Road roughness characteristics in car and truck wheel tracks

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Acknowledgments

The authors would like to express their thanks to the staff of Main Roads Western Australia particularly Mr. Jan Karpinski and Mr. David Kennedy for their support in providing all data and information relevant to this study.
Road roughness characteristics in car and truck wheel tracks

Road longitudinal profile data were collected in both car and truck wheel tracks for a number of road sections to study the differences in their surface roughness characteristics. Roughness was measured in terms of the Heavy Articulated Truck Index (HATI), a measure of pavement ride quality as perceived by heavy truck occupants. Roughness variation between the outer and inner wheel tracks was also investigated. The results showed that lane average values of HATI in truck wheel tracks were higher than in car wheel tracks for about 60% of the studied network. These differences are relatively small but are statistically significant. The results also revealed that subgrade soil type and shoulder seal width influenced roughness variations between the truck and car wheel tracks. Overall, HATI values determined from profile data collected in car wheel tracks resulted in ride perception ratings that matched those determined from measurement in truck tracks for 90% of the studied network.

Keywords: truck ride; expansive soils; frost action; profile data; HATI; IRI

1. Introduction

The International Roughness Index (IRI) is the current common measure used by Australian road agencies to trigger investigation into pavement rehabilitation for ride quality improvement. However, anecdotal evidence indicated that occupants of heavy articulated trucks complain of roads sections that have low IRI values. Accordingly, Australasian road agencies initiated and sponsored a number of research studies to address this issue (Austroads, 2000; Jamison and Cenek, 2003; Hassan et al, 2006) and develop suitable roughness indices.

A roughness index that characterises vertical vibrations of a truck body in the frequency range of 1-4 Hz was deemed reasonable, although truck ride is also influenced by longitudinal, lateral and rotational vibrations. The reason behind this was that surveys of whole body vibration exposure levels experienced by Australian heavy
truck drivers indicated that the weighted vertical vibrations were the dominant ones (Sweatman and McFarlane, 2000) with the highest being in the range of 1-4 Hz (Hassan and McManus, 2007). At normal highway speeds (i.e. 60-100 km/hr), these low frequency modes are excited by long roughness wavelengths (i.e. 4 - 27 m). The wavelength (m) equals the speed (length per second) divided by the frequency (cycles per second). Vehicle suspension design has been successful in minimizing vehicle vertical motions at the frequency range 4-10 Hz to which human body is most sensitive (Sayers and Karamih, 1998).

Heavy Articulated Truck Index (HATI) is one such index that is currently being used by some Australian road agencies to detect rough sections to heavy truck occupants and trigger investigation into pavement rehabilitation. Details of HATI development and validation can be found in (Hassan et al, 2006) and a brief description is provided in section 2. HATI is a profile-based roughness index determined by processing the longitudinal profile data through a quarter truck filter (QTF), similar to that of the quarter car model used for calculating the IRI, but with different parameters.

HATI captures the vertical motions associated with excitation of the low frequency body bounce and pitch vibration modes of the truck body (frequency range 1-4 Hz) due to its sensitivity to long wavelength roughness (LWR). The influence of the latter on truck ride has been confirmed in a number of studies other than those mentioned before including (Papaiannakis and Gujarathi, 1995; Granlund et al, 2000). LWR is typically associated with expansive subgrade soils due to differential movement caused by seasonal moisture variation (Mann, 2002) and soft fine graded subgrade soils affected by frost action (Dore’ et al, 2002).
Truck ride is also influenced (to a lesser extent than vertical vibrations) by lateral, longitudinal and rotational motions induced by excitations of body roll and pitch vibrations modes. These excitations are induced by variations in road crossfall and elevation variations between the two wheel tracks. These surface characteristics are not considered in this study however, the reader can refer to Hassan and others (2007) for measures to assess their effects on pavement rideability to truck occupants.

It is important to note that the use of IRI is still important in detecting sections with poor ride for car occupants and heavy trucks with poor suspension systems. The latter include articulated trucks and rigid trucks with and without trailers as their ride is also affected by the short wavelength roughness to which IRI filter is most sensitive.

1.1 Study objectives
Currently, HATI is calculated using longitudinal profile data measured in car wheel tracks. The data are collected using multi-laser profiler with lasers located at 750 mm to the left and right of the test vehicle centreline, referred to here as 750 mm offset. During data collection, the survey vehicle follows the most common wheel tracks used by cars within the lane being surveyed. Where the most common wheel tracks used by cars are not clear, the survey vehicle follows the centre of the lane (Austroads, 2007).

However, truck outer wheel tracks are located closer to the pavement edge, which is closer to the zone of seasonal moisture variation. Thus, it is logical to expect these wheel tracks to contain higher content of LWR and consequently higher values of HATI. Dore’ and others (2002) found LWR content in the outer wheel tracks to be greater than in the inner tracks for pavements built on soft fine grained (e.g. low-stiffness silty) subgrade soils affected by frost action. If this assumption is true, some of the rough sections to truck occupants are not being detected by the current HATI measurements. Therefore the objectives of this study are:
To compare surface roughness characteristics from profile data measured in truck and car wheel tracks. The comparison includes only the characteristics that affect pavement ride quality perceived by heavy truck occupants.

Test the validity of the assumption that HATI values are higher in truck tracks than in car tracks, and

Assess the impacts on network’s level of service as perceived by truck occupants, if road agencies continue to only use data collected in car wheel tracks.

For this study, the longitudinal surface profile data of sections from three rural highways in Western Australia are used. The data were collected at the standard 750 mm offset position and at the 1150 mm offset position (i.e. 1150 mm to the right and left of centreline of the test vehicle). The first offset represents car wheel tracks and the latter represents truck wheel tracks. The raw longitudinal profile data were measured using a multi-laser class 1 profiler. They were done simultaneously in the outer and inner wheel tracks at both offsets in the wavelength range of 0.5-50 m at the relevant operating speeds.

2. Heavy Articulated Truck Index (HATI)

As mentioned earlier, the development of HATI and its calculation are published elsewhere so only aspects that are relevant to the current study analysis are repeated herein. HATI is a distance-domain index determined by processing longitudinal surface profile data of a section through HATI QTF. The QTF parameters are presented in Table 1 and are based on the parameters of the quarter truck model reported in Austroads (2000). The vertical response of HATI QTF to road input is displayed in Figure 1. The highest gain (> 0.9) occurs in the frequency range 2-3.5 Hz, which can be
excited by roughness wavelengths between 8 and 14 m when travelling at 100 km/hr. This speed is the maximum speed limit for heavy trucks on Australia’s rural highway network.

HATI is calculated by converting the profile data to slope and then filtering it through the QTF. The simulated vertical response of truck body to road input, referred to herein as Profile Index for HATI (PI_{HATI}), is accumulated using an exponent of two for root mean square (RMS) slope. HATI is then determined as the RMS average of PI_{HATI} values of the outer (PI_{HATI,OT}) and inner (PI_{HATI,IN}) wheel tracks using Equation 1. HATI has units of slope, mm/m or m/km. It is easy to calculate using the same software used for calculating the IRI but requires replacing the parameters of the Quarter Car Model by those of HATI’s QTF.

\[
HATI = \sqrt{\frac{(PI_{HATI,OT})^2 + (PI_{HATI,IN})^2}{2}}
\]  

To give the users an indication of what HATI values mean, a scale (Table 2) for HATI values and corresponding perceptions and ratings of pavement ride quality was developed. The scale was developed using a statistical transform, called HATI Truck Ride Number (TRN_{HATI}), shown in Equation 2, and validated using actual drivers’ ratings. This transform predicts drivers’ ratings of pavement ride quality from HATI values (in mm/m) with a coefficient of determination (r^2) of 0.90 (Hassan et al, 2006). This scale is suitable for operating speeds \( \geq 90 \text{ km/hr} \), which were the operating speeds of trucks used in HATI’s development and also apply to the test sections of the current study.

\[
TRN_{HATI} = 5e^{-255HATI^{0.92}}
\]  

<table>
<thead>
<tr>
<th>TRN_{HATI}</th>
<th>Perception</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Smooth</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>Medium</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Rough</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Rough</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Rough</td>
<td>1</td>
</tr>
</tbody>
</table>

This table is designed to help users interpret HATI values in terms of their perceived ride quality.
HATI threshold value between acceptable and unacceptable ride is 1.7 m/km, which results in a TRN$_{HATI} < 2.5$ and corresponds to a fair ride (see Table 2). This value can be used as an investigatory threshold to trigger investigation into rehabilitation. A HATI value of 2.2 m/km, which corresponds to a poor ride (TRN$_{HATI} < 2$), can be used to trigger rehabilitation intervention to improve pavement rideability for heavy articulated truck occupants.

3. Study data and analysis approach

3.1 Sections details

Three sections from three rural highways in Western Australia (WA) were selected for the study. They were anecdotally identified to have poor ride for heavy truck occupants. Table 3 presents the details of these sections including lengths, subgrade soil type, climate in terms of the Thornthwaite Moisture Index (TMI), speed limits and shoulder seal width. All three are single carriageway roads comprising of two lanes (or more, where overtaking lanes or intersections are present) with either sealed or unsealed shoulders. Their pavements consist of thin granular bases and subbases with chip seal or thin asphalt surfacing. The average lane width for all three highways is 3.5 m. Lane width data relevant to each subsection considered in the analysis were not available to the authors.

Hwy 2 carries the highest truck traffic volume of all three followed by Hwy 1 with long articulated trucks (B doubles) making up the majority (41%) of the fleet in both, followed by small rigid trucks. Truck traffic on Hwy 3 is very minor compared to the other two (about 10%) with small rigid trucks making up the majority of the fleet.

Most of the sections from the three highways are on straights with few located on horizontal curves of different radii. Hwy 1 has 20% of its length on curves with...
relatively large radii. Hwy 2 has 33% of its length on curves with few of them having small radii. For Hwy 3, the curves cover 13% of its length with the majority having radii smaller than for the other two and few have very small radii.

3.2 Roughness data and analysis approach

The profile data of the three sections were supplied by state road agency of WA. They were collected during normal network condition survey. The supplied data were assumed to be correct and were used with no verification. The data consist of profile measurements at 25 mm sample intervals in wheel tracks at the 750 mm (to either side of the test vehicle) and the 1150 mm (to either side of the test vehicle) offsets. All measurements were done in the outer lanes. The profile data of each road were segmented into 1000 m sections and each profile was then processed through HATI QTF. The output included \(PI_{\text{HATI}}\) values in the outer and inner wheel tracks reported at 100 m intervals (reporting length Australian road agencies, Austroads (2007)) for the 172 km sample network, thus providing 1720 data points. HATI values were then determined, using Equation 1, for both offsets.

The analysis involved comparing road surface characteristics in both offsets using graphical and statistical analysis. The comparisons included the differences between lane values of HATI in both offsets, their values in the outer and inner wheel tracks and their statistical significance. Relevant \(TRN_{\text{HATI}}\) values were also determined to compare the resulting ratings or perceptions. The analysis also included an assessment of the number of rough sections in truck tracks that cannot be detected by roughness indices determined from data collected in car wheel tracks.

4. Data analysis and observations

The assessment results of road surface characteristics affecting truck ride in both offsets
are presented herein for all sample sections. This is followed by an assessment of the characteristics of the rough sections only i.e. with HATI ≥ 1.70 m/km in both offsets. For these sections, a comparative assessment of roughness in terms of the IRI is also provided. HATI values calculated in the 750 mm and 1150 mm offsets will be referred to herein as HATI_{750} and HATI_{1150} respectively. A similar naming approach has been used for lane IRI values.

4.1 Characteristics of all study sections

The overall findings based on the 1720 sections are presented in the following order: frequency distributions and statistical descriptions of lane HATI values in both offsets, differences between the two data sets and an assessment of the number of mismatches between the two data sets in terms of ride perception.

4.1.1 Frequency distributions and statistical descriptions

The frequency distributions of HATI values in both offsets are presented in Figures 2a and 3a for HATI_{750} and HATI_{1150}, respectively. Relevant statistical descriptions indicate that the mean (1.03 for HATI_{750} and 1.07 for HATI_{1150}) and standard deviation (0.48 HATI_{750} and 0.49 for HATI_{1150}) values of both data sets are similar. Distributions of both data sets are skewed to the right which is an expected trend for a well maintained network. Skewness values for both data sets are high but were decreased with the application of log (base 10) transformations. The resulting distributions became normal as shown in Figures 2b and 3b for HATI_{750} and HATI_{1150}, respectively. Using ANOVA, the differences between log HATI_{750} and log HATI_{1150} values were found to be significant at 95% confidence with a P value of 0.02.
4.1.2 Differences between the two data sets

The differences between HATI values in both offsets are summarised below.

(1) HATI\textsubscript{1150} values are greater than HATI\textsubscript{750} values for about 62\% of the total sample. HATI\textsubscript{750} values for all 1,720 sections were arranged in ascending order and plotted in Figure 4. Corresponding HATI\textsubscript{1150} values were plotted in the same figure to show the variation across HATI\textsubscript{750} values. Generally, the variations are higher at high HATI\textsubscript{750} values.

(2) HATI values in both offsets correlate well with each other with a coefficient (r) of 0.97 and can be predicted from each other with a coefficient of determination (r\textsuperscript{2}) of 0.93 and a standard error of 0.125, see Figure 5. In the same figure, observed HATI\textsubscript{1150} values are plotted against the predicted values, which clearly indicate that higher residuals occur at high HATI values >2.5 m/km, which corresponds to a poor ride.

(3) The number of sections with HATI\textsubscript{1150} values greater than the threshold of 1.7 m/km is 191 comprising 11\% of the total length of the sample. Of these sections, 51 have poor ratings and the rest have fair ratings. In the 750 mm offset, 182 sections (10.5\% of the sample network) have HATI\textsubscript{750} \geq 1.7 m/km. Of these sections, 115 have fair ratings and 43 have poor ratings. Poor ratings are associated with HATI values \geq 2.2 m/km and cover TRN\textsubscript{HATI} scale values of 1 - 1.99. Fair ratings are associated with HATI values \geq 1.7 and < 2.2 m/km and cover TRN\textsubscript{HATI} scale values of 2 - 2.99.

The number of sections that have HATI values \geq 1.7 m/km in both offsets is 158. This means that the remaining 33 (= 191 - 158) sections with HATI\textsubscript{1150} \geq 1.7 m/km have HATI\textsubscript{750} values < 1.7 m/km. Similarly, the remaining 24 (= 182 - 158) sections with HATI\textsubscript{750} > 1.7 m/km have HATI\textsubscript{1150} < 1.7 m/km.
4.1.3 Assessment of ride perceptions

TRN_{HATI} values for both offsets were determined and compared in terms of the number of sections that fall within the different perception categories of the scale. TRN_{HATI} scale values in the 750 mm offset include 43 poor, 476 fair, 1087 good and 110 very good ratings. TRN_{HATI} data set in the 1150 mm offset has 51 poor, 517 fair, 1065 good and 83 very good ratings. The total number of sections with unmatched perceptions, in all categories, between the two data sets is 170, i.e. approximately 10% (= 170/1720) of the sample network.

4.2 Characteristics of the rough sections

As mentioned in section 4.1.2, the number of sections that have HATI values \( \geq 1.7 \) m/km in both offsets is 158. HATI_{1150} values are higher than HATI_{750} values for 55% of these sections, with differences ranging between 0.01 and 0.53 with most being < 0.2 m/km. The majority of them are from Hwy 2 (93 sections) followed by Hwy 3 (46 sections) and the least are from Hwy 1 (19 sections) as presented in Figure 6.

4.2.1 Roughness characteristics of the outer and inner wheel tracks

Figure 7 shows the trendlines of scatter plots for PI values in the outer and inner wheel tracks for these sections in both offsets. It can be noticed that generally, PI_{OT} in the 1150 mm offset is higher than all and PI_{IN} in the 1150 mm is the lowest of all. The first can be explained by the closeness to pavement edges affected by subgrade-related problems and the latter by the closeness to the road centreline. In both offsets PI_{OT} is higher than PI_{IN} and the differences between them are statistically significant. The differences between PI_{OT} and PI_{IN} in the 1150 mm offset increase with increasing HATI value. The differences between PI_{IN,750} and PI_{IN,1150} are not statistically significant but
they are for PIOT of the two offsets. These differences diminish at lower HATI values.

4.2.2 Roughness characteristics in terms of the IRI

Roughness values in terms of the IRI for these sections were also determined and compared. Relevant 1000 m profiles were processed through the IRI filter and reported at 100 m intervals. Lane IRI values for the 158 rough sections were then determined by averaging the values in the two wheel tracks. Figure 8 shows the variations in IRI values for these sections in both offsets. The majority of the sections have $\text{IRI} \geq 3.5$ m/km and many of them have IRI values $> 4.5$ m/km.

A lane IRI threshold value of $\geq 4$ m/km is currently used to trigger investigation into pavement rehabilitation on these types of roads. This is done under a maintenance program that aims at improving pavement rideability for car occupants and reducing vehicle operating costs. The values of IRI$_{1150}$ are higher than those of IRI$_{750}$ for 58% of the sections. Out of the 158 sections, 72 have IRI$_{750}$ values $\geq$ threshold and 69 in the 1150 mm offset. This means that IRI$_{750}$ or IRI$_{1150}$ would have a success rate of about 45% only, if used in detecting sections that provide poor ride to truck occupants instead of HATI.

4.2.3 Comparison in terms of ride perception ratings

Figure 9 presents the variations in TRN$_{\text{HATI}}$ values for these sections in both offsets. When comparing TRN$_{\text{HATI}}$ values and relevant perceptions for these sections, it was found that only 136 sections (92% = 136/158) have similar perceptions (fair or poor) in both offsets. This means that only 22 sections of the 158 rough sections do not have matching perceptions. Out of the 51 sections rated poor in the 1150 mm offset, HATI$_{750}$ can correctly detect 36 of them i.e. has a 71% (= 36/51) success rate. The 22 sections with unmatched perceptions were investigated further and the following observations
were made:

- Fifteen sections rate poor in the 1150 mm offset and fair in the 750 mm offset. Twelve of them are from Hwy 2. This can be explained by the higher variations within the outer wheel track in the 1150 mm offset compared to the 750 mm offset. Nevertheless, nine of these sections have IRI_{750} \geq 4 \text{ m/km} and would be triggered for rehabilitation under another ride improvement program. This means that if both HATI_{750} and IRI_{750} are used as triggers, the number of false detections would be reduced to from 29\% (= 15/51) to 12\% (= 6/51).

- Seven poor sections in the 750 mm offset rate fair in the 1150 mm offset. No specific characteristics, including geometry, were observed for these sections to explain this except for having lower HATI values. Four of them have IRI values in both offsets > 4 \text{ m/km}, which would be considered for rehabilitation anyway under another program.

5. Discussion

The findings presented above indicate that the assumption of higher roughness in truck wheel tracks is only true for the outer wheel track. The low PI_{IN} values clearly influence the resulting lane HATI values hence; imply that the assumption is not always true. Using the lane values is more accurate when assessing pavement rideability for trucks as it combines excitations from both wheel tracks.

For the sample network tested herein, these findings indicate that HATI calculated from longitudinal profile data measured in car wheel tracks can detect problematic sections to truck drivers correctly 71\% of the time. Furthermore, it can correctly detect ratings of all ride perceptions (very poor to very good) 90\% of the time. To eliminate the number of false detections, then road agencies need to collect profile
data in the 1150 mm offset to provide high level of service for the freight industry. Alternatively, to reduce the number of false detections, the proposed regression model can be used. The model uses HATI values determined from car wheel tracks to predict HATI values in truck tracks with an accuracy of ± 0.15 m/km.

It is also worth noting that most of the sections with false detections (i.e. rough to truck occupants but are not detected by HATI750) have IRI750 values > threshold and would be triggered for investigation into rehabilitation to improve ride quality for car occupants. This means that using both HATI750 and IRI750 would help to further reduce the number of falsely detected sections, if the above two options were not considered.

Variations within and between the three highways are believed to be due to the influence of the subgrade soil type and climate. Most of the Hwy 2 and Hwy 3 sections are located in areas of sand-clay (sand surface with clay at depth) with patches of cracking clay. Their soil/climate combinations are prone to the development of significant levels of LWR due to heave and subsidence of the subgrade caused by seasonal moisture variation and the presence of roadside vegetation. This observation is confirmed with the fact that Hwy 1 sections with HATI values greater than the threshold are only found in the first 19 km, which are located in areas of sand-clay soil.

The lack of sealed shoulders for many of Hwy 2 and Hwy 3 sections clearly contributed to the higher variations within the outer wheel track of the 1150 mm offset. Although Hwy 2 and Hwy 3 have similar soil/climate combinations, more rough sections are found in Hwy 2 than in Hwy 3. This is believed to be related to the impacts of traffic loadings and their dynamic effects on Hwy 2 pavement. It carries higher volume of truck traffic with high percentage of long heavy vehicles.

Many studies (Cebon, 1999; De Pont, 1994; OECE, 1997; Papagiannakis and Gujarathi, 1995) have shown that, for all truck suspension types, excitations induced by
LWR are the major contributors to pavement dynamic wheel loading (DWL) and the resulting damage. Using a whole of life pavement performance model (WLPPM) to simulate DWL, Cebon (1999) reported that the simulation indicates that DWL and pavement stiffness variations can have a significant effect on pavement surface roughness. Supported by limited experimental evidence, the simulation predicts that short wavelength roughness components are smoothed out and long wavelength components increase in amplitude (Cebon, 1999). The latter may explain the high number of rough sections found along Hwy 2 due to the interaction between its high traffic loads and problematic subgrade soil.

Considering HATI’s sensitivity to LWR, it has been found to be a good indicator of pavement sections subject to high DWL (Hassan, 2012). This implies that HATI could be used to indicate the need for applying load restrictions on roads built on problematic subgrade soils to reduce DWL and associated pavement damage caused by the heavier loads. Such subgrades include soft fine grained soils subject to freeze/thaw conditions and reactive soils subject to seasonal moisture variation.

6. Conclusions

The conclusions that can be drawn from this study are summarised below.

(1) The differences in roughness characteristics between the two offsets in terms of HATI are small but are statistically significant (P = 0.02).

(2) The assumption that lane roughness in truck wheel tracks is higher than car wheel tracks is not always valid. This is due to the fact that roughness variation in the outer wheel track in the 1150 mm offset is higher than the 750 mm offset and lower for the inner wheel track. Hence; resulting in HATI being higher in the 1150 mm offset for only 62% of the sample network tested herein.
(3) Ride perceptions of HATI values calculated from longitudinal profile measured in car wheel tracks do not match those determined from measurements in truck tracks for only 10% of the studied network.

(4) HATI\textsubscript{750} values associated with poor ratings correctly detect poor sections in truck tracks 71% of the time. However, most of the undetected sections have IRI values greater than the relevant threshold and would be triggered for investigation into rehabilitation under another ride improvement program. This would help reduce the number of rough sections to articulated truck occupants if data is not collected in truck tracks.

(5) Subgrade soil type, climate, shoulder seal width, traffic loading and DWL certainly influence surface roughness characteristics in both offsets.

It is important to note that the sample network used in this study is limited and does not cover all possible environmental and operational conditions of the road network in WA. However, the results of the sample network tested herein, including roads with different environmental and operational conditions indicate that roughness characteristics in the two offset are different. Hence, to ensure acceptable network level of service for heavy freight industry, it is recommended that road agencies collect profile data in the 1150 mm offset, in addition to the standard 750 mm offset. The cost of collection and processing is expected to be relatively small considering that a laser is already available in the truck wheel tracks for rutting measurements. Alternatively, the regression model proposed herein could be employed to predict HATI values in truck tracks and reduce/eliminate the number of falsely detected sections.
7. References


Austroads, 2000. A Road Profile Based Truck Ride Index (TRI), AP-R177/00, Austroads, Sydney, Australia


OECD, 1997. Dynamic Interaction of Vehicle and Infrastructure Experiment (OECD IR6 Project: Dynamic Interaction of Heavy Vehicles with Roads and Bridges,
DIVINE Project), Proceedings of the Asia-Pacific Concluding Conference, Melbourne.


Table 1. Parameters of HATI quarter truck model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ms= sprung mass</td>
<td>1</td>
</tr>
<tr>
<td>Ks= suspension stiffness</td>
<td>250 sec(^{-2})</td>
</tr>
<tr>
<td>Cs= suspension damping</td>
<td>30 sec(^{-1})</td>
</tr>
<tr>
<td>µ= unsprung mass</td>
<td>0.150</td>
</tr>
<tr>
<td>Kt= tyre stiffness</td>
<td>400 sec(^{-2})</td>
</tr>
<tr>
<td>b= tyre enveloping (base length)</td>
<td>300 mm</td>
</tr>
<tr>
<td>V= travel speed</td>
<td>100 km/hr (rural), 60 km/hr (urban)</td>
</tr>
</tbody>
</table>

Table 2. HATI and TRN\text{\textsubscript{HATI}} scale

<table>
<thead>
<tr>
<th>HATI (m/km)</th>
<th>Perception</th>
<th>TRN\text{\textsubscript{HATI}} Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.5</td>
<td>Very Good</td>
<td>4-5</td>
</tr>
<tr>
<td>0.5 – 1.20</td>
<td>Good</td>
<td>3-4</td>
</tr>
<tr>
<td>1.20 - 2.20</td>
<td>Fair</td>
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<td>2.20 – 4.0</td>
<td>Poor</td>
<td>1-2</td>
</tr>
<tr>
<td>&gt; 4.0</td>
<td>Very Poor</td>
<td>0-1</td>
</tr>
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</table>
Table 3. Details of study Sections

<table>
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<tr>
<th>Hwy</th>
<th>Length included in study, km</th>
<th>Subgrade soil type</th>
<th>Climate/TMI</th>
<th>Speed limit</th>
<th>Shoulder seal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hwy 1 (H004)</td>
<td>59</td>
<td>First 19 km, Sand-Clay and the rest Sand</td>
<td>-15 to -25 (first 20 km) -25 to -35 Rest</td>
<td>110</td>
<td>Yes~0.5 m</td>
</tr>
<tr>
<td>Hwy 2 (H006)</td>
<td>57</td>
<td>First 18 km Sand and the rest Sand-clay with patches of cracking clay</td>
<td>-20 to -35 (first 20 km) -50 Rest</td>
<td>100</td>
<td>None for most and some parts with 0.3m seal</td>
</tr>
<tr>
<td>Hwy 3 (M041)</td>
<td>56</td>
<td>Sand-clay with patches of cracking clay. Rocks in few sections</td>
<td>-15 to -40</td>
<td>110</td>
<td>None</td>
</tr>
</tbody>
</table>

Figure 1. Frequency response function of HATI QTF to road input.
Figure 2. Frequency distribution of HATI_{750} values; (a) original data, (b) transformed data

Figure 3. Frequency distribution of HATI_{1150} values; (a) original data, (b) transformed data
Figure 4. Variation of HATI\textsubscript{1150} with HATI\textsubscript{750} for the sample network

Figure 5. Regression model for predicting HATI\textsubscript{1150} from HATI\textsubscript{750}

\begin{equation}
\text{HATI}_{1150} = 0.98 \times \text{HATI}_{750} + 0.058
\end{equation}

\begin{equation}
R^2 = 0.93
\end{equation}
Figure 6. Distribution of the rough sections for both offsets across the three highways

Figure 7. Lane IRI values of the rough sections in the two offsets
Figure 8. Comparison of PI values in the outer and inner wheel tracks within and between the two offsets

Figure 9. \( \text{TRN}_{\text{HATI}} \) values for the rough sections in both offsets