considered, and this suggests that the traffic terms were surrogates for other unexplained variables, possibly rainfall effects. The signs of the coefficients of the remaining terms are the same as for Model (4.1), and therefore the response is as for Model (4.1). Interestingly the change in roughness for a truck is 3.2 times that of a car, but again care should be taken in the application of this type of equivalency factor. Rainfall has a beneficial effect in the development of roughness in that it reduces the rate of change. This finding is in accordance with the wet season effect in Model (4.1).

The consistency between the significant effects found in models (4.1) and (4.2), as well as the similarity of the statistics related to the prediction equations suggest that either model may be used. In the event that rainfall data were available, Model (4.2) would be used, while Model (4.1) would be used in the absence of rainfall data.

In the discussion of the analysis approach a logit model was proposed as an alternative model. By transformation, the logit model reverts to a linear regression. The same linear combination of the independent variables as used for the exponential model were again evaluated. For comparison of the predictive capabilities of the logit with the exponential Model (4.1) the mean squared deviations of the log of the actual QI* values from the log of their respective predicted values were computed. A difference existed only in the fourth significant digit, and there is thus no difference between the predictive capabilities of either the exponential or logit functions for the data set analyzed.

The factors, bar one, found to be significant in the exponential function were also found to be significant for the logit model. Two additional two-factor interactions with time were found to be significant for the logit model. Thus, both models have similar characteristics. This could, however, change for the logit model if sufficient high roughness data were available. Because of this, and the fact that the exponential model is easier to handle computationally, the use of Model (4.1) or (4.2) is recommended rather than the logit model.

4.4 ROUGHNESS AFTER BLADING

Coordinating maintenance activities and the measurement program to coincide on all 48 study sections was impossible, and roughness measurements were usually taken a few days before and after blading. Equation (4.1), together with the measurements obtained, *i.e.*, the last measurement before and the first measurement after blading, were used to estimate the roughness immediately before and immediately after blading. The standard deviation of roughness was related to the magnitude of the measured roughness. Therefore, log transformations of the roughness before and after blading were used to derive the prediction equation. The independent variables that were evaluted were: (1) grade; (2) radius of curve; (3) road width; (4) percentage of surfacing material passing the 0.074 mm sieve; (5) plasticity index of the surfacing material; (6) natural logarithm of roughness before blading; (7) qualitative descriptors of surfacing type, *e.g.*, laterite, quartzite, or clay; (8) average daily car and truck traffic; (9) uphill or downhill lane; (10) time of the previous blading; (11) season during which the blading occurred; (12) interaction of season and variables (4), (5), (6), and (7). The following model was developed:

$$\begin{aligned} LRA = {} & 1.4035 - 0.0239\ W - 0.00480\ SV + 0.01694\ PI \\ & + 0.6307\ LRB + 0.1499\ T1 + 0.3096\ T2 \\ & + 0.00020\ NT + 0.2056\ BS \\ & - 0.01183\ PI \times BS \end{aligned} \tag{4.3}$$

where

LRA = natural logarithm of roughness (QI* counts/km) after blading;

LRB = natural logarithm of roughness (QI* counts/km) before blading;

T1 = surface type dummy variable:
T1 = 1 if surfacing type is quartzite,
T1 = 0 otherwise;

BS = season during which blading occurred:
BS = 0 in dry season,
BS = 1 in wet season.

The t-values associated with each coefficient are shown in Table 4.4.

A total of 1308 observations were used to develop the model which has an R-squared value of 0.61. The standard error of the model is 0.340, which means that the 95 percent confidence interval is LRA + or - 0.663. In untransformed roughness terms, if the predicted roughness after blading is 100, then the confidence interval is 52 to 194.

Roughness after blading is mainly a function of the expertise of the grader operator. The standard deviation of $\log_e$ roughness values after blading, for equal roughness values before blading on the same section was 0.297, which reflects operator variability. This value is similar to the standard error of the model, and thus the model explains the roughness after blading with the same order of accuracy as operator influences.

Roughness after blading is highly dependent on the roughness before blading, as would be expected. As the road width increases, the roughness after blading decreases, probably because of the larger number of lateral position options for a vehicle, and thus, the chance of finding a "smooth" path is increased. An increase in plasticity index increases the roughness after blading in the dry season because if the surface is well compacted, a high plasticity index signifies a high clay content and the surface is very hard from pore water suction in the clay particles. Increasing the percentage of fine material reduces the roughness after blading because of the greater ease in spreading and cutting the surfacing material. However, the surfacing material properties did not fully explain the variation in surfacing type, and the qualitative surfacing type descriptors were found to be significant. Despite this statistical significance it is believed that the differences probably reflect differences in maintenance quality, because the sections with the same surfacing type were frequently located in the same maintenance regions. The average daily truck traffic increases the roughness after blading, probably because of a higher degree of compaction of the upper part of the surfacing, which implies difficulty in cutting this material. If a road section is bladed in the wet season, and if the plasticity index is greater than 17, then the roughness is lower than in the dry season. For a plasticity index less than 17, the roughness is great-

TABLE 4.4 - REGRESSION ANALYSIS OF LOG_e ROUGHNESS AFTER BLADING.

Parameter	Estimate	Standard Deviation	t-value
Intercept	1.4035	0.1434	9.78
W	-0.0239	0.0097	-2.46
SV	-0.00480	0.00105	-4.55
PI	0.01694	0.00366	4.63
LRB	0.6307	0.0189	33.30
T1	0.1499	0.0245	6.11
T2	0.3096	0.0493	6.28
NT	0.00020	0.00007	2.82
BS	0.2056	0.0461	4.46
PI x BS	-0.01183	0.00384	-3.08

er. The wet season effect appears to reflect an adjustment for the very hard upper layer that exists on road sections with a high plasticity index.

4.5 *DISCUSSION OF THE MODELS*

Roughness at any point in time, within the same season, is determined as the exponential of the sum of the logarithm of the change in roughness over time and the logarithm of the roughness at time zero. Thus, the roughness can be determined by using Equation (4.1) or (4.2), together with a known initial roughness, or the roughness after blading can be estimated from Model (4.3). Data from several sections having different surfacing types and maintenance strattegies together with the roughness prediction from Model (4.1) are shown in Figures 4.1, 4.2 and 4.3. In each case, the first observed roughness after blading was used as input for RA, the roughness after blading variable. Therefore, the position of the predicted curve is dependent on the first roughness value. If the value is low relative to the other roughness observations, then the prediction is low, and vice versa if the first roughness value is high. This phenomenon is particularly accentuated in Figure 4.1, where errors in roughness prediction are amplified because no blading occurred during the observation period on section 205. The data points shown apply to a specific section, whereas the model was developed on 48 sections and therefore represents an average over all sections. For this reason, the data points shown may not appear to fit the models very well at all data points. Furthermore, the data points do not follow a pattern but rather fluctuate haphazardly over time, thus emphasizing the statement that because of the variations in wheel path positions with time, a high correlation between roughness and time is not expected. This type of roughness development could have been forced by arranging that vehicles always travel within the same wheel paths, but this would not represent what actually occurs in the field.

As was found in the regression analysis, Model (4.1) underpredicts the roughness development on the high frequency maintenance sections, and this is illustrated by Figure 4.3. This figure stands in contrast to Figure 4.2, which also applies to Section 251, where Model (4.1) realistically predicts the roughness development. As was

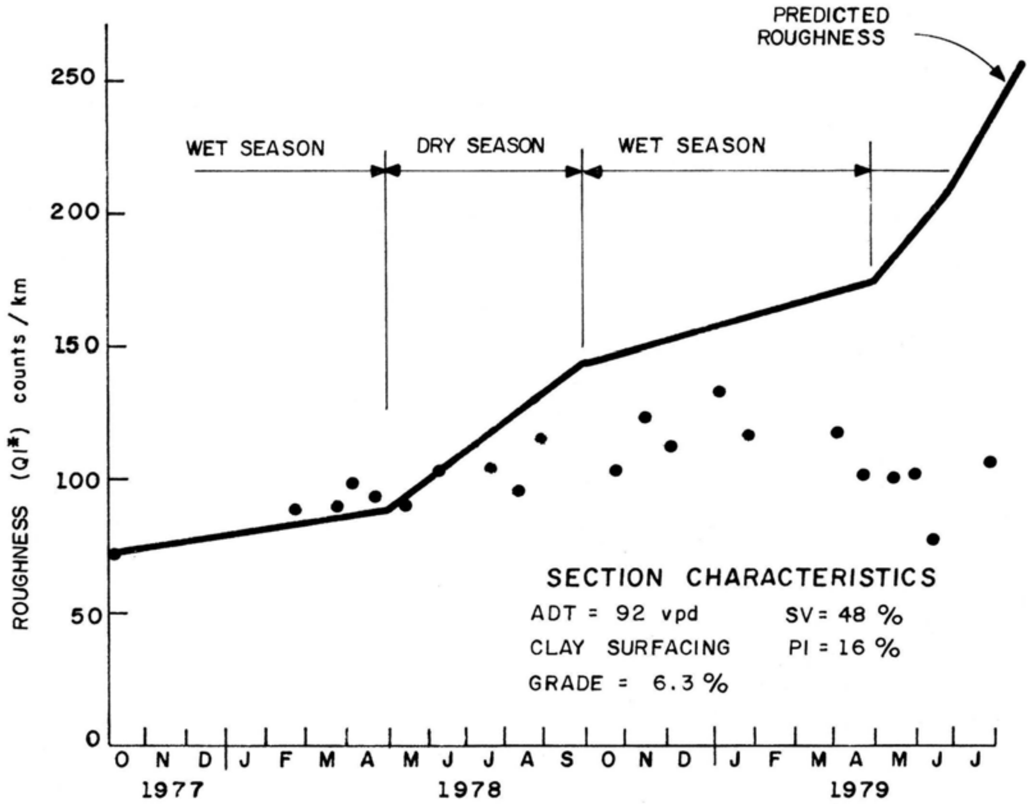

FIGURE 4.1 - MEASURED AND PREDICTED ROUGHNESS ON SECTION 205 WHICH WAS NEVER BLADED DURING THE OBSERVATION PERIOD.

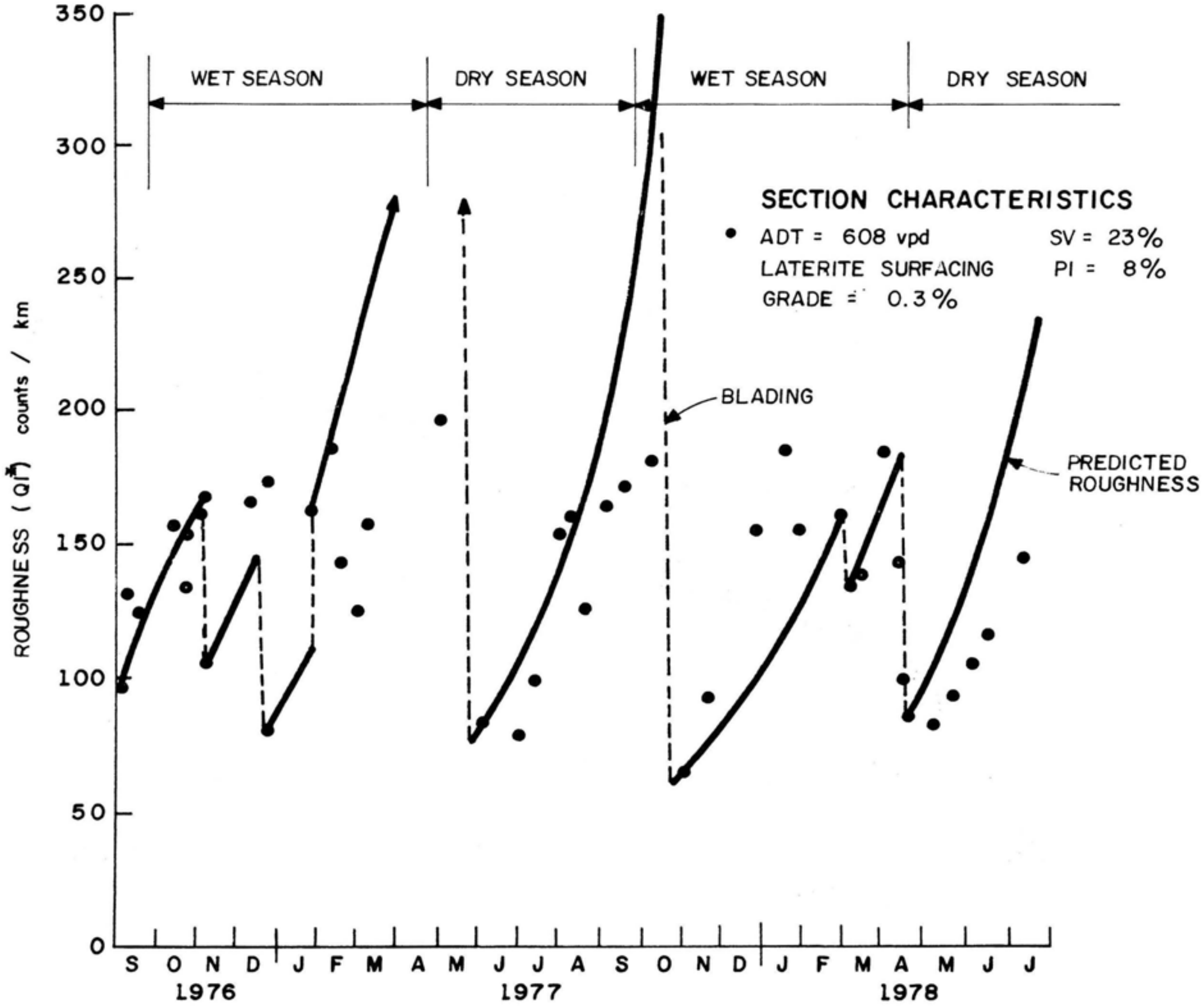

FIGURE 4.2 - MEASURED AND PREDICTED ROUGHNESS ON SECTION 251 UNDER INFREQUENT MAINTENANCE.

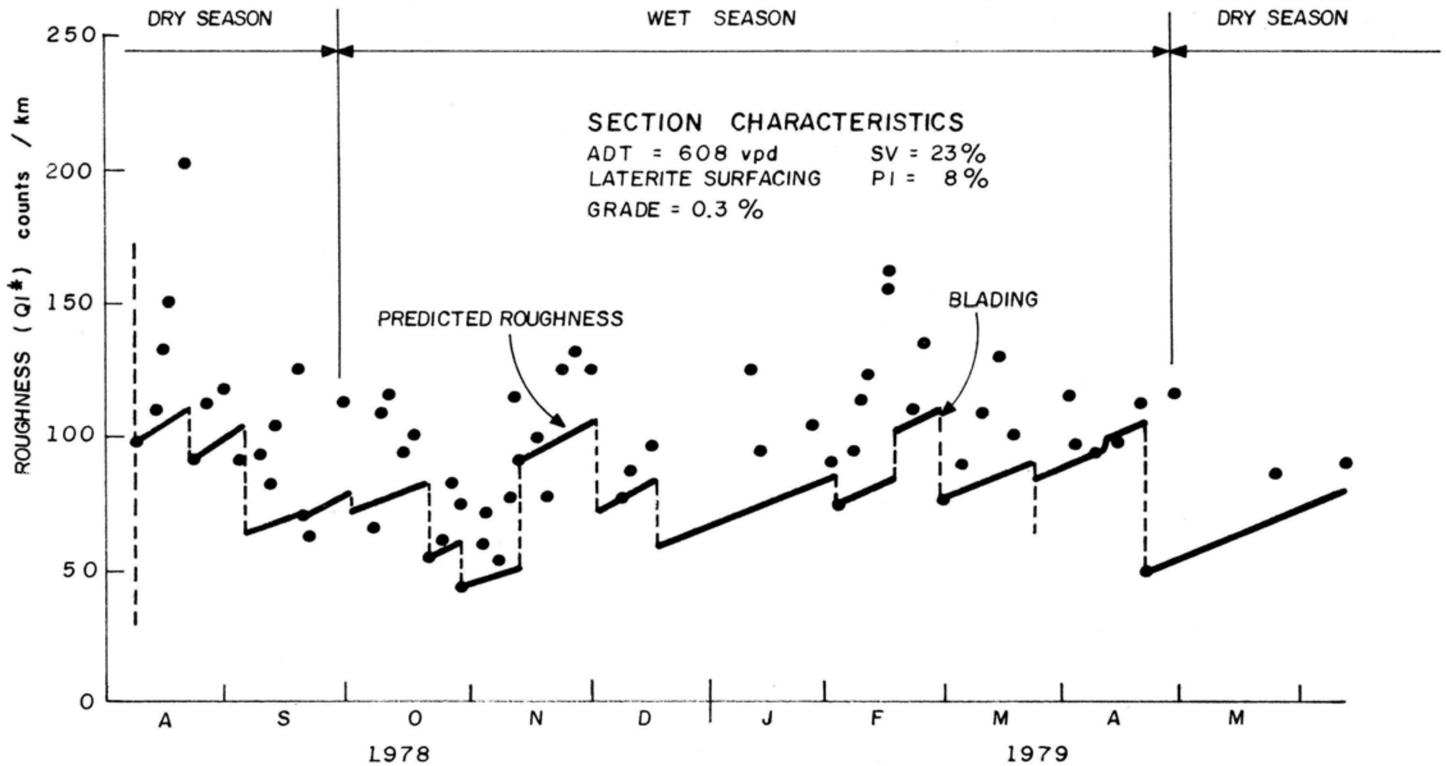

FIGURE 4.3 - MEASURED AND PREDICTED ROUGHNESS ON SECTION 251 WHEN ROAD WAS BLADED EVERY TWO WEEKS.

indicated before, the difference between measured and predicted roughness on the high frequency maintenance section is attributed to the method used in conducting the experiment. When the conditions for blading are non-optimal, water should be added if the road is dry, or if over wet, the road should be left to dry somewhat. Motorgrader operators know from experience which strategy to apply.

As a further comparison of the similarity of the exponential and logit functions, both models were superimposed for Section 205, as shown in Figure 4.4. Very close agreement is apparent, at least at the lower levels of roughness found on this section.

Road closures from the road becoming impassable were not considered in the roughness evaluation. On several occasions during the wet season, clay sections became impassable for several weeks. Roughness before and after these closures were relatively low. Thus, roughness does not seem to adequately characterize road closures. Although high roughness (QI* greater than 400) were measured on some sections, traffic continued to use the road. From an operational point of view, very high roughness will not force a road closure, but may detrimentally affect vehicle operation.

The material properties studied do not fully explain surfacing type differences in the prediction of the change of roughness with time. Clay surfacings exhibit a binding of the surfacing in the dry season, which is attributed to pore water suction in the clay particles. In future studies an evaluation of the clay content of unpaved road surfacing materials may discriminate between the different surfacing types. For evaluating vehicle type influences on roughness it is essential to ensure that all vehicle types be represented on all the study sections, and that a sufficiently wide range exists in the traffic figures to draw meaningful conclusions. In the Brazil study, normal maintenance procedures were applied, and no quantification of the maintenance was attempted. Future work should evaluate this aspect to reduce the large confidence band which applies to Model (4.3).

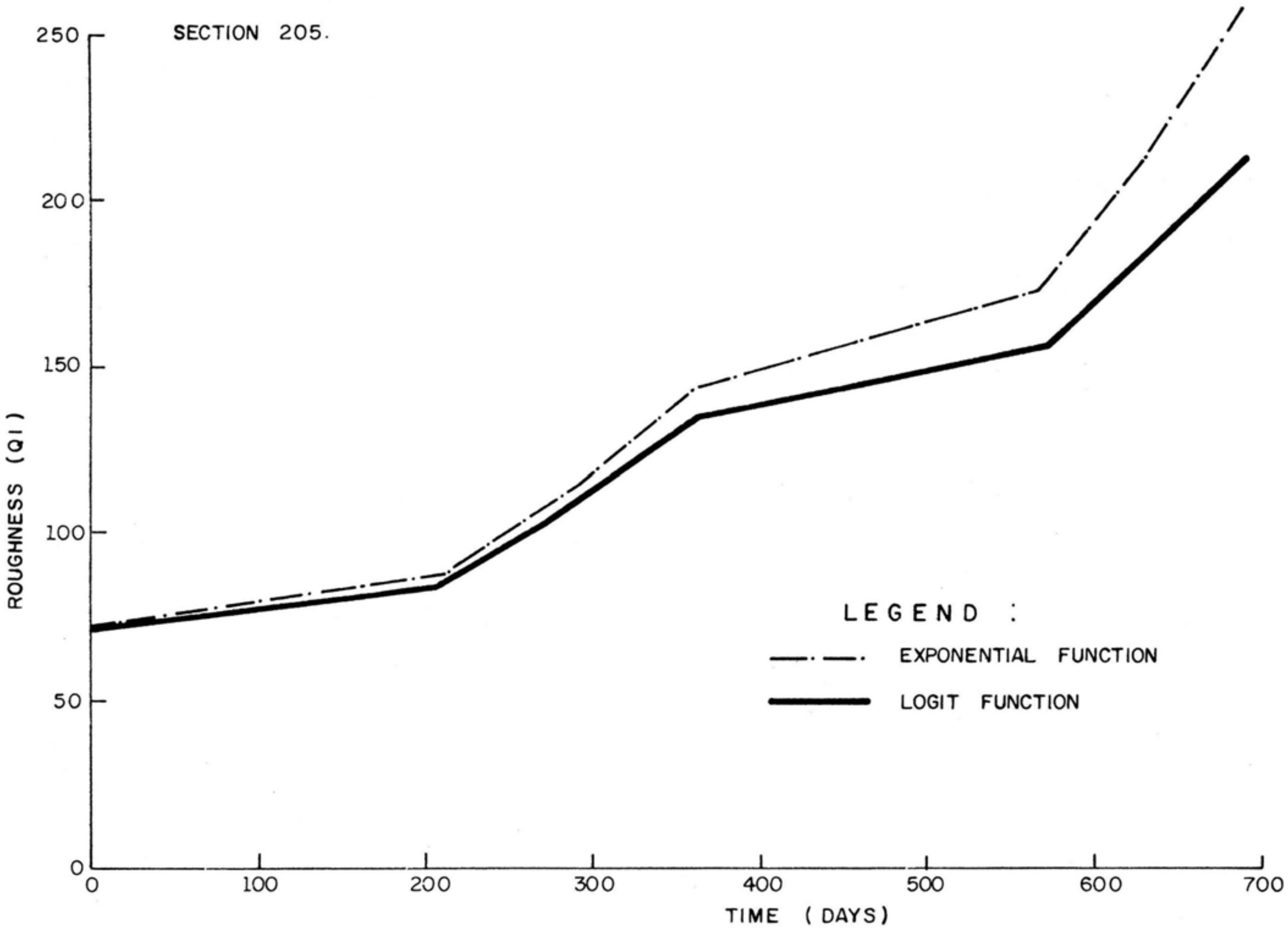

FIGURE 4.4 - COMPARISON OF PREDICTED ROUGHNESS BY THE EXPONENTIAL AND LOGIT FUNCTIONS.

4.6 CORRUGATIONS

One of the road conditions that has a major impact on road roughness is the existence of corrugations. A number of theories and hypotheses were developed since the phenomenon of corrugations was first observed to influence the comfort of the unpaved road user. The majority of these theories were laboratory developed, are oriented towards one wheel and require detailed soil parameter information. During the research study the Maysmeter personnel were required to note whether corrugations existed. Thus the conditions under which many of the theories were developed are not applicable to the conditions that existed in the research project.

Consequently the investigation into the development of corrugations was restricted to an empirical one. Of the 42 study sections, 11 were found to corrugate, where the definition of corrugation related to the observation of this phenomenon on at least three ocasions during the 12-month period in which this information was recorded.

Since two distinct populations of sections exist, those that corrugate and those that do not corrugate, discriminant analysis was attempted. Discriminant analysis relates to deciding on the membership of an observed section in one of a given set of populations to which it may belong (Rao, 1973). The SAS discriminant analysis procedure was used to perform the analysis. Factors such as road geometry, traffic and material properties were included as discriminatory variables.

The analysis showed that the variances of the two populations were significantly different, and that the variance of the sections that corrugate was smaller than that of the other population. This is an expected result since corrugation is a specific road condition, whereas the other population may contain a number of conditions which were not quantified. Because of the non-homogeneous variances, the variances cannot be pooled, and a quadratic discriminant function is used in the program (Rao, 1973). The use of this procedure results in the misclassification of two of the 42 sections. However, the discriminant fucntion is not explicitly stated, as would be for the case if the variances were homogeneous and could be pooled. The SAS procedure also does not have the computational capability to indicate which factors have the most significant effect, and which may be deleted from the analysis.

A further investigation was performed by pooling the variances although it was known that they were non-homogeneous. A total of seven of the 11 sections that corrugated were misclassified as not corrugating, and this is an unacceptable result.

4.7 *CONCLUSIONS AND RECOMMENDATIONS*

The quadratic discriminant function is able to satisfactorily discriminate between sections that corrugate and those that do not. Assuming that the variances of the two populations were homogeneous, while it was proven that they were not, resulted in a very poor discrimination. Since the SAS package is not able to give the quadratic discriminant function explicitly, the recommended procedure to evaluate whether any new section will corrugate is to add the characteristics of the section to the computer file of existing sections, assuming whether the section will corrugate or not, and to rerun the discriminant analysis program and test the assumption.

4.8 *SUMMARY*

Based on a hypothesized model for the development of roughness on an unpaved road, an exponential and logit function were evaluated. These models provided similar predictive qualities and because of simpler application the exponential model is recommended for general use. Two forms of the exponential model are available for use. The one uses a wet/dry season differentiation whereas for the other the cumulative rainfall profile is necessary. Maintenance influences on the exponential model were studied and it was found that blading every two weeks resulted in a larger rate of increase of roughness than when bladings occurred when the road surfacing conditions were optimal. This conclusion is believed to be the result of the experiment rather than a condition that would occur in pratice. A model for predicting the roughness after blading was developed which predicted roughness with the same variance as that of operator variability in blading a section. A comparison with other data sources was not possible because of a lack of a standard roughness scale and a lack of correlations between different roughness measuring instruments. An attempt was also made to separate those factors that would have a major impact on the formation of corrugations, but unfortunately the computational ability was insufficient to draw any conclusions.