NCHRP Project 1-44:
Measuring Tire-Pavement Noise at the Source

APPENDIX A

Measuring Tire-Pavement Noise at the Source:
Review of Literature

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INTRODUCTION

Tire-Pavement noise has become an increasingly important consideration for highway agencies. However, there are no widely accepted procedures for measuring solely tire-pavement noise under in-service conditions. As a result, this research is undertaken to evaluate potential noise-measuring procedures and identify or develop appropriate procedures applicable to light and heavy vehicles and all paved surfaces. Such procedures will provide highway agencies with an appropriate means for (1) measuring and rating tire-pavement noise levels on existing pavements, (2) evaluating new pavements incorporating noise-mitigating features, and (3) identifying design and construction features associated with different noise levels.

The objectives of this research are to (1) develop rational procedures for measuring tire-pavement noise at the source and (2) demonstrate applicability of the procedures through testing of in-service pavements. To achieve these objectives, a search of the literature was conducted to gain understanding of what approaches have been used in the past to quantify tire-pavement noise source levels. The purpose of this report is to communicate the results of that search, the information obtained, and implications for developing a rational test procedure. The report consists of an overview of the literature search, discussion of measurement methods in different categories, a discussion of the implications of these on developing on developing a test procedure.

OVERVIEW OF LITERATURE SEARCH AND REVIEW

Many hundreds of papers have been written on the subject of tire/pavement noise. To conduct the specific search for this project, some criteria or “filters” were established before reviewing these in detail. The first level of filter was that the work was not entirely analytical and that the measurements were not exclusively passby or wayside measurements. The second level was that measurements were performed on pavement, not on “road-wheels” in a laboratory environment. After these filters, all papers were examined to determine if they contained a novel approach, if they described the development of source level measurement approach, or if they gave results comparing passby to source level measurements. Papers in this latter category were reviewed in the most detail. However, there were exceptions for cases in which the paper presented information on testing parameters and/or variables that effect tire noise measurements. The references deemed to be appropriate were read, summarized, and grouped into categories based on the measurement types employed. As will be noted in the References Section, more than 86 sources of information were evaluated in this manner.

The primary source of reference material has been found to be papers written for various noise conferences. To date, the proceedings of well over 100 national and international conferences and symposia have been search for work related to tire/pavement noise measurement at the source. The Tyre/Road Noise Reference Book[1] written by Sandberg and Ejsmont has been used as a check on being certain that the relevant work prior to 2001 has been included in the search. However, material from the 1970’s through 2001 was searched independent of this extensive reference in order to assure inclusion of all related work. In more recent years, 2002 through 2005, there have been many additional papers published on this subject from ongoing work in Europe, the United States (US), and Asia.

The literature falls into three general categories of acoustic measurement. These include sound pressure level (SPL) measurement, sound intensity (SI) level measurements, sound field measurements using acoustic array technology (AAT). The sound pressure level measurement approaches breakdown into three subcategories. Historically, the first of these are variations "behind the tire" or "BTT" measurements where a microphone is placed directly behind the tire typically close to both the tire and pavement. This position was chosen as it was thought to reduce wind noise on the microphone. The second subcategory is the so-called "close proximity" measurement where several microphones are placed at various points around the tire. This approach evolved into the formal ISO Draft Standard procedure, ISO 11819-2[2], which is commonly referred to as the Close Proximity (CPX) method. Included in this category are not only the draft standard itself, but also a number of other studies in which alternate, although somewhat similar, microphone positions were used. The CPX approach also includes techniques where the microphones are protected from airflow by trailers surrounding the test tire and those where the microphones are exposed to flow. The third subcategory is for sound pressure measurements that are different from the previous two and are typically unique to a single study or set studies by an individual researcher or research group. This subcategory is simply referred to as "SPL Other". In the SI category, the bulk of the reported studies follow the approach developed at General Motors Corporation (GM) and documented in the relevant GM Test Procedure[3]. However, several other unique approaches are also reported. In the AAT category, almost all of on-road work uses a near-field acoustic holography approach (NAH) and has been done largely by single research effort at Penn State University[4].

Each of the three major measurement categories have been used both for on-road and road-wheel (RW) testing. Although it is the intent of this Project to develop a procedure for in-situ measurement of tire/pavement noise at the source, some of the RW work is of interest and was included in this review. Also included in this review are a few references that rely on passby measurements, but give results important to understanding tire/pavement noise variables as they relate to a test procedure.

PREVIOUS TIRE/PAVEMENT NOISE MEASUREMENTS AT THE SOURCE

The results of the literature search into tire/pavement noise measurement at the source are presented in this section. These are grouped into the major categories of SPL, SI, and AAT.

SPL - Sound Pressure Level Measurements

Measurements using SPL methods are subdivided into the categories of BTT, CPX, and SPL Other as discussed in the previous section.

BTT – Behind the Tire

In the early 1970's, tire-pavement noise studies began to appear in which SPL was measured directly behind the test tire with the microphone relatively close to the pavement and tire[5,6,7]. Two of these investigated truck tires (Ref. 6 and 7), while one dealt with passenger car tires (Ref. 5). Unfortunately, the latter study was only presented and not reported. For the truck tire studies, the microphone positions varied somewhat. In several of the early studies, the correlation between passby and the onboard SPL measurements were also documented.

In the Miller/Thrasher study[6], the microphone was suspended directly behind the tire at height of 150mm (6 in.) above the pavement and 460mm (18 in.) diagonally from the rear edge of the tire contact patch. Passby measurements simultaneous made at distances of 6, 12, 25, and 50m from the centerline of vehicle travel. The test tires were mounted on the single rear axle of a flatbed truck. Comparison of the onboard and passby data at 15m (50 ft) indicates the same frequency content for the lug-type truck tires, but relative levels are different. The differences between the onboard and passby levels range from 8-17 dB for the fundamental frequency, 27-29 dB for the 2nd harmonic, and 30-37 dB for the 3rd. The authors argue that this is due to near field effects as onboard measurement distance is not very much greater than an acoustic wavelength (λ).

In an extensive study of truck tire noise, Reiter, et al.[7] used a BTT microphone location 200mm (8 in.) above the road surface and 150mm (6 in.) from the closest point of the tire circumference. The 1 in. diameter microphone was fitted with a 3 in. windscreen. The test vehicle was again a flatbed truck with four tires on the single rear axle. The measurements were made behind the outboard tire. Five different tread patterns were tested in multiple states of wear for both asphalt concrete (AC) and Portland cement concrete (PCC) pavements. In this work, no comments were made on validity of technique and passby data was not taken. However, tire tread acceleration was measured and a general correspondence between noise and vibration was documented.

Throughout the later 1970's and early 1980's, BTT measurements continued to be reported. However, no common microphone positions were adopted across the measurements. In a study of both light and heavy-duty tires, Landers et al.[8] employed microphone positions directly behind the tire, spaced equally between the tire and pavement as close as possible to each without endangering the microphone. The microphone was then thought to be positioned in a "dead air pocket" behind the tire. However, no information on correlation to passby or on technique development was discussed. The same researcher also used this microphone position description for other investigations of vibration related noise mechanisms[9]. In 1984, another study with yet another BTT microphone position also appeared[10]. In this case, the microphone was positioned 0.56m above the ground and 0.24m behind the tire, however, no passby to onboard data comparison was provided.

In an on-going series of the studies, Reiter along with Eberhardt [11,12] continued to use the BTT microphone position of 200mm above the road surface and 150mm from the closest point of the tire. In Ref. 11, data is given to allow plotting of passby levels versus onboard SPL (Figure 1). These data indicate that there is some relation between the two sets of levels. Although there is considerable scatter, typically 3 to 4 dB, a linear regression of the results yields an R^2 value of 0.7. The slope of the regression deviates considerably from a one-to-one, best fit relationship. For the one-to-one fit, the standard deviation of the data points from the fit is 2.3 dB. In the second reference (Ref. 12), Eberhardt discusses the relationship between the on-broad and passby data in more detail, particularly in terms of near and far sound field effects. He states that the far field can be considered starting at 4 times the largest source dimension and at least $\lambda/4$ away from any bounding surface, which in this case is either the tire or road. From his vibration measurement and sound radiation modeling work on truck tires, he states that characteristic source dimension is about the tire width or 8 in. (200mm). As a result, he concluded that the 200mm by 150mm microphone position at the rear of the tire is in the near field. He further concludes that a distance of 1m or more would be considered the far field.

In summary, the BTT SPL approach was commonly employed in early tire-pavement noise measurement at the source. This approach was not standardized to any degree and various researchers used different microphone locations. Although there is some evidence the onboard levels did show the similar trends to passby levels, rigorous correlation was not demonstrated. The approach seems to have fallen from favor by the 1980's which may have resulted improved approaches developed in that time frame and other research that indicated that the noise generated at the forward side of the tire is similar in level to that from the rear of the tire.

SPL Other

In the time period from about 1980 to now, a variety of other microphone positions have been used for onboard SPL measurements. Some of these are somewhat similar to those which finally ended up in the draft ISO 11819-2, and some are not. In this subsection, the chronological progression of these measurements is reviewed. For reference to the ISO 11819-2 draft standard, the primary and secondary microphone locations are provide in Figure 2.

Several studies were found that reported in the 1980's. In an investigation of pavement texture effects reported in 1980[13], Osman and May used a single microphone positioned 150mm above the pavement, 150 mm out from the tire, and 220mm behind the axle. Using CPX convention, this produced an angle of 145° to the direction of travel. The microphone was supported by a fixture which was in turn attached to the body of the test car. Photos indicate that microphone was fitted with a nose cone and that no windscreen screen was used. A-weighting was used to "diminish wind effects which occur primarily in the 30-300 Hz frequency region". The results concentrated on 500 to 2000 Hz range and no data to support use of method was provided. In the development of an extensive tire noise data base of 130 sets of tires on both AC and PCC pavements, Ungar and Bronsdon[14] used a single microphone located 300mm from the tire on the wheel axis (90° from the direction of travel). This microphone was fitted with a windscreen and shielded

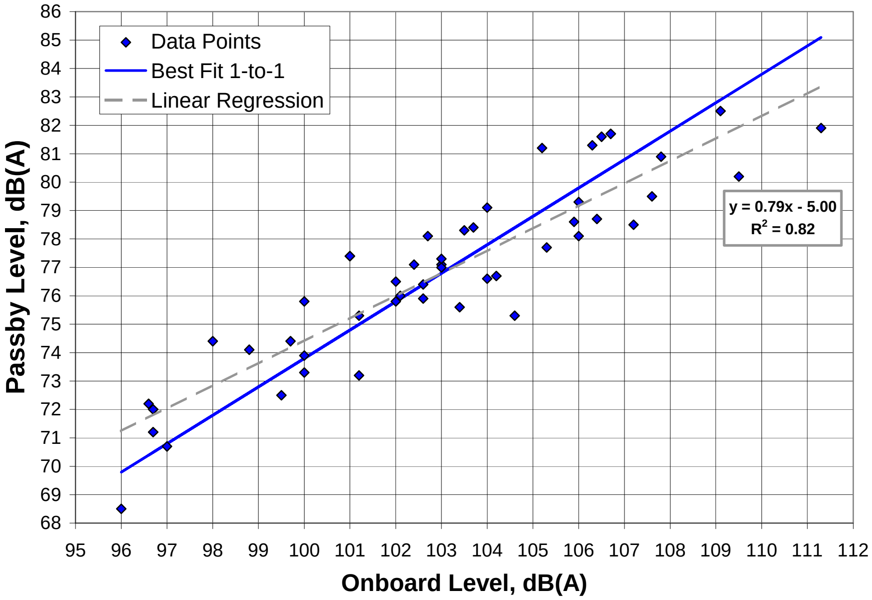


Figure 1: Comparison of on-board sound pressure level measured with the Behind-the-Tire method and passby levels for truck tires (11)

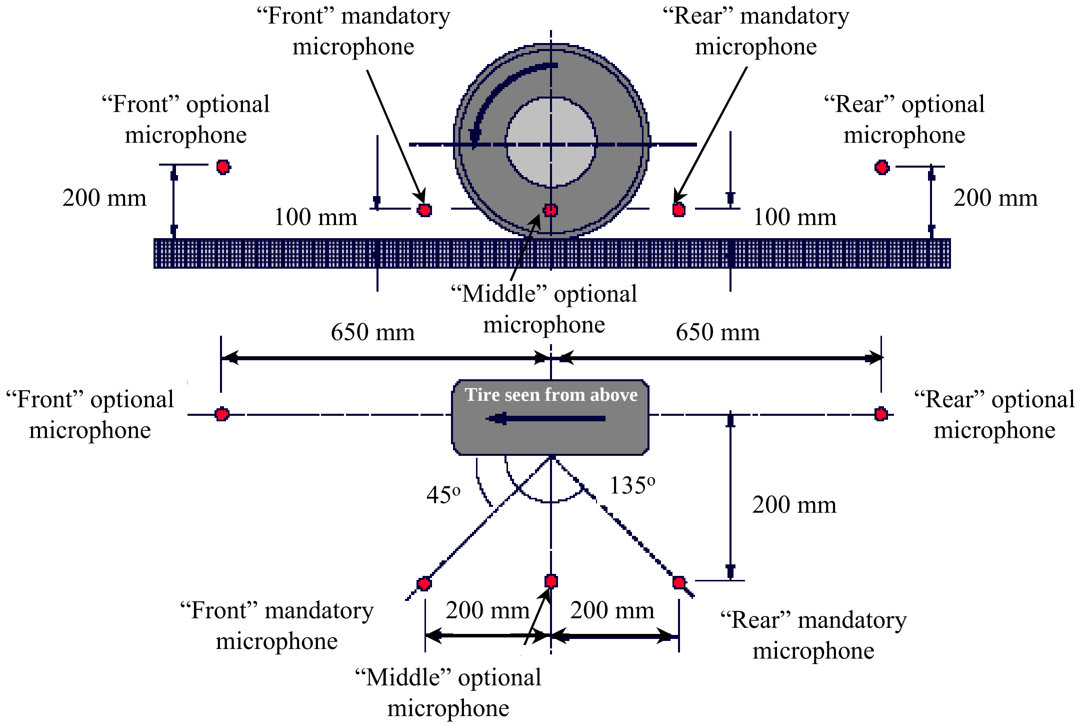


Figure 2: Mandatory and optional microphone locations for the ISO CPX draft standard procedure (2)

from wind noise and turbulence by a "protective enclosure" attached to the front fender of the test vehicle. Unfortunately, no photographs of this device or data documenting its performance were provided. In a third study, passenger car tire noise mechanisms were investigated using an onboard technique with one microphone in front of and one behind the tire. They were 120mm above the ground and 70mm from the "contour of the tyre". They found that a simple windscreen worked better than a noise cone to reduce wind noise effects and SPL levels down to about 250 Hz are reported for test speeds from 60 to 75 km/h. No supporting data for the approach was given and there was no passby data.

At the International Tire/Road Noise Conference in 1990, several papers could be considered as precursors to the ISO CPX method. In one study, a trailer was used to measure SPL levels at two locations, one to the rear of the tire and one to the side[15]. Specific dimensions not given, but the author does say measuring conditions had been recently standardized. In a second trailer-based study, three microphones locations were used with one each to the front and rear of the tire, and one directly to the side[16]. The side microphone location was about twice as far away as the ones to the front and rear although no specific dimensions were given. The paper reports an average of all three microphones with no apparent factors for differences in distance. The study also included some comparison between onboard trailer levels and coastby levels. These overall A-weighted levels indicate a consistent relationship between the onboard and passby levels, with scatter of about 2 to 4 dB when all test speeds and tires are considered together. The author also noted that in testing five tires, the rating of road surfaces "is to a great extent independent of the test tire". In a third study, a light chassis van/truck was modified by removing body panels around rear drive axle to expose the test tire and allow testing with or without torque applied to the drive wheels. The flow-exposed microphones were fitted with windscreens and located at four positions: to the front, rear, 45° and 135°[17]. All positions were 500mm from the center of the contact patch and 125mm above the pavement. Coastby levels were also measured at 7.5m and compared to the onboard SPL for 9 tires on 4 pavements. Averaging the four onboard SPL measurements and plotting these data against each other produced a nearly one-to-one relation for the entire span of the data with individual data points being typically ± 2 dB about such a line (Figure 3). The author further concluded:

- the best correlation to coastby was found with the onboard microphone at 45°
- the rear microphone was least correlated to the coastby data and was equal to or greater than the 45° and 135° microphones (0 to 2.0 dB)
- the front microphone was correlated to the coastby almost as well as the 45° and produced the highest level of all four microphone locations
- pavement differences are not dependent on the tires used
- correlation between near & far field exhibits pavement specific differences with porous pavements being about 3 dB quieter than non-porous for the same, normalized source level

In the 1990's, new studies reported using other onboard SPL measurement approaches. In one study, Chalupnik used a trailer towed by a full-sized van with a long tongue to evaluate onboard data to test trailer passbys[18]. Two onboard microphone positions were

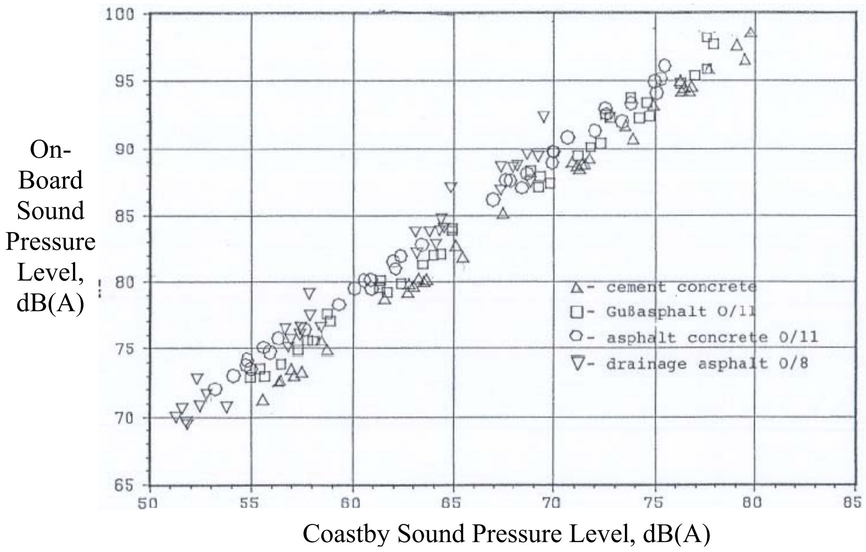


Figure 3: Comparison of on-board tire-pavement noise sound pressure level measured on a trailer to coastby levels (15)

used, one 90° to the direction of travel at a distance of 200mm out from the edge of the tire contact patch at angle of 45° above the road surface. The "European style" location was 135° to the direction of travel. The microphones were protected by non-commercial windscreens fabricated from welding rod with a nylon stocking (panty hose) stretched over them. For the trailer passby measurements, a noise shield was attached to the microphone to block the noise from the tow vehicle at the time of closest approach of the trailer. The testing was done on six pavements; new and old samples of AC, porous AC, and PCC. The resultant data was processed into 1/3 octave band differences of the onboard and passby levels. For the 90°-microphone position, the spread in the differences was large, 8 to 10 dB for individual 1/3 octave bands. For the 135° microphone, the differences had smaller scatter, more 5 to 6 dB. The author concluded neither position completely recorded the tire noise as measured on the roadside.

In 1996, Oshino and Tachibana reported on a study they performed to investigate the effects of pavement texture on tire noise[19]. Onboard SPL measurements were made on both a passenger car and medium duty truck. The microphone positions are not well documented, however all were 100mm above the pavement and 100mm away from the tire. Different positions were used for different types of tires. For a passenger car tires, the microphone was in the "leading area", while for lug type truck tires, it was in the "contact area", and for rib type truck tires, it was in the "trailing area". The microphones were suspended from the vehicle underbody, no details on wind noise effects or precautions were given. In 2001, the authors report additional measurements where the onboard microphones are now the ISO CPX primary locations, 200mm from the tire sidewall, 200mm forward and aft of the axle centerline, and 100mm above the pavement[20]. They also add a third position, which is under the floor of the car and in the same relative position as rear CPX microphone. The overall A-weighted levels from this underbody location are plotted against the average of levels of the two CPX positions. A one-to-one relationship is demonstrated with scatter of less than 1 dB. This underbody position is used in further research into surface roughness effects, however, there is no data given comparing the underbody levels to passby levels[21].

In 2000, McNerney, et al reported on research into the effect of pavement on tire-pavement noise[22]. Onboard SPL measurements were made using an open trailer and two microphone locations. One microphone position was directly behind the tire, 100mm from the tire and 141mm above the ground. The second microphone was at 45° from the rear outside corner of the tire contact patch (135° from the direction of travel) in both the vertical and in plane directions at a distance of 200mm form the corner. This resulted in the microphone being 141mm above the ground, 100mm out from the corner of the contact patch and 100mm behind the corner. The microphones had both nose cones and windscreens. The trailer was towed by a minivan with the same test tires and passby measurements were made with the complete assembly in a cruise mode. The maximum noise level was measured when the vehicle was opposite the microphones at 7.5m from the centerline of the lane of vehicle travel. The authors present both onboard and passby data which can be cross-plotted to examine the relationship the two onboard microphones as well as their relationship to the passby measurements. Figures 4 and 5, the individual onboard microphone is plotted vs. the passby levels. These give r^2 values of 0.58 for 180° microphone regression and 0.52 for 135°. The slope of the regression lines is less than the best fit 1-to-1 in both cases. Using an energy average of the two onboard microphones does not improve this relationship (Figure 6). The correlation of the two onboard microphones is much better with an r^2 value of 0.93 and a slope only slightly greater than 1-to-1 (Figure 7). The average of offset between onboard locations is 2.3 dB with the 180° position being higher. As would be expected from the results of Figures 4 through 6, the rank ordering of pavements is different for passby and the two onboard microphone positions. The authors believe correlation could be improved by improving the microphone holder, the trailer being farther from the tow vehicle, reducing wind noise from the trailer, and shielding the test tire from the non-test tire on the trailer. All of results are for one tire and a test speed of 100 km/h. The authors also note that knowledge of the sound absorption performance of the pavement may explain some of the differences noted between the onboard and passby comparisons.

In a very recent study of tire noise as it relates to exterior vehicle emissions, Chuang, et al. used a single onboard microphone position that was 0.25m above the ground and 0.5m away from the tire sidewall centered on the contact patch (90º from the direction of travel)[23]. The microphone was fitted with a conventional foam windscreen. As part of this research, the relationship between onboard, passby (7.5m from centerline of vehicle travel), and road-wheel measurements of tire-pavement was examined. In comparing onboard to passby, the authors report quite good correlation as measured for four test tires, at four test speeds on the same test vehicle and pavement (Figure 8). The linear regression of data produces a slope of very nearly one with an r^2 value of 0.99. The standard deviation from a best 1-to-1 fit of the data points is 0.5 dB. However, in comparing the on-road results to the in-lab, road-wheel data taken without a test vehicle present, the in-lab levels were lower and less consistent. The authors speculate that the higher on-road levels may be due to wind influence around the body, the tire, and/or the

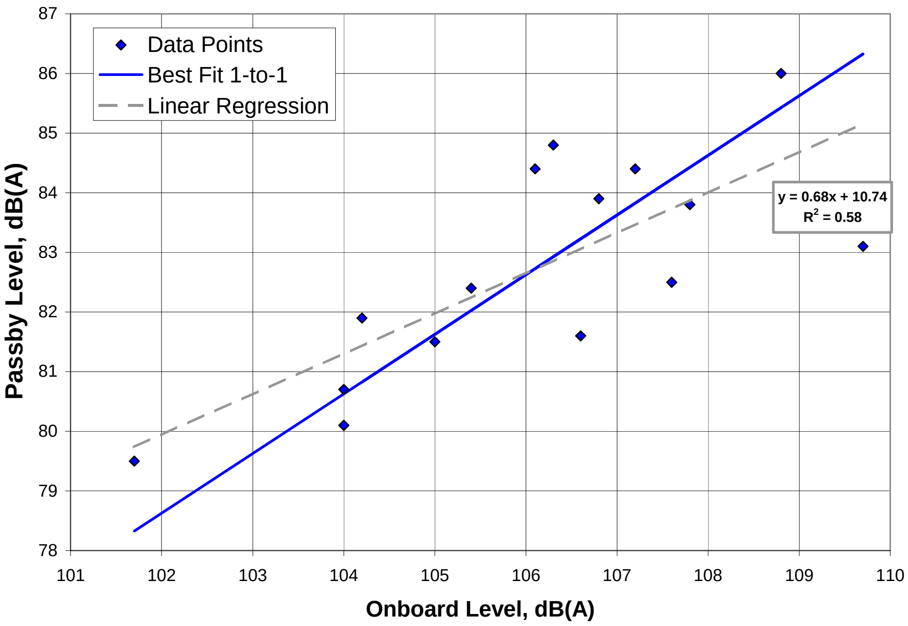


Figure 4: Comparison of on-board tire-pavement noise sound pressure level measured on a trailer to coastby levels for a trailer microphone position at 180° to the direction of travel (22)

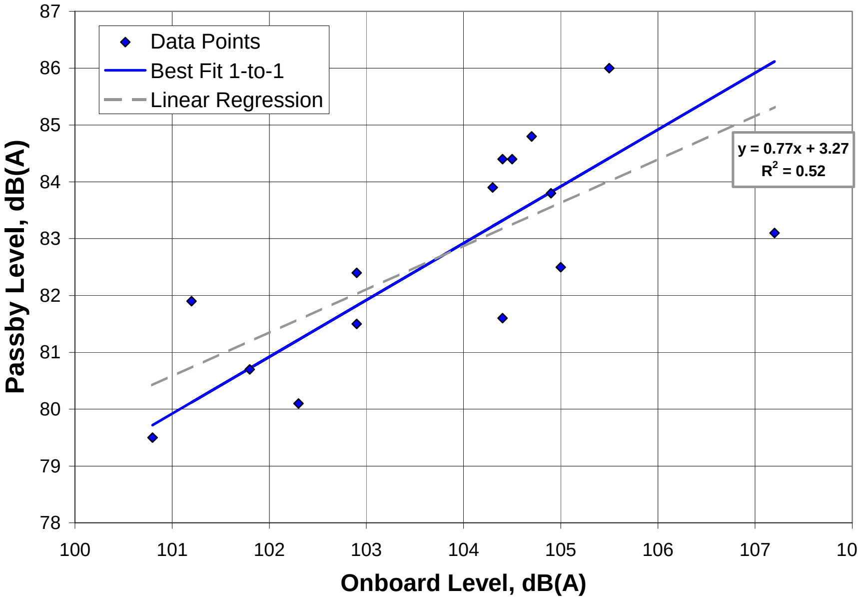


Figure 5: Comparison of on-board tire-pavement noise sound pressure level measured on a trailer to coastby levels for a trailer microphone position at 135° to the direction of travel (22)

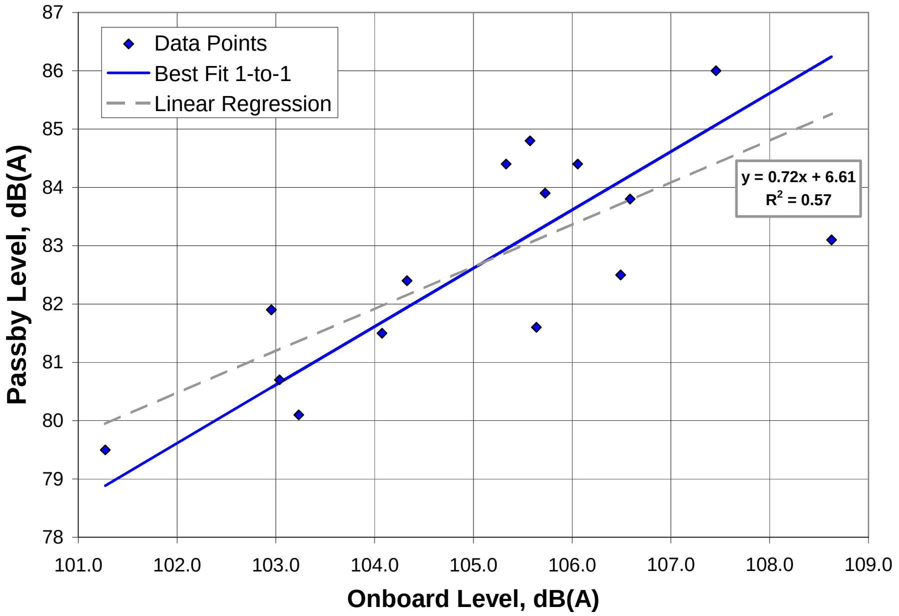


Figure 6: Comparison of on-board tire-pavement noise sound pressure level measured on a trailer to coastby levels for the average of trailer microphone positions at 180° and 135° to the direction of travel (22)

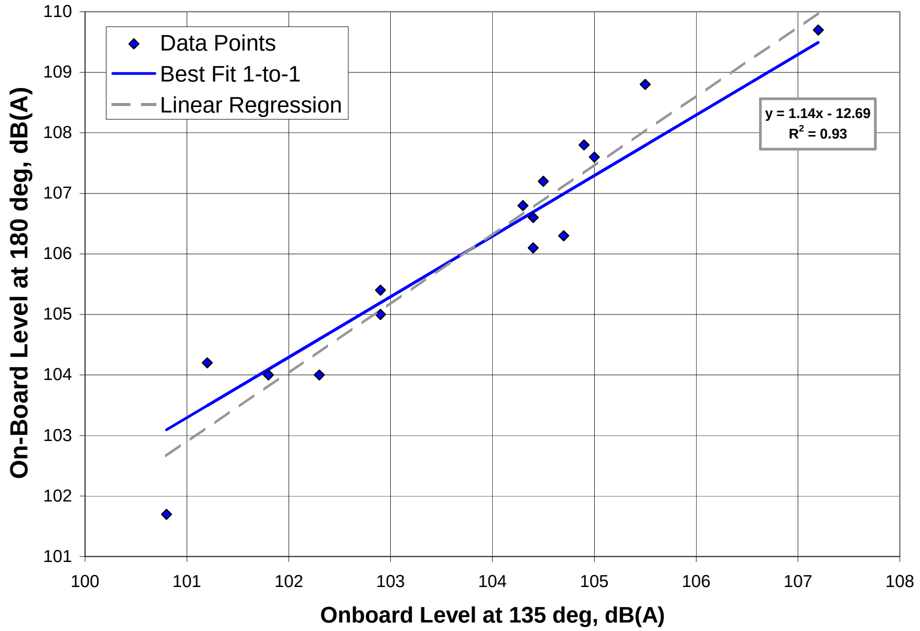


Figure 7: Comparison of on-board tire-pavement noise sound pressure level measured on a trailer for microphone positions at 180° and 135° to the direction of travel (22)

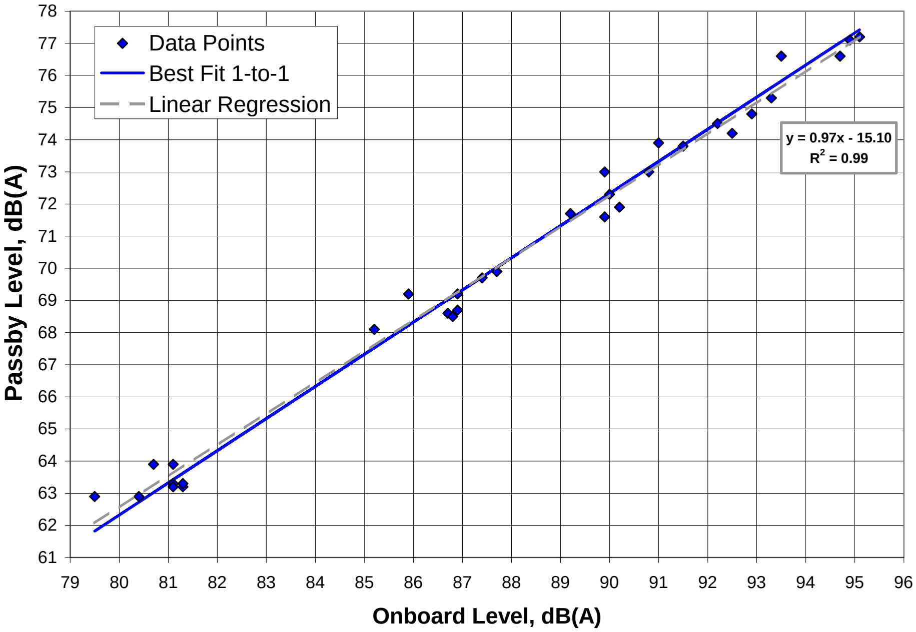


Figure 8: Comparison of coastby levels and on-board tire-pavement noise sound pressure level measured on a test vehicle for a microphone position at 90° to the direction of travel, 0.5m from the tire (23)

microphone and its fixture. An interesting side note to this study is that after to attempting to control variables as much as possible, the authors found very little evidence that tire noise level is a strong function of tire width

In summary, a number of "other" microphone positions have been used for onboard SPL measures of tire-pavement noise. In most cases, the work has been self-contained with no real emphasis for developing standardized tests. Both on-vehicle and on-trailer approaches have been documented. In some instances, correlation to passby measurements was been attempted with varying degrees of success. The best correlation to passby was for a limited study in which a microphone location 500mm (19.7 in.) away from the plane of sidewall was used with all measurements taken on a test track with one pavement. Positioning a microphone this far away from the side of a vehicle would not be practical for in-situ highway measurement of tire-pavement noise. Other studies that included multiple pavement types tended to not to give very good correlation between onboard and passby data.

CPX – ISO Close Proximity

As pointed out in the previous sections, early tire-pavement noise measurements using onboard SPL techniques were made with a variety of microphone numbers and locations. In 1980's interest in standardizing onboard SPL measurement procedures began to emerge, particularly in Europe. Through the early 1990's, a variety of microphone locations were still in use and being considered by various researchers. In the mid 1990's, standardization of the CPX method began when this topic was taken up by ISO

Working Group 33 which is concerned with measuring the effect of pavement on traffic noise emission. By 1997, a first draft of a CPX procedure was produced followed by a second draft in 2000. Since this time frame, numerous European studies have used the draft procedure to investigate tire-pavement noise and the influence of pavements. There has also been a considerable amount of effort spent on developing measurement validation techniques and correlating the onboard measurements to statistical and controlled vehicle passbys and, more recently, to OBSI measurements.

Work Prior to the ISO Draft CPX Standard: Much of the procedure that developed into the current ISO CPX Draft Standard follows closely from a paper published in 1986 by Sandberg and Ejsmont[24]. At that time, an hoc group within the U.N. Economic Commission for Europe chaired by Sandberg had chosen a microphone position which is identical to the 135º that is now in the draft CPX standard. A position at 45º, also identical to that in the CPX, was also used in the testing along with one at 90º. This paper also describes methods for validating the performance of a trailer used to perform the CPX measurements. These test for two different concerns, background noise in the trailer enclosure and reflections within it. For reflections, these are later identified in the draft ISO standard as the "Removed Reflections Method" and the "Enclosure Fitting Method"[2]. For background noise, these are identified as the "Lifted/removed Tyre" and the "Optimum Tyre/road Combination" methods[2]. Based on road-wheel tests, the authors conclude that the 135º microphone position, rather than 90º, is the best when high correlation with coastby level (CB) and traffic noise is desired. The authors present some comparisons between overall A-weighted CPX and CB measurements and conclude that rank ordering is identical by either method if a 1 dB tolerance is allowed. They also found a 20 dB offset between the CPX and CB results and suggest an averaging time of 4 seconds to maintain run-to-run variation at less than 0.5 dB. As an interesting side note, the authors recommend against using the newly emerging sound intensity method[25] saying, "Before it (sound intensity) is used in this particular application, it should be shown that the increased complexity, cost, and risk of mistakes are justified when weighed against a possibly increased level of accuracy".

After the 1986 Sandberg and Ejsmont paper, other research in the earlier 1990s was still investigating optimum microphone positions for the "trailer" method. As cited in the previous section, Steven[17] was reporting the best correlation to passby levels with a microphone position at 45º to the direction of travel for measurements taken on actual road surfaces. In another study also reported at the International Tire/Road Noise Conference of 1990, Ronneberger and Preuss[26] were reporting the best correlation to passby levels using two microphone positions, one at 90º to the direction of travel and one at 22.5º. In this case, the microphones were 80mm above the pavement and 500mm from the center of the contact patch. This conclusion was made based on measurements were taken at every 22.5º angular increment around the test tire and included 20 tires, 2 pavement surfaces and 3 road-wheel surfaces.

In 1993, Sandberg and Ejsmont[27] provided an update on tire-pavement noise methods following on from their 1986 paper. At this time, there were several conflicting studies regarding which of many CPX-like microphone position would correlate well with coastby levels. The authors still advocated the 135º position (only) as is now one of the primary positions in the CPX procedure. However, as noted earlier[26], data was also available that indicated microphone locations more toward the front of the tire may be useful in capturing the tire noise as it relates to passby levels. In addition to microphone placement, the paper brings out several points of note. It cites findings that loading and tire pressure are not an important variables tire noise generation, a finding that has been supported by earlier studies reported in the United States[28,29,30]. The paper further contends that wheel width is important as is tire temperature, particularly as it relates to tire rubber hardness. It cites wind-induced noise as the largest background noise issue for trailer measurements without enclosures and even with enclosures, it limits the lowest, usable frequencies. The authors also present data showing non-constant relationships between pass-by and near field trailer levels indicating that differences between them depend on pavement type. In particular, these results suggest that porous pavements are not fully accounted for relative to their far field effect.

Development of ISO Draft CPX Standard: By 1998, preliminary microphone locations for the CPX method had been adopted by ISO WG 33 as described in the 1997 version of the draft standard[31]. These were at 45 and 135 to direction of travel, however, the preferred distance from the tire was 400mm. A distance of 200mm could also be used, but if it was, 4 dB were to be added to the measured value. Since it was not considered economical or practical to apply the method to heavy-duty vehicles, one of the specified light vehicle test tires was chosen to replicate the behavior of heavy-duty vehicles on various pavements. Altogether, four different tires were selected as the test tires for the standard labeled A through D with the winter tire, D, intended to replicate a heavy duty vehicle tire.

To resolve some of issues considered to under development in the 1997 draft of the CPX standard, an extensive comparative test program was carried out in 1998[32]. This was cooperative testing which included eight CPX measurement devices, six trailers and two vehicle-based systems. The microphone positions included the "inner" positions 45º and 135º from the direction of travel, 200mm from the tire sidewall, and 100mm above the pavement and "outer" positions, 400mm from the sidewall, 200mm above the pavement. Different trailers used either one of these two pairs of microphone locations, and one used both. One of the trailers only used an "extreme" outer position with microphones 700mm away from the tire sidewall. Another trailer measured levels on the left side of the tire as well as the right. These two permutations ended up giving a total of ten different measurement sets. Four tires were included in the test, tires A, B, and C according to the 1997 draft of the CPX standard and another winter tire to substitute for tire D. The testing included 13 pavements at the three speeds given in the 1997 draft, 50, 80, and 110 km/h (31, 50, and 68 mph). In comparing the results across vehicles, it was found that even with the results normalized by 4dB to account for distance between the inner and outer positions, there was no common value for differences between these positions. The difference between trailer/vehicles for an average of 3 tires (A, B, C) displayed a range of about 3 to 4 dB or larger even they rank ordered pavement all fairly consistently. The authors attributed much of these differences to variance in microphone position and acoustical properties of the vehicle/trailer enclosures. The scatter between vehicle/trailer was found to become greater for quieter pavements. The report also provides comparison between the CPX results and statistical passby (SPB) data both in terms of overall level comparison and 1/3 octave band (OB) comparisons. The spectral comparisons typically show higher relative levels for CPX data in the frequencies from about 800 to 2000 Hz than for the car and truck SBP data. The variation in shape ranged from about 3 dB to over 5dB depending on tire. Below 630 Hz, the SPB levels for the trucks were typically about 5 dB higher than the CPX levels. Unfortunately, controlled passbys were not included in the testing which may have helped separate measurement differences from tire differences.

By 2000, the ISO WG33 produced a revised draft standard for the CPX method[2]. At this time, two mandatory microphone positions had been establish at the inner locations used in the 1998 comparative study, that is, one at 45º and one at 135º, 200mm from the undeflected tire side wall, 200mm from the centerline of the test tire, and 100mm above the ground. Three optional microphone positions were also specified at angles of 0º, 90º, and 180º. The microphones at the front and rear of the tire were specified at a distance of 650mm from the centerline of the tire at a height of 200mm. The microphone at 90º was 200mm from the sidewall and 100mm above the ground. Performance specifications for the test vehicle (or trailer) were given in three categories; sound reflections, background noise, and sensitivity to other traffic. Alternative methods for addressing each were given. It was also noted that checking the performance requirements of the enclosure was cited as one of the most difficult issues addressed in the standard. Four different, specific test tires are specified in the draft and either two (A and D) or all four (A through D) are used depending on whether the test is "Survey" or "Investigatory", respectively. Reference test speeds are set at 50, 80, and 110 km/h. Specifications are given for tire load and inflation pressure and the tire are required to be "normal" operating temperature. The draft standard provides for both speed correction and air temperature correction normalized to 20º C. In terms of reporting the data, the draft standard discusses three types of averaging. For a single identified pavement segment, the sound pressure signals are to be averaged on an "equal energy" basis, that is, a "linear" average of the root mean-squared (rms) pressure over the corresponding time period. An alternative method using exponential averaging is also provided. For each segment, the sound pressure level from the mandatory 45º and 135º microphones are to averaged together arithmetically, that is, a simple average of the numerical values of the levels. It is stated that this preferred over an "energy average", that is, an average of the root mean-squared (rms) pressure, because it reduces the effect of transient disturbances. For averaging the results of multiple samples of the same or consecutive pavement sections, the standard also calls for arithmetic averaging thereby treating segment as different samples of the same noise.

Application and Ongoing Development of the ISO Draft CPX Standard: From the earlier 2000s through now, many studies have been reported using data obtained following the ISO CPX draft standard. A number of these give further insight into the technique in the areas of design and validation of test apparatus, correlation to other tire/pavement noise measurement methods, and other applications of the approach. References in each of these areas are reviewed in this subsection.

Design and Validation of Test Apparatus: Perhaps because of the acoustic variance in the performance of different CPX vehicle/trailers noted in the 1998 comparative study, several references on certification methods have appeared since 2000. In 2001, Ejsmont provided an updated discussion of methods to perform these evaluations[33] following on from earlier work[24,27] and the methods described in the draft standard[2]. The author notes that direct measurement of background noise is very difficult to nearly impossible. He does, however, review some methods for accomplishing this depending on the vehicle/trailer design and available facilities. He also expresses concern over bearing and other suspension related sources that will not be detected in the "lifted tire principle" and suggests special wheel hub constructions to eliminate bearing noise. For addressing reflections, he suggests measurements with and without the enclosure as tested on a road-wheel.

In 2004, an example of CPX qualification is reported in the validation of a third generation test trailer[34]. This investigation compares the third and second generation designs using road-wheel tests and absorption/reflection performance test with a dummy tire loudspeaker source. The main difference between the two trailer designs is that third generation enclosure is larger (the single test tire is mounted in the middle of the trailer) and improved sound absorbing liner. The speaker tests comparing data in the trailer to that outside in a free field indicate attenuation and amplification in the Gen 2 design of about 2.3 dB while the Gen 3 design is flat to within 0.6 dB between 400 and 4000 Hz. The road-wheel data show that the older trailer is typically about 1 dB louder. For comparing data between the two trailers, it is concluded that 1 dB should be subtracted from the Gen 2 trailer to make it comparable to the new one. The overall conclusion is that both the increased size and improved absorptive lining are important in achieving good performance.

Under the Sustainable Road Surfaces for Traffic Noise Control (SILVIA) project in Europe, a monograph was published in 2005 that provides information on various approaches to the implementing the ISO CPX procedure and validation testing done for each[35]. Included are reviews of five CPX measuring devices, 3 trailers and 2 vehicles. This document elaborates further on methods of validating these devices such as the use of road wheels and tire loudspeaker simulators and others mentioned in the draft standard. It particularly details the use of tire simulators and provides data on all systems for free field versus enclosure (or on car) comparisons. It also examines the differences between different tire simulators that each research team uses. For two of these, differences in the influence of reflections within the same enclosure varied somewhat with a range of a few tenths of a dB to over 2 dB in the frequency range from 315 to 4000 Hz. The influence of reflections within various enclosures also ranged few tenths of a dB to over 2 dB. Depending on the enclosure and the tire simulator used, the more sensitive frequencies for reflections were in the lower range, the 315 and 400 Hz one-third octave bands, and the mid range, 800 and 1000 Hz. This reference does not describe or report any validation testing comparing the tire-pavement noise source measurements to either statistical or controlled passby levels.

One of the more elaborate CPX vehicles is that designed and used by the Transport Research Laboratory (TRL) in the United Kingdom. This is a medium duty truck-based CPX test vehicle referred as TRITON[36]. Given the dimensions of the truck, it was possible to install a sophisticated test tire suspension system which includes hydraulics to raise, lower, and load the test tire. Special sound absorbing panels could also be installed to provide improved low frequency performance down to 250 Hz. Using simulated point sources positioned at the leading and trailing edges of the tire contact patch, the influence of reflections within the enclosure was found to be minimal, less than 1 dB from 315 to 4000 Hz.

On the simpler end of the spectrum, several researchers have reported making CPX measurements alongside a light vehicle with the microphones suspended to the outside of the tire and exposed to airflow. In France, the Laboratoire Central des Ponts et Chaussées (LCPC) developed a mini van based system which was developed in a wind tunnel to minimize wind-induced noise on the microphones[37,35]. The microphones are positioned at the primary CPX microphone locations opposite the right rear tire as well as one 800mm from the axle directly behind the tire. The microphone supports are airfoil shaped and extend out horizontally from the underbody. Even though there is no enclosure for this approach, measurements with a tire simulator with the vehicle present and not indicate an influence of reflections of about 1 to 2 dB in the frequency range from 315 to 4000[35]. In somewhat different approach, Storeheier used microphones suspended with vertical supports that were attached to the vehicle body above the right rear tire opening[38]. Unfortunately in this reference no further details of influence or lack of influence of reflections and wind-induced noise are provided.

Also under the SILVIA project, round robin testing of CPX trailers/vehicles was conducted in Europe in 2003[39]. This included four CPX trailers and the vehicle mounted system of LCPC. Measurements were made on 29 pavements at speeds of 50 and 80 km/h. The range and standard deviation of the measurements on each surface was reported for both speeds. At 50 km/h, the range varied between 0.9 and 2.2 dB while the standard deviation was from 0.4 to 1.0. At 80 km/h, the range was 0.8 to 2.8 dB with standard deviations of 0.4 to 1.3 dB.

In recent years, two research activities in the United States began acquiring CPX data using trailers and the draft standard methodology. The first of these was the Arizona Department of Transportation (ADOT) that starting using the trailer in 2002[40]. This was closely followed by project initiated at the Center for Asphalt Technology (NCAT) using a “sister” trailer to that of ADOT[41]. Although some validation testing has been completed on at least the ADOT trailer, the performance of neither trailer is documented in the literature. In November of 2003 these two trailers met for comparison testing. Measurements were conducted on four different pavement types for three different tires. The results of this testing is shown in Fig. 8. These data indicate the relationship between the two sets of measurements is very nearly 1-to-1. The standard deviation of the data fall into to range noted for the SILVIA round robin test at 0.8 dB.

Correlation between CPX and other Tire-Pavement Noise Measurement Methods: There have been several studies that have reported on the comparison of CPX measurements to other types of the tire-pavement noise measurement. In comparison to wayside measurements, most of the work has concentrated on comparison to Statistical Pass-by Measurements following the ISO 11819-1 Standard[42]. As part of the work done in 1998 as a validation of the CPX method addresses this in some detail[32] as discussed in the subsection, "Development of the ISO Draft CPX Standard". Other references have also addressed comparison controlled pass-by tests as well as sound intensity measurements to CPX results.

In a recent study comparing SPB & CPX measurements, measurements were made at seventeen different including porous and nonporous AC pavements and PCC pavements[43]. The SPB measurements were conducted on both cars and trucks and CPX measurements using all four test tires identified in the CPX draft standard. For the CPX measurements, the primary microphone positions at 45° and 135° were used as well as the optional "outer" positions to the front and rear of the tire, 650mm away and 200mm above the pavement. In regressing the SPB and CPX indices for 110 and 80 km/h, R^2 values of 0.79 and 0.73 were found for the investigatory method, respectively and 0.71 for survey method at both speeds. The standard errors ranged from 1.3 to 1.5 dB. The results were sorted into porous and non-porous categories and better correlation for porous pavements using the outer positions. For the non-porous using the primary positions provided better correlation. Based on this and other work, authors recommend the use of the outer microphone positions and call for further investigation. They also suggest that it may be necessary to use just one tire (tire B in the draft standard) to predict SPB data.

A large study comparing CPX data to controlled pass-by measurements was completed by Abbott and Watts and reported in 2003[44]. This investigation included measurement of 29 cars, 4 vans, and 8 trucks on 7 different pavements at three test speeds, 80, 100, and 110 km/h. The CPX measurements were made TRL TRITON vehicle described previously. In this reporting of the results, the authors found that ISO 10844 test track pavement surface did not represent tire noise performance well for other pavements. They also examined the parameters of tread width, tire depth, load and wheel diameter for car and truck tires. In second paper from this study, the authors examined the relationship between coast-by and CPX noise for passenger car tires[45]. Plotting the CPX levels versus the coast-by data produced nearly a 1-to-1 relationship between the two methods with an R^2 of 0.89. Typical maximum deviations were about 2 dB with average deviations of about 1dB. The offset between CPX levels using the primary microphone locations and coast-by data was about 20 dB which is identical to that reported by Sandberg and Ejsmont in 1986[24]. In addition to the primary CPX microphone positions, the outer position in front and behind the tire were used as well as a microphone at 90º, 200mm from the tire sidewall, 100mm above the pavement. Analysis of CPX microphone levels versus coastby levels indicated the highest R^2 were obtained for the microphone positions in the CPX primary locations, followed by the one at 90º, and then ones directly behind and in front of the tire. No spectral data are provided comparing the CPX data to that of the coast-bys.

Other comparisons between controlled passbys and CPX levels have been reported, but not in such detail. Of particular interest from these is the level offset between the two types of data. Using the LCPC exposed CPX microphone approach, Anfosso-Lèdèe reported offsets of 22.5 dB for a dense graded AC pavement and 23.3 dB for a porous AC[37]. As noted above, Sandberg and Ejsmont[24] and Abbott and Watt[45] have both reported an average 20 dB offset for a wide range of pavements. On the other hand, Hanson reports an offset of 23 dB between CPX measurements made with the NCAT trailer and controlled passby levels[46].

Comparisons between CPX and OBSI measurements have also been reported from data collected on the ADOT trailer. An initial comparison provided data from AC pavements from both California and Arizona[47] using a single SI probe design following the approach provided in the General Motors test procedure[3]. These results displayed about a 3 dB offset between the levels with OBSI being higher. When fit to a 1-to-1 line, the average deviation from the line was 0.7 dB. In later testing, simultaneous CPX and OBSI measurements were at both CPX microphone positions and both OBSI probe positions on 54 rubberized AC and PCC pavements using one tire at a speed of 97 km/h[48]. This more complete data set gave a 3.3 dB offset between the measures. These data were also used to examine the coherence between the 45º and 135º primary CPX microphone positions. This measure would indicate the degree to which noise from the front of the tire is related to that from the rear. Over the frequency range from 400 to 4000 Hz, the coherence typically ranged between 0 and 0.5. At 1000 Hz, the coherence reached 0.7, corresponding to the passage frequency of the uniformly transversely tined PCC under test. Generally, these data indicated very little relationship between the front and rear microphone positions and further substantiates the need for measuring at both locations.

Other Applications of the CPX Approach: The current generation of the CPX draft standard only applies to passenger car tires. The test tire D is intended to at least partially replicate the behavior of truck tires on different pavements. A CPX-like approach has been recently applied in an extensive study of truck tire noise and pavement[49,50]. It used 15 truck tires, 5 each for steering axle group, drive axle group, and trailer group. The pavements were some of those of the located at Sperenberg test track in Germany and included 21 surfaces, 12 AC and 9 PCC. The measurements included both coastby and onboard sound pressure level, however most of the analysis used the coastby results. The onboard measurements were made on the drive wheels of a (truck) tractor with shielding around the tire removed. CPX levels. Four test speed ranges were used spanning 45 to 85 km/h. The microphone locations were significantly different than those specified in the CPX draft standard. Seven microphones were used, all at 0.25m above the ground (compared to 0.1m in the draft standard). They were positioned radial out from the center of the tire contact patch at a distance of 1.0 m (compared to 0.2m in the draft standard. One microphone was placed directly in front of the tire and one directly behind. Five microphones were then positioned to the side of tire, one on the axle centerline, two at ±45° from the centerline and two at ±67.5° from the centerline. The microphone at the front of the tire was mounted directly below a gas tank which was treated with absorbing material, however the authors question using that data. The microphones were shielded with windscreens, but otherwise exposed to airflow. The analysis of the onboard data was done using an average of the 2 microphones at ±45° from the centerline axle (the same angle used for the primary microphones of the CPX draft standard) and for a test speed of 70 km/h. Directivity analysis is also provided indicating that the levels to side of the tires are slightly lower (~ 1 dB) than the average, except for 2 non-porous pavement where the -45° is about 3 dB lower. The maximum levels occur at +67.5° (to the front of the tire). The authors did not investigate any relationships between the coastby and onboard data, however, it is noted that differences between the data span from 9.3 to 17.6 dB. Unfortunately, the authors do not provide any discussion of the rationale for the 1m distance to the tire relative to the standard CPX locations. Also, there appears to be no method of comparing onboard truck tire levels to those of passenger car tires measured under the CPX draft standard.

CPX Summary: The sound pressure level measurement method as defined in the ISO CPX draft standard has followed an extensive progression from early SPL measurements and trailer methods to a well-documented procedure of measuring tire-pavement noise at the source. At this point, it is virtually an “off-the-shelf” technology that relies on uncomplicated acoustic measurements. It has been extensively used for measuring the in-situ noise performance of different roadway pavements. From the investigations to date, it appears that acceptable levels of correlation can exist or could be further developed to relate passby and CPX levels in the case of passenger cars. One of the areas of on-going concern has been the validation of trailers and other measurement vehicles as a large variety of these approaches are permitted under the draft standard. This could be addressed by deciding on a single trailer/vehicle design that is optimized and validated using the techniques advocated in the literature and draft standard. This should overcome the issue of varying offsets between CPX and controlled passby levels that currently are reported as being 20 to 23 dB even when pavement porosity issues are excluded. Accommodating truck tires within the CPX approach to produce compare source levels for truck and cars remains an open issue and would require further development.

SI – Sound Intensity Level Measurement

At about the same time that interest in Europe was developing on using trailer methods to measure tire-pavement noise SPL at the source, research was underway in the US to investigate the use of the newly pioneered sound intensity measurement technology[51] to tire-pavement noise research. Unlike the work in Europe, the development of this technology to tire-pavement noise measurement was done almost exclusively in the private domain at the General Motors Corporation (GM) throughout the 1980’s. In the early 1990’s, the application of SI to tire-pavement noise measurement at the source became more widely reported in the literature. Since 2001, its application to study the performance of pavements for tire noise generation has become more wide spread, particularly in the realm of investigating “quieter pavements”. Prior to discussing the development of SI to tire-pavement noise, it is worthwhile to clarify the differences of sound pressure and sound intensity.

Sound Intensity vs. Sound Pressure

Physically, sound pressure and sound intensity are significantly different quantities even though in many practical cases their behavior and level are similar to each other. Sound pressure is the amplitude of an acoustic disturbance at a point while sound intensity is average rate of flow of acoustic energy through a unit area. As a result, sound pressure is a scalar quantity while sound intensity is a vector quantity with a direction of flow associated with it. Sound intensity (**I**) is in fact a product of two acoustic quantities, the sound pressure at a point (*p*) and the acoustic velocity at that point (**U**), or

$$\mathbf{I} = p\mathbf{U}$$

where there bold symbols represent three-dimensional vector quantities. Sound intensity also has a definable relationship to the strength of an acoustic source or its sound power (W) unlike sound pressure. Sound power is the rate at which a sound source transfers energy to its surrounding media and has the units of Watts. Sound intensity is related to sound power through the relationship:

$$\mathrm{W} = \int_{\mathrm{s}} \mathrm{I}_{\mathrm{s}}\, \mathrm{ds}$$

where I_{s} is the sound intensity normal to an arbitrary surface completely enclosing the source and is given in Watts/m^2. For steady noise sources, sound power is property of the source and does not vary no matter where it is measured in relation to the source. Sound intensity, however, does vary depending on the position of the enclosing surface. As an example, if the surface area enclosing the source were doubled, the average sound intensity would be halved, equivalent to a 3 dB reduction. In the case of spherical surfaces, if the radial distance to the source were doubled, the surface area would increase by a factor of 4 thereby reducing the average intensity by a factor of 4 or 6 dB. This 6 dB per doubling of distance fall-off rate which mimics that of sound pressure from an ideal point source in a free field.

Unlike sound pressure, sound intensity is not measured directly. This is because of the difficulty of measuring acoustic velocity. Instead, the acoustic velocity is calculated using a finite difference approximation in which the velocity is derived from the measurement of sound pressure at two closely spaced microphones. The acoustic velocity is then that component of the vector lying along the line determined by the two microphones. The value of this component can have either a positive or negative sign depending on which way the energy is flowing. The measurement of sound intensity using this approach was standardized by both ISO and ANSI in the early 1990's and modern reference books provide more information on its theoretical development and practical applications[52].

Early Development of SI for Tire-Pavement Noise Measurement at GM

Shortly after the initial development of sound intensity measurement methods in the late 1970's, researchers realized that this technology could be well suited to onboard measurement of tire noise. In other work, it had shown that SI had the ability to localize noise sources, reject background noise, and detect the propagating energy in the acoustic near field. With these traits, it was envisioned that sound intensity could be used to localize source regions alongside of a moving tire.

The first investigation of the application to SI to tire noise measurement was reported by Oswald and Donavan in 1980[53]. One issues addressed in this work was the effect of flow noise on the microphones and the accuracy of the intensity measurement. Flow noise was of considered both in terms of the effect of microphone self noise and the effect of turbulence the vehicle, tire, and SI probe support structure. To address self-noise, a series of tests were performed in a small, quiet, anechoic, open jet wind tunnel. Measurements of noise from a loudspeaker placed outside of the flow were made using an intensity probe fully enveloped in the flow. Sound intensity produced by the loudspeaker was measured with and without the flow for different levels of noise and different levels of inflow turbulence. As expected theoretically[54], for higher loudspeaker levels, it was found that the SI levels were identical with and without the flow. As the level of the loudspeaker was reduced, it was demonstrated that the noise floor for the SI measurement was about 15 dB below the SPL of self-induced and turbulence-induced flow noise on the microphones. Further, it was noted that as the SI noise floor was approached, the direction of intensity randomly flipped between positive and negative providing a means of determining when background wind noise was a problem. This study also addressed the issue of optimum microphone size (¼, ½, and 1 inch diameter) and microphone spacing (0 to 1 diameter separation). Microphones were fitted with nose cones for diameters considered. The study concluded that ½ inch diameter microphones spaced 16mm apart produced the optimum probe design considering the factors of microphone sensitivity, self-noise, and spacing relative to finite difference error. To confirm the results of the wind tunnel testing, on-road, onboard sound intensity measurements were made a loudspeaker suspended from a trailer for different speeds. These data demonstrated that the effect of flow for on-road measurement produced no additional effect over that seen in the wind tunnel.

After preliminary investigations described above, sound intensity was applied to localizing and quantifying sources regions on operating truck tires[55,56]. Following the wind tunnel work, ½ inch microphones spaced at 16mm in a side-by-side configuration and fitted with nose cones were used for the SI probe configuration. The Microphone outputs were high pass filtered at 150 Hz and phase mismatch was accounted by using "physical switching" of microphones[51]. Initially, tests were performed to define optimal probe distance from the tire. For this purpose, SI was measured at points 0.6m behind and 0.6m below the centerline of tire, approximately opposite the rear edge of the tire contact patch. The test speed was 80 km/h and a blank tread tire was used to provide the worst of tire noise signal to background wind noise. SI was measured at distances of 30, 50, 100, 200, and 400mm from the tire sidewall in narrow bands from 0 to 4000 Hz. These measurements indicated that above 1 kHz, the SI level decreased with increasing distance from the tire beginning at 100mm, while the SI did not increase for closer in positions (Figures 9 and 10). Below 700 Hz, the amount of wind noise on increased at distances closer than 100mm and remained the same at farther distances. The 100mm

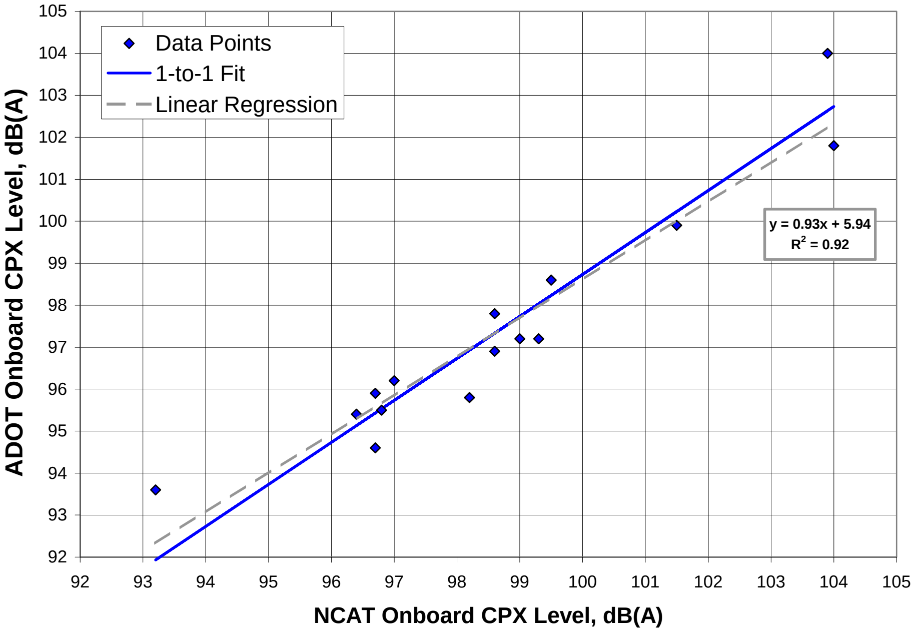


Figure 9: Comparison of on-board tire-pavement noise sound pressure level measured using two similar trailers (ADOT & NCAT) and identical tires using the ISO CPX procedure (41)

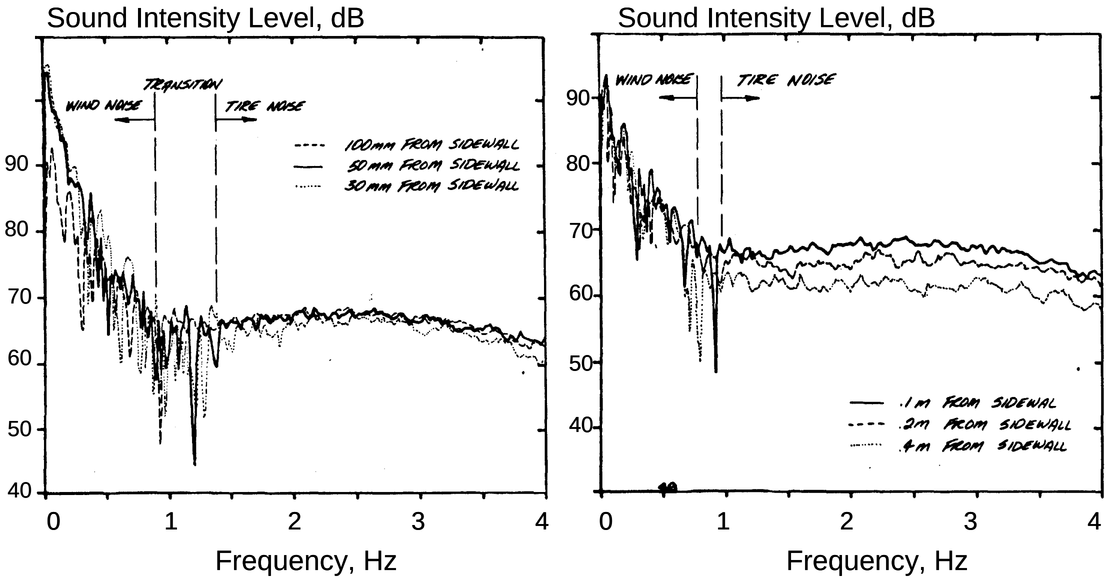


Figure 10: Sound intensity measured near the trailing edge of the contact patch of a blank tread truck tire for purposes of optimizing tire to probe separation (55)

distance was selected as the optimum for maximizing tire noise while minimizing wind noise. With this measurement distance defined, a 75 x 75mm grid system was defined consisting of 58 to 60 points for each tire (Figure 11). The minimum row of grid point was 70mm above the ground to avoid damage to the microphones. Using this approach, the sound fields for 3 tires (a blank tread, a zig-zag rib, and a cross-bar tread) on 2 different AC surfaces were mapped and contours of constant SI level for 500 Hz wide bandwidths were plotted. The results for cases indicated the highest source levels were produced close to the ground and generally at the leading and trailing edges of the tire contact patch (Figure 12).

Following on from the truck tire noise source mapping, sound intensity was applied to mapping the source distribution of passenger car tires as mounted on a test vehicle[57]. In this application, the probe was suspended along side of the front (non-driven) tire of a passenger car (Figure 13). The same 75 x 75mm grid system was used with the probe again positioned 100mm out from the tire sidewall. Four different "all seasons" passenger car tire designs were tested. As for rib tread truck tires, the contours of constant sound intensity for passenger car tire show source regions low to the ground and at the leading and trailing edges of the contact patch (Figure 14).

In the mid 1980's, SI development continued at GM, but moved into the product development domain. Studies that were conducted in this time have only recently been released for external distribution. In one of these studies, Hamill addressed the application of SI to non-research evaluation of tire noise for purposes of rank ordering tires[58]. For this work, the SI probe consisted of two ½ in. diameter microphones fitted with nose cones spaced 16mm apart (center-to-center). The signals were high-pass filter at 350 Hz and recorded for later analysis. To develop a test methodology, measurements were with treaded and blank tread tires operating on a smooth DGAC pavement at 35 and 50 mph and on an coarse, exposed aggregate PCC surface at 35 mph. The test tire was mounted in the right rear tire position of a front-wheel drive test car. Based on the results of earlier studies[57], the probe was located 100mm from the tire sidewall and successively opposite the leading and trailing edges of the tire contact patch. Two probe heights above the pavement were investigated, 50 and 100mm. It was found that although excellent results were obtained for both tire types in the lower position, it ultimately resulted in damage to the microphones. In the upper position, it was found that lower SI levels were measured and wind noise contamination occurred at frequencies below 2000 Hz for the quieter tire. Based on these findings, a height of 60mm was selected and found to produce the same SI level as 50mm with very little flow contamination. Using this height, six tires were measured for exterior SI level and interior SPL. Although the interior SPL contained additional other noises, it was found the interior and exterior SI rank ordering was relatively the same in the frequency range from 750 to 2500 Hz. For purposes of rank ordering tires and comparing to interior level, the SI data from the leading trailing edges of the tire contact patch were averaged together on a logarithmic or "energy" basis to better represent the total noise emission of the tire.

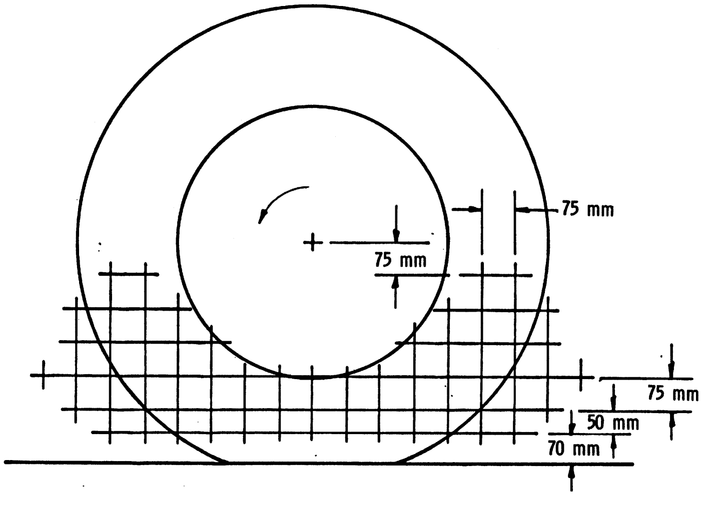
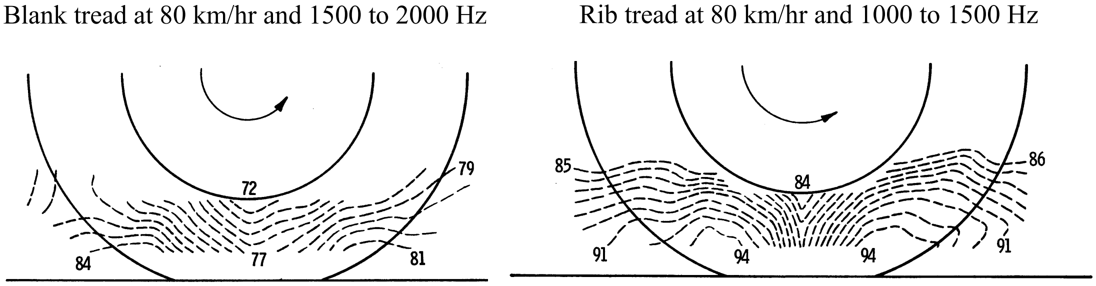


Figure 11: Grid system for measuring tire noise sound intensity mapping of truck tire source regions (55)


Blank tread at 80 km/hr and 1500 to 2000 Hz

Rib tread at 80 km/hr and 1000 to 1500 Hz

Figure 12: Contours of equal sound intensity level indicating source regions at the leading and trailing edges of the tire contact patch for two different tire types: blank tread and zig-zag rib tread pattern (55)

Figure 13: Early application of sound Intensity to mapping source regions of a passenger car tire (57)

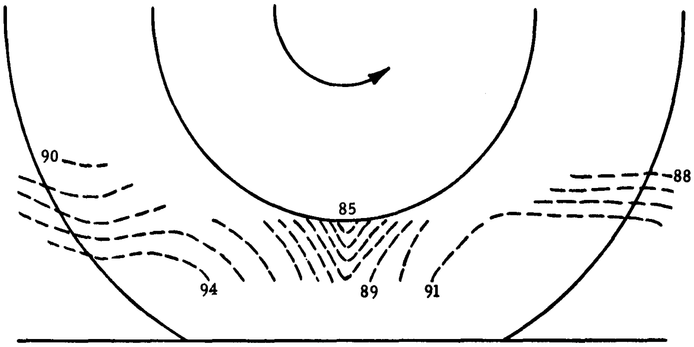


Figure 14: Contours of constant sound intensity level alongside of a passenger car tire indicating source regions at the leading and trailing edges of the tire contact patch, 1100 to 1800 Hz (57)

In a 1988 study, Cantrell investigated the effect of several test variables on tire-pavement noise SI measurements[59]. These included tire loading, inflation pressure, toe, and camber. To accomplish this testing, a trailer was used in which each of parameters could be varied dependently. The SI measurements were made using the same probe locations as the 1985 study[58] with the data from the leading and trailing edges of the contact patch being logarithmically average to produce a single spectrum level for each measurement condition. The test was completed using a Uniroyal Tiger Paw tire operated at 80 km/h (50 mph) on smooth, dense asphalt. In the test matrix, camber was measured at 0°, ±1°, and ±2°, toe at 0°, ±1°, and ±2°, inflation pressure at 20 to 40 psi in 5 psi increments, and axle weight from 1200 to 2000 lbs in 200 lb increments. It was found that SI was most sensitive to toe, "moderately" sensitive to inflation pressure, "slightly" to camber, and insensitive to load on an overall level basis. In terms of overall SI level change in the frequency range from 500 to 5000 Hz, it was determined that to produce a 1 dB increase in level, parameter changes from neutral conditions had to be +0.8º or –1.0º for toe angle, -2.6º for camber angle, or +16 psi for inflation pressure. As a side note, it was reported that the wake from the initial tow vehicle, a full size passenger van, created wind noise contamination in the SI measured on the test trailer. Switching to a compact SUV eliminated this problem.

Applications of SI in the 1990's

By 1990, others outside of GM were reporting the use of SI to measure tire-pavement noise at the source. At the International Tire/Road Noise Conference in 1990, three applications were reported, two on-road and one on a road wheel. In one of these, Oshino and Tachibana used an automated scanning system to measure truck and bus tire sound intensity in the plane of the tire sidewall as mounted on a test trailer[60]. The measurement plane was 100mm from the sidewall and SI contours were produced using a 50 x 50mm grid system. SI was measured with a side-by-side probe configuration using with microphones fitted with nose cones. Sources regions were found to be close to the pavement for each of three test tires including a wavy rib, crossbar lug, and discrete block rib design, specially for overall A-weighted level and higher frequency. For the wavy rib and discrete block rib design, the source regions were concentrated at both the leading and trailing edges of the tire contact patch. For the crossbar tire, the source region extended over the entire patch length. Although test speeds included 40, 60, & 80 km/h, results were only reported for 80 km/h. The SI level for wavy rib and discrete block rib tires were found to be virtually identical. No discussion is provided in the paper on the verification of the method or possible relation to passby data.

In a second SI paper from 1990 Conference, Rasmussen presented results of the SI measurements measured onboard near the leading and trailing edges of a tire contact patch[61]. No specifics were given on exact probe locations as testing appeared to be intended to showcase a new instrumentation system. In this approach, a face-to-face microphone configuration was used with the probe being protected from the airflow be a "football" shaped windscreen. Measurements were made at 50 km/h on two different pavements. This work is of special note in that it was first application of the time domain approach to measuring SI instead of fast Fourier transform (FFT) approach that had been used up until that point for tire noise measurement. In a final SI paper at the 1990 Conference, lab measurements of SI over small areas completely enclosing a tire on a road wheel were reported[62]. These were summed to determine total sound power for tire and to rank order different radiating parts. For tire under test, this analysis found that noise from the tread pattern area dominated over the sidewall area in terms of overall A-weighted level. It was also found trailing edge of the contact patch generated slightly higher levels (~1 dB) than the leading edge.

In work reported in 1993, Donavan reported the first comparative data for passby and onboard SI (OBSI) measurements[63]. Although the purpose of this work was to investigate the effect of torque applied to a tire during vehicle acceleration, the relation between coastby levels measured at 7.5m and OBSI level was examined in order to determine the contribution of tire noise to overall vehicle noise as measured under the ISO 362, full-throttle passby test used for vehicle noise regulation. Testing was done with 7 different tire designs at 56 and 80 km/h on a DGAC test surface. The SI probe was supported 100mm from the tire sidewall with measurements being at two points, opposite the leading edge and trailing edges of the tire contact patch. The probe was 60mm above the pavement and data from each probe location were averaged together logarithmically to yield the average intensity propagated out from the tire. The signals from the probe microphones were high-pass filtered at 500 Hz to minimize effects of inflow turbulence on the measurements. To accommodate a range of tire sizes, two vehicles were used in the testing. For each tire/vehicle combination, 2 or 3 coastby runs were measured for each side of the vehicle and averaged together. For the SI measurements, two samples of each tire type were measured and averaged. Linear regression analysis of these data yielded an r^2 value of 0.96 and nearly 1-to-1 slope of 0.953. Compared to the 1-to-1 fit of the data, an offset of 24.5 was found with an average deviation from the 1-to-1 line of 0.8 dB (Figure 15). The tires were found to rank order the same between the SI and CPB data within 0.2 dB. Spectral comparison of the SI and CPB data indicated similar behavior in comparing one tire to another. In regard to the effect of torque, it was found that under acceleration of up 2.3 m/s^2, tire noise SI levels could increase anywhere from 0 to as much as 9 dB depending on tire design.

Applications of OBSI to Evaluating Test Track Surfaces

From the 1990's, OBSI has been by several research teams to evaluate the noise characteristics of test track surfaces. Under the ISO 362 passby test procedure, it was know that up 41% of the total noise emission of light vehicles was due to tire-pavement noise even though this procedure is conducted at full throttle[64]. As this procedure is used for regulating vehicle noise, the effect of the pavement on the tire-pavement noise generation and propagation were considered to be critical. As a result, a number of investigations of were undertaken to evaluate the standard ISO 10844 test track surface in comparison to other standard surfaces such as the SAE J1470 surface.

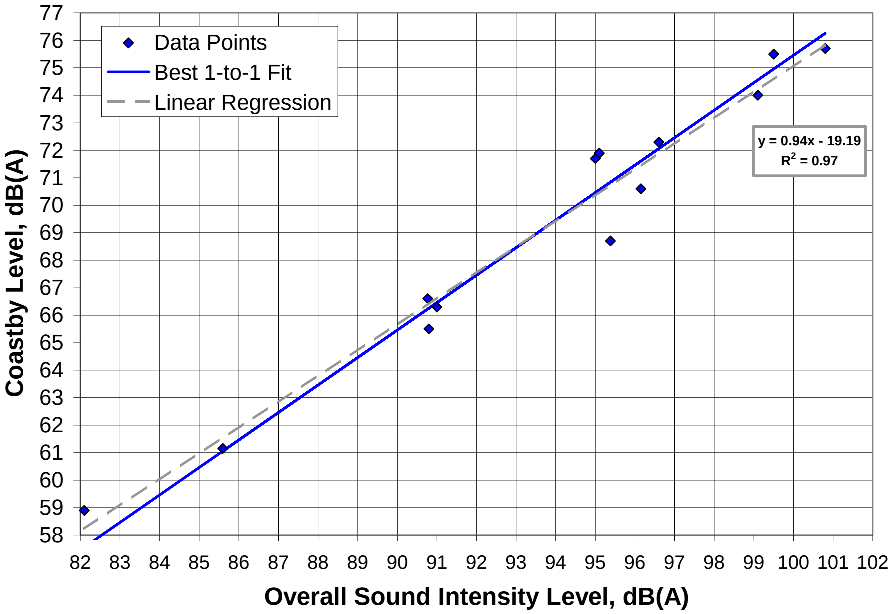


Figure 15: Comparison of on-board tire-pavement noise sound intensity levels measurements to coastby levels for 2 different tires at 56 and 80 km/h (63)

In 1993, an extensive study was conducted by researchers from Purdue University to compare the characteristics of the SAE J1470 asphalt surface, both sealed and unsealed, and the ISO 10844 (slightly) porous AC surface[65,66]. Cruiseby, coastby, and OBSI measurements were made on a total of 14 different test tracks with 5 different vehicles with unique tires. In addition to investigating the differences between test tracks, the intent was also to establish a “transfer function” between the OBSI and passby data. The OBSI levels were measured with a probe supported 100mm from the tire sidewall, 66mm above the pavement. Measurements were made separately opposite the leading and trailing edges of the tire contact patch. A minimum of two OBSI measurements were made in each position. The probe was mounted on the front wheel of the test cars, all of which were front-wheel drive. The test speed was nominally 35 mph. During OBSI data acquisition, it was found that wind noise contamination was present for the trailing edge measurement position. Methods for minimizing this effect, such as the use of nose cones and/or windscreens or high-pass filtering are not described in the reports. As a result, only leading edge OBSI data were used in the analysis comparing OBSI levels to the passby levels. Plotting the coastby data against the leading edge OBSI yields a 25.5 dB offset for a best fit 1-to-1 relationship with an average deviation of 0.9 dB and standard deviation of 1.1 dB (Figure 16). A linear regression of the data gives an r^2 value of 0.8 and a slope of 0.90. For cruisebys, the offset is reduced by 1 dB. In recommended future work, the researchers propose band pass filtering of the microphone signals to reduce the effect of turbulent wind inflow for trailing edge position.

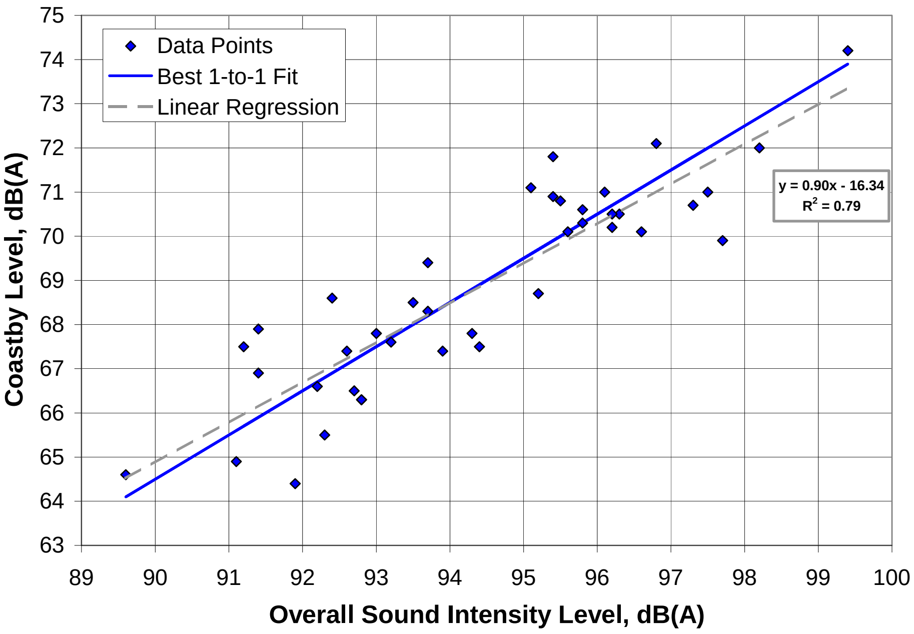


Figure 16: Comparison of on-board tire-pavement noise sound intensity levels measured at the leading edge of the tire contact patch (only) to coastby levels for 5 different tires on 14 test surfaces (65)

Additional research regarding test track surfaces was reported by Donavan in 1997[67]. As in the Purdue study[65], the purpose of this work was to examine differences between SAE and ISO test tracks at two different facilities. Wayside measurements were made at 7.5m from the centerline of vehicle travel for both 56km/h coast and accelerating (ISO 362) passby conditions. OBSI data was obtained also for each operating condition using the methods described in Reference 63. Testing was conducted on a single vehicle, but with five different tires, one of which was testing at inflation pressures of 20, 30, and 40 psi yielding seven comparison points. In analyzing the coastby results, it was found that, on average, the levels on the sealed SAE surface were 2 dB greater than the somewhat porous AC ISO surface. For the OBSI data, the SAE produced 0.9 dB higher average levels than the ISO surface. In the paper, the coastby levels are plotted against OBSI for both surfaces as well as similar measurements from an earlier reported study[63]. This produced 23.9 dB offset for a best fit 1-to-1 relationship with a average deviation of 1.0 dB and standard deviation of 1.2 dB (Figure 17). A linear regression of the data gives an r^2 value of 0.95 and a slope of 0.87. For both the SAE and ISO surfaces, comparison of the OBSI and the coastby spectra for the different tires displayed very similar differences over the frequency range from 500 to 5000 Hz. After additional analysis, is concluded that although primary difference for passby data between the test surfaces was in tire noise generation, some of the 2 dB difference could be attributed to propagation effects due to the slightly lower acoustic impedance of the ISO surface. In regard to the effect of inflation pressure, it was found that on average the 10 psi increase above 30 psi produced a noise level increase (both in CPB and OBSI) of about 0.5 dB, while the 10 psi decrease from 30 psi reduced the noise level by about 0.8 dB, results consistent with those reported by Cantrell[59].

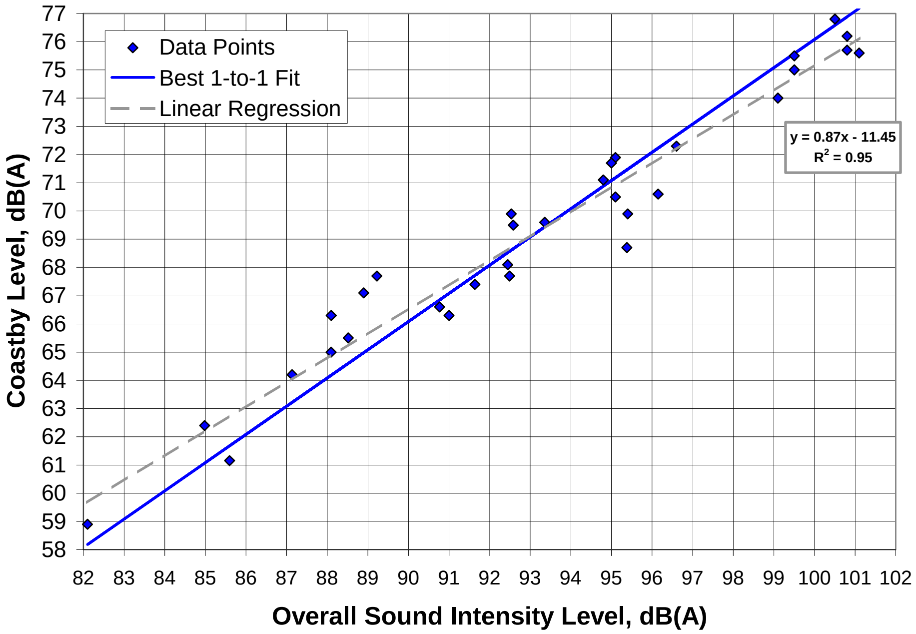


Figure 17: Comparison of on-board tire-pavement noise sound intensity levels measurements to coastby levels for 5 different tires, with 1 tire at 3 different inflation pressures on 2 different test track surfaces (67)

Another form of comparison of the ISO 10844 test surface was reported by Sakamoto, et al in which OBSI tire noise taken on-road was compared to an ISO replica surface on a 1.6m diameter road wheel[68]. In this research, OBSI measurements were 0.2m away from the tire sidewall in the plane of the sidewall and 0.15m above the ground starting from the center of the contact moving to positions fore and aft in 0.3m increments for a total of seven locations. OBSI was measurement using a three dimensional (four microphone) probe. Protection of the exposed probe from wind noise contamination was not stated, however, test speed was relatively low at 55 km/h. Two tires were tested; a blank tread tire and one with more typical passenger car tire tread. Consistent with other research[55,60], the on-road OBSI data indicates that the stronger source regions are at the leading and trailing edges of the contact patch, at least in the range from 400 to 2500 Hz. No comparisons between OBSI and passby levels are provided. It is worth noting that the three dimension OBSI vectors all had a definite upward component to them as measured at the height of 150mm and distance of 200mm from the tire and that they “pointed” back to a source region right at the tire-road interface. This is consistent with OBSI contour plots from other studies that show the component of OBSI normal to the plane of the sidewall decreasing with increased measurement height above the pavement[55,57,60]. It is interesting to that significant differences were observed between the road and road wheel with a replica surface. On the road wheel, the strongest source region was indicated as the center of the contact rather than the edges. Levels measured on the road wheel were typically 5 to 10 dB higher for 1/3 octave bands beginning at about 1250 Hz and higher.

The three-dimensional OBSI approach was also applied to examining the effects of torque on tire noise during vehicle acceleration[69]. In this which. The probe positions remained the same as those identified previously[68], however, in this report, it was identified that Brüel & Kjaer were the suppliers of the three-dimensional probe and that it was wrapped with two layers of "windbreak netting". In this case, all testing was conducted on road using 3 treaded tires and 1 blank tread tire. The data range was from 500 to 2500 Hz, and was sampled every 50 ms with 5 samples averaged together to define any one data point. From 800 Hz, levels toward the edges of the contact patch were higher than the center, with the forward points being highest. For 2000 Hz, the leading and trailing edges are 2.5 to 3 dB higher than the center and the two edges are close in level. Consistent with earlier reported work[55], tire noise was found to increase with applied torque.

Application of OBSI to Evaluating Pavement Noise Performance In-Situ

Up until the early 2000's, the applications OBSI had been in test track or laboratory environments. In 2003, the first paper appeared which detailed the use of OBSI measurements to quantifying the noise performance of highway road surfaces in-situ[70]. The test method followed closely that which had been developed at GM. The SI probe consisted of two ½ in. diameter microphones and preamplifiers in a face-to-face configuration spaced 16mm apart. The microphones were fitted with nose cones and cover with a commercial spherical foam windscreen. Measurements were made individually opposite the leading and trailing edges of contact patch and later averaged together on a logarithmic basis. The probe was positioned 100mm out from the tire sidewall and 75mm above the pavement. Comparative results are given for coastby measured at 7.5m and OBSI measurements on two test tires, one AC pavement, three test speeds, 74, 88, and 97 km/h. Plotting the coastby levels against OBSI produced a 23.9 dB offset for a best fit 1-to-1 relationship with a maximum deviation of ±0.5 dB and standard deviation of 0.4 dB (Figure 18). A linear regression of the data gives an r^2 value of 0.98 and a slope of 1.09. Differences in the one-third octave band spectral comparisons between the two tires were found to be similar for coastby and OBSI data. For the purposes of amassing a consistent data base of in-service pavements in the State of California, measurement protocols were implemented which allowed comparison of one highway pavement to another. For this purpose, a test speed of 60 mph (97 km/h) and a Goodyear Aquatred 3 P205/70R15 test tire were selected. The test speed was selected based on the compatibility with other traffic as it was intended that measurements would be made at any freeway without closures or other special consideration. OBSI data was typically averaged over a 5 second interval using a "linear" or energy average. Using this protocol, data for 11 pavements are presented.

In 2003, the use of OBSI as part of an evaluation of tire-pavement noise produced by different PCC texturing methods was reported[71]. In this study, OBSI, controlled cruiseby, and a pseudo statistical passby method were all applied to assessing the performance of longitudinally, uniformly transversed, and randomly transversed PCC. For the OBSI and controlled passbys, measurements were made for two different tire

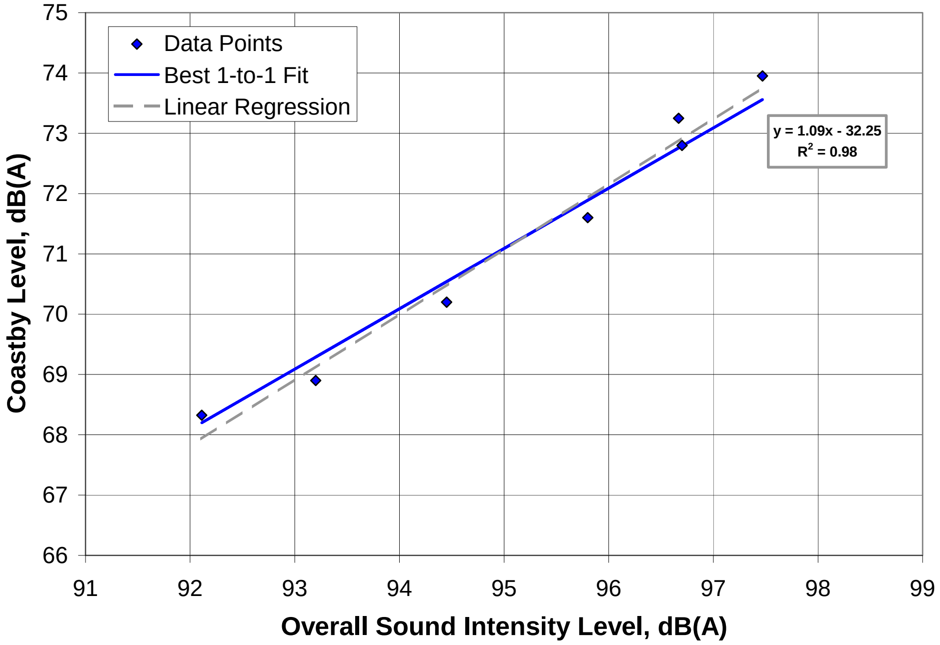


Figure 18: Comparison of on-board tire-pavement noise sound intensity levels measurements to coastby levels for 2 different tires on 1 test track pavement at 74, 88, and 97 km/h (70)

designs on the three pavements at a speed of 60 mph. The vehicle and one of the sets of test tires were those used in the California study[70], and the OBSI measurement protocol used was identical to this earlier work. A comparison of OBSI to CPB data is provided which shows the data from the PCC study as well as data from five AC pavement test sites in California and the data reported in Reference 70. These combined data produced a 23.8 dB offset for a best fit 1-to-1 relationship with an average deviation of ±0.5 dB and standard deviation of 0.7 dB (Figure 19). A linear regression of the data gives an r^2 value of 0.99 and a slope of 1.07. It was further found that the difference in overall level for the three pavements was virtually identical for the 27 (pseudo statistical) light vehicles tested, the controlled vehicle passbys, OBSI measurements.

In 2004, Donavan and Rymer reported on a number of investigations sponsored by the California Department of Transportation (Caltrans) of tire/pavement noise using OBSI[72]. This included a summary of the all OBSI to cruiseby comparisons reported in previous work along with some new test data acquired on AC test sections in California[70,71,73]. In all, six different AC pavement sites and six PCC sites were included in this data for range of test speeds and tires. Passby data at both 7.5m (25 ft) and 15m (50 ft) were available. For 7.5m, these combined data produced a 23.6 dB offset for a best fit 1-to-1 relationship with an average deviation of ±0.6 dB and standard deviation of 0.8 dB (Figure 20). A linear regression of the 7.5m data gives an r^2 value of 0.98 and a slope of 1.06. For 15m, the offset was 30.4 dB with an average deviation of ±0.7 dB and standard deviation of 0.8 dB and linear regression results of $r^2 = 0.99$ and slope of 1.09. Comparison of 1/3 octave

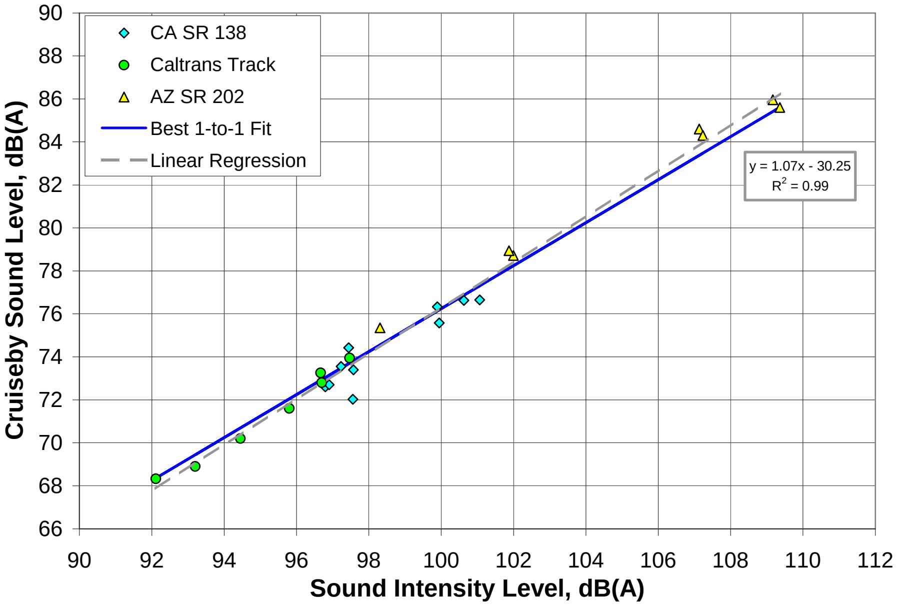


Figure 19: Comparison of on-board tire-pavement noise sound intensity levels measurements to cruise-by levels measured at 7.5m for 2 different tires on 6 AC pavements and 3 PCC pavements (71)

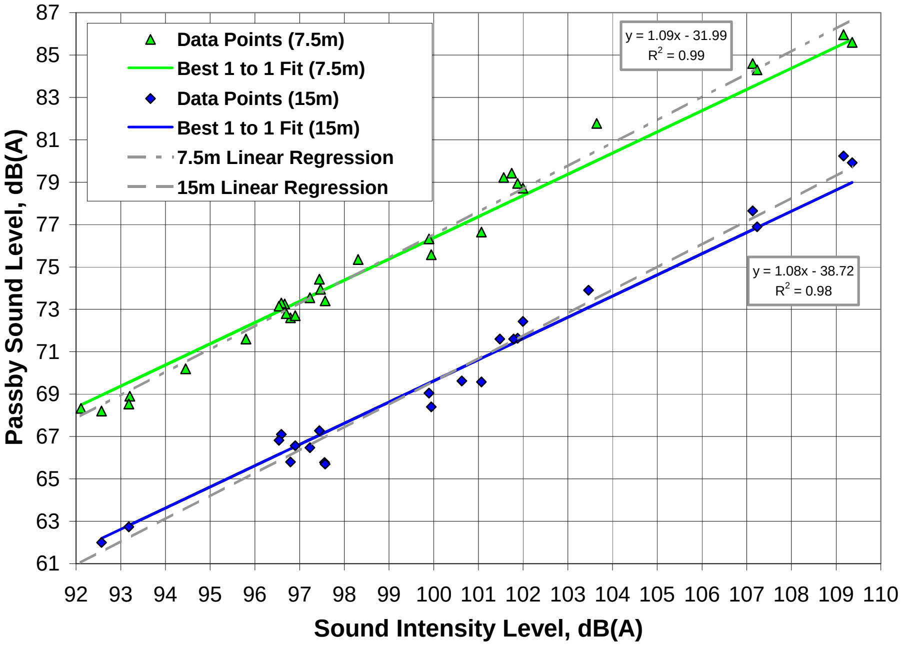


Figure 20: Comparison of on-board tire-pavement noise sound intensity levels measurements to cruise-by levels measured at 7.5m and 15m for various tires and speeds on 6 AC pavements and 6 PCC pavements (72)

band spectra for OBSI and 7.5m and 15m passby data are also presented for the AC test pavements. These all indicated similar differences between pavements for the three data sets with any differences between the OSBI and passby data being as great as those between the two passby distances.

There has been some reporting of differences in traffic noise and OBSI for different pavements in cases where the traffic flow is not acoustical dominated by trucks or other heavy vehicles[70,74,75,76]. In general, these have indicated that when reductions in tire-pavement noise are achieved, reductions in traffic noise follow. However, the amount of wayside reduction can vary from the OBSI reductions depending on distance from the roadway, fidelity of the before and after measurements, and site geometry.

Other Related Tire-Pavement Noise OBSI Work

In related OBSI work, a study was reported in 2003 which developed a relationship between overall tire noise sound power and sound intensity as measured opposite the leading and trailing edges of the tire contact patch. These measurements were performed on a road wheels with replicate rough and smooth pavements at 60 km/h and 80 km/h, respectively, at two different laboratory facilities using eleven different tires. The sound power was determined using conventional SPL measurements on a hemispherical surface surrounding the tire in a hemi-anechoic room according to the ANSI S12.35-1990 standard for sound power measurement. The OBSI measurements were made 100mm from the tire sidewall, 75mm above the road wheel surface. Data from the leading and trailing were averaged together and compared to the sound power levels on a 1/3 octave band basis. Although there were some differences between, laboratories, surfaces and tires, the offset between OBSI and sound power level was about 3 dB across the spectrum from 315 to 6300 Hz with the OBSI levels being higher. Standard deviations from the average were less than 1 dB for the coarser surface and 1.5 for the smooth. The authors concluded that OBSI on-road measurements could be used to reliably estimate sound power used as input to Statistical Energy Analysis models used to predict interior tire noise levels.

Using a mounting system similar that employed in ADOT trailer testing[48], the use of a two-probe method of measuring OBSI attached to a test vehicle and exposed to air flow was investigated by Donavan and Scofield in late 2005[77]. The configuration of the probes was vertical, with the microphones suspended from above opposite the leading and trailing edges of tire contact. In preliminary testing, using the horizontal, single probe orientation[3,70], it was found that the nose cones could be replaced with a commercial spherical windscreen only with little loss in the ratio of wind-induced noise to OBSI levels. The report uses analysis of previously reported studies on windscreen performance, nose cone performance, and typical tire noise levels to support the use of OBSI without nose cones. Test results for dual probe approach are compared to the horizontal, single probe method showing that difference in level is ½ dB or less. No consistent trend of one approach producing higher levels than the other was found for four test pavements spanning an eight dB range in level. The coherence and difference in SPL to OBSI levels for these measurements are analyzed to assess the validity of the two-probe approach. There was no evidence of the trailing edge probe measurements having excess wind induced noise or turbulence from the leading edge probe. It is concluded that the horizontal single probe method with nose cones and a windscreen provides the best performance relative to wind induced effects and should be used as the benchmark of investigating other probe configurations. However, based on the results obtained, the two-probe, vertical orientation configuration with windscreens and no nose cones can also obtain accurate results.

Summary

Although the sound intensity method of measuring tire-pavement noise at the source dates back to the early 1980's, its application to evaluating pavements in-situ is fairly recent. By following the approach developed and documented at General Motors, this technology could easily become "off-the-shelf" for the pavement application. It can be implemented directly on most test vehicles with little adaptation or modification. As it was initially developed for truck tire applications, OBSI is suitable for measuring both truck and light vehicle tires under comparable conditions. Acceptable levels of correlation between OBSI and controlled passenger car coast/cruise passbys have been demonstrated under some circumstances and could be developed further. Although OBSI inherently requires more sophisticated data analysis than SPL measurement, it is a menu item on most dual or multi-channel acoustic analyzers. It also can be processed to provide internal indicators of data quality. Unlike the draft CPX method, there has not been the inter-comparison of data collected from multiple users and data acquisition systems leaving the expected range of data reproducibility largely unknown.

AAT – Acoustic Array Technology

The bulk of the acoustic array technology application to tire noise measurements has been in a lab, road-wheel environment. However, some interesting work has also been reported for on-road application. Because of the generally limited application of AAT, the studies using both types of facilities are included in this discussion.

In-Lab Road-Wheel Applications

The first of AAT technology to tire noise measurement was published in the proceedings of the International Tire/Road Noise Conference in 1990[78]. This paper describes the use of the Spatial Transformation of Sound Fields (STSF) technique developed by Brüel and Kjaer to measure tire noise on a road-wheel. STSF is essentially a Near-field Acoustic Holography (NAH) technique coupled with a routine to propagate the sound to the far field using the Helmholtz integral. In this application, a rake of 12 microphones was successively scanned over 20 positions in a plane parallel to the tire sidewall. Three stationary microphones used as references. Measurements on single tire were reported to be completed in less than 30 minutes. For sampling the sound field, the author advises that the grid spacing on the measurement plane should be closer than ½ λ (75mm for 2k, 38mm for 4k), and the distance from the array to the tire should be the same as the grid spacing. For this application, scan plane was 70mm from the tire sidewall. The size of the grid should cover the whole source area (lower tire) and up 45° from the edge of the tire. The results show the sources down near the contact patch. There is no discussion of on-road application. The STSF approach was also much later in research work to relate lower frequency tire noise production as measured on a road wheel to a theoretical tire noise model[79].

A rather complete discussion of different AAT methods is described in 1995 paper by Dumbacher, et al[80]. This reference describes three approaches to using AAT techniques to measure and localize sources on tires operating on a road wheel: traditional near-field acoustical holography, temporal array techniques (summing signals with time delays to converge on source points), and inverse frequency response function (IFRF) techniques (where path transfer function from artificial point sources to the array microphones are measured). The measurements were for a specific tire mounted in the left front wheel position of a test car operating at 30 km/h on a rough road wheel surface. For the NAH measurement, a 16 microphone vertical linear rake was traversed in 32 discrete 380mm steps in a plane 50mm from the tire. The measurement time was 1½ hours. Temporal method used 2 microphones spaced 800mm apart traversed in a circular direction in 18° increments in the plane parallel to the sidewall at a distance of 1.44m. This produced 10 pairs of microphone locations. The acquisition time was 30 minutes. It should be noted that this is equivalent to "beam forming" accept that multiple positions of the microphone pairs were used instead of a stationary array. For the IFRF method, a rectangular, planar array of 56 microphones 180mm from the tire sidewall was used. To determine the source to receiver transfer functions, 6 source locations were used. It was noted that unlike the other two AAT methods, IFRF is not useful for visualizing noise source distributions as the suspected source locations are assumed up front. For better visualization, the number of source locations would have to be increased. The authors do attempt to compare the methods quantitatively, however, each show similar trends with the source regions being concentrated close to the tire/road wheel interface. A table comparing the features of each approach is provided. Application to on-road measurement is not discussed and may not be feasible with some of the systems as used in this study. More tire noise source analysis of the NAH testing was reported separately by Kwon, et al in 1998[81].

Another example of essentially the IFRF technique was reported in 1999[82]. Purpose of this work was to quantify the contribution of different parts of a tire to far field noise. In this case, a U-shaped fixture is used to hold 16 microphones surrounding the tread band and sidewalls of a test tire with each microphone 30mm from the nearest point of the tire. The source pressures for the tire are measured as the fixture is moved incrementally around tire while is operating on a road wheel resulting in 336 data points. Far field sound levels are also measured at 3 points. The measurements are then repeated made with a small loudspeaker (volume velocity) source at 84 points on the surface of the stationary tire. The near field SPLs measured for the operating tire were then be used to estimate volume velocities at the surface for the 84 speaker points and the far field contribution of these points determined. The application is toward lower frequency noise generation, below 1000 Hz and sources in the tire contact patch are essentially ignored.

The authors state that this method as currently implemented is not “well-suited for real road applications”.

On-Road Applications

In 1995, results of research at Penn State University regarding on-road investigation of tire noise sources using NAH by researchers began to appear[83]. Testing was done on a smooth AC test track using the GM open wheel tire noise trailer[59] allowing unobstructed access to the side of the tire. For this work, vertical linear rake of 5 microphones spaced 102mm apart was used and incremented manually in 24 steps across a plane parallel to the sidewall spaced 100mm away. Three fixed reference microphones were used, two directly in front and behind the tire 220mm from the contact patch and 60mm above the ground, and one opposite the center of the contact patch, 50mm outboard and 60mm above the ground. The signals from the reference microphones were found to have coherence values less than 0.5 indicating very little relationship between these suspected source regions. As a result, all three reference locations were used throughout the study. The tests were conducted at a speed of 56 km/h using a Uniroyal Standard Reference Test Tire. The noise source regions were found to be concentrated low on the tire, near the tire contact patch. Although the microphones were protected by windscreens, wind noise reduced coherent levels below about 300 Hz. The results of these measurements were discussed later in a 1998 paper in which the source regions at the center and leading and trailing edges of the tire contact patch were more thoroughly documented[84].

A second phase of the Penn State research was reported in 1999[4]. In this testing two different tires were evaluated, a production passenger car tire and one hand cut experimental tire with longitudinal and transverse grooves. The measure methods were the same as reported previously[84] with a few exceptions. Two NAH measurement planes were added to that parallel to the sidewall. These were perpendicular to the ground and to the direction of travel and located in front and behind the test tire. These arrays were 120mm from the vertical tangent to the tread band. The vertical array of microphones was now longer using nine elements with a 100mm separation. The same front and rear reference microphone positions were used, however, the one opposite the sidewall was now 35mm outboard and 85mm above the ground. The results indicated that the highest sound power levels were through the plane parallel to the sidewall, then the front, followed by the rear for both tires in measurement range of 300 to 1600 Hz. This frequency range was set by spatial resolution of the NAH grid.

In a more unique application NAH, a two-dimensional stationary array of microphones was used to capture tire/pavement noise source distributions of a moving tire as it passes the array in a test track environment[85]. The technique uses a “moving” window to track the tire as it passes in a manner akin to a beam forming approach. Doppler corrections are applied to account for the source movement. The array consists of 64 microphones in an 8 by 8 configuration and the reconstruction is done over a 1m by 1m plane. The distance to tire sidewall is not stated. Results show source regions very low to the ground and dominated by the leading and trailing edges (at 800 Hz). The author uses the same approach with a road wheel to examine source mechanisms.

Summary

The applications of AAT methods have been exclusively in the research domain with the majority of the work done on road wheels. There has been no reported work attempting to correlate the AAT measurements with actual vehicle passbys. All of the methods rely on acquiring data at many points alongside the test tire either by using a large number of microphones or incrementing a linear array of microphones. Without considerable development and streamlining, the use of these methods to date does not appear to be compatible with in-situ measurement of tire-pavement noise source levels in highway environments.

IMPLICATIONS FOR TEST PROCEDURE DEVELOPMENT

Tire-pavement noise measurements at the source can be generally grouped into three categories, measurement of sound pressure levels, measurement of sound intensity level, and acoustic array techniques. Of these three overall approaches, AAT methods appear to be the furthest away from being a usable technique for highway agencies to use to evaluate their pavements for noise. These techniques have never been applied to measurements in a highway environment and no comparison to any kind of passby data has been reported. The measurement systems are far from "turn-key" and require acquisition and manipulation of many channels of acoustic signals. Considering the similarity of results between sound intensity and AAT mapping, there appears to be little justification for pursuing this technology over the simpler OBSI methods.

For SPL measurements, a lot of different approaches have been cited in the literature. Some of the early work using BTT methods did display some limited level of correlation to passby measurement for trucks. However, more recent research work has shown that the noise region at the front of the tire is equally important to overall tire noise and that there is little correlation between the two. Of the remainder of the SPL methods, there appears to be no justification for following anything other the method defined in the ISO CPX draft standard. Comparisons between onboard measurements and passby show about the same degree of correlation as any other approach using SPL methods. Within that umbrella, some consideration of trailer versus exposed microphones should be given. With the trailer method, concern has been expressed about reflections in the enclosure. Tests to evaluate reflections have been defined, however, recent round robin work comparing these different tests and equipment have also indicated some variation. An attractive alternative is the exposed microphone technique that should avoid the build up of reflections and should less expensive to implement. However, the issue of flow noise contamination of the SPL data is unresolved and methods for testing for it are not defined.

As with the CPX method, the OBSI method using the GM methodology has been used extensively for in-situ highway pavement noise measurements. This method has been shown to correlate reasonably well with both CPB data and CPX data. Unlike the test tires specified in the ISO CPX draft standard, those used today in OBSI testing seemed to be somewhat arbitrary relative to "typical" tire noise as little data comparing OBSI to SPB for light vehicles has been reported. Further, the use of consumer tires for standardized testing is quite problematic as tire suppliers discontinue current production tires. This has been experienced both by users of the CPX and OBSI methods. International availability of test tires has also been an issue as some test tires used in Europe are not available in the US and vice versa. For the purpose of the of onboard procedure to be used by highway agencies in the US, the issue of selection and availability OF test tires is an issue no matter what test procedure is developed.

An issue that remains an unknown is the effect of porous pavements in relating either CPX or OBSI measurements to passby levels. Differences between CPX to CPB or SPB relationships have reported in some European studies. Similarly, in one US study, porosity was thought to play a role in comparing CPB and OBSI data for two test surfaces, one slightly porous and one non-porous. Differences may also exist between the way in which these two methods respond to porous pavement and how they relate to passby.

To date, there has been no research to compare OBSI to CPX and both to CPB within the same study. Such information is necessary in order to assess the technical merits of both approaches or to determine if they equivalent. If there is technical advantage in one of the approaches, then this would factored into the decision on test method selection along with other, non-technical issues.

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