DETECTING LOCALIZED ROUGHNESS USING DYNAMIC SEGMENTATION

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ABSTRACT
Monitoring pavement surface characteristics is an essential element of pavement management systems. The objective of this paper is to develop guidelines for analyzing the measurement of longitudinal pavement profile using two dynamic segmentation methods and to demonstrate the benefits of refining the monitoring of pavement conditions.

In the Canadian Long-Term Pavement Performance database, C-LTPP, a representative average value of the international roughness index (IRI) is stored for each of the longitudinal profiles. However, for maintenance work, it is useful to store the changes in roughness at a higher level of detail.

The roughness profiles for all C-LTPP sections are calculated based on a constant base length. The roughness profiles have been analyzed to evaluate the effect of localization of roughness values. The IRI range, which is the difference between the maximum and minimum IRI is calculated for each of the 1332 roughness profiles. It is found that most of the monitored profiles have an IRI range that exceeds 1.0 m/km. These high ranges mean that the average IRI for a section is not sufficient to give detailed information about how rough the section is. For these sections, segmentations are required to distinguish the localized roughness and extract homogenous segments.

Two methods for segmentation are used to divide the roughness profile into segments which have a specified IRI range. Dynamic segmentation is applied using values of IRI range between 0.2 m/km and 0.7 m/km. The correlation between the IRI range and the segment length is tested based on the average segment lengths. A proposed relationship between IRI range and average segment length is given.

A quadratic mathematical model is introduced to estimate the required interval for reporting roughness profiles so that the reported segments would have an IRI range that falls within a specified range.
1 INTRODUCTION

C-LTPP Profile Data
The dipstick measurements for the longitudinal profiles in the Canadian Long-Term Pavement Performance database, C-LTPP, are collected in a continuous, closed loop. When using the closed-loop method, the start point at each section (loop) is measured at the beginning and end of the loop. Then, the survey closure error which is the difference in the measured elevation at this point is recorded. In this study, the survey closure error for each section was redistributed uniformly over the measurements before computing the roughness.

Roughness Profile
In the C-LTPP database, a representative average value of the international roughness index (IRI) is stored for each of the longitudinal profiles. However, for maintenance work, it is useful to store the changes in roughness at a higher level of detail. Although the roughness of a very long segment provides a single number that functions as a summary value, it fails to identify locations along the road in need of corrective action.

To add another dimension to the description of the road roughness, a roughness profile is required. Roughness profiles show the details of how roughness varies with distance along a road section rather than providing a single index that summarizes the roughness of road section. Profile is generated for a fixed length \( L \) and at any point in the profile; the IRI is taken for the interval starting at \(-L/2\) prior to the current location, and ending \(+L/2\) past the current location (1).

In this paper, the roughness profiles for all C-LTPP sections were calculated based on a fixed length of 12 m using the static level method described in the American society for test and materials ASTM (2). This relatively small fixed length was chosen to be close to the 11 m used in ASTM (2); and to be consistent with the 300mm dipstick foot spacing which is used for the majority of the 1332 measurements.

2 ROUGHNESS ANALYSIS

Figure 1 shows the calculated roughness profile for the outer wheel path of the test site 810404, section 1. The dipstick measurements which were recorded in 1990 and prior to overlay have a roughness profile ranging from 1.36 m/km to 3.82 m/km with a mean of 2.45 m/km. Figure 1 shows that representing roughness with a single value for the whole section does not reveal enough information on where the section is rough or smooth due to the large difference between the maximum and minimum IRI.

The IRI ranges were calculated for all roughness profiles. Figure 2 shows that 12 profiles, about 1% of the monitored profiles, have an IRI range of less than 1.0m/km and most of the profiles have an IRI range that exceeds 1.0m/km. These large ranges indicate that the average IRI for a section is not sufficient to give detailed information about localized roughness. For sections with high ranges, segmentations are required to distinguish localized roughness and extract homogeneous segments.

3 ROUGHNESS PROFILE SEGMENTATION

Two methods for segmentation are used to divide the roughness profile into segments based on a specified IRI range. The basic concepts for these segmentations will be described in the
following sections followed by an illustrative example showing the differences between the two methods.

**Cumulative Differences Approach**

The cumulative difference approach, CDA, is a relatively straightforward and powerful analytical method for delineating statistically homogenous units from pavement response measurements along a highway system (3). This approach can be used for a wide variety of measured pavement response variables such as IRI. Figure 3 illustrates the concept using the initial assumptions of a continuous and constant response value \( r_i \) within various intervals \((0\) to \( x_1;\ x_1\ to\ x_2;\ x_2\ to\ x_3)\) along a profile. As shown in Figure 3a, the three unique segments having different response magnitudes \( r_1, r_2, \) and \( r_3 \) exist along the profile.

The cumulative area at any point within the profile can be calculated by integrating the response variable over the distance associated with the given point. For example, at the point \( x \), the cumulative area is given by the integral:

\[
A_x = \int_0^{x_1} r_i \, dx + \int_{x_1}^{x_2} r_2 \, dx
\]

The cumulative area with distance along the profile is plotted in Figure 3b. In this figure, the solid line indicates the results of the actual response curves and the dashed line represents the cumulative area caused by the overall average profile response.

It should be recognized that the slopes of the cumulative area curves are simply the response for each unit \( r_1,\ r_2, \) and \( r_3 \) while the slope of the dashed line \( \bar{r} \) is the overall average response value of the entire profile length considered. For example, at the point \( x \), shown in Figure 3b, the cumulative area based on the average response is given by:

\[
\bar{A}_x = \int_0^x \bar{r} \, dx
\]

Where,

\[
\bar{r} = \frac{\int_0^{x_1} r_i \, dx + \int_{x_1}^{x_2} r_2 \, dx + \int_{x_2}^{x_3} r_3 \, dx}{L_s} = \frac{A_x}{L_s}
\]

Where, \( A_s \), is the cumulative area over the profile length \( L_s \). From the preceding equations, the cumulative difference, \( Z_x \), at any point within the profile is evaluated as follows:

\[
Z_x = A_x - \bar{A}_x
\]

\( Z_x \) is simply the difference in cumulative area values, at a given \( x \), between the actual and profile average line. If the \( Z_x \) value is plotted against distance \( x \), Figure 3c results. The location of unit boundaries always coincides with the location (along \( x \)) where the algebraic sign of the slope of this difference is changed (3).
**Absolute Differences Approach**

The absolute differences approach, ADA, depends on the absolute differences between response values. A graphical illustration of the ADA concept is shown in Figure 4. The absolute difference between the response \( r_i \) at \( x_i \) where the segment is started and the response \( r_d \) at \( x_d \) is calculated according to the following:

\[
Z_i = |r_i - r_d|
\]  

(5)

Segment border is determined when \( Z_i \) is equal to the target range and a new segment will start from this border. This concept is based on a sliding window with a height equal to the target range. Each new segment will start from the point of intersection between the upper limit of the previous window and the pavement response profile. The target range is an arbitrary value and should be specified according to the required level of details.

**Illustrative Example**

Figure 5 introduces an illustrative example that shows the difference between the two methods of segmentation. In this example the pavement response changes from \( r_1 \) to \( r_2 \) and from \( r_2 \) to \( r_3 \) gradually (Figure 5a and b). Applying the concept of CDA, There will be two borders as same as the example shown in Figure 3 because the algebraic sign of cumulative difference slope (Figure 5d) will be changed only twice.

Using ADA method will provide different results based on the selected target response range. The segmentation is finer when a smaller response range is selected. The outcome of ADA will have a number of segments of greater than or equal to that of CDA depending on the target response range.

The main reason for the difference between the two methods of segmentation is that CDA is affected by the overall average profile response \( \bar{r} \) where ADA is affected by the target range. For any profile, the overall average profile response \( \bar{r} \) is constant where the target range is arbitrary and can be changed.

**Combining Segments**

After the roughness profiles are divided by both of the above methods, the possibility of combining adjacent sections must be checked. There are many statistical parameters which can be used to control how segments could be combined. Ping et al. (4) used minimum segment length, minimum difference between the means of adjacent segments, and statistic critical \( t \)-value. Kennedy et al. (5) used standard deviations to control adjacent segment combinations. The difference between maximum and minimum, the “Range”, is another statistical parameter which is used in this paper because it is already included in the ADA method.

Each two adjacent segments will be combined into one segment if the difference between the maximum and minimum does not exceed the target range according to the following:

\[
|r_i^1 - r_j^2| \leq \text{Range} \quad \text{for all} \quad x_i, x_j
\]  

(6)

Where;

- \( r_i^1 \) is the response \( r_i \) at \( x_i \) for segment 1.
- \( r_j^2 \) is the response \( r_j \) at \( x_j \) for segment 2.
$x_i$ is any distance within segment 1.
$x_j$ is any distance within segment 2.
$r_{\text{range}}$ is the specified target response range controlled combination of segments 1 and 2.

The process of combining adjacent segments is iterated until no more segments could be combined. By using CDA, some segments will have response range that falls outside the specified response range because the first step of this method mainly depends on the overall average response value, $\bar{r}$, of the entire profile length regardless the target range. Conversely, all segments resulted from applying ADA method will have response range within the target range because the ADA segmentation is a mainly range segmentation.

4 ANALYSIS OF SEGMENTED PROFILES

The roughness profiles for all C-LTPP sections were segmented using CDA and ADA methods. Segments were combined based on different values of IRI range starting from 0.2 m/km to 0.7 m/km. Figure 6 shows a part of the roughness profile for the outer wheel path of the test site 810404 corresponding with the two segmented profiles. For target IRI range of 0.2 m/km, the CDA segmented profile has one segment with length of 19.5 m however ADA profile has four segments with lengths of 2.1, 2.4, 2.1 and 12.9 m respectively.

If this section will be repaired considering that rehabilitations should be applied to segments with $\text{IRI} \geq 1 \text{ m/km}$ then using ADA method will require a rehabilitations of segment of length of 34% less than that of using CDA. This percentage of length reduction will vary depending on the required IRI range and can be adjusted for each profile.

Statistical Comparison

For each IRI range, the segment lengths for all the profiles were recorded and statistically analyzed. Table 1 summarized the general statistical data for the segment lengths based on different IRI ranges using the CDA method. For ADA method, the statistical data for the segment lengths are summarized in Table 2. For all IRI ranges, the number of ADA segments is higher than those of CDA. Conversely, all other statistical measurements for ADA segmentation are less than those for CDA.

Relationship between IRI Range and Segment Length

Based on the average segment lengths given in Tables 1 and 2, Figure 7 shows the relationship between the segment length and the IRI range for both type of segmentations. For all IRI ranges, the segment lengths based on CDA are about 30% greater than those based on ADA.

For both methods, the rate of change in segment length is decreased with the increase of the IRI range. For CDA, segment length increases with IRI range increase of 0.1 m/km by as much as 3.0 m at 0.3 m/km and by 0.7 m at 0.7 m/km and for ADA, segment length increases by as much as 3.3 m at 0.3 m/km and by 0.2 m at 0.7 m/km.

Reporting Interval Model

The required interval for reporting roughness profiles so that the reported segments would have IRI range that falls within a specified range can be estimated based on the average of the CDA and ADA results given in Figure 7. The relationship between the reporting interval (m) and the IRI range (m/km) were investigated using the following models:
Linear:
\[ L = a \cdot IRI_{\text{Range}} + b \]

Logarithmic:
\[ L = a \cdot \log_e (IRI_{\text{Range}}) + b \]

Quadratic:
\[ L = a \cdot IRI_{\text{Range}}^2 + b \cdot IRI_{\text{Range}} + c \]

Where;
- \( L \) is reporting interval length (m).
- \( IRI_{\text{Range}} \) is the target IRI range (m/km).
- \( a, b \) and \( c \) are regression coefficients

The goodness of fit was examined by the coefficient of determination, \( R^2 \) and the standard error \( SE \). The results of regression analysis and comparison of the three models are shown in Table 3 and Figure 8. The linear equation has the smallest \( R^2 \) of 0.92 and the largest \( SE \) of 1.29 where the quadratic equation has the largest \( R^2 \) and the smallest \( SE \) of 0.99 and 0.09 respectively.

Although the quadratic model has the best correlation, the model is valid until the slope of the equation is zero at \( IRI_{\text{Range}} = 0.7 \) m/km.

The quadratic model would be the best model to estimate reporting interval for IRI range up to 0.7 m/km. The proposed models can be used to study the effect of changing reporting interval on the level of information extracted from the roughness profile.

## 5 RECOMMENDATIONS

A sample of 1332 roughness profiles has been analyzed to evaluate the effect of localization of roughness values. Two methods for segmenting the roughness profile were used to divide the roughness profiles into segments which have a specified IRI range. These methods of segmentation were applied for the 1332 sections. Segments were combined based on different values of IRI range starting from 0.2 m/km to 0.7 m/km.

Using ADA method will provide different results based on the target response range which should be determined before applying the ADA. The outcome of ADA will have a number of segments of greater than or equal to that of CDA depending on the target response range.

By using CDA, some segments will have response range that falls outside the specified response where all segments results from applying ADA method will have response range within the target range. The main reason for the difference between the two methods of segmentation is that CDA is affected by the overall average profile response \( \bar{r} \) where ADA is affected by the target range.

The relationship between IRI range and segment length is estimated based on the average segment lengths. For all IRI ranges, the segment lengths based on CDA are about 30% greater than those based on ADA.

A quadratic mathematical model is introduced to estimate the required interval for reporting roughness profiles so that the reported segments would have an IRI range that falls within a specified range. The model would be valid for IRI range up to 0.7 m/km.
Road sections can be divided into segments according to the corresponding profile data. In this paper, the dynamic segmentation was applied based on IRI data where other profile data can be used, e.g. Ping et al. (4) used rut data. It is envisioned that building a complex system for segmenting data based on both IRI and rut profiles would be more effective and will retain more information about road conditions.
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<table>
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<tr>
<th>Statistic</th>
<th>IRI Range (m/km)</th>
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<td>Standard Error</td>
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**TABLE 2 General Statistical Summary for Segment Lengths (m), ADA Approach**

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<th>IRI Range (m/km)</th>
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### TABLE 3 Models for Correlating IRI Range (m/km) and Reporting Interval (m)

<table>
<thead>
<tr>
<th>Model</th>
<th>Equation</th>
<th>$R^2$</th>
<th>SE</th>
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<tbody>
<tr>
<td>Linear</td>
<td>$L = 21.2 \text{IRI}_{range} + 3.1$</td>
<td>0.92</td>
<td>1.29</td>
</tr>
<tr>
<td>Logarithmic</td>
<td>$L = 8.8 \log_e(\text{IRI}_{range}) + 20.4$</td>
<td>0.98</td>
<td>0.54</td>
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<tr>
<td>Quadratic</td>
<td>$L = -42.5 \text{IRI}<em>{range}^2 + 59.4 \text{IRI}</em>{range} - 4.3$</td>
<td>0.99</td>
<td>0.09</td>
</tr>
</tbody>
</table>
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