MEASUREMENT AND COMPARISON STUDY OF ROAD ROUGHNESS CONDITIONS BY USING TWO COMPACT ROAD PROFILER FOR EVALUATING RIDE QUALITY

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ABSTRACT - More recently, it is strongly required that road management involves a wide range of topics over the world and it must be considered from a perspective of customer-oriented levels of service and road administrators are requested to present a visual map of road network in terms of road network monitoring among others. To fulfill these requirements, firstly, this paper introduces new topics, which is related to two Compact Road Profiler (CRP) to monitor the road roughness conditions including localized distresses. In addition, we analyze road profile data considering two wheel paths by the survey vehicle, known as inner and outer wheel paths, and using a sophisticated driving simulator (DS) to evaluate ride quality conditions based on Power Spectrum Density (PSD) function to identify the sensitive range of ride quality. Finally, we calculate the Root Mean Square (R.M.S) and Crest Factor (CF) using vertical acceleration data of the passenger seat in DS. Consequently, it is shown that advanced evaluation of the ride quality under two wheel paths is performed. As regards standard for ride evaluation, ISO 2631 standard is adopted.

1. INTRODUCTION

Pavement roughness is the deviation of the vertical amount of the road surface, and it is one of the major technical indicators of the pavement quality evaluation. Pavement roughness is not only related to traffic safety, comfort and economy, but also has a direct impact to carrying capacity and life cycle of the pavement. In recent years, the Ministry of transport (MOT) in China has requested the local road administrators to monitor and check road surface conditions of different road levels as a routine activity. In this case, International Roughness Index (IRI) is used as an index to monitor road roughness, which is related to ride quality.

This research aims at monitoring road roughness conditions in local area in terms of road network level and evaluating ride quality by using DS based on ISO standard. From this purpose, firstly, this
study carried out by using two Compact Road Profiler, which is developed by Kitami Institute of Technology (KIT) Japan based on Quarter Car Model (QCM). In this research work, it mainly for collecting road profiles by two wheel paths of the survey vehicle, which is known as Inner Wheel Path (IWP) and Outer Wheel Path (OWP). Secondly, the road roughness conditions of the different two wheel path’s road profiles on a high-standard highway are statistically analyzed and evaluated based on comparison with both wheel paths of survey vehicle. Finally, ride quality of road surface is analyzed by use of the DS originally developed for evaluation of road characteristics from stand point of road users based on Power Spectral Density (PSD) function. Furthermore, by evaluating the comfortability of road surface, this research work calculated the different ride quality indices, known as R.M.S, Peak Acceleration and CF, at three different levels: highest, middle and lowest of the vertical acceleration data based on ISO standard 26311). 

2. TOOLS FOR MONITORING AND EVALUATION OF ROAD PROFILE

2.1 Compact Road Profiler in Pavement Monitoring

There are a lot of profilers in various countries and the high-speed profilers are mainly used laser sensor technology. Against this background, KIT have developed the new profiler called STAMPER, that is the short name of ”System with Two Accelerometers for Measuring Profile, Enabling Real-time data collection” this is a kind of new and advanced small size mobile profiler by using two accelerometers principled for a quarter car model to calculate IRI, this system enables acquire profile data and monitor pavement roughness in real-time at ease and effectively. STAMPER consists of two small accelerometers, a GPS (Global Positioning System) sensor, an amplifier and a portable computer. Principle of the system of profiler is based on the conventional quarter-car (QC) model used for calculating IRI. Therefore, two accelerometer are mounted at the sprung and unspring mass of a vehicle, and road profile is calculated by back calculation analysis correcting vehicle speed as shown in Figure 12). The information of road roughness is displayed on a PC screen in real-time during surface monitoring and analyzed together with GPS data and the ArcGIS while off-line. This system can be installed in any automobiles in the market place so as to facilitate to monitoring road roughness for road administrators of local governments.

![Figure 1 Overview of Compact Road Profiler (CRP)](image)

2.2 Advantages of DS for Road Surface Evaluation

The application of DS in the field of road research mainly focused on the visibility of the road such as traffic sign. Kitami Institute of Technology has introduced a new type of a driving simulator (KITDS) in 2003. It has been developed to evaluate road safety and comfort initially. The prototype of KITDS based on a conventional DS to evaluate traffic safety for driver training. In the resent years, KITDS has added many advanced functions, such as: Evaluate the actual road surface characteristic data and vehicle actual motion data. It also enables replay of the visual images while driving. It can evaluate the comfort...
of the passenger’s safety, stability and controllability of the vehicle, vehicle fuel consumption and tire noise associated with the roughness of actual road. This paper mainly mentioned DS to evaluate the peak acceleration data to maximum instantaneous acceleration at any time during to measurement period for analyze frequency weighting, PSD, and for calculate R.M.S and CF. KITDS specializes in road surface evaluation. It is the first device in the world that can evaluate the relationship between the road surface characteristics and vehicle behavior. As shown Figure 2.

Figure 2 Overview of KITDS

3. OVERVIEW OF THE PAVEMENT EVALUATION
Pavement evaluations are conducted to determine functional and structural conditions of a highway section either for purposes of routine monitoring or planned corrective action. Functional condition is primarily concerned with the ride quality or surface texture of a highway section. Structural condition is concerned with the structural capacity of the pavement as measured by deflection, layer thickness, and material properties.

At the network level, routine evaluations can be used to develop performance models and prioritize maintenance or rehabilitation efforts and funding.

At the project level, evaluations are more focused on establishing the root causes of existing distress in order to determine the best rehabilitation strategies.

3.1 IRI As Ride Quality Parameter
IRI is the International Roughness Index and measures pavement smoothness. The lower the calculated IRI, the smoother the pavement will ride. The higher the IRI, the rougher the pavement will ride. The units of IRI are usually in/mile, m/km, or mm/m. The equation of IRI is, as following Eq. 1.

\[
IRI = \frac{\int_{0}^{L/v} (\ddot{z}_s - \ddot{z}_u) \, dt}{L}
\]

Where:
- \(L\) = Traveling distance (m).
- \(v\) = Vehicle speed (m/s).
- \(\ddot{z}_s\) = vertical speed of the sprung mass.
- \(\ddot{z}_u\) = vertical speed of the unspring mass.
- \(dt\) = time increment
3.2 Analyzing Of Ride Quality On Object Route Line

May 2020, the measurement of road roughness has been carried out on a high-standard highway, which located at outskirts of Urumqi city by use of two compact mobile profilers. The total section length of the highway is 7900 meters. The profiler mounted at unspring and sprung masses of right and left sides of the survey vehicle (The system introduced above Figure 1). The IRIs of most smooth and rough sections analyzed by ProVAL software.

To improve, comfort of the driving safety, secure and stability on highway and expressway. MOT, strongly requested, the local road administrations to improve road surface conditions from a viewpoint of the material and construction process. In contrast, JTG 3450-2019 (Field test specification for highway subgrade and pavement) introduced a maintenance standard for expressway in China. That is, IRI over than 2.0 m/km need to rebuilt, on the other hand IRI less than 2.0 m/km is acceptable.

Figure 3 is a summary of the object section (high-standard highway) and it clearly shows that, the smoothest and roughest sections of each 10meters IRIs to evaluate and compare roughness conditions of inner and outer wheel paths, by JTG 3450-2019 road maintenance standard. The road surface conditions of those sections are shown in following figures.

![Figure 3 Road roughness conditions of both wheel paths](image)

From Figure 4 are the results of IRI on smooth sections for each 10 meters of the two wheel paths, the figures clearly shows that, the range of IRI of each 10 meters are less than maintenance standard, but comparison results of the total IRI between inner and outer wheel path on whole 100 meters sections shows that, the inner wheel path surface conditions are better than those of outer wheel path.
Figure 4  Roughness conditions for smooth sections

Following Figure 5 shows the correct measurement location of the smooth section, and it can show the difference of inner and outer wheel path's surface conditions clearly. And it is possible to determine that, the inner wheel path is smoother than those of outer wheel path.

Figure 5  Measurement location of smooth section

From Figure 6 are the results of IRI of each 10 meters on rough sections, the figures clearly shows that, the majority range of both wheel paths IRIs are over than maintenance standard, road administrators need to carry out rebuilt construction and improve the road surface conditions on these sections because road surface conditions of this section will be affect to the comfort of the drivers safety and stability. In addition, the comparison results between inner and outer wheel path of whole traveling distance shows that, there are no much more difference between the both wheel tracks. The road surface under the both wheel path are deteriorating poor year by year. But according to the total IRI of the rough sections shows that, the outer wheel path's road surface conditions are better than those of inner wheel path.
Following Figure 7 shows the correct measurement location of the rough section, and it shows the some pavement distress (rut and crack) under the inner and outer wheel path's surface clearly. And it is possible to determine that, the outer wheel path is better than those of inner wheel path.

3.3 Power Spectral Density
PSD function is a statistical representation of the importance of various wave numbers. The uneven road surface, since those show irregular shape with a change in amplitude and different wavelengths is large, PSD were performed to evaluate uneven road surface at a frequency band; will be evaluated using (Power Spectral Density) method is common.

The function of the power spectral density is, as following Eq. 2.
\[
G_n(v) = G_n[1 + (\nu_n/v)^2]/(2\pi v)^2
\]

Where:
- \(G_n(v)\) = Power spectrum density (m²/cycle/m)
- \(v\) = Wave number (cycle/m)
- \(G_n\) = Uneven parameter (uneven level)
- \(\nu_n\) = Cutoff wave number

To calculate and analyze PSD of those eight different smooth and rough sections road condition.

Figure 8 PSD results for smooth section

**Figure 8** shows the statistical analysis of the PSD with ISO standard for smooth section. The ISO standard shows the road condition from A level to H level respectively, it also shows that, the road surface condition gradually deteriorate, according to those results of smooth sections, inner and outer wheel paths are not much different and ride quality on these sections are quite well, because the sensitive of those sections of PSD are located in level A.

But the comparison results between the IWP and OWP based on sensitive range of Figure A, C and D shows that, the road surface conditions under the IWP are better than these of OWP, sensitive range of Figure B shows that, there is no much difference between the IWP and OWP’s wave numbers (Note from 1.1 to 1.4 cycle/m section caused by our Compact Road Profiler, it is out of the analyzing process).
The Figure 9 shows statistical analyzing results, of the PSD with ISO standard criterion for rough sections, the results obtained by using same method with smooth section, according to the results of rough sections, most of the inner and outer wheel path located on level B to F. It means the ride quality on these rough sections is going to deteriorating. (Note from 1.1 to 1.4 cycle/m section caused by our Compact Road Profiler, it is out of the analyzing process).

3.4 Ride Quality Analysis by KITDS Based on Vertical Acceleration Data

Road roughness have a certain affects to driver’s safely traveling their journey on a highway, it means, improvement of the ride quality is very important issue for different levels highways. As introduced some advantages of the KITDS, on the above sections, which is possible to evaluate and study different kind of road surface topics, such as taking actual road surface characteristics and vehicle actual motion data into DS to evaluate relationships between road surface and human body, comfort of the passengers, safety, stability, and so on. According to this kind of advantages of the DS, this experiment conducted to simulate the vertical acceleration of both wheel paths based on real measurement location’s profiles to evaluate the ride quality. The simulated time was 350 sec (around 6 min) and vehicle speed at 70 km/h. For evaluate the ride quality it is necessary to calculate R.M.S, peak acceleration and CF.

Because there is a certain relationship between these three index to define ride quality conditions of measurement locations.

Mathematically, R. M. S. can be expressed as Eq. 3.

$$ a_{w\_r.m.s.} = \frac{1}{T} \int_{0}^{T} a_{w}(t) \, dt $$

Where:

- $a_{w\_r.m.s.}$ = frequency-weighted r.m.s. acceleration.
- T = measurement duration.
- $a_{w\_w}(t)$ = frequency weighted acceleration at time t.

Equation of CF as;
\[ CF = \frac{\max(a_w(t))}{r.m.s.(a_w)} \] 

The following Figures 10-13 shows the correct positions and sensitive ranges of the whole vertical acceleration data as highest, middle and lowest level respectively, and the results of those three different levels R.M.S. peak acceleration and CF are shown in Table 1.

| Index     | Level       | R.M.S. (m/s²) | Peak Acceleration (m/s²) | F  |
|-----------|-------------|---------------|--------------------------|----|
| Lowest    | 0.17        | -0.81         | -4.76                    |
| Middle    | 0.46        | 1.50          | 3.28                     |
| Highest   | 0.74        | 3.25          | 4.39                     |

Figure 10 shows frequency weighted of the whole vertical acceleration data obtained by DS, it is clearly shows the shocked vibration on different three level to determine the vibration instantaneous of the 350 sec.

Figure 10 Vibration conditions of whole vertical acceleration

Figure 11-13 shows the frequency weighted of the vertical acceleration at three different levels picked up from each 10 seconds of whole vertical acceleration data, the lowest level picked up from the beginning to 10 sec section, middle level form 30 seconds to 40 seconds and highest from 20 seconds to 30 seconds, these data are easy to determine ride quality of shocked range of the peak acceleration and CF.

The results of R.M.S. Peak acceleration and CF will be shown above Table 1.
A short acknowledgement section can be written between the conclusion and the references. Sponsorship and financial support acknowledgments should be included here. Acknowledging the contributions of other colleagues who are not included in the authorship of this paper is also added in this section. If no acknowledgement is necessary, this section should not appear in the paper.

The Crest Factor ($CF$) is a dimensionless quantity defined as the ratio of the peak acceleration to the $R.M.S.$ The lowest possible $CF$ is 1, which occurs for a square wave. $CF$ is useful in assessing the applicability of $R.M.S.$ averaging. Therefore $CF$ for the random signal is 2.8 and $CF$ for the signal with shock is 4.3. In this study, range of the $CF$ are located, $CF$ for the random signal and $CF$ for the signal with shocks representatively.

ISO 2631 standard is especially used to for assess ride quality levels by weighted $R.M.S.$ acceleration. Range of the $R.M.S.$ for evaluating comfort is categorized in Table 2.

| Category of ISO 2631 standard | $R.M.S.$ Range ($m/s^2$) |
|--------------------------------|--------------------------|
| Comfortable                    | $\leq 0.315$             |
| a little uncomfortable         | 0.315–0.63               |
| fairly uncomfortable           | 0.5–1                    |
| Uncomfortable                  | 0.8–1.6                  |
very uncomfortable | 1.25~2.5 (m/s²) 
Extremely uncomfortable | ≥2 (m/s²)

According to the last results of the R.M.S. highest level, middle level and lowest level are applicable for “fairly uncomfortable”, “a little uncomfortable” and “comfortable” respectively. Those results show that the ride quality of the measuring location is acceptable. Because there are no value included, uncomfortable or over than this.

4. CONCLUSIONS AND NEW FINDINGS
The results of this study are summarized below:

1. Regarding frequent measurement of road surface at ease, the compact road profiler makes it possible to acquire road profiles over two wheel paths, IRI and acceleration data at one, and in real time.

2. KITDS shows special feature for taking actual profile data as to analyze the localized road surface distress condition in terms of ride quality of the passengers.

3. The results of comparison study between the inner and outer wheel paths, by using JTG 3450-2019 maintenance standard, show the road surface conditions on smooth and rough sections clearly, according to the road surface conditions of rough sections, the pavement conditions under the inner wheel paths deteriorating poor year by year, it might be caused by traffic value, heavy track and over speed conditions.

4. The PSD with ISO standard of the rough sections shows that, the sensitive ranges under the inner and outer wheel paths located on normal to fairly uncomfortable, that means the ride quality on these sections is going to deteriorate, and local road administrators need to carry out Maintenance.

5. The R. M. S. Peak acceleration and CF are considerably useful indices for evaluating a variety of vibration conditions from the vertical acceleration. The last results of this study are established by CF, based on the value of the CF set on random and shocks vibration-levels. The indices help to identify the locations where it might be happed pavement distress (irregularity pothole, rut and fault) or there are some joints.

ACKNOWLEDGEMENT
This work was supported by Xinjiang natural science foundation, Grant Number 2020D01B21.

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