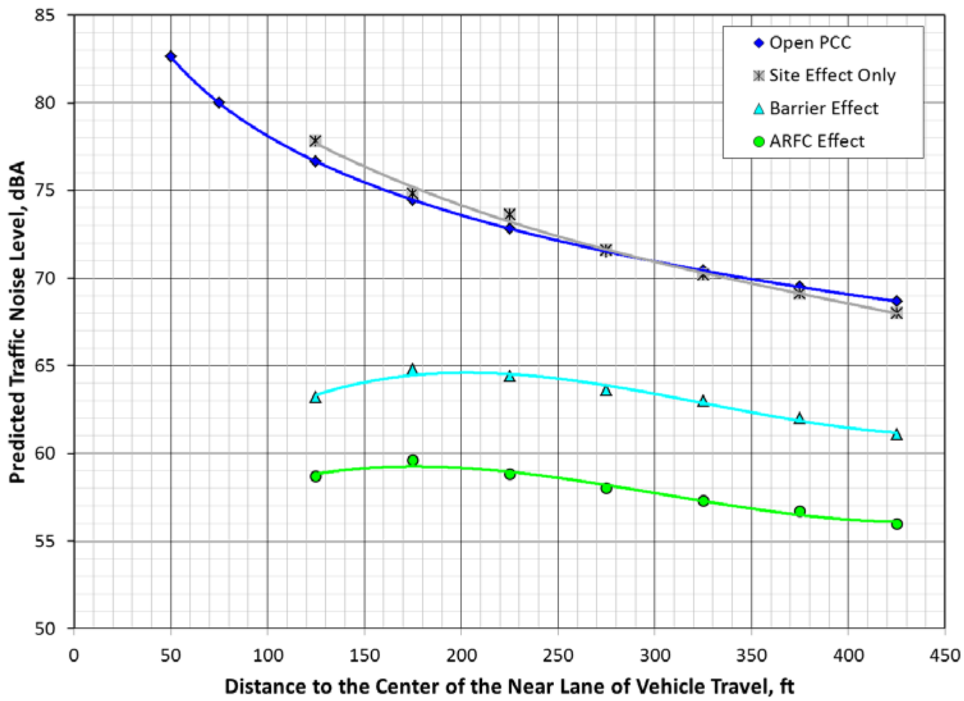

FIGURE 5 Example of TNM predictions for a flat, unobstructed site (site effect), with an added 12 ft barrier 110 ft from the roadway (barrier effect) and with ARFC added (ARFC effect)

case. Just behind the barrier at 125 ft (38.1 m) from the roadway, the reduction is large, about 13 dB. At farther distances from the freeway (250 to 425 ft [76.2 to 129.5 m]), the reduction is smaller providing about 7 to 8 dB. When the AFRC is applied, the levels drop another 5 dB. with a 3 ft (0.9m) K-rail at the edge of the roadway are shown in Figure 6 with the K-rail providing a fairly constant 5 to 6 dB reduction with distance. When the ARFC is applied in this case, an additional reduction of 5 to 6 dB occurs.

The noise reductions predicted to occur with the ARFC overlay for each of the 52 Type 2 locations used in this analysis are shown in Figure 7, along with a logarithmic curve fit through the data points. The average reductions as a function of receiver distance measured for the Type 3 locations are also shown. Based on this analysis, the Type 2 reductions should fall below that for the flat, open Type 3 locations which receive reduction only through the application of the ARFC and not through other noise-reducing features. Of the 52 Type 2 locations, only four correspond to the flat, open Type 3 locations without barriers. In Figure 7, the noise reductions for these four sites are those that are 7 dB or greater. The three noise reductions produced by the ARFC that fall between 6 and 7 dB in Figure 7 have K-rails near the roadway and are either elevated roadways or flat sites. These cases are represented in the Figure 6 by those reductions falling into a range of 4.4 to 6.9 dB. All the other noise reductions in Figure 6 correspond to measurement locations where existing barriers occur. Of these, 32 have recessed roadways for which the noise reduction produced by the ARFC ranges from 3.7 to 5.5 dB. The remaining 16 locations are either flat terrain or elevated roadway with barriers for which the predicted reductions with the ARFC range from about 4.4 to 5.7 dB. The curve through the predicted Type 2 reductions parallels the Type 3 curve with an offset of 3.1 to 3.2 dB. Adding this offset to the

Type 2 average brings the reductions for all three measurement Types within less than 1 dB of each other.

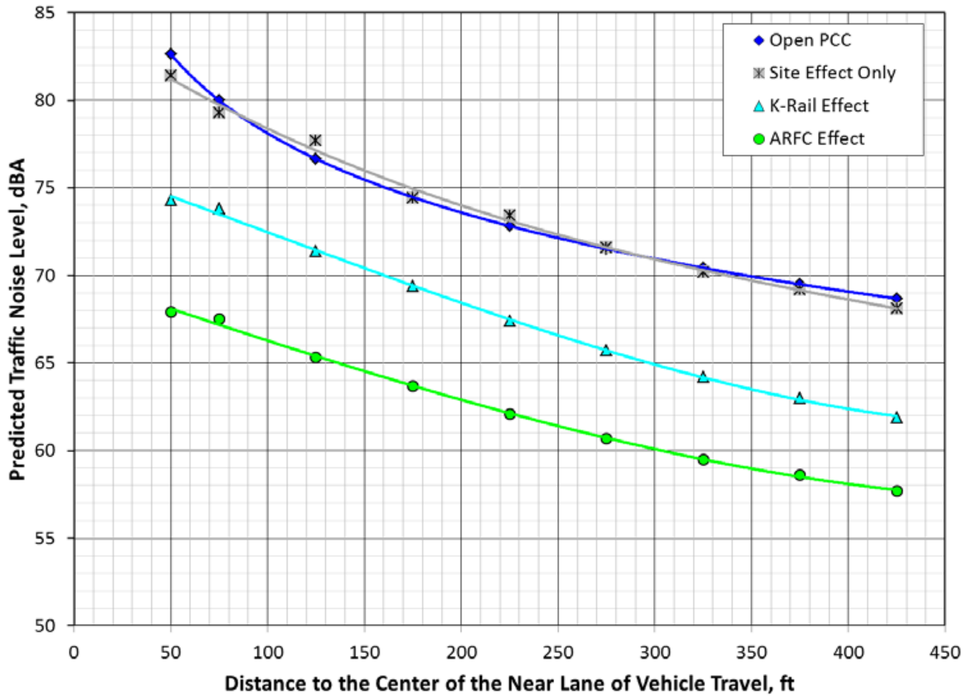

FIGURE 6 Example of TNM predictions for a 4 ft elevated roadway (site effect), with an added 3 ft K-rail at the edge of the roadway (barrier effect) and with ARFC added (ARFC effect)

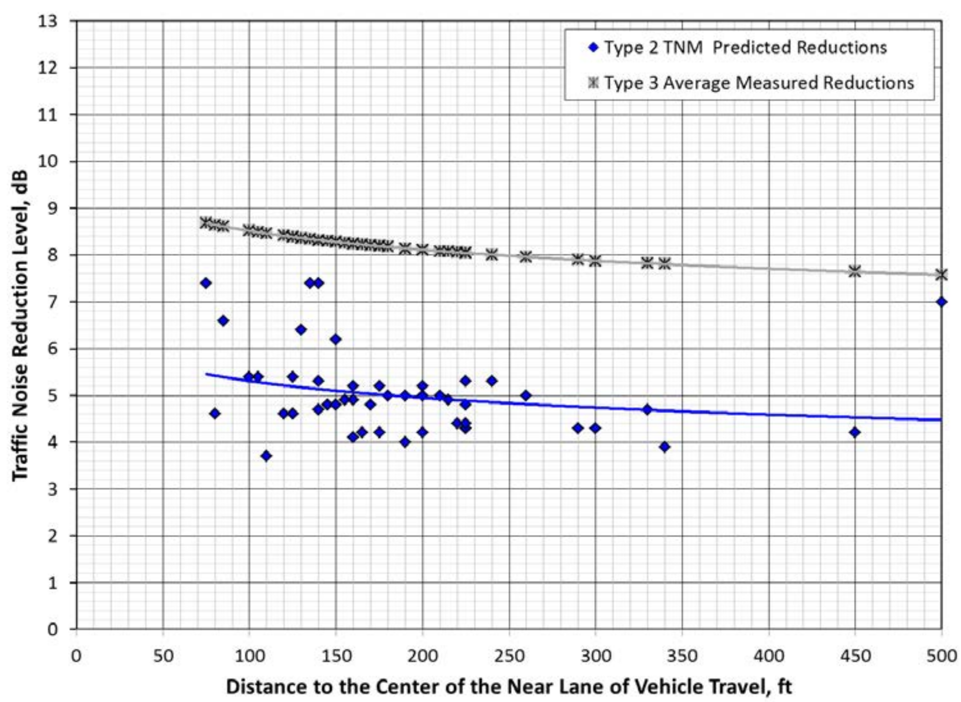

FIGURE 7 Predicted noise reductions for the Type 2 sites with logarithmic regression compared to the average of noise reduction from the Type 3 measurements

Uncertainty in Type 2 Noise Reductions

The results of Figure 7 provide a reasonable basis for the Type 2 measurements yielding a lower average noise reduction than the Type 1 and 3 reductions. However, the TNM results do not account for variance in individual points or the large scatter in the measured Type 2 reductions. In Figure 8, the measured Type 2 reductions are plotted versus distance along with the logarithmic regression curve defined by these data points. Although there is a large scatter in the

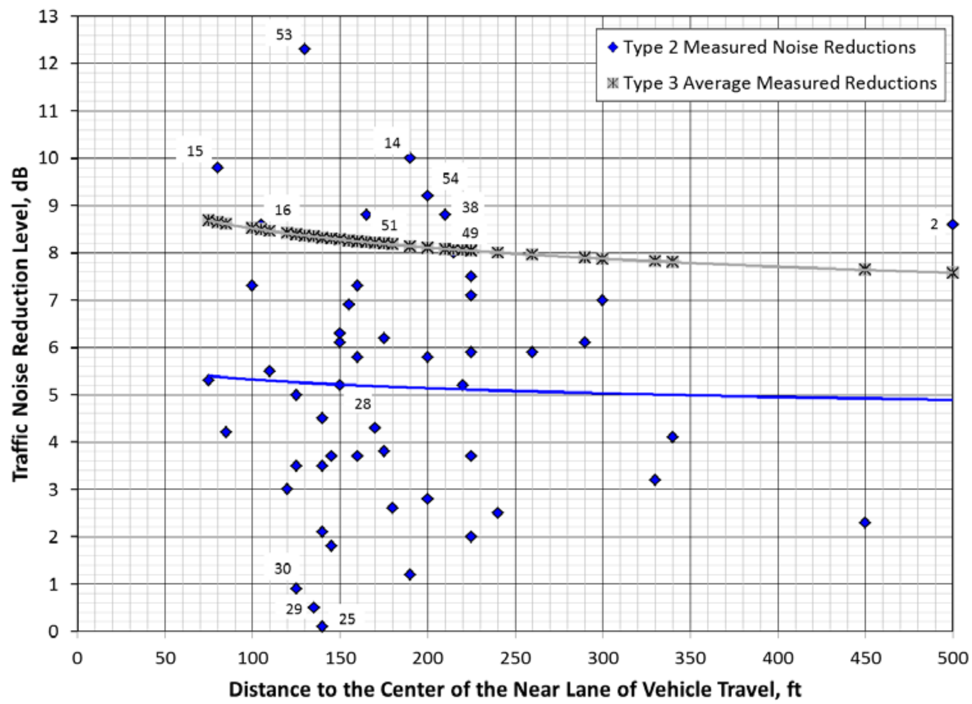

FIGURE 8 Measured noise reductions for the Type 2 sites with logarithmic regression compared to the average of noise reduction from the Type 3 measurements

measured reductions, the average, as represented by the logarithmic curve fit, is almost identical to (within 0.4 dB) that of the TNM predicted noise reductions of Figure 7. However, for the measured Type 2 reductions, the average deviation from their regression curve is 2.2 dB while the average deviation for the predicted reductions of Figure 7 is only 0.6 dB. The measured reductions of Figure 8 display a range of 0.1 to 12.3 dB compared to 3.7 to 7.4 for the TNM predicted reductions.

Some of the outlier points of Figure 8 were examined in more detail in an attempt to understand the scatter. Shown in Figure 8, nine data points, identified as sites 2, 14, 15, 16, 38, 49, 51, 53, and 54, exceed the Type 3 average post-overlay curve. Six of these data points were found to be among seven data points that lay more than 9 dB below the average of the post-overlay levels for the Type 3 sites. The pre-overlay levels were typical of the average of the other sites. This implies that these sites had unusually low post-overlay levels contributing to their high noise reductions. The site information for these sites did not show any consistent factors to indicate why these post-overlay levels are so low. Of the remaining 3 points above the Type 3 average reduction shown in Figure 8, 2 had pre-overlay levels that were among the highest. One of these is flat and open with no barrier, and the other is recessed with a barrier.

The excessively low noise reduction data points (e.g. 25, 29 and 30 in Figure 8) were also examined in more detail. As with the high noise reduction sites, these had no consistent characteristics or attributes that could explain the low noise reductions. Further, the pre- and post-layer levels were largely inconsistent with other similar Type 2 sites and with the Type 3 results.

CONCLUSIONS AND OBSERVATIONS

The differences in the noise reductions produced by quieter ARFC as determined in neighborhood traffic noise measurements and CTIM and OBSI was found not to be a lack of "correlation" for the effects of quieter pavement, but rather to be in the nature of the types of measurements. OBSI and CTIM measurements are designed to isolate the performance of pavements from other noises and obstacles to sound propagation. The Type 2 measurements are intended to measure community noise under any circumstance of the site. By taking into account the geometries and parameters of the Type 2, it was found that the lower noise reductions in Type 2 are to be expected at these sites based on using a research version of TNM that accounts for differences in tire-pavement noise source levels. Many of the Type 2 sites had features that provided noise reduction even prior to the overlay. The application of the overlay did produce reductions in the neighborhoods consistent with the reductions predicted with TNM using the measured OBSI levels. In this sense, the effectiveness of the overlay was correlated between the different measurement types.

The Type 2 measurements of QP3 also demonstrate the effectiveness of using a quieter pavement even when there are other noise reducing measures in place. On average, the pavement change produced a reduction of more than 5 dB, which would be considered to be a "feasible" reduction under the FHWA 23 CFR 772 and ADOT policy. Additionally, of the 52 Type 2 locations, 30 locations would be defined as noise impacted using the ADOT Noise Abatement Criterion (NAC) of 64 dBA even with barriers in place and reductions due to recessed roadways. After the overlay, the number of impacted receptor locations was reduced to 7. Further, 28 of the 52 locations would be classified as "benefited" receptors under ADOT policy as reductions of 5 dB or more were provided by the overlay. Of these 28 locations, 14 achieved a reduction of 7 dB or more, meeting the ADOT reasonableness design goal of at least half of the benefitted receptors receiving this level of reduction.

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