COMPUTING EFFECT OF JOINTS ON RIDE QUALITY AND ROUGHNESS INDEX

Chiu Liu[1], and Zhongren Wang[2]

ABSTRACT
Periodic vertical vibrations in moving vehicles can be induced by regularly spaced joints on pavement surfaces. These vibrations discomfort drivers and passengers and even be annoying on a long road section. Conventionally, two important indices, International Roughness Index (IRI) and Present Serviceability Index (PSI) have been chosen to characterize pavement ride quality. In this paper, reduction of both IRI and PSI in the presence of pavement joints is analytically derived by using a vehicle model and by considering the different geometries of joints. Equations related PSI and IRI to the joint geometries and vehicle characteristics are programmed into Excel worksheets to perform numerical evaluations. The dependence of ride quality reduction on joint width, the vertical fault, and tire pressure, are explicitly displayed in figures. Two cases, joints with vertical faults and joints without vertical faults are examined carefully. Equations that relate both IRI and PSI to joints of random vertical faults are also provided to address practical concerns. Moreover, the effect of smoothing rough joints on both PSI and IRI are analytically estimated. Theoretical predictions are found to agree well with the FHWA reported data. These research results are of great importance for maintaining/monitoring pavement systems and possibly for setting quality control and rehabilitation criterion.

KEY WORDS
Concrete Joints, Joint Width, Fault, Vehicle Model, Serviceability, International Roughness Index, Ride Quality, and Serviceability Index.

INTRODUCTION
Considering a jointed concrete pavement with slab length of 10m. Driving a passenegr vehicle at 112 kph (70 mph) on the jointed pavement, one would feel 370 pulses per minute. This situation can be exasperated if the vibration induced by the joints is sever. In order to maintain high ride quality, engineers should carefully controll the joint width and the joint faults in the early stage of construction and subsequent stages of the pavement life. Ride quality is characterized by present serviceability index (PSI) (AASHTO, 1993) and in part by the international roughness index (IRI). The importance of the serviceability concept and

[1] Assistant Professor of Department of Civil & Environmental Engineering, Villanova University, Villanova, PA 19085, USA, Phone 610-519-4967, FAX 610-519-6754, chiu.liu@villanova.edu
[2] Senior Engineer, Division of Traffic Operations, California DOT, Sacramento, CA 95814, Phone 916-654-5672, FAX 916-653-3055, Zhongren_wang@dot.ca.gov

index IRI in design is discussed in details in the past (Liu, 2000; and Smith et al 2004). Index IRI has been accepted by many agencies as a pavement performance indicator (Yew & Friedman 2002; and Sayers et al 1986) . Recently, the IRI was further related with pavement test methods and specification (Killingworth, 2004). In order to give good estimation to these quantities, one must find a way to compute the PSI and IRI based on vehicle models and road profile information. It is known that in order to know PSI precisely (liu & Herman, 1999), one should compute the dynamic jerk experienced by drivers and relate the jerk intensity to PSI via Fechner's Law. Quantity IRI, refelceting the relative vertical displacement of sprung mass and vehicle axles, can be computed by uderstanding the vehicle dynamics (Liu & Herman, 1996; and Liu 2001]. Since joint width and joint fault may cause violent vibration in vehicles, both PSI and IRI are subjected to change with the depth of the fault and/or width of the joint.

FORMULATION

The influence of different joint geometries on PSI and IRI will be derived on an analytic setting by taking into account the vehicle-road interaction. The dynamic vehicle-road interaction can be quantitatively understood using the known quarter vehicle model (see Fig. 1), which has been successfully applied to understand vehicle excitation on roads of various profiles (Cebon 1999).

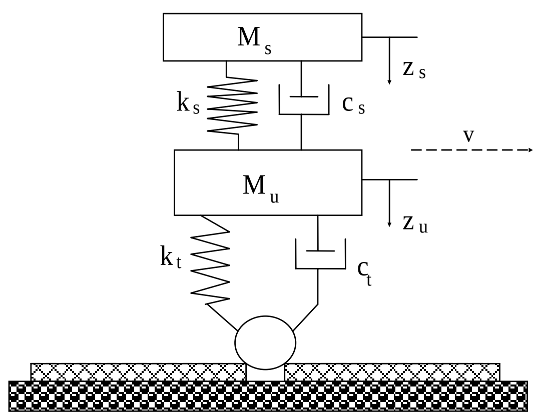

Figure 1: A model for a Moving Vehicle

Consider a vehicle traverseing across a concrete joint shown in Figure 2. In order to isolate the vibration due to joints only, one must first assume that the bulk pavement surface flat and later superimposes the rough features of road profiles into the flat surface. Namely, the road profile appears to be smooth everywhere except at the joints in between two adjacent slabs. Describing the displacements from the equilibrium positions of the sprung mass and the unsprung mass as $z_s(x)$ and $z_u(x)$, and the surface profile by $z(x)$, one can write down the equations relating road profiles to the induced vertical vibrations of vehicles (Cebon, 1999):

$$M_s\ddot{z}_s + k_s\left(z_s - z_u\right) + c_s\left(\dot{z}_s - \dot{z}_u\right) = 0 \tag{1}$$

$$M_s\ddot{z}_s + M_u\ddot{z}_u + c_t\left(\dot{z} - \dot{z}_u\right) = k_t\left(z - z_u\right) \tag{2}$$

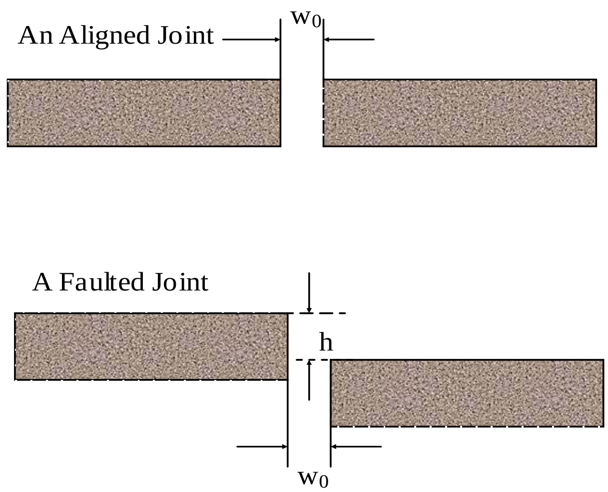

Figure 2: Two Possible Types of Concrete Joints

Shown in Figure 1 is a sprung mass M_s rested on top of a spring k_s and a dashpot with a viscous parameter c_s, an unsprung mass M_u, and a spring a viscous parameter c_t, and a constant k_t characterizing the tire mechanical properties. A road profile characterized by a spatial period of $\tilde{L}$ can be expanded in terms of a Fourier series, namely

$$A_n \cos\phi_n = \frac{2}{\tilde{L}}\int_0^{\tilde{L}} z(u)\cos(2n\pi\, u / \tilde{L})du \tag{3}$$

$$A_n \sin\phi_n = \frac{2}{\tilde{L}}\int_0^{\tilde{L}} z(u)\sin(2n\pi\, u / \tilde{L})du \tag{4}$$

Where the integer $n \geq 1$. The vertical displacement $z_u(x)$ of the unsprung mass and $z_s(x)$ the sprung mass for Eqs. (1) & (2) are found to be

$$z_u(x) = \mathrm{Re}\left\{\sum_{n=1}^{\infty} A_n \frac{(k_s - M_s\omega_n^2 + i\omega_n c_s)(k_t - i\omega_n c_t)}{\Theta} e^{i\omega_n t - i\phi_n}\right\} \tag{5}$$

$$z_s(x) = \mathrm{Re}\left\{\sum_{n=1}^{\infty} A_n \frac{(k_s + i\omega_n c_s)(k_t - i\omega_n c_t)}{\Theta} e^{i\omega_n t - i\phi_n}\right\} \tag{6}$$

$$\Theta = (k_t - M_u\omega_n^2 - i\omega_n c_t)(k_s - M_s\omega_n^2 + i\omega_n c_s) - M_s\omega_n^2(k_s + i\omega_n c_s) \tag{7}$$

where angular frequency $\omega_n = 2n\pi v/\tilde{L}$. In addition, the vehicle parameters are set to $k_s / M_s = 62.3$, $k_t / M_s = 653$, $m_u / M_s = 0.15$, $c_t / M_s = 0.1$, and $c_s / M_s = 6.0$ (Gillespie et al 1980). The jerk relative to ground, the rate of change of acceleration experienced by riders, can be found by differentiating Eq. (6) repetitively three times:

$$J_s(t) = -\mathrm{Re}\left\{\sum_{n=1}^{\infty} A_n \frac{i(k_s + i\omega_n c_s)(k_t - i\omega_n c_t)\omega_n^3}{\Theta} e^{i\omega_n t - i\phi_n}\right\} \quad (8)$$

The jerk intensity, which matches with the variance of the jerk when it is considered approximately a random variable (Liu & Herman, 1998), can be determined using

$$\sigma_J^2 = \sum_{n=1}^{\infty} \omega_n^6 A_n^2 (k_s^2 + \omega_n^2 c_s^2)(k_t^2 + \omega_n^2 c_t^2) / 2\Theta\Theta^* \quad (9)$$

Equation (9) relates the road profile spectrum and vehicle mechanical characteristics to the vibration environment inside a moving vehicle. It is directly related to a ride quality index such as RQI and PSI, via the following equation (Liu et al, 1999):

$$PSI = 5 - \beta \times \log\left(\sigma_J / \sigma_{J,0}\right) \quad (10)$$

where quantity β is found to be approximately 2.80. Quantity $\sigma_{J,0}$ depending on measurement devices is the sensitivity threshold of human beings for jerk. Similarly, one can express the International Roughness Index (IRI) as

$$\mathrm{IRI} = \frac{1}{\mathrm{vT}} \int_0^{\mathrm{T}} \left|\dot{z}_s(t) - \dot{z}_u(t)\right| dt \quad (11)$$

Where speed v is set at 80 kph (50mph). When time derivative of the relative displacement, i.e. $\dot{z}_s - \dot{z}_u$, is considered random, equation (11) can be expressed by

$$\mathrm{IRI} = \frac{1}{\mathrm{v}} \sqrt{\frac{1}{\pi}} \left\{\sum_{n=1}^{\infty} \frac{M_s^2 \omega_n^6 A_n^2 (k_t^2 + \omega_n^2 c_t^2)}{\Theta\Theta^*}\right\}^{1/2} \quad (12)$$

Joints with or without Vertical Faults

The road profile at an aligned joint can be found by rolling a wheel across the joint. In the absence of fault at joints, the road profile is approximated by

$$z \cong \begin{cases} -w_0^3 / 24Rw_c & 0 \le x \le w_c \\ 0 & w_c < x \le L + w_0 \end{cases} \quad (13)$$

The road profile $z(x)$ with a vertical fault of depth h, approximated by rolling a wheel across the joint with enveloping effect taken into account, is given as

$$z(x) \cong \begin{cases} h(1-2x/w_c)/2 & 0 \le x < w_c \\ -\mathrm{h}/2 & w_c \le x < L_1 \\ -h[1-2(x-L_1)/w_c]/2 & L_1 \le x < L_2 \\ \mathrm{h}/2 & L_2 \le x < \tilde{L} \end{cases} \qquad (14)$$

where quantity h represents the magnitude of the vertical fault at joints; and lengths L_1 and L_2 are respectively equal to $L + w_0$ and $L + w_0 + w_c$. It is further assumed that $h << R$ and $w_0 << w_c$. These two conditions are well satisfied by noting that both the joint width and the vertical fault are in the order of 1 cm or less, and the radius of a vehicle tire is around 0.406m (16"). In addition, the spatial period $\tilde{L}$ of the concrete pavement is equal to $2(L + w_0)$.

By knowing Equations (9)-(14), one in principle can calculate both the jerk intesity and the IRI caused by joints with and without vertical faults. The calculation can be done by first (1) performing Fourier Transformation to the road profiles at joints expressed respectively by Eq. (13) & (14) and figuring out all the spectral wieght of the profile associated with each vibration mode; and then (2) plugging these spectral weights Equation (9), (10), and (12) to obtain the PSI and the IRI. All these steps can be programmed into Excell worksheets and then both the IRI and PSI can be computed numerically when depth and width of the joints vary to fit various practical situations. Our computational results are displayed in Figures 3 & 4:

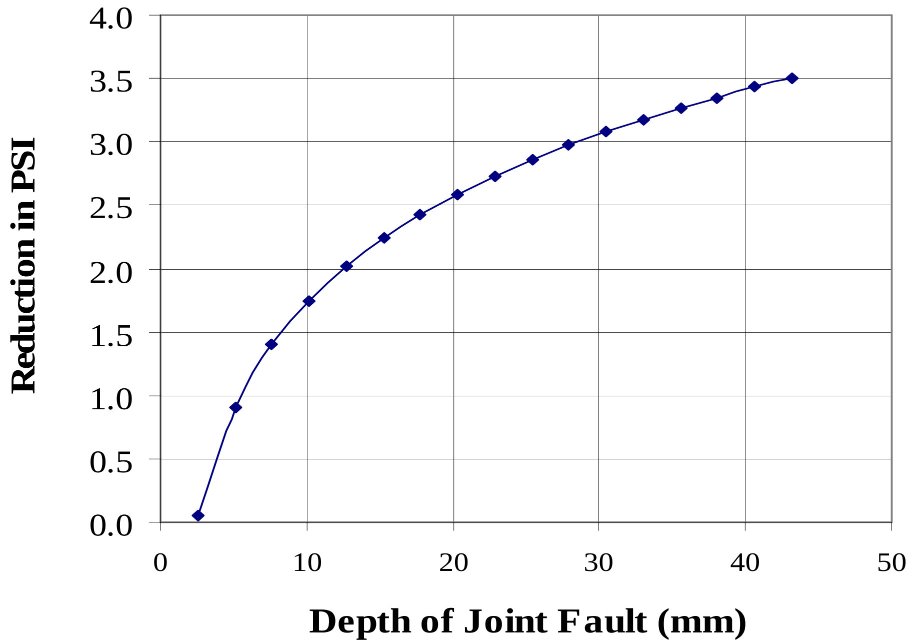

Figure 3. PSI Reduction is Plotted against the Depth of Joint Fault

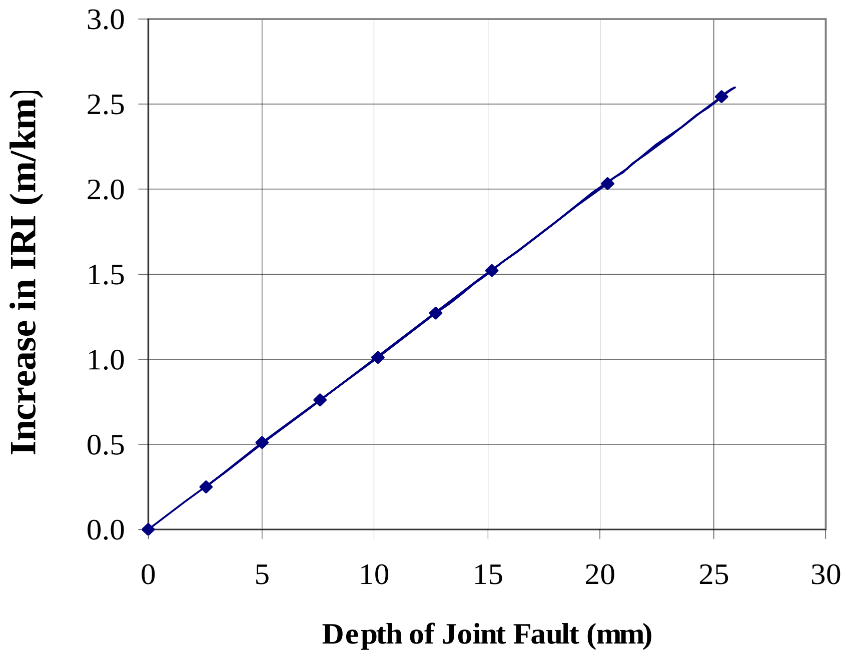

Figure 4: Increase of IRI is plotted against the Depth of Joint Fault

The results of the above computation agree well with data collected and reported in some NCHRP studies carried out in the past, showing our modeling on general valid. Becuase the reduction in PSI and increase in IRI is found negligible in computation so long they are less than 1.2 inches if the joint is perfectly aligned, we aren't showing those data here.

The next obvious question is how IRI and σ_J can be evaluated when the fault depth isn't uniform but random for a pavement with an arbitrary number of joints. In this case, both IRI and σ_J are found to be

$$IRI = \sqrt{\sum_{i=1}^{M} IRI_{J_i}^2} \tag{15}$$

$$\sigma_J = \sqrt{\sum_{i=1}^{M} \sigma_{J_i}^2} \tag{16}$$

Joints Embedded along a Road Profile

In a practical situation, joints are embedded along a road section. The question then could be what would be the reduction in IRI or increase of PSI when the joints were smoothed out along a road with an arbitrary profile? Lets use the subscripts 'm', 's', and 'o' to denote an quantity that is measured in the presence of untreated joints, measured in the presence of smoothed joints, measured when the road is nearly perfectly smooth/flat but the joints are rough. Both the increase of PSI and decrease of IRI when joints are smoothed out can be found via the following equations

$$IRI_s = \sqrt{IRI_m^2 - IRI_o^2} \tag{17}$$

$$PSI_s = \sqrt{PSI_m^2 - PSI_o^2} \tag{18}$$

Note that both PSI_o and IRI_o can be calculated using the existing programmed Excel worksheets.

6. CONCLUSIONS

The construction quality of jointed concrete is closely associated with both pavement ride quality PSI and pavement deterioration indicator IRI. In this investigation, both the PSI and IRI for pavements in the presence of joints are computed by programming joint and vehicle characteristics into Excel worksheets. The computation results are displayed in two figures for different joint depths. In particular, it is found that (1) the joint width has little effect on both IRI and PSI if the joints are aligned well; (2) the IRI are approximately proportional to the fault depth at joints, and (3) the chane in PSI is quite dramatic when the fault depth is small, reflecting the high public sensitivity to ride quality. Thus, controlling the joint width and joint unevenness of the pavement is of vital importance for enhancing quality of construction. This quality control can be realized by keeping the fault depth below 1mm in pavement serviceable life span. This may be achieved in part by smoothing the joint with asphalt sealing or by keeping the joint unevenness below the above-suggested critical values during construction and pavement's life time. These research results can be implemented in a quality control/quality assurance (QC/QA) process to monitor the construction quality of a jointed concrete pavement. The importance of controlling the fault depth and width cannot be overlooked because prevention measures are vital to prolong pavement life (Hansen, 2004). Because the large dynamic force induced by joints can accelerate pavement deterioration (Liu & Gazis, 1999), sealing joints to smooth pavement profile not only improve ride quality and index IRI but also extend pavement life.

REFERENCES

AASHTO(1993). *Guide for Design of Pavement Structures*, American Association of State Highway and Transportation Officials, Washington D. C.

Gillespie, T. D., M. W. Sayers, and L. Segel (1980). Calibration of Response-Type Road Roughness Measuring System, *NCHRP Report*, No. 228, TRB, NRC, Washington D. C.

Hansen, K. (2004). Pavement Preservation through Prevention, *HMAT* (NAPA), **9** (3) 23-26.

Killingsworth, B. (2004). Quality Characteristics and Test Methods for Use with Performance Related Specification of Hot Mixed Asphalt Pavements, NCHRP Report 9-15, 2004

Cebon, D. (1999) *Handbook of Vehicle-Road Interaction*, Swets & Zeitlinger B. V., Lisse, the Netherlands.

Liu, C. (2001). "Pavement Response to Moving Loads," *International Journal of Road Materials and Pavement Design*, **2** (3) 263-282.

Liu, C. (2000). "Vehicle-Road Interaction, Evolution of Road Surface Profiles, and Present Serviceability Index," *International Journal of Road Materials and Pavement Design*, **1**(1) 35-51.

Liu, C. and D. C. Gazis. (1999), "Dynamic Surface Roughness Effect on the Response of a Pavement structure," *J. Transp. Eng*. **125** (4) 332-337.

Liu, C. and Herman, R. (1998). Roadway Profile, Vehicle Dynamics, and Human Rating of Serviceability of Roads, *J. Transp. Eng*. **124** (2) 106-111.

Liu, C., Gazis, D. C., Kennedy, T. W. (1999). "Human Judgment and the Analytic Derivation of Ride Quality," *Trans. Sci*. **33**(3) 290-297.

Liu, C., and Herman R. (1997). Vehicle-Road Interaction, Physical Indices and Human Judgment of Ride Quality, *TRB* 1570 55-59.

Liu, C., and Herman R. (1996). New Approach to Roadway Performance Index, *J. Transp. Eng*. **122** (5) 329-336.

Sayers, M. W., Gillespie, T. D., and Quieroz, C. A. V. (1986). "The International Road Roughness Experiments," *World Bank Tech. Report*, Vol. 45, World Bank, Washington D. C.

Smith, K., Zimmerman, K., and F. Finn F. (2004). AASHO Road Test-the Living Legacy for Highway Pavements, *TR NEWS*, **232** 14-24.

Yew, C. and Friedman, P. (2002). "Measuring the Road to Improvement," *Public Roads*, USDOT & FHWA, **66** (3) 18-22.