Technical Note

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Rumble Strip Design Parameter Determination Based on Dynamic Jerking

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Abstract: Rumble strips have been installed on highway pavements to reduce vehicle collisions involving vehicles either running off road and/or crossing over centerlines. The rumbling effect may be understood in part as tactile inputs to waken inattentive and/or fatigue drivers. The tactile jerking effect, characterized by jerk intensity experienced by drivers, is analyzed for milled-in rumble strips with different geometric parameters using a quarter vehicle model. Our analysis shows that the optimal rumble strip width lies somewhere around 180 mm, and the ranges of the design parameters can be selected to control the jerking magnitude to alarm a driver in an errand vehicle. These parameter ranges are in part confirmed by experimental data reported in literature. This new rumble strip design strategy, practically more adaptable and effective, can be widely applied on highways of various functional classes.

***Key words**: Jerk, Rumble strips, Spatial periodicity, Strip depth, Strip width.*

Introduction

Approximately 40,000 fatalities and 2 millions disabling injuries occurred annually on US highways. Various engineering devices have been applied for reducing highway vehicle collisions in the past. These devices help to reduce collisions by catching driver's visual, kinesthetic, auditory, and/or vestibular attention. In United States, small cities and/or towns are usually connected by 2/3 lane highways with some 4-lane highway segments at occasions. Fatal accident rate measured by per million vehicle mile traveled is substantially higher in the 2/3 lane than on multilane highways. It is of great importance to keep collision rate low on 2&3 lane highways by reducing the risk of vehicle's running-off a lane. A run-off to the right accident is classified as run-off-road collision; and a run-into the opposite lane accident is classified as cross-centerline collision. Either collision type is highly dangerous because a run-off-road vehicle could collide with some fixed objects before losing most of its kinetic energy and a cross-centerline vehicle could collide at a high speed with an oncoming vehicle moving the opposite direction before dissipating its energy to the ground through its frictional tire-road contacts. In the past two decades, both shoulder and centerline rumble strips have been installed on highways to reduce run-off road and cross centerline collisions respectively [1].

Since the mill-in rumble strips can be installed on both pavement shoulders and highway centerlines, it is of practical interest to understand and engineer the rumble strip design by controlling its design parameters, such as rumble strip width, depth, and its spacing. In this paper, we analyze the strip induced dynamic jerking in conjunction with these three basic parameters via a vehicle model. This investigation and analysis will not only enhance our understanding of the rumble strip design but help engineer to choose the right ranges of the design parameters.

Formulation

Consider a vehicle moving over rumble strips shown on Fig. 2 along a given direction. In order to pin down the vibration due to rumble strips only, the road surface is assumed to be flat first; and the vibration induced by a rough profile can always be added on if necessary. Then, the road profile appears to be smooth except where the rumble strips are present. Denoting 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 assess the dynamic vibrations of the quarter vehicle by [4]:

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

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

Shown in Fig. 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 rumble strip profile characterized by a spatial period of L can be expanded in terms of a Fourier series, formally

$$z(x) = A_0 + \mathrm{Re}\sum_{n=1}^{\infty} A_n e^{-i\phi_n + i2n\pi x/L} \tag{3}$$

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

where the expansion coefficient A_n is real, quantity φ_n is a phase angle, and the integer $n \geq 1$. Constant A_0 is not of any concerns because it can be set to zero by vertically shifting the x-axis.

Using Eq. (3), the vertical displacement of the unsprung mass and the sprung mass for Eqs. (1) and (2) are found to be

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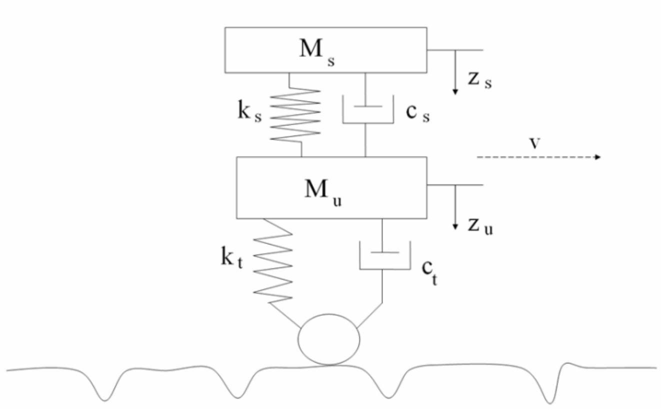

Fig. 1. Sketch of a Quarter Vehicle Moving over Rumble Strips.

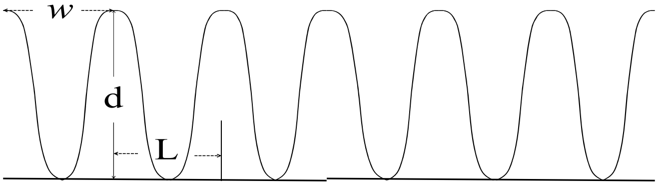

Fig. 2. Sketch of Longitudinal Rumble Strips Cross Section.

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

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

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

where angular frequency $w_n = 2n\pi v / L$ and the vehicle moving position x is replaced by vt plus an offset, which is adjusted to zero for convenience. 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 $c_s / M_s = 6.0$ [3]. The jerk relative to ground, the rate of change of acceleration experienced by riders, can be found by differentiating Eq. (6) repetitively three times:

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

Eq. (8) is a periodic function of time with a period T equal to L / v. Within a moving vehicle, a rider was found to be sensitive to the jerk intensity, which matches with the variance of the jerk when a road profile behaves as a random variable [4].

$$J^2 = \frac{1}{T}\int_0^T J_s(t) \times J_s^*(t)dt \tag{9}$$

or

$$J^2 = \sum_{n=1}^{\infty} \omega_n^6 A_n^2 (k_s^2 + \omega_n^2 c_s^2)(k_t^2 + \omega_n^2 c_t^2) / 2\Theta\Theta^* \tag{10}$$

Eq. (10) relates the rumble strip geometry and vehicle mechanical characteristics to the vibration environment inside a moving vehicle. Next, we consider jerk intensity produced by the milled-in strips.

Milled-in Rumble Strips

The milled in rumble strip may be approximated by the following parabolic profile

$$z(x) \cong \begin{cases} -4d(x - w/2)^2 / w^2 & 0 \le x \le w \\ 0 & w < x \le L \end{cases} \tag{11}$$

where the profile is sketched in Fig. 2, quantities L, d, and w, represent the spatial period, the depth, and the width of the rumble strips. In practices, the spatial period varies from 15 cm (6 in) to 50 cm (20 in), the depth ranges from 0.6 cm to 1.6 cm, and width is chosen in between 5 cm and 12.5 cm. The physical sizes of *L*, *d*, and *w* in engineering practices are chosen according to standard specifications or special construction details.

Using Eq. (4), the coefficient A_n for each sinusoidal component of a profile is computed to be

$$A_n = \frac{4dw}{\phi_n^2 L}\left|\cos(\phi_n) - \sin(\phi_n)/\phi_n\right|, \tag{12}$$

$$\phi_n = n\pi w / L \tag{13}$$

Substituting Eq. (12) into Eq. (10) yields

$$J = 32d\left(\frac{v}{L}\right)\left(\frac{v}{w}\right)^2 \times \sqrt{\sum_{n=1}^{\infty} R_n^2 a_n^2 \phi_n^2 / 2} \tag{14}$$

$$R_n^2 = (k_s^2 + \omega_n^2 c_s^2)(k_t^2 + \omega_n^2 c_t^2) / \Theta\Theta^* \tag{15}$$

$$a_n^2 = [\cos\phi_n - (\sin\phi_n / \phi_n)]^2 \tag{16}$$

While decreasing with the increase of the rumble strip width *w*, the jerk magnitude increases proportional to the rumble strip depth *d*. The ratio of *v/w* physically represents the inverse of the contact time between tire and rumble strip. The ratio of *d/L* measures the jerk severity. The jerk magnitude is modified by vehicle dynamic characteristics factor according to Eq. (14). A few consequences of practical significance may be drawn from Eq. (14). First, in order to increase jerk magnitude effectively, one should decrease the tire-rumble-strip contact time by decreasing *w* as much as that can be done practically. Second, the jerk magnitude increases proportionally with the rumble strip depth '*d*'. Since a deeper cut into pavement or paved shoulder may degrade pavement structural integrity, it is better to change the rumble strip width to the control jerk intensity experienced in moving vehicles. According to Eq. (14), jerk intensity grows proportionally with the rumble strip depth '*d*'. Shown in Fig. 3 is a straight line, verifying the prediction given by this equation. From a design point of view, we should have '*d*' big enough but not too deep to cause a driver to panic and overcorrect the vehicle moving direction. One may choose the depth '*d*' approximately in between 5 mm and 15 mm.

In Fig. 4, we plot the normalized jerk intensity J / J_0 was plotted against the rumble strip width by setting vehicle speed at 80

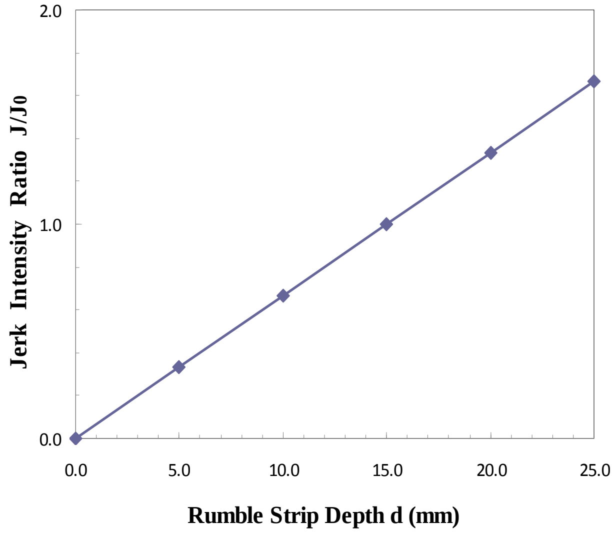

Fig. 3. Jerk Density Ratio Plotted Against Rumble Strip Depth '*d*'.

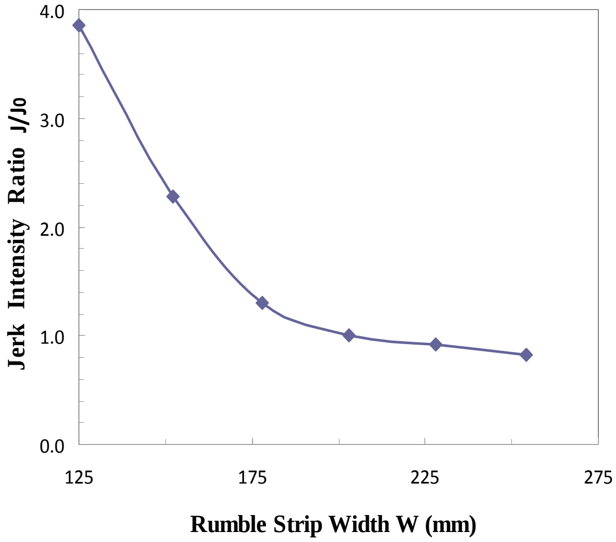

Fig. 4. Jerk Density Ratio Plotted Against Rumble Strip Width **'*w*'.**

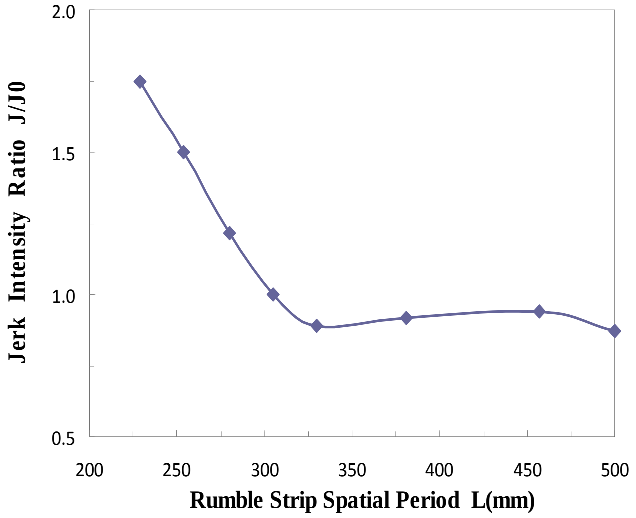

Fig. 5. Jerk Density Ratio Plotted Against Rumble Strip Spacing '*L*'.

kmph, rumble strip spacing at 0.305 m, and rumble strip depth at 9 mm (~3/8 in). The jerk intensity J_0 was the intensity induced on a moving vehicle by rumble strips with a regular spacing of 0.305 m, a depth of 9 mm, and a width of 0.203 m. It is inferred from Fig. 4 that the jerk intensity dramatically increase with the decrease of width '*w*' when '*w*' is below 150 mm, and the jerk intensity decreases slowly when width '*w*' is below 150 mm, indicating an optimal spacing for rumble strip design is in the neighborhood of 180 mm. This inference becomes more probable when bicycle riding is considered. A bicyclist prefers riding over rumble strips with larger width '*w*' because it makes a smoother ride. However, keeping the rumble effect at a high enough level to awake a driver should be placed at a higher priority than providing bicyclists a more comfortable riding environment. Therefore, the appropriate choice for resolving this conflict is choosing the rumble strip width in the neighborhood of 180 mm, and incidentally this rumble strip spacing has been employed by national and various state highway agencies [1, 2].

The spatial period '*L*', i.e. the rumble strip spacing certainly has influence on the jerk intensity experienced by drivers. Since decreasing the rumble strip spacing '*L*' is making the rumble strip longitudinal profile rougher, it is expected that that the jerk intensity will increases as shown in Fig. 5. On the other hand, when '*L*' goes beyond 30.5 cm (1 foot), the jerk intensity appears to be relatively flat. The rumble effect experienced by drivers is substantially intensified when decreasing '*L*' toward the magnitude of the rumble strip width but 'unnoticeable' as '*L*' goes beyond a foot. In addition, increasing '*L*' may substantially shorten the rumble time to awake a fatigue or an inattentive driver when a vehicle drifts across this 'soft' barrier onto the shoulder or the opposite lane. In order to keep the '*L*' as small as practical, constructible, and sensible, an engineer may need to select the spacing '*L*' approximately between 30 and 45 cm.

Conclusion

Detailed analysis on the rumble effect induced by milled-in rumble strips is discussed in this paper. The ranges of the rumble strip design parameters are determined based on vibrational environments sensed by drivers riding over the strips with a vehicle. Our analysis indicates that the width of rumble strip should be close to 180 mm for attaining higher jerk intensity, or inducing stronger rumble effect. The periodical spacing '*L*' between two adjacent strips should not be greater 45 cm, and the depth of grooves should be controlled between 5 to 15 mm to provide a sufficiently high intense jerk ratio. Our investigation supports the current practice very well [2], and it is believed that the methodology presented here may be employed to improve rumble strip designs in the future.

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