

**Analysis of Bystander Noise Generated by Vehicle/Road  
Surface Interactions**

**Final Report**

**May 23, 2003**

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**TESTING AND RESEARCH SECTION  
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<p>16. Abstract</p> <p><b>A sound quality jury study was performed to determine which pavement types people would prefer to live next to based on the sound generated at the tire/road surface patch. Measurements were taken using a binaural head placed 50 ft. from the center of the near lane of traffic. Two different vehicles were then driven past the stationary binaural head at 60 mph, the two vehicles were a Saab hatchback and a Chevrolet Suburban. Care was taken to ensure that the test vehicle was the only vehicle in the recorded sound signature. The captured sound files were then organized and several different sound quality metrics calculated for each vehicle/surface pair. The sound files were then used in a paired comparison jury test where each juror was exposed to a set of sounds and ranked their preferences as to which surfaces they would prefer to live near. Upon analyzing the jury test, the results were combined with the calculated sound quality metrics and regression analyses performed to find a correlation between a measured sound quality metric and the juror's preferences. While no single sound quality metric was able to produce a high quality correlation for all surfaces and both vehicles there were several different metrics that had very acceptable fits for different subsets of the data, for instance the Saab on a concrete surface. The common trait about each of the metrics which had some degree of correlation as well as from juror feedback forms was that listeners preferred sounds without pavement discontinuities. This leads to the conclusion that one of the most important aspects of pavement and road design from a noise perspective is to minimize the size and number of discontinuities such as expansion joints. This could lead to the realization that the full grinding of concrete road surfaces is not necessary from a noise perspective, it may be possible to only grind the joints and still obtain a very large percentage of the benefits realized by grinding the entire road surface. This finding also implies that the quality of the road construction and the size of the expansion joints is probably more important than the type of tining on the road surface from a bystander point of view.</b></p>			
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## *Executive Summary*

The Keweenaw Research Center (KRC) of Michigan Technological University, upon completion of a literature search in the Fall of 2000, performed an in-depth sound quality study to gain the most useful information about the subjective nature of the vehicle tire/road surface interaction noise. The timeframe for this study was approximately two years. This report documents the overall findings of the research.

Two vehicles, a small passenger car and a large sport utility vehicle were each run over four different concrete pavements and four different asphalt pavements. High-quality binaural recordings of these single-vehicle passby sounds were made for the purpose of subjective jury analysis. Four separate jury evaluations were conducted- one for each vehicle, which was repeated for each of the two pavement categories (concrete and asphalt).

The jury evaluations were presented to a large sample size. Over 300 jurors were evaluated in this study. The jurors auditioned the binaural recordings in pairs and were asked to vote for the sound that they would prefer to live next to. The evaluations yielded a relatively low juror success ratio. On average, only 40% of jurors were able to meet the minimum consistency and repeatability thresholds. Unlike previous pavement noise evaluations, the tests were constructed such that jurors were tasked with differentiating between pavements within the concrete or asphalt categories. This proved difficult, as the different pavement designs within a category have very similar sounding tire/pavement interaction noises.

Written questionnaires completed by the jurors after testing provided valuable subjective juror feedback on pavement noises. 82% of the jurors described the sounds they evaluated as "similar with subtle differences." Approximately 40% of the jurors stated that they would not want to live next to **any** of the pavement noises they evaluated. From previous research, it was found that a significant number of jurors based their voting strategy on the smoothness of the sounds. In this survey, over 30% of the jurors used the term "choppy" to describe the displeasing or annoying portions of the sounds. Another 7% made specific references to "joints", "expansion joints", or "cracks in the pavement" when describing the unfavorable qualities of the sound.

The analysis of the data from this study provided good correlation between juror preferences and standard sound quality metrics for both asphalt and concrete pavement categories. The statistical confidence in the correlation is both vehicle and surface dependant, so not all vehicle/pavement category combinations yielded good correlation with the sound quality metrics. Those combinations that correlate well were modeled best using sound quality metrics that relate to the transient nature of sound. This correlation indicates that juror preferences weigh heavily upon the discontinuities in the pavement noise, such as those that occur when the vehicle tires pass over expansion joints, cracks in the pavement, or any other feature that causes an impact type of event.

All regression analyses performed on the jury data attempted to correlate juror preferences with sound quality metrics. While the metrics are quickly computed and can be compared with properly formatted past and future sound data, they do not directly

provide insight to the physical pavement parameters that effect the quality of the noise. If these parameters were identified and understood, noise could be included as a pavement design. Therefore, it is recommended that the physical pavement parameters be collected from the pavements for which the binaural noise data exists. At that time, a correlation between juror preferences and the pavement parameters could be attempted. This correlation would be a very quick and cost-effective process, as the juror evaluation and results database tabulation are the most time-consuming and expensive portion of this type of effort.

The two most important facts learned from this study were that the sound quality results are somewhat vehicle dependent and the important aspect of the road surface in these evaluations appeared to be transients. It is believed that the vehicle dependence is a result of different engine sounds and tire construction which affects the overall noise generated by the vehicle traveling on the road. The transient noise responses are generated each time a tire travels over joints or cracks in the road surface. In general, most people probably associate much of the other portions of the noise generated by the tire/road surface interaction to be part of the overall vehicle noise and not directly related to the road.

## ***Background***

Increased pass-by noise levels along trafficked urban highways and other populated areas have resulted in an interest in understanding the perceived nature of sound generated by the vehicle tire/road surface (vt/rs) interaction.

A report generated by Marquette University and HNTB Corporation, titled "Noise and Texture on PCC Pavements" showed that "traditional" noise studies have been unable to establish a relationship between the sound pressure level in a vehicle and the pavement texture. Another conclusion presented by the report was that overall sound pressure levels, even at a bystander position, are not sufficient to rank the human response to a specific vt/rs interaction. These conclusions indicated that different noise criteria combined with subjective ratings must be used.

The Keweenaw Research Center (KRC) of Michigan Technological University proposed to Michigan Department of Transportation in the spring of 2000 that sound quality jury testing would be an appropriate mechanism to rank vt/rs interaction noise. Upon completing a literature search in the fall of 2000, KRC verified that this type of sound quality approach has not been undertaken to understand the bystander noise generated from the vt/rs interaction.

As a result, MDOT funded an in-depth sound quality study to gain the most useful information about the subjective nature of the vt/rs sound. The timeframe for this study was approximately two years. A progress report delivered to Frank Spica in March 2002 documented the information learned from a preliminary data acquisition and jury analysis. This report documents the overall findings of this research.

## ***Field Testing Description***

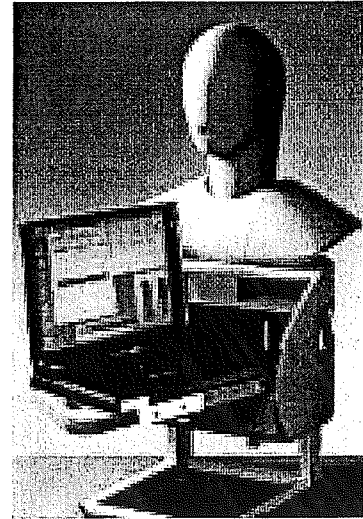
In September of 2002, KRC engineers traveled to various locations in southern Michigan to record single vehicle passby noises for use in the sound quality study.

Recordings of the single vehicle passby events were made using a Head Acoustics Head Measurement System (HMS III) shown in Figure 1. The artificial head's binaural recordings provide exceptional realism or "virtual reality" when played back, making it the industry standard for sound quality data acquisition.

The binaural head was placed on a tripod, along the side of the road, at a distance of 50 feet from the center of the outside traffic lane. The height of the tripod was adjusted for each road surface, such that the height of the head was consistently level with the road surface. Specific measurement locations were chosen that possessed reasonably level roadways and roadsides, no nearby manmade structures or obstructions (medians, overpasses, etc.), and average vegetation and surroundings.

Two control vehicles were run individually over the different road surfaces for the binaural recordings. These vehicles were a 1985 Saab 900 Turbo Friction Tester and a 1994 Chevrolet Suburban. The speeds of these vehicles were held constant at 60 mph for every passby run. Special care was taken to ensure that the only vehicle audibly present for the recordings was the control vehicle. Runs containing noise from adjacent vehicles or vehicles in the oncoming direction were rejected.

The noises from nine different road surfaces were recorded for both vehicles. These surfaces included longitudinally and transversely tined concrete, stone matrix asphalt, and astro-turf dragged concrete. Eight of the nine surfaces were used for the subjective analysis. The names and descriptions assigned to each of the measurement locations are listed in Tables 1 and 2.



**Figure 1: Head Measurement System**

**Table 1: Concrete Pavement Naming and Description**

<i>Pavement Name</i>	<i>Description</i>
Site 2	Telegraph Road between Square Lake and Orchard Lake Astro Turf Drag Concrete (2000) GPS: N 42° 36.711' W 83° 18.404'
Site 3A	I-69 South at 4 Mile Transverse Tined Concrete w/ 1/8" Unsealed Joints (2001) GPS: N 41° 49.184' W 84° 59.957'
Site 3B	I-69 South at 20 Mile Longitudinal Tined Concrete w/ 1/2" Joints (2001) GPS: N 42° 02.330' W 84° 58.648'
Site 3C	I-69 South at 8 Mile Transverse Tined Concrete w/ 1/2" Joints (2001) GPS: N 41° 52.527' W 84° 59.480'

**Table 2: Asphalt Pavement Naming and Description**

<i>Pavement Name</i>	<i>Description</i>
Site 5	US-131 from N M22 N'ly to S of 135 <sup>th</sup> Ave. SMA (1993) GPS: N 42° 38.392' W 85° 39.719'
Site 8	I-96 from W of Meridian Road to M-52 SMA (1993) GPS: N W
Site 11	US-131 from S of M-222 to S of 124 <sup>th</sup> Ave SMA (1997) GPS: N 42° 33.671' W 85° 39.724
Site 15	I-94 West of 24 <sup>th</sup> Street E to 9 <sup>th</sup> Street SMA (2001) GPS: N W

In addition, the Saab Friction Tester vehicle was used to measure the coefficients of friction of the five pavement surfaces for which the binaural recordings were made. This data can be used in the sound quality analysis to determine if there exists a correlation between measured surface friction and people's subjective noise preferences.

### ***Jury Evaluation***

The binaural recordings were processed using *MTS Sound Quality 3.75* software, making them suitable for jury auditioning. The individual recordings were trimmed to equal length (8 seconds) with the vehicle passby event centered in the recording. The retained portions of the recordings were then filtered to remove some of the background noises occurring in a frequency range well above that of the tire pavement interaction.

The recordings were assembled into paired comparison jury tests via the Ross Method, using the *MTS* Jury Evaluation software. Jurors were asked to vote for the sound within a pairing that they would prefer to live next to. The Ross Method generates pairs of sounds for evaluation according to a sequence that maximizes the distance between pairs containing the same sound. This method ensures that there is no bias toward any particular sound during the tests. Consistency and repeatability checks were also implemented in the tests, so those jurors with inadequate hearing or poor concentration could be removed from the analysis.

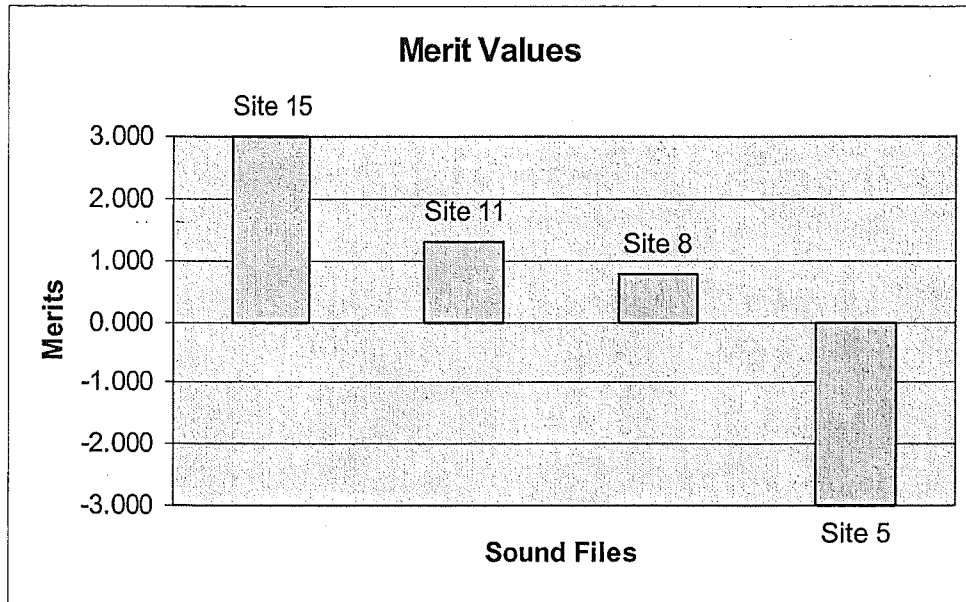
An individual test was designed for each vehicle on both concrete and asphalt surfaces, for a total of 4 unique tests. These tests required each juror to evaluate 10 pairs of sounds, which takes approximately 7 minutes. According to accepted jury testing guidelines, the duration of a jury test should not exceed 20-30 minutes to avoid juror fatigue.

Each jury test was administered to separate juries, multiple times for each of the four vehicle/pavement combinations. The *MTS* Jury Evaluation software was configured to allow each test to be evaluated by up to 6 jurors at one time. The sound preferences of each juror were logged into a database. Out of 311 jurors who participated in the evaluations, only 119 were found to be sufficient for inclusion in the analysis. To qualify for the analysis, a juror's preferences must have repeatability and consistency scores greater than 66%. A juror whose scores are lower than 66% indicates that he or she could not differentiate between the pairs of sounds in a repeatable or consistent manner.

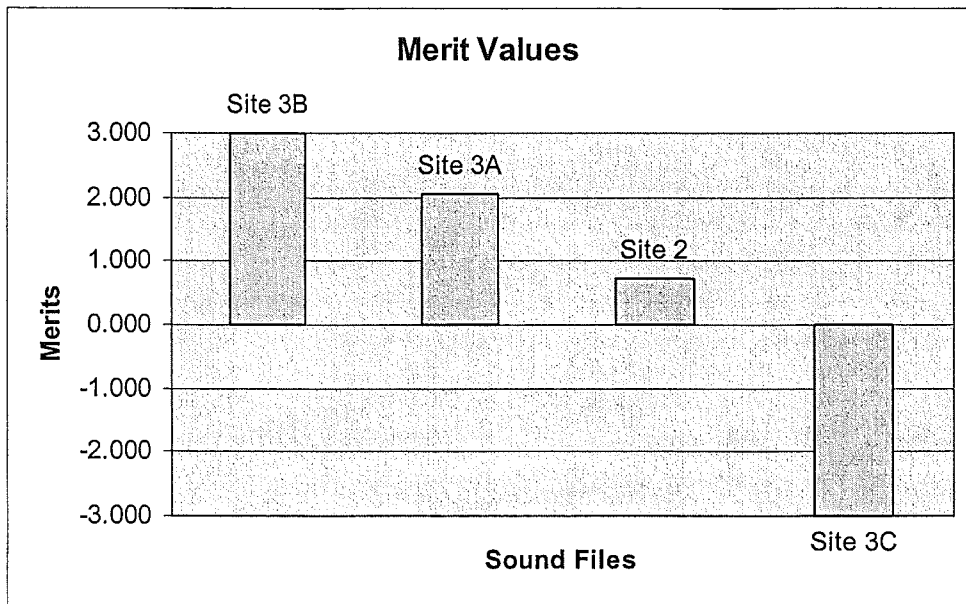
Upon completion of the jury test, each juror was asked to complete a juror feedback questionnaire, which is included in Appendix A. The goal of the questionnaire was to better understand the demographics of the jurors and the criteria by which they judge road noises.

The relative preferences of the acceptable jurors were normalized based on preference proportions into respective merit values for each evaluation. The *MTS* Jury Evaluation software uses a Bradley-Terry statistical model to transform the actual juror preferences into merit values. These merit values describe the liking or disliking of a particular sound, ranging from +3 to -3. From these merit values, correlation between juror preferences and objective sound quality metrics can be derived. Figures 1 through 4 show the normalized merit values for each of the four vehicle/pavement combinations.





**Figure 1: Juror Preferences for Saab Vehicle on Asphalt Pavements**



**Figure 2: Juror Preferences for Saab Vehicle on Concrete Pavements**

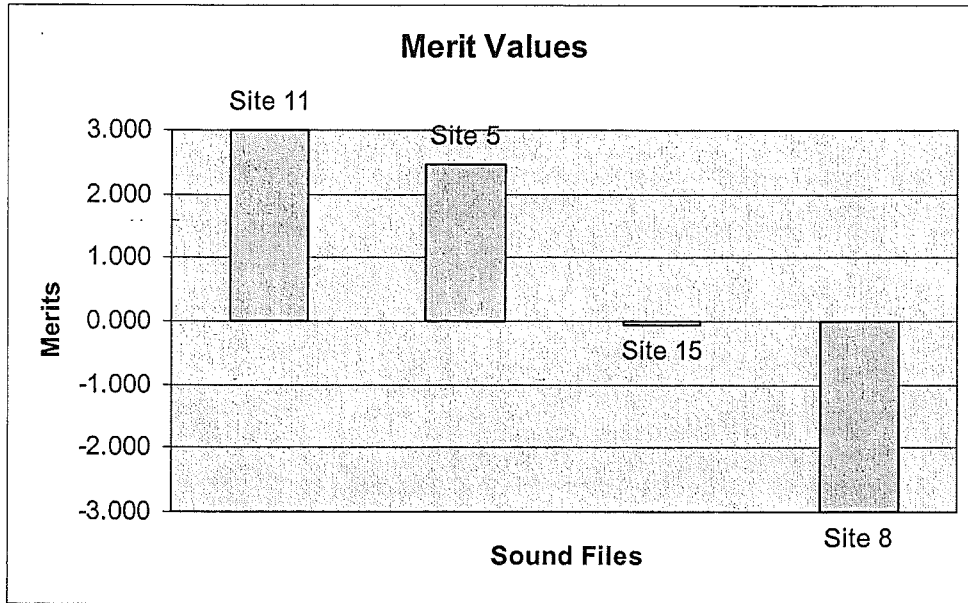


Figure 3: Juror Preferences for Suburban Vehicle on Asphalt Pavements

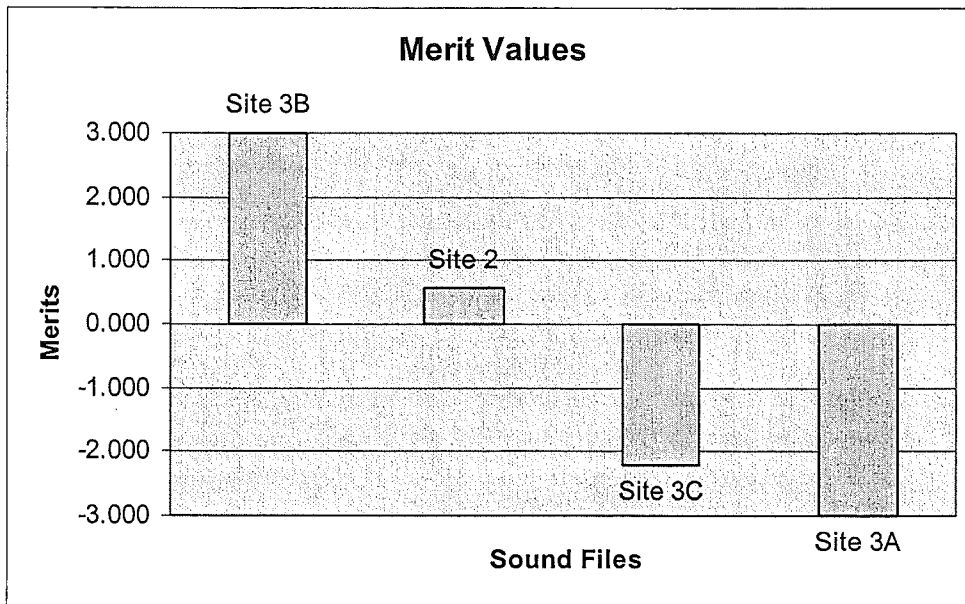


Figure 4: Juror Preferences for Suburban Vehicle on Concrete Pavements

Consistent with KRC's preliminary research effort is the fact that the relative preferences change from vehicle to vehicle. As seen in Figures 1 through 4, the merit trends are different for the Saab and Suburban vehicles travelling over the same surfaces. This further reinforces the theory that the vehicle specific noises (tire, powertrain, and aerodynamic noises) have a significant influence on the human perception of the sound. It is expected that different tire/pavement combinations will produce different quantities and, more importantly, different *qualities* of noise.

The inconsistent merit trends combined with the low juror success ratio suggest that the majority of jurors have difficulty distinguishing between the sounds from a specific vehicle within a category of pavements, such as concrete or asphalt. This is particularly evident with the asphalt pavements. Jurors were able to identify extreme preferences for concrete pavements with some consistency, however, ranking Site 3B the highest and Site 3C nearly the lowest for both vehicles.

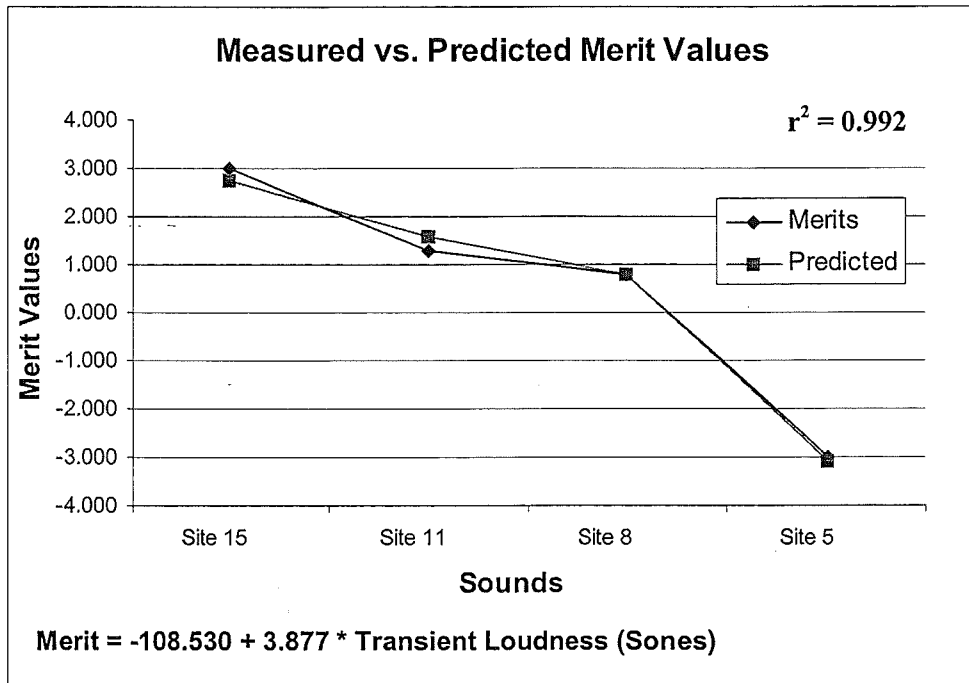
The similarity of the sounds within a pavement category is consistent with the juror's perceptions, as 82% of the jurors described the sounds as "similar with subtle differences" in the feedback questionnaires. From previous research, it was found that a significant number of jurors based their voting strategy on the smoothness of the sounds. In this survey, over 30% of the jurors used the term "choppy" to describe the displeasing or annoying portions of the sounds. Another 7% made specific references to "joints", "expansion joints", or "cracks in the pavement" when describing the unfavorable qualities of the sound. The fewer discontinuities present in the asphalt pavements (compared to concrete pavements with standardized expansion joints) may explain why jurors appeared to have added difficulty in ranking asphalt pavements.

### *Analysis of Jury Results*

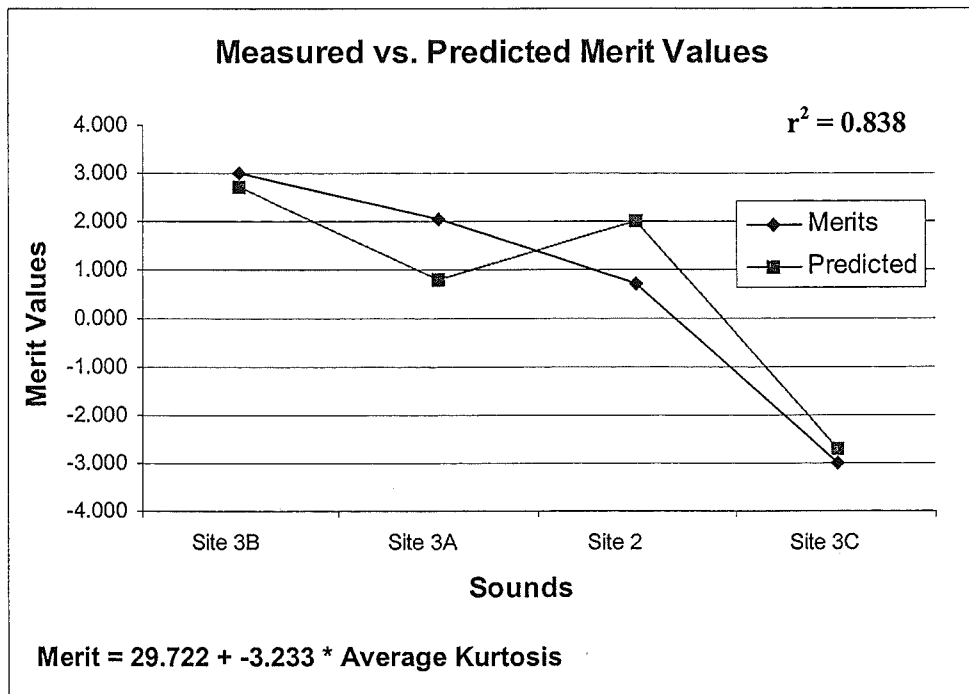
Having a database of totaled and normalized juror preferences, it is now possible to attempt a correlation between various sound quality metrics and the juror merit values. The ultimate goal of this particular analysis is to identify a metric(s) that can predict jurors' subjective preferences with a reasonable degree of statistical confidence.

Twenty-four of the most common sound quality metrics were computed for both the left and right microphone channels of each binaural recording using the MTS Sound Quality software. The relative pavement ages were also included as a metric to which the juror merits could be correlated with. A sample metric file is listed in Appendix B.

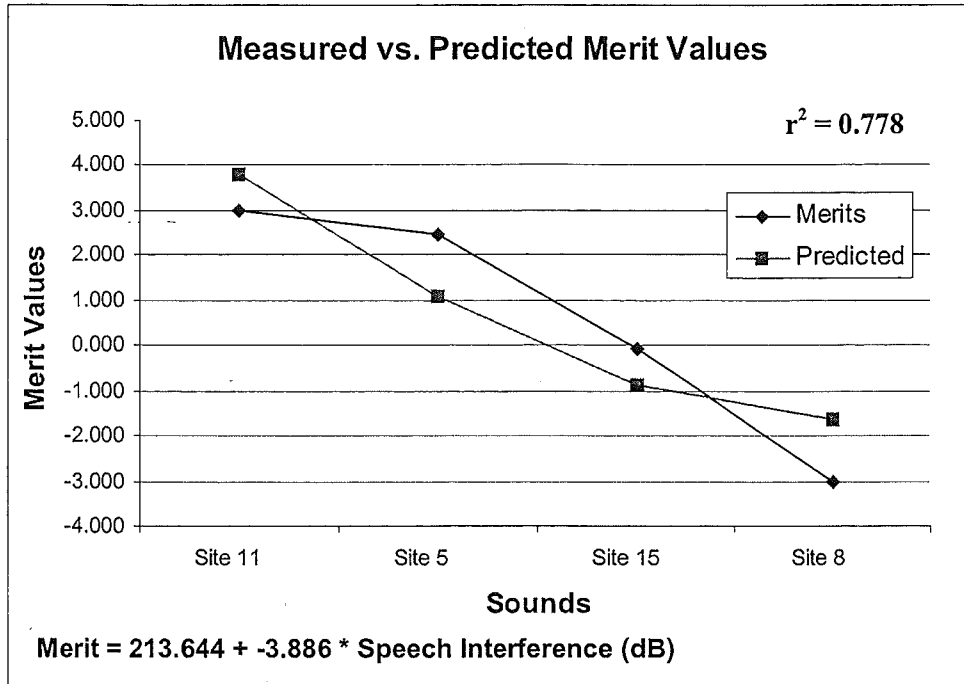
A multiple regression analysis was then performed for each set of jury data using the MTS Jury Evaluation software, in an attempt to correlate the computed metrics with the juror merit values. Figures 5 through 8 show a graphical comparison between the actual jury merit values, and those predicted by the regression model. Each graph contains an equation that explains which sound quality metric(s) was used to build the regression model, and the corresponding coefficient of determination ( $r^2$ ) value that describes the quality of the curve fit.



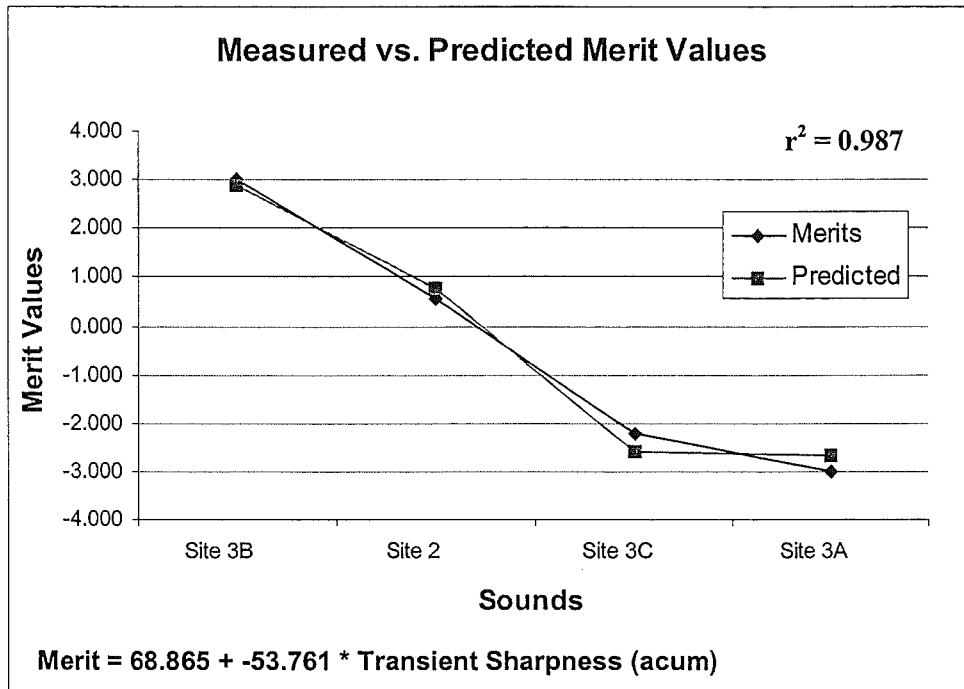
**Figure 5: Measured vs. Predicted Merit Values for Saab Vehicle on Asphalt Pavements**



**Figure 6: Measured vs. Predicted Merit Values for Saab Vehicle on Concrete Surfaces**



**Figure 7: Measured vs. Predicted Merit Values for Suburban Vehicle on Asphalt Pavements**



**Figure 8: Measured vs. Predicted Merit Values for Suburban Vehicle on Concrete Pavements**

It can be seen that the regression models for two of the vehicle/pavement category combinations have better correlation with the actual juror merit values than the other combinations. Since the order of juror preferences was shown to be different for the two

vehicles on the same surfaces, it is not surprising that different sound quality metrics are preferred for correlation with the juror merit values. Juror preferences from the Saab vehicle on asphalt pavements, and Suburban vehicle on concrete pavements correlate very well with the transient loudness and transient sharpness models, respectively.

The metrics for transient loudness and transient sharpness both focus on the time varying nature of the sound. In general, sounds that fluctuate are perceived to be louder (and more annoying) than steady state sounds with the same RMS amplitude. It is believed that the fluctuations in most sounds presented to the jurors were caused by the discontinuities in the pavements, which jurors identified as objectionable in the feedback questionnaires. Complete statistics from the feedback questionnaires can be found in Appendix C.

The Saab vehicle on concrete pavements and Suburban vehicle on asphalt pavements are not adequately modeled by the regression analysis using the provided sound quality metrics. It is suspected that the objectionable portions of the sounds from these tire/pavement interactions are masked by the vehicular sounds (powertrain, aerodynamic, etc). Hence, the juror preferences for these test conditions are less reliable and do not correlate well with sound quality metrics.

## ***Conclusions***

The analysis of the data from this study provided good correlation between juror preferences and standard sound quality metrics for both asphalt and concrete pavement categories. The statistical confidence in the correlation is both vehicle and surface dependant, so not all vehicle/pavement category combinations yielded good correlation with the sound quality metrics. Those combinations that correlate well were modeled best using transient loudness and transient sharpness. Both of these sound quality metrics focus on the transient nature of sounds.

This correlation indicates that juror preferences weigh heavily upon the discontinuities in the pavement noise, such as those that occur when the vehicle tires pass over expansion joints, cracks in the pavement, or any other feature that causes an impact type of event. In fact, over 30% of the jurors used the term "choppy" to describe the displeasing or annoying portions of the sounds, and another 7% made specific references to "joints", "expansion joints", or "cracks in the pavement" when describing the unfavorable qualities of the sound.

The majority of jurors felt that they were able to differentiate between different types of asphalt and concrete. As a result, 82% of the jurors described the sounds they evaluated as "similar with subtle differences." Somewhat discouraging, however, is the relatively large number of jurors who find road noise, in general, objectionable. Approximately 40% of the jurors stated that they would not want to live next to any of the pavement noises they evaluated.

All regression analyses performed on the jury data attempted to correlate juror preferences with standard sound quality metrics. While the metrics are quickly computed and can be compared with properly formatted past and future sound data, they do not directly provide insight to the physical pavement parameters that effect the quality of the noise. It is easily seen that the joint quality and number of pavement cracks certainly plays a role in the perception of road noise, but it is not clear how texture, porosity, and other pavement parameters affect the noise. This would be especially problematic if only pavements without joints and cracks, or those treated to a sufficient degree, were included in an analysis.

If a sufficient correlation between physical parameters and juror preference were identified and understood, noise could be included as a pavement design. Therefore, it is recommended that the physical pavement parameters be collected from the pavements for which the binaural noise data sets exist. At that time, a correlation between juror preferences and the pavement parameters could be attempted. This correlation would be a very quick and cost-effective process, as the juror evaluation and results database tabulation are the most time-consuming and expensive portion of this type of effort.

# Appendix A

First Name \_\_\_\_\_ Last Name Initial \_\_\_\_\_

1) What is your profession: (circle one)

- |                           |                  |
|---------------------------|------------------|
| A. Student                | D. Skilled Trade |
| B. Professional/Technical | E. Retired       |
| C. Sales/Marketing        | F. Other _____   |

2) Which best describes where you live: (circle one)

- A. Next to a city street.
- B. In an apartment building or college dorm
- C. Next to a rural road
- D. Next to a highway (US-41, etc)

2) How would you best describe the sounds that you heard today: (circle one)

- A. All sounded the same. Impossible to tell apart.
- B. Very similar, but subtle differences.
- C. Similar, but easy to tell apart.
- D. Obviously different.

3) Briefly describe the characteristics (i.e. loud, rough, choppy, etc) of the sounds that you found displeasing or annoying.

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4) Which statement best describes your opinion of the road noises you auditioned today: (circle one)

- A. I wouldn't mind living next to any of the sounds
- B. I would prefer to live next to some of the sounds more than others
- C. I wouldn't want to live next to any of the sounds



# Appendix B

Table 3: Sample Metric File

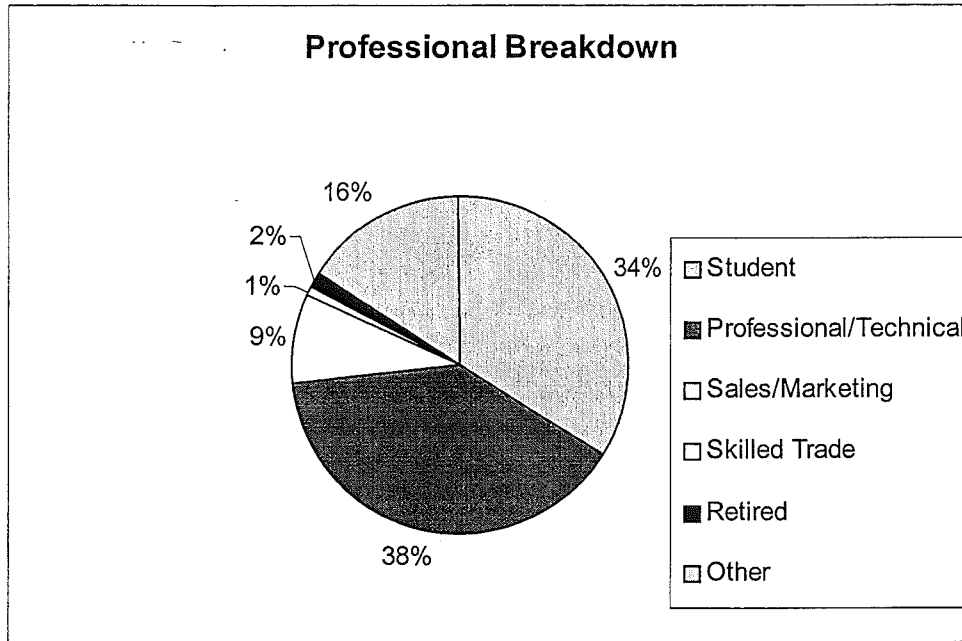
Metric Results for Sound File <3A\_Saab2f.wav>  
Between 0.0000 and 8.0000 Seconds

Subject: Left  
Test Condition:  
Test Engineer:  
Test Date:  
Created: 1899/12/30 0:0:0  
Correction: NONE

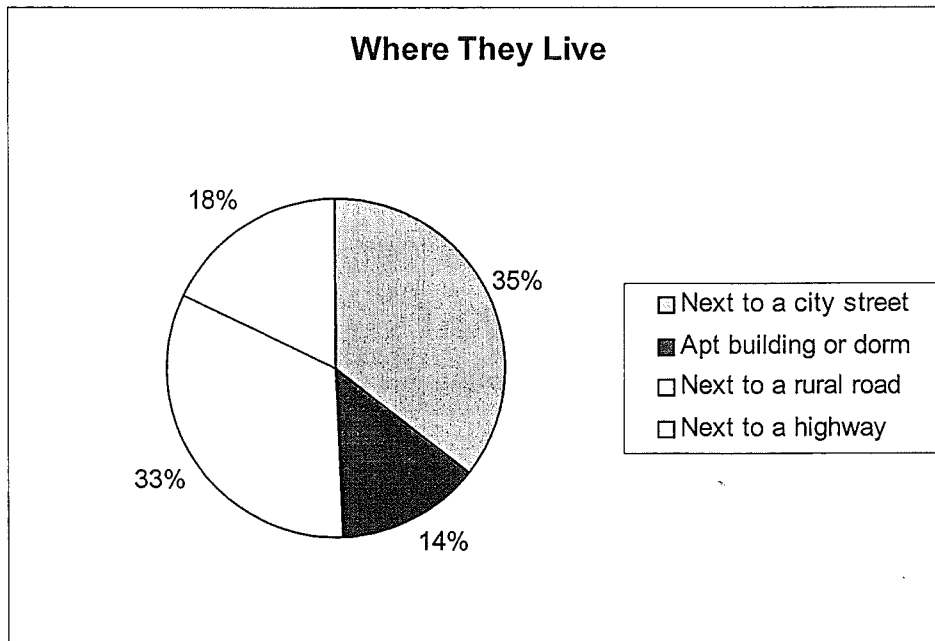
MTS Sound Quality 3.7.5  
Wed Nov 20 11:48:21 2002

Metrics	Units	Left	Right	Avg.
Linear SPL	dB	69.4	69.3	69.3
A-weighted SPL	dBA	69.4	69.3	69.3
B-weighted SPL	dB	69.2	69.1	69.2
C-weighted SPL	dB	69.3	69.2	69.3
D-weighted SPL	dB	73.2	73.1	73.2
Speechband SPL	dB	68.6	68.5	68.6
Linear SPLT	dB	69.3	69.4	69.3
Intelligibility	%	59.7	59.3	59.5
Pref Speech Interference	dB	59.2	59.2	59.2
Speech Interference	dB	56.6	56.6	56.6
Frame Kurtosis		3.172	3.146	3.159
Average Kurtosis		9.284	8.617	8.951
Zwicker Loudness (Sones)	sone	18.8	19.0	18.9
Zwicker Loudness (Phons)	phon	82.3	82.5	82.4
Sharpness	acum	1.187	1.188	1.188
Transient Loudness (Sones)	sone	28.6	28.8	28.7
Transient Loudness (Phons)	phon	88.4	88.5	88.4
Transient Sharpness	acum	1.323	1.340	1.331
Time Varying Loudness (Sones)	sone	30.6	30.3	30.5
Time Varying Loudness (Phons)	phon	89.3	89.2	89.3
Roughness	asper	0.324	0.326	0.325
Fluctuation Strength	vacil	0.250	0.213	0.231
Tonality		0.043	0.032	0.038

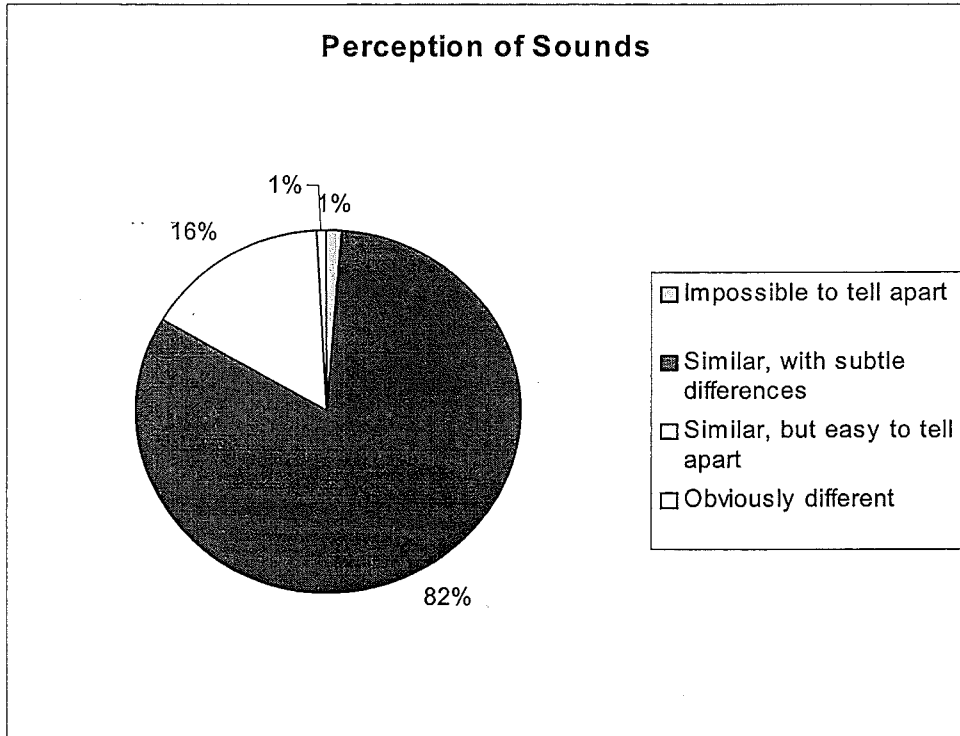
# Appendix C



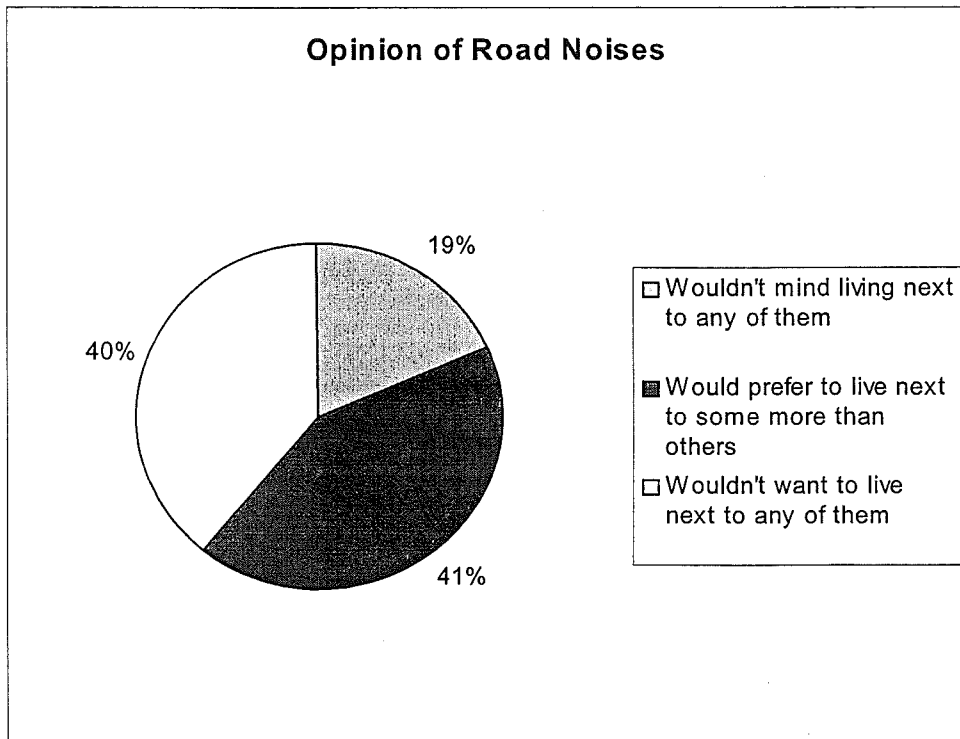
**Figure 9: Juror Breakdown by Profession**



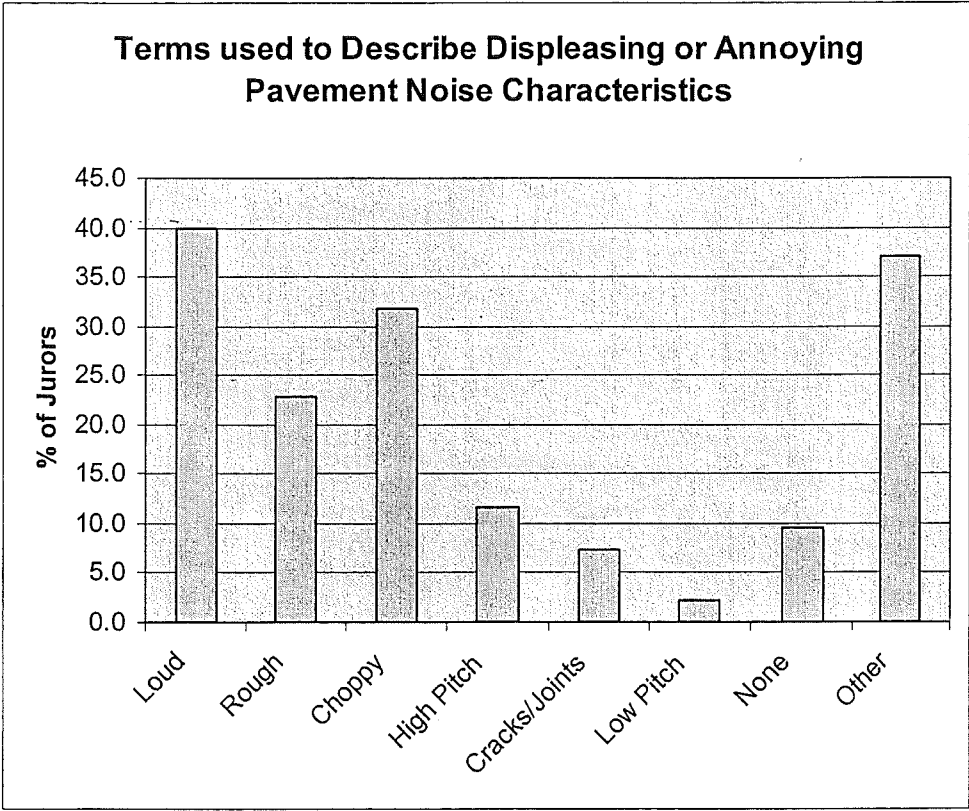
**Figure 10: Juror Breakdown by Location**



**Figure 11: Juror Breakdown by Perception**



**Figure 12: Juror Breakdown by Opinion**



**Figure 13: Juror Descriptions of Pavement Noise**