

Case Studies of a Low-Noise Road Surface

MICHAEL J. BRENNAN^{a*}, ALAN M. KAVANAGH^{b†} and JEROME N. SHEAHAN^{c‡}

^aDepartment of Civil Engineering, National University of Ireland, Galway, Ireland, ^bColas Teoranta, Bluebell Industrial Estate, Dublin, 12, Ireland and ^cDepartment of Mathematics, National University of Ireland, Galway, Ireland

(Received November 2, 1999; In final form January 23, 2001)

The Statistical Pass-By Index (SPBI) for assessing the noise levels of road surfaces was used successfully on suburban roads where individual vehicles could be targeted with a sound meter and a radar speed meter. Reductions in SPBI of the order of 5 dB(A) were obtained when two noisy surfaces, a surface treatment and an overlaid jointed concrete pavement, were replaced with a rubber crumb modified bituminous surface. The noise reductions were strongly supported by a fundamental statistical analysis of the same data that was used to establish the indices. On an inner-city street with a heavy traffic density, it was necessary to rely entirely on a statistical analysis of the relationship between other sound parameters, L_{eq} , L_{10} and L_{50} , and noise weighted traffic flow to assess the benefit of the low-noise surface.

Keywords: Statistical pass-by method, noise, low-noise surface, rubber crumb

INTRODUCTION

Measures that reduce the generation of traffic noise directly at the source are conceptually preferable to noise barriers and the acoustic insulation of dwellings. Since the early 1990s, there has been an increased interest in the use of thin (< 40 mm) bituminous surfaces that possess noise-reducing qualities. These products have become known as "low-noise" surfaces. In general, they are designed to provide a uniform indented macro-texture that minimises the generation of noise caused by the interaction of the vehicle tyre and the road surface, which is the dominant noise source at speeds above 50 km/h, European Commission (1996). When they have a high voids

content, of the order of 19%, Pederson *et al* (1996), they have the extra advantage of absorbing noise, Organisation for Economic Co-operation and Development (1995). However, with interconnected voids, these surfaces may require remedial unclogging to maintain their sound absorption properties over time.

The noise abating performance of thin bituminous surfaces has also been enhanced by incorporating small quantities of crumb rubber in the mixture. Colsoft, a rubber crumb modified material developed in France by Colas S.A., has been awarded the *Décibel d'Or* award by the French National Council on Noise and the French Environmental State Administration, Chaignon, F. (1996). A voids content between 12 and 16% is specified for a Duriez compacted specimen,

* michael.brennan@nuigalway.ie

† akavanagh@colasteo.ie

‡ jerome.sheahan@nuigalway.ie

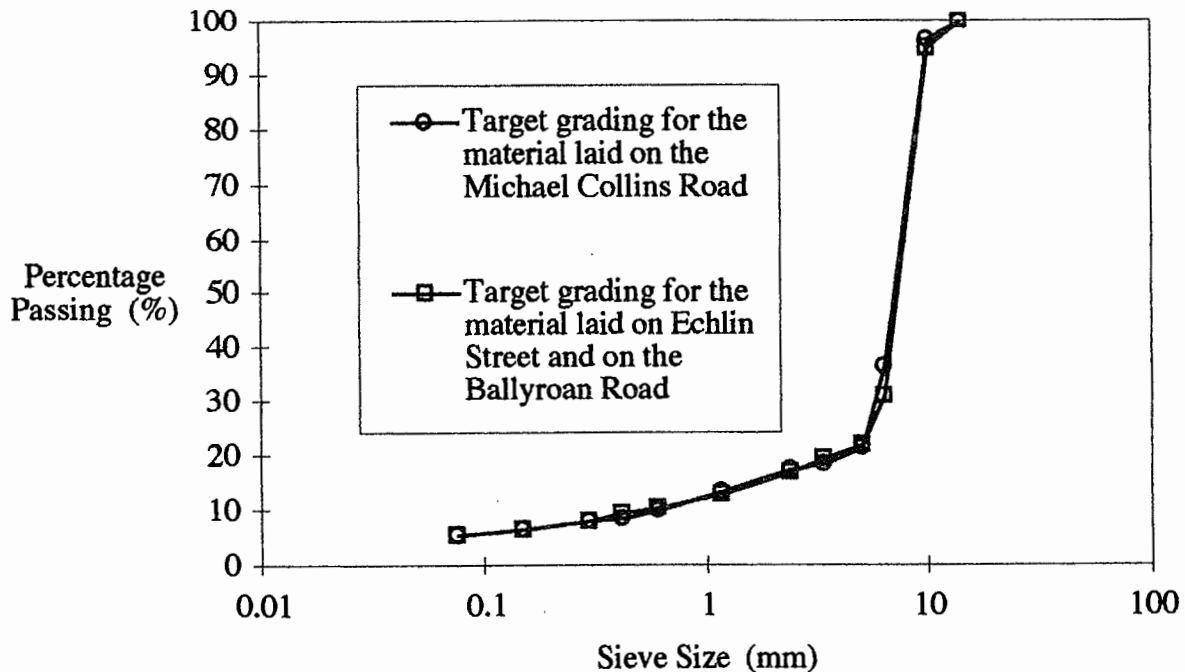


FIGURE 1 Target Grading Curves for the Two Rubber Crumb Modified Materials

Colas (1998). In 1998, it was laid on three sites on the public highway in Ireland to assess its acoustic performance. It was timely that a new ISO standard, ISO 11819-1:1997(E), had just been published for assessing 'so-called' low-noise surfaces, International Organisation for Standardisation (1997).

This paper describes how the Statistical Pass-By Index (SPBI) was used to assess the performance of the low-noise surface on two test sites and goes on to support the results with an alternative statistical analysis of the experimental data. For the third heavily trafficked test site, the SPBI was not suitable and it was necessary to rely on an alternative analysis technique.

EXPERIMENTAL SITES

In June 1998, the rubber crumb modified surface was laid for the first time in Ireland on 3500 m² of the Michael Collins Road, a busy collector road that

passes through a residential area in Galway City. The existing surface was a 12.5 mm (half inch) surface dressing with a rugose macro-texture that generated high noise levels. It had an average texture depth of 2.41 mm.

Echlin Street in Dublin City was the second site to be resurfaced with the material. This heavily trafficked local urban road is located in the inner-city area. Approximately 25% of its existing surface, a 14 mm dense bitumen macadam, had been reinstated using hot rolled asphalt with rolled-in coated chips. The proximity of the housing to the road resulted in the residents being subjected to high noise levels.

A 730 m section of the Ballyroan Road, Dublin City, was the third and largest site to be resurfaced with the material. This is a heavily trafficked collector road in a residential suburb. The existing road was a jointed concrete pavement that had been overlaid with a 10 mm dense bitumen macadam. Reflective cracking in the surface due to the traverse joints of the concrete pavement exacerbated the noise levels.



FIGURE 2 The Michael Collins Road before Resurfacing

RUBBER CRUMB MODIFIED MATERIAL

The target aggregate plus rubber gradings are shown in Figure 1. The material consisted of a combination of 10 mm nominal size greywacke coarse aggregate, limestone dust, limestone filler, rubber crumb and an SBS polymer modified binder. The crumb rubber content was 2% (by mass of the aggregate plus rubber). The aggregates for the Michael Collins Road came from one source and the aggregates for the two Dublin based sites came from a different source. Using the 'dry process' mixing system, the crumb rubber was pre-blended with the aggregate before the bitumen was added. The target binder content was 6.3% (by mass of the aggregate plus rubber) for the Michael Collins Road. For Echlin Street and the Ballyroan Road, the target binder content was 6.5%. Compacted specimens of the material used on the Michael Collins Road had voids contents of 14% and 12%, respec-

tively, using 50 blows and 75 blows of the Marshall hammer. It could, therefore, be classified as a semi-dense material. It was laid to a thickness of 35 mm.

ROADWORKS

Initially, the Michael Collins Road was paved using an integrated paver, which applied the tack coat just ahead of the screed. The tack coat was a polymer modified 70% bitumen emulsion, and it was applied at a rate of 0.6 litre/m². When, at a later stage, the tack coat was applied using a conventional bitumen distributor in advance of the paver, the tack coat tended to stick to the tyres of the delivery lorries and also to the tracks of the paver. A total of 160 tonnes of the rubber crumb modified material were laid during a three-day operation.

At Echlin Street, the material was laid with a conventional paver. The tack coat was applied at a rate of 0.6 litre/m² using a bitumen distributor equipped with the patented Colnet spraying process, developed by Colas S.A. With this process, the tack coat is applied using a three-phase system in which an adhesive agent is sprayed onto the receiving surface, followed by the bitumen emulsion and by a chemical break-agent to reduce the risk of sticking to tyres.

Before the Ballyroan Road could be resurfaced, the concrete slabs over which the existing asphalt concrete surface had been laid were excavated and replaced with a 60 mm dense bitumen macadam base course. This work was carried out over several weeks prior to the resurfacing operation. A total of 407 tonnes of material was laid. Once again, the tack coat was sprayed using the patented spraying process.

NOISE INDICES FOR THE MICHAEL COLLINS AND BALLYROAN ROADS

Experimental Procedure

Views of the Michael Collins Road and the Ballyroan Road are shown in Figures 2 and 3. As there was no location on either road that fully complied with the ideal site requirements of ISO 11819-1 for taking acoustic measurements, it was necessary to set up the microphone with concrete boundary walls within the 10 m limit of the microphone position. Hence, the measurement procedures were described as 'special' cases.

Ideally, 4 days must have elapsed since the latest precipitation before measurements can be recorded. Alternatively, compressed air is blown into the surface, or blotting paper is used to ensure that no water is present. Consequently, during the course of the year in which the study was carried out, much of the late autumn, winter and early spring was unsuitable for data collection.

Two operators were required to record the measurements. One was responsible for measuring the sound pressure level as a vehicle passed in front of a micro-

phone located 1.2 ± 0.1 m above the plane of the road and 7.5 ± 0.5 m from the centre of the near traffic lane. As required, the microphone was placed on a tripod and connected to the sound meter using a 10 m long cable. It was pointed horizontally and perpendicular to the direction of the traffic. The second operator was responsible for determining the speed of vehicles, as they passed in front of the microphone, from a concealed downstream position. Both operators communicated using two-way radios to ensure that they were both targeting the same vehicle. Ambient air temperature readings were also recorded at 15 minute intervals using a mercury thermometer positioned at the roadside.

The sound pressure level from a passing vehicle was recorded in A-weighted decibels, dB(A). By watching the display screen of the sound meter, it was possible to see whether the sound pressure levels recorded just prior to and after the passage of a vehicle in front of the microphone were at least 6 dB(A) below the maximum recorded during the pass-by, as required by ISO 11819-1. This requirement is designed to ensure that the recorded pass-by sound pressure level is due only to noise that is generated by the targeted vehicle and not to a combination of noises from several vehicles travelling closely together. In practice, it was necessary to limit measurements to vehicles that were relatively isolated on the road.

The speed meter was equipped with a trigger that enabled the operator to freeze the speed of the targeted vehicle as it passed the microphone. On a two-way road, the radar signal spans traffic going in both directions. As it processes the strongest signal that is reflected, it will usually detect the speed of the nearest vehicle. However, a large vehicle that is further away than a small vehicle can return a stronger signal when it deflects more radar waves back to the meter. Hence, to ensure that the reading displayed by the speed meter was the speed of the vehicle that was being targeted, only vehicles that were relatively isolated could be targeted for the analysis. Finally, the speed measurements were corrected for 'cosine error' that is due to the displacement of the meter from the line of travel of the vehicles.



FIGURE 3 The Ballyroan Road after Resurfacing

Calculating the Statistical Pass-By Index

ISO 11819-1 requires that recorded vehicles be separated into three vehicle categories, i.e. cars, dual-axle heavy vehicles and multi-axle heavy vehicles. The categories are denoted 1, 2a and 2b, respectively. For the car vehicle category, a minimum of 100 measurements is required. For the two heavy vehicle categories, a minimum of 50 is required for either of the two and 30 for the other.

The maximum A-weighted sound pressure level is plotted against the logarithm of the corresponding speed of the vehicle for each vehicle category. Regression equations are fitted through the data points from which a reference sound pressure level, L_{veh} , is calculated for a reference speed, V_{veh} . The appropriate reference speeds are specified in ISO 11819-1 as a function of the average measured vehi-

cle speed. Then, the resulting reference sound levels are combined using the following equation to give the Statistical Pass-By Index, SPBI, in dB(A) for a standard mix of light and heavy vehicles:

$$SPBI = 10 \lg \left[W_1 10^{L_1/10} + W_{2a} \left(\frac{v_1}{v_{2a}} \right) 10^{L_{2a}/10} + W_{2b} \left(\frac{v_1}{v_{2b}} \right) 10^{L_{2b}/10} \right] \quad [1]$$

where

L_1 , L_{2a} and L_{2b} are the reference sound levels for vehicle categories 1, 2a and 2b; W_1 , W_{2a} and W_{2b} are the weighting factors that are the assumed proportions of the vehicle categories in the traffic – appropriately 0.9, 0.075 and 0.025, respectively, for this study; and v_1 , v_{2a} and v_{2b} are the reference speeds of individual vehicle categories.

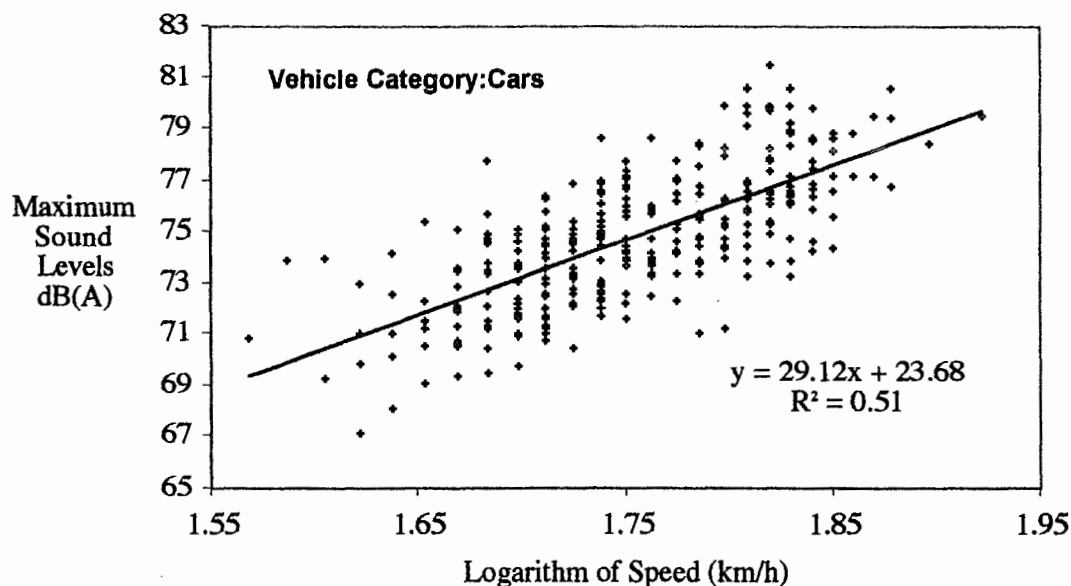


FIGURE 4 Data for the Michael Collins Road

The data for the car vehicle category for the Michael Collins Road, before resurfacing, are shown in Figure 4. The wide scatter of the points reflects the variations in the noise level that resulted from the mix of different makes, age, condition, size and shape of vehicle on the road. The apparent bias in the regression line is due to the coincidence of data points. As illustrated in this particular case, the R^2 values were relatively poor. Indeed, it was this data scatter and poor correlation that prompted the corroborative analysis using multiple linear regression.

Experimental Results

Due to the almost complete absence of multi-axle heavy vehicles on the Michael Collins Road, a value for the parameter L_{2b} in Equation 1 could not be estimated. Therefore, this vehicle category was omitted from the calculation of the SPBI. Instead, weighting factors of 0.9 and 0.1 were used for W_1 , and W_{2a} , respectively. Moreover, it was necessary to take measurements on three different days to record the required number of vehicles for the dual-axle heavy

vehicle category. A statistical analysis on the three sets of results established that they were statistically similar enough to be pooled together. This limitation did not prevail on the Ballyroan Road.

It is recommended in ISO 11819-1 that measurements be made at air temperatures as close as practical to the reference air temperature of 20°C. For the Michael Collins Road, the temperature was sufficiently high for measurements to be made two weeks after resurfacing. Due to low temperatures, measurements were not taken on the Ballyroan Road until 20 weeks had elapsed, when the ambient air temperature was 13°C on average.

Comparisons of the SPBIs were made by comparing the before and after indices that were obtained both with and without corrections for temperature differences. The correction factor stipulated in the French standard NF S 31-119 was used to correct for the effects of temperature, l'Association Française de Normalisation (1993). In this case, the noise levels were adjusted for the reference temperature of 20°C by decreasing the measured noise levels by 0.1 dB(A) for each degree below 20°C. Both the corrected and uncorrected SBPIs are presented in Table I.

TABLE I Noise Measurements at the Michael Collins Road and the Ballyroan Road

<i>Michael Collins Road</i>				
<i>Vehicle</i>	<i>Reference</i>	<i>Reference Sound Pressure Levels, dB(A)</i>		
Category	Speed (km/h)	Before	2 weeks After	40 weeks After
Car	50	73.1	67.5	66.9
Dual-Axle Heavy	50	77.2	74.2	74.5
SPBI (unadjusted) dB(A)		73.9	68.9	68.6
Average temperature (°C)		13.0	20.0	13.0
SPBI (corrected for temp.) dB(A)		73.2	68.8	67.8
Texture depth (mm)		2.41	1.32	1.03
<i>Ballyroan Road</i>				
<i>Vehicle</i>	<i>Reference</i>	<i>Reference Sound Pressure Levels, dB(A)</i>		
Category	Speed (km/h)	Before	20 weeks After	
Car	50	72.6	67.7	
Dual-Axle Heavy	50	79.4	75.0	
Multi-Axle Heavy	50	82.9	78.5	
SPBI (unadjusted) dB(A)		74.4	69.7	
Average temperature (°C)		18.0	14.0	
SPBI (corrected for temp.) dB(A)		74.3	69.1	

STATISTICAL ANALYSIS OF DATA FROM THE MICHAEL COLLINS AND BALLYROAN ROADS

Multiple Regression Model

The primary purpose of the present section is to access statistically the effect that road surfacing has on noise level. Essentially, a model is required to quantitatively estimate the noise levels that can be expected before and after resurfacing. Noise levels may vary also with other variables such as the type of vehicle on the road, the speed of the vehicle, and the ambient air temperature. Therefore, a model that relates noise levels to a factor that represents whether or not a road is resurfaced might then consider incorporating these other variables as possible causal agents. In deciding what input or explanatory variables to include in the model, it is desirable to add only variables that successfully reduce the variation in noise levels after allowing for the effect of other vari-

ables that have been tentatively included. To ensure manageability and ease of interpretation of any regression model, the selection of input variables should be parsimonious while maintaining as near statistical optimality as possible. Empirical studies by other authors, International Organisation for Standardisation (1997), and diagnostics performed on the data of the present study justify the use of the logarithm of vehicle speed (rather than vehicle speed itself) in modelling, in a linear fashion, the dependence of noise level on vehicle speed.

For the purpose of the ensuing regression analysis, it is convenient to quantitatively identify the classes of the qualitative variables "vehicle type" (car, dual-axle heavy vehicles and multi-axle heavy vehicles) and "road status" (before resurfacing, after resurfacing) by introducing suitable indicator variables (see e.g. Neter et al 1996). A multiple linear regression model to describe the effect of several input variables on the noise level is given by the following surface:

$$Y = \beta_0 + \sum_{i=1}^5 \beta_i X_i + \varepsilon \quad [2]$$

where

Y = noise level (in dB(A)),

X_1 = logarithm of the speed;

$$X_2 = \begin{cases} 1, & \text{for a car} \\ 0, & \text{for a dual-axle heavy vehicle} \\ -1, & \text{for a multi-axle heavy vehicle;} \end{cases}$$

$$X_3 = \begin{cases} 0, & \text{for a car} \\ 1, & \text{for a dual-axle heavy vehicle} \\ -1, & \text{for a multi-axle heavy vehicle;} \end{cases}$$

X_4 = ambient air temperature;

$$X_5 = \begin{cases} 0, & \text{for observations taken} \\ & \text{before resurfacing} \\ 1, & \text{for observations taken} \\ & \text{after resurfacing;} \end{cases}$$

the β_i are regression parameters to be estimated; and ε denotes random error distributed as $N(0, \sigma^2)$.

A total of $n = 1,203$ data points were available for the analysis. Each of these data points is, prior to sampling, a vector $(Y, X_1, X_2, X_3, X_4, X_5)$ in which the random variable Y is related to the X_i through equation [2]. Note that linearity of the model [2] and the assumption made above that the random error term ε has a normal distribution with mean 0 and variance σ^2 imply that the expected value of Y at any given combination of the input variables is

$$E(Y|X_1, \dots, X_5) = \beta_0 + \sum_{i=1}^5 \beta_i X_i \quad [3]$$

and, hence, ε is a random variable representing the deviation of a random response from this surface.

It is helpful to note the practical interpretation of the parameters in equation [2]. Note, for example, that β_0 is the intercept of the response surface. By considering the population mean noise levels for various types of vehicles in turn, i.e.

$$E(Y|X_2 = 1, X_3 = 0) = \beta_0 + \beta_1 X_1 + \beta_2 + \beta_4 X_4 + \beta_5 X_5$$

$$E(Y|X_2 = 0, X_3 = 1) = \beta_0 + \beta_1 X_1 + \beta_3 + \beta_4 X_4 + \beta_5 X_5 \text{ and}$$

$$E(Y|X_2 = -1, X_3 = -1) = \beta_0 + \beta_1 X_1 - \beta_2 - \beta_3 + \beta_4 X_4 + \beta_5 X_5,$$

the particular coding employed for the indicator variables means that – in the language of Analysis of Variance – the *effect* of a car on noise level is β_2 , the effect of a dual-axle heavy vehicle is β_3 , and the effect of a multi-axle heavy vehicle is $-\beta_2 - \beta_3$.

The Leastression Equation and Model Diagnostics

When model [2] was fitted to the $n = 1,203$ data points, the following estimated regression surface was obtained:

$$\hat{Y} = 33.8 + 26.6X_1 - 5.60X_2 + 0.751X_3 - 0.0328X_4 - 5.15X_5 \quad [4]$$

The coefficient of multiple determination is about 83%, so that the fitted model explains about 83% of the variation in the data points. The residuals, $e_i = Y_i - \hat{Y}_i$, $i = 1, 2, \dots, 1203$, were used to perform diagnostics to check for adequacy of the model [2] and assumptions upon which the statistical analysis below depend. No violations were detected and no important variables (including interactions terms) could be added to the existing model.

Statistical Inferences

The constants $\hat{\beta}_i$ in the fitted model [4] above are the observed values of estimators of the β_i , $i = 0, 1, \dots, 5$, in [2]. For each fixed $i = 0, 1, \dots, 5$, consider testing the alternatives $H_0: \beta_i = 0$, $H_1: \beta_i \neq 0$. Under the null hypothesis, it is well known that $t = \hat{\beta}_i / s(\hat{\beta}_i)$ is a value of a t variable with $n - k = 1203 - 6 = 1197$ degrees of freedom; here, $s(\hat{\beta}_i)$ is the estimated standard deviation of the estimator. The estimated standard errors and t -values are given in Table II. Clearly, the larger (in absolute value) the value of t , the more evidence there is against the null hypothesis. The observed value of t can be compared with a tabulated value corresponding to a given level of significance α , and reject H_0 if $|t| > t_{\alpha/2, n-k}$ where $t_{\alpha/2, n-k}$ is the upper $\alpha/2^{\text{th}}$ percentage point of a t -distribution with $n-k$ degrees of freedom. Here, k is the number of parameters in the model, including the intercept.

Obviously, this method is equivalent to the following one: reject H_0 if the p -value of the test is less than α . Note that the p -value of a test is the probability of obtaining a value of t at least as far away from its expected value (which is 0 under H_0) as the value that was actually obtained in the experiment. Note then that the p -value is a measure of how unlikely the observed data are when the null hypothesis is true. Evidently, the smaller the p -value, the more evidence there is against the null hypothesis.

Suppose that an experiment-wise error rate of only 0.01 is desired for testing the individual slope parameters (i.e. the probability of incorrectly rejecting at least one of the null hypotheses, $i = 0, 1, \dots, 5$, is to be at most 0.01). Then, from the t -ratios or p -values in Table II, it can be concluded that all variables except temperature (X_4) are affecting the response in the full model [2]. Thus, all variables except temperature are useful for predicting noise levels.

The estimate of $E(Y | X_5 = 1) - E(Y | X_5 = 0) = \beta_5$, the difference between the population mean noise levels after and before resurfacing, is -5.15 . Thus, the mean reduction after resurfacing is 5.15 dB(A).

The result that there is insufficient statistical evidence (p -value = 0.052) that temperature has an effect on noise level is important. This is because a suggestion was made that noise reductions may be due not only to the status of the road but to ambient temperatures. The large sample size utilised in the experiment suggests that the power of the test (i.e. the probability that the test will detect an effect if such an effect were actually present) should be large also. It is thus reasonable to proceed as if no temperature effect were present.

Confidence intervals for the individual β_i can easily be obtained from the entries in Table 2. These intervals have the form $\hat{\beta}_i \pm t_{\alpha/2, n-k} s(\hat{\beta}_i)$. Thus, for example, a 95% confidence interval for β_5 is $-5.151 \pm 1.96(0.109)$, or $-5.36 < \beta_5 < -4.94$. The correct (frequentist) interpretation of this interval is as follows. If the experimental procedure were repeatedly conducted with samples of the same size as were actually used in the present study, then 95% of all possible intervals (obtained using the above formula) would contain the unknown parameter β_5 . Hopefully, the particular interval $(-5.36, -4.94)$ is one of these 95%.

TABLE II Inferences on Individual Coefficients in the Regression Model

β	β_0	β_1	β_2	β_3	β_4	β_5
$\hat{\beta}$	33.835	26.556	-5.603	0.751	-0.033	-5.151
$s(\hat{\beta})$	1.466	0.822	0.095	0.108	0.017	0.109
t -ratio	23.08	32.29	-59.07	6.97	-1.94	-47.37
p -value	0.000	0.000	0.000	0.000	0.052	0.000

The t -values in Table II for the slope parameters are measures of the effect that each input variable X_i has on the response, when all other input variables are in the model [2]. In an attempt to reduce the number of input variables in the model [2] that are useful for predicting noise levels, a standard stepwise regression procedure was employed to find a parsimonious selection of predictors. The forward selection essentially develops a number of regression models, starting with each individual input variable, and adding or deleting a variable at each step. Critical t -values of 2 and -2 were used to decide at each step of the procedure whether to enter another variable or whether to remove a variable already entered. (Note that for the large sample size employed in the experiment, less than 5% of values of each of the relevant t -variables lies outside the interval $(-2, 2)$. Essentially then, a variable is added at each stage if its t -value is significant at the 5% level of significance and if this t -value is larger in absolute value than that of the other variables which could be added at that stage.) Using this procedure, the final prediction model chose variables X_2 , X_5 , X_1 and X_3 in that order. However, if the last of these four variables were omitted, the reduction in the coefficient of determination is only 0.6%. The resulting model gave a coefficient of multiple determination of 83.4%. A potential prediction model turns out then to be

$$\hat{Y} = 34.20 + 26.12X_1 - 5.62X_2 - 5.10X_5. \quad [5]$$

In interpreting this model, recall that the indicator variable X_2 has values of 1, 0 and -1 for cars, dual-axle vehicles and multi-axle vehicles, respectively, and the indicator variable X_5 has values of 0 and 1 for before and after resurfacing, respectively.

Hence, dual-axle vehicles and multi-axle vehicles increased the noise level by about 5.6 dB(A) and 11.2 dB(A), respectively. After resurfacing, the reduction in noise was 5.1 dB(A).

Statistical Analysis of Sustained Acoustic Performance

A regression model representing the data obtained at two weeks and at forty weeks after the Michael Collins Road had been resurfaced was used to establish whether the acoustic performance had changed over this time period. The regression model differed from model [2]. The indicator variables, X_2 and X_3 , were replaced with a single indicator variable to represent cars and dual-axle heavy vehicles. The X_5 indicator variable was used to indicate whether the measurements were taken at two weeks or at forty weeks. The analysis showed that the estimated slope parameter

corresponding to X_5 was close enough to zero (p -value = 0.840) to conclude that this indicator variable had no effect on the response. Therefore, the acoustic performance had not deteriorated.

ASSESSING THE ACOUSTIC PERFORMANCE AT ECHLIN STREET

Echlin Street is shown in Figure 5. As it was heavily trafficked in both directions and only 97 m long, traffic frequently came to a standstill in front of the microphone position and it was impossible to measure the speed or noise level of individual vehicles. For this reason, it was not possible to assess acoustic performance in accordance with ISO 11819-1. Consequently, the L_{eq} , L_{10} and L_{50} sound parameters were used to quantify the traffic noise that was generated by vehicles travelling in both directions.



FIGURE 5 Echlin Street after Resurfacing

To assess the traffic noise before the road was resurfaced, measurements were made over eight 15 minute periods. The microphone was positioned 5.0 m from the middle of the near southbound traffic lane and at a height of 1.2 m above the plane of the road. A traffic count and ambient temperature readings were also recorded for each 15-minute period. The 15-minute counts were multiplied by 4 to provide hourly flows.

For the purposes of recording traffic flow, the traffic was classified into two categories, namely, light and heavy vehicles. Vehicles such as cars and vans were classified as light while vehicles having six or more tyres, such as buses and lorries, were classified as heavy.

Motor cycles, which tend to be louder than light vehicles, were excluded from the measurements. By using the 'pause' and 'back erase' functions of the sound meter, it was possible to omit noises such as sirens or horns sounded by vehicles, noisy vehicles at a standstill in front of the microphone, church bells and other interfering noises. The 'back erase' function enabled the operator to erase the previous 3 seconds of recorded noise levels. In practice, it took up to three hours to gather data for eight 15-minute periods. Fluctuations in the hourly temperatures and the risk of encountering rainfall limited the observation periods to three-hour intervals.

For motorways, heavy vehicles have been assumed to generate a noise that is seven times louder than cars, Woodside *et al* (1997). For an urban area, an alternative would be to use a factor of ten, European Commission (1996). In the earlier analysis of the data obtained on the other two roads, dual-axle heavy vehicles were found to be 5.6 dB(A) louder than cars and multi-axle heavy vehicles were found to be 11.2 dB(A) louder than cars (See Equation [5]). These figures would correspond to factors of 3.6 and 13.2, respectively, in noise intensity relative to cars. As the composition of the heavy vehicles on Echlin Street was mainly dual-axle vehicles, the factor of seven seemed more appropriate for converting heavy vehicles into an equivalent number of passenger car units (pcu) in this study. Hence, in calculating the total traf-

fic count for each of the eight measurement periods, the number of light vehicles was added to a factored number of heavy vehicles to provide a noise adjusted pcu count:

$$\begin{aligned} \text{Noise adjusted pcu count} = \\ \text{No. of Light Vehicles} + \\ 7 \times (\text{No. of Heavy Vehicles}) \quad [6] \end{aligned}$$

The eight values for the noise adjusted pcu count were then plotted against the L_{eq} , L_{10} and L_{50} values obtained for each measurement period. Subsequently, the average L_{eq} , L_{10} and L_{50} values that corresponded to the average noise adjusted pcu count were calculated using the regression lines fitted to the data points. The relationships for the L_{10} parameter for the 'before', '2 weeks after' and '20 weeks after' study periods are shown in Figure 6. Two of the R^2 values, 0.80 and 0.66, are better than the value of 0.51 in Figure 4: the third, 0.49 is of the same order of magnitude. The corresponding R^2 values for the L_{eq} and L_{50} plots were lower at 0.63, 0.60 and 0.37, and 0.67, 0.52 and 0.41, respectively.

To assess the immediate acoustic performance of the new surface, measurements of traffic noise were taken two weeks after resurfacing. Measurements were taken again twenty weeks after resurfacing to investigate the effect of the passage of time on its acoustic performance. Comparisons were made using the values for the sound parameter at a reference noise adjusted pcu count of 774 per hour. This was the mean noise adjusted pcu count for the measurement periods. Table III shows the reduction in the L_{eq} , L_{10} and L_{50} sound parameters that accrued after the resurfacing operation. The reduction in the L_{10} of 4.2 dB(A), from 73.8 to 69.6 dB(A), is equivalent to a reduction of 62% in noise intensity. The results obtained twenty weeks after the road had been resurfaced would indicate that the surface material maintained its noise abatement properties over that period of time. Adjustments for temperature change were not possible with this method of analysis. However, if the temperature after resurfacing had been the same as before, it would seem reasonable to expect greater reductions.

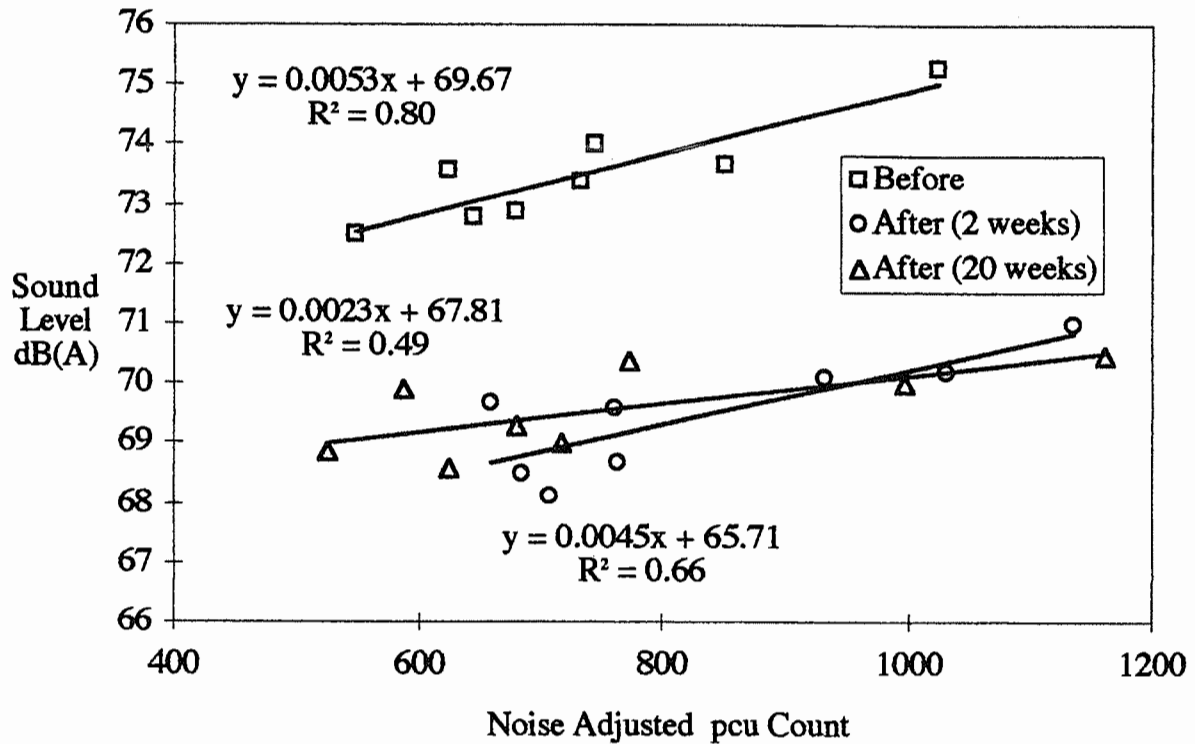
FIGURE 6 Relationship between L_{10} and Noise Adjusted pcu Count

TABLE III Results for Echlin Street Before and After the Resurfacing Operation

Sound Parameter:	L_{eq}	L_{50}	L_{10}	Average Temp.
(a) Before Resurfacing 769 light vehicles + 99 heavy vehicles	71.1	63.5	73.8	21 °C
(b) 2 Weeks After Resurfacing 864 light vehicles + 115 heavy vehicles	67.1	60.4	69.2	10 °C
(c) 20 Weeks After Resurfacing 773 light vehicles + 92 heavy vehicles	67.9	60	69.6	13 °C
Average reduction:	3.6	3.3	4.4	dB(A)

STATISTICAL ANALYSIS OF DATA FROM ECHLIN STREET

The results obtained before and at two weeks after Echlin Street had been resurfaced were also statistically analysed. However, because a different measurement procedure was used to assess the noise levels, an alternate multiple regression model was required. Separate analyses were performed with L_{eq} ,

L_{10} and L_{50} as the response variables instead of individual vehicle pass-by noise levels. The following regression models were employed:

$$Y_i = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \varepsilon, \quad i = 1, 2, 3$$

where

Y_1 Y_2 Y_3 denote L_{eq} , L_{10} and L_{50} , respectively;

X_1 = the noise adjusted pcu count;

$$X_2 = \begin{cases} 0, & \text{for observations taken} \\ & \text{before resurfacing} \\ 1, & \text{for observations taken} \\ & \text{after resurfacing;} \end{cases}$$

$$X_3 = X_1 X_2.$$

For $i = 1, 2$ and 3 , a test of the effectiveness of the resurfacing material is equivalent to a test that both β_2 and β_3 are zero. Indeed, if these slope parameters were both 0, the regression models for both the old surface and the new surface would be $Y_i = \beta_0 + \beta_1 X_1$, $i = 1, 2, 3$. A total of 24 observations were available to fit each model. The appropriate F -statistics values are 33.07, 148.75 and 48.92 for the models involving L_{eq} , L_{10} and L_{50} , respectively. Since each of these values is highly statistically significant (the critical point for a 1% level of significance is in each case $F_{2, 20, 0.01} = 5.85$), it can reasonably be concluded that resurfacing was acoustically effective.

SOME STATISTICAL NOTES

Note from Figure 4 that two data points could be outliers [in the y and/or x directions]. These data points are (1.587, 73.9) and (1.605, 74.0). They are not in fact outliers in the y -direction. However, the data point (1.587, 73.9), whose standardised residual is an insignificant 0.98, turns out to be a leverage point (i.e. it is extreme with respect to the x direction). A regression analysis after removing this data point showed that the slope estimate is still highly significantly different from 0 (the t -value for the effect of maximum sound levels on logarithm of speed changed from 10.55 to 10.77, so that it became even more significant). The 'trend line', i.e. fitted equation, barely changed.

Note also that some of the coefficients of determination that resulted from the analyses are rather low (see the R^2 values placed on Figures 4 and 6). Such low values occurred only in cases where the sound level was modelled as a function of only *one* input variable. The graphs shown in Figures 4 and 6 certainly suggest positive trends and it seemed pointless to fit a non-linear model to the data in an attempt to

improve the R^2 values. (Such a practise is not uncommon, and of course one can get an exact fit to n data points by fitting a polynomial of order $n-1$.) It can be argued that the simple linear models employed in the analysis surrounding Figures 4 and 6 were designed only to exhibit some overall trend. If one requires a better fit (in terms of the value of R^2 , for example) adding more terms to the model could be recommended. This would force a fitted surface that better captures/fits the data, by analogy with Equation [2].

CONCLUSIONS AND RECOMMENDATIONS

In using the Statistical Pass-By Index to assess the benefits of a low-noise surface on two suburban roads, it was not possible to find ideal sites that fully complied with ISO 11819. With the likelihood of low garden walls in such areas, measurement sites are likely to be classified as special cases creating some doubt in making comparisons. The method is not suited to downtown areas as high traffic densities prevent vehicles from being targeted individually. The alternative of comparing regression relationships with the L_{eq} , L_{10} or the L_{50} as the response variable and the noise adjusted pcu traffic flows, using 15 minute counting periods, as the input variable was used successfully. The L_{10} plots produced better R^2 values. In computing the noise adjusted pcu flows, a heavy vehicle (six tyres or more) was equated to seven light vehicles in line with the findings of the study. Ideally, the temperature should be the same in making before and after comparisons. It must be recognised, however, that this parameter may be beyond control.

The three sites analysed in this study could be classified as noisy surfaces before resurfacing: a rugose surface treatment, an asphalt concrete with reflective cracks from the underlying jointed concrete pavement, and a reinstated surface in an inner-city area. Resurfacing with a rubber crumb modified surface in such circumstances can result in large reductions in traffic noise levels. On the two sites where it was possible to calculate the Statistical Pass-By Index (SPBI), reductions of over 5 dB(A) were obtained after many weeks of trafficking. These results were corroborated

by statistical regression analyses that showed, in particular, an estimated noise reduction of about 5 dB(A) even in a model that accommodated a temperature factor. However, over the ambient temperature range of 9°C to 22°C and the prevailing traffic conditions in which measurements were recorded, no temperature effect was discernible in the experimental data. It is possible that the effect of temperature would become evident in data for a much wider range of temperatures. On the inner-city site, where the SPBI was not applicable, the L_{10} sound level was reduced by over 4 dB(A).

The effect of type of vehicle was quite prominent also. From Equation 5, cars produced the least noise level. Also, the estimated increase in mean noise level from cars to dual-axle vehicles is 5.6 dB(A) and a further increase of 5.6 dB(A) is attributable to multi-axle vehicles.

References

- European Commission (1996) *Future Noise Policy*. Green Paper. Brussels.
- Pederson, E., and Laderhoff, L. (1996) Combifalt, an Ultra Thin Wearing Course Placed in a Bituminous Membrane. *Eurasphalt and Eurobitume Congress*, Strasbourg, E&E 7.171.
- Organisation for Economic Co-operation and Development (1995) *Roadside Noise Abatement*. Road Transport Research. Paris.
- Chaignon, F. (1996) Bituminous Concrete with Rubber Crumb – Noise Reduction Bituminous Concrete, *Eurasphalt and Eurobitume Congress*, Strasbourg, E&E 3.005.
- Colas (1998), Laboratoire Central de Recherche, Magny les Hameaux, France.
- International Organisation for Standardisation (1997) *Acoustics – Measurement of the influence of road surfaces on traffic noise – Part 1: Statistical Pass-By Method*. ISO 11819-1:1997(E), Switzerland.
- L'Association Française de Normalisation (1993). *Caractérisation in situ des qualités acoustique des revêtements de chaussées – Mesurages Acoustiques au Passage*. Normalisation Française, S 31-119, Paris.
- Neter, J., Kutner, M.H., Nachtsheim, C.J. and Wasserman W. (1996) *Applied Linear Regression Analysis*, WCB/McGraw-Hill, Boston.
- Woodside, A.R., Woodward, W.D.H. and Anderson G. (1997) Reducing Road Traffic Noise by Altering the Surface Texture. *Proc. 2nd European Symposium on the Performance and Durability of Bituminous Materials*, Leeds, pp. 617-630.