Ride Quality Investigation of Passenger Cars on Different Road Conditions

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ABSTRACT

Objective: The ride qualities of the six passenger cars were evaluated in 4 subjects on the highway and uneven road. The relation between vibration with driving velocity and driving posture were also investigated separately. **Background:** Ride comfort plays an important role in the vehicle design. Vibration is the one of the principal components associated with ride comfort. **Method:** The acceleration of the foot, hip and back were measured using B&K accelerometers in this study. The velocity of the passenger cars was maintained at a constant speed of 80km/h on the highway and 40km/h on the uneven road. For evaluating the effects of driving velocity and driving posture on vehicle's vibration level, separate experiments were performed on the highway with 5 different vehicle speeds and 5 different backrest angles, respectively. **Results:** The overall ride value of the luxury car showed the best result while the smaller car showed the worst value on the highway. On the uneven road the overall ride value level was increased 75~98%. All the vehicles had the SEAT value less than 1. Faster the velocity lowers the SEAT value. The ride quality in terms of vibration gets worst when the backrest angle increased. **Conclusion:** The smaller car had a first mode at the higher frequency and showed higher vibration level. SEAT value was mostly affected by the seat property not by vehicle. We ranked the luxury car seat had a best vibration reduction quality than others based on SEAT values. When the driving velocity increased, the overall ride values were increased proportionally and the SEAT values were somewhat decreased. **Application:** Evaluation of whole-body vibration in the passenger car.

Keywords: Passenger car, Driving velocity, Driving posture, Ride values, Ride comfort, SEAT value, RMS, Vibration

1. Introduction

Recent years, cars have become the essential transporting tools in the modern life. Along with technological development and life-quality improvement, users have higher and higher demand for ride quality and car performance. Ride quality concerns the driving personnel's comfort (Park et al., 1997, 1998, 2001; Kim et al., 2001; Nahvi et al., 2006). The ride comfort plays an important role in the vehicle design. The vibration is one of the principal components associated with ride comfort (Reed et al., 1991; Park et al., 1997, 1998, 1998a, 2001; Paddan and Griffin, 2002; Nahvi et al., 2009; Lin et al., 2006). Vibration transmitted to the buttocks and back of the occupant along the vertebral axis via the base and back of the seat has a large influence on comfort, performance, and health; in particular the whole-body vibration plays an important role in it (Griffin, 1990, 1998).

The ride quality is inherently a subjective measure and

the perceived comfort levels are different for people even with the same stimulus (Park et al., 1998). To improve the ride quality, past studies were attempted to identify the factors contributing to the ride quality and to match the ride quality with the subjective feeling (Griffin, 1990; Parsons and Griffin, 1983; Pardko and Lee, 1966; Reed et al., 1991; Wambold, 1986; Valasek et al., 2008; Lin et al., 2006). Few studies were measured the vehicles ride qualities using the ride value (Wambold, 1986; Park et al., 1998, 2001; Kim et al., 2001).

The major components contributing to the ride quality of the vehicle are the tire, suspension, road conditions and seat. The optimization schemes have been developed to increase the ride quality with such design variables as the tire, suspension, and seat property (Berger and Gilmore, 1993; Amirouche et al., 1994; Nahvi et al., 2009; Lin et al., 2006). The important design considerations in the car seat development are human health (Kelsey, 1975; McLain and Weinstein, 1994; Necking et al., 1992; Troup, 1978) and comfort (Dupius and Zerlett, 1986; Griffin, 1990; Park et al., 1997, 1998a). The seat dynamics may become significant in the ride quality since the seat directly transmits the vibration to the passenger. Hence studies were measured the seat characteristics and improved the seat performance (Park et al., 1998; Fouladi et al., 2011; Paddan and Griffin, 2002). Seat vibrational comfort was evaluated by developing several experimental test methods (Giacomin and Bracco, 1995; Meier et al., 1998; Staszewski and Giacomin, 1997; Park et al., 2001).

The level of perceived vibration is different according to the frequency and the axis of vibration; the equivalent comfort contours based on the subjective rating were formed and adapted in ISO 2631 and BS 6841. Griffin suggested some ride values regarding that the level and duration of the root mean square acceleration of the whole-body is closely related with the subjective ride quality by frequency weighting functions which are the inverse of equivalent comfort curve (Griffin, 1990, 1998; Parsons and Griffin, 1983; Park et al., 1998, 2001; Nahvi et al., 2006, 2009).

In this study, we evaluated the ride qualities of the six passenger cars in 4 subjects on the highway and uneven road. The effects of variation in the driving velocity and driving posture on vibration were also investigated. Seat dynamics were investigated for the transmissibility in the seats and seat effective amplitude transmissibility (SEAT)

value.

2. Method

2.1 Experimental setup

Whole-body vibration mainly transmitted through the seat surfaces, backrests, and through the floor to an individual sitting in the vehicle (Park et al., 1998). The experimental setup for measuring the whole-body vibration at the feet, hip and back is shown in Figure 1. The vibration was measured at 8 axes based on measuring scheme proposed in 1990 by Griffin. The measured axes - three translations (X_f, Y_f, Z_f) at feet, 3 translations (X_s, Y_s, Z_s) of hip and two translations (X_b, Z_b) of back. As of BS 6841, 12-axis measuring system is accepted in the vehicle industry. In this study, we have omitted four minor axes (3 rotations of hip and y-translation of the back), which showed a small contribution to the ride values (Park et al., 1998). The acceleration of the foot was measured by B&K 4326 accelerometer and the accelerations of the hip and back was measured by B&K 4322 accelerometer. The output signal was amplified through B&K 8-channel charge amplifier Type 5974 and was recorded with 1kHz sampling rate by 16-bit digital recorder (Sony DAT 216A) (Park et al., 1998).
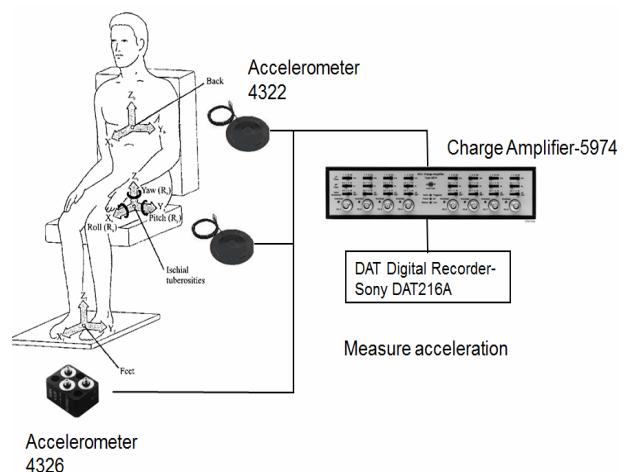

Figure 1. Schematic configuration for the measurement of whole-body vibration (Park et al., 1998)

The subjects were seated in the front passenger seat and

the experimenter with the equipment was placed in the rear seat. The subjects sat on a B&K 4322 3-axis translational sensor fastened on a seat cushion and another B&K 4322 3-axis translational sensor fastened on the backrest. The B&K 4326 3-axis translational sensor was attached to the floor of the vehicle along with the global coordinate: fore-and-aft as x direction, lateral as y direction and vertical as z direction.

2.2 Experimental procedure

This experiment was conducted for six vehicles (Table 1) on the highway and uneven road in the driving test field. Four subjects were participated in this experiment (Table 2). The velocity was maintained at a constant speed of 80km/h on the highway and 40km/h on the uneven road for keeping the same vibration condition of road. The experiments were repeated for 3 times at the same condition. Since the posture of the subject is important in measuring the human vibration, the backrest angle was fixed and the subjects were asked to keep their posture straight up during signal collection and not to fasten seat belt for the pure seat dynamics. This experiment executed for 1 week. So the road condition might have changed during the experiment. But this change was almost ignorable in highway and small in the uneven road.

Table 1. Characteristics of vehicles

Vehicle	Displacement (cc)	Type
V1	800	Passenger
V2	1500	Passenger
V3	1800	Passenger
V4	2500	Passenger
V5	3000	Passenger
V6	5000	Passenger

Table 2. Physical characteristics of subjects

Subject	Height (cm)	Weight (kg)
S1 (Female)	156	48
S2 (Female)	167	51
S3 (Male)	173	68
S4 (Male)	184	94

The car vibration level in driving is much affected by the driving velocity. To test this factor, separate experiment was performed on the highway with variations in the driving velocity. The driving velocities considered were 60, 70, 80, 90 and 100km/h. We have asked all the subjects to remain constant in a comfortable posture during data acquisition. As explained earlier, the posture of the subject is important in measuring the human vibration. Generally people feel comfortable when they lean to the backrest with larger angle. To test this factor, separate experiment was performed on the highway by considering different sitting postures. The backrest angles considered were 10, 20, 25, 30 and 40°. In this case, the vehicle's velocity was maintained at 80km/h.

2.3 Data analysis

The manner in which vibration affects health, comfort, perception and motion sickness is dependent on the vibration frequency content (Griffin, 1990). As ISO 2631 and BS 6841 indicated, the comfort rating was determined by means of the frequency weighting filters. We have considered 4 functions of frequency weightings (W_b, W_c, W_d, W_e) and 8-axis. The weighting functions and axis multiplying factors are described in BS 6841. Many researchers have tried to quantify the ride value and developed many ride values. In this study, we evaluate the ride values such as the component ride value, the overall ride value and the seat effective amplitude transmissibility (Parsons and Griffin, 1983; Griffin, 1990; Park et al., 1998; Kim et al., 2001).

2.3.1 Component ride value

The contribution of each axis can be quantified as the ride value according to the contact points between the human and the seat. The component ride value (CRV) is defined as the acceleration r.m.s value of each axis. These values are enabling to evaluate the relative contributions of each axis. The component ride value was obtained using the Eqn. (1).

$$CRV_i = m_i \times \sqrt{\int P_{ii}(f) w_i(f)^2 \, df} \qquad (1)$$

Where, m_i is the axis multiplying factor; $P_{ii}(f)$ is the power spectral density of each axis; w_i is the weighting function of the each axis.

2.3.2 Overall ride value

The overall ride value (ORV) is evaluated as the 2-norm of the CRV as Eqn. (2). The ORV gives the total vibration level; it is adequate for making simple comparisons between vehicles with different seat, suspension, etc. In the view of vibration, the seat with highest ORV expected to be the most uncomfortable seat.

$$ORV = \sqrt{\left[\sum_{i=1}^{N} (Component\ ride\ value_i)^2 \right]} \qquad (2)$$

2.3.3 Seat Effective Amplitude Transmissibility (SEAT) value

SEAT value is defined as the weighted vibration ratio between Z_f of the floor and Z_s of the hip. SEAT value greater than 1 means the vibration at the seat is greater than the vibration at the floor, SEAT value lower than 1 indicates that the level of vibration is decreased by the seat (Griffin, 1990; Park, 1998; Kim, 2001). The seat effective amplitude transmissibility is given by Eqn. (3)

$$SEAT = \sqrt{ \frac{\int P_{ss}(f)\, w_b(f)^2\, df}{\int P_{ff}(f)\, w_b(f)^2\, df} } \qquad (3)$$

Where $P_{ss}(f)$ and $P_{ff}(f)$ are the seat and floor acceleration power spectra, and W_b is the same weighting function in both the numerator and denominator (Griffin, 1990; Niekerk et al., 2003). W_b is the frequency weighting for the human response to vibration which is of interest: this is the weighting for vibration occurring on the seat and not the weighting for vibration on the floor.

3. Results

3.1 Component ride value

The RMS level of acceleration of each axis for the vehicles is presented (Figure 2). The vehicles CRV for each axis were calculated using Eqn. (1) and is presented (Figure. 3). We can see from the Figure 3 that three significant

directions (foot-z, hip-z, and back-x) have larger magnitude of CRV than other directions and these three directions contributed to ORV about 80~90%.
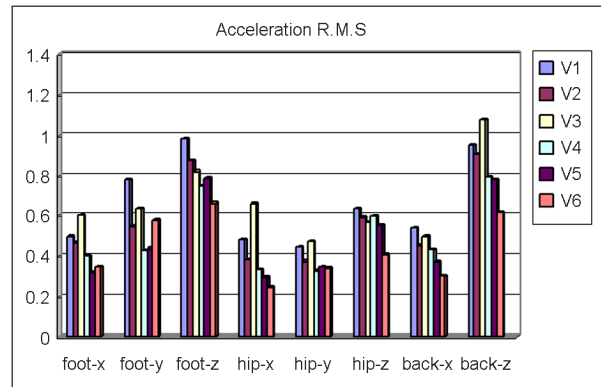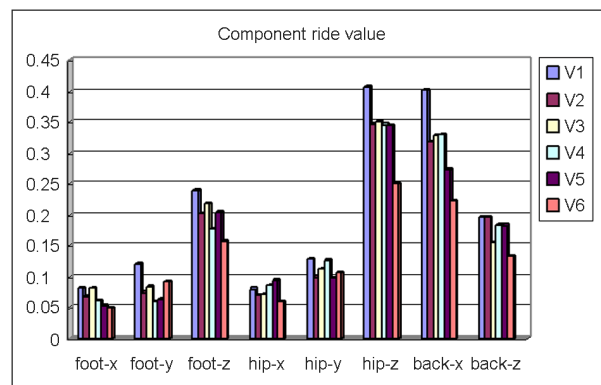

Figure 2. Acceleration R.M.S for 6 vehicles

Figure 3. Component ride value for 6 vehicles

3.2 Overall ride value

The vehicles ORV were evaluated using Eqn. (2). The ORV for the subjects and vehicles is presented (Figure 4), which was obtained on a highway. On the highway the ORV were similar for four subjects in all the vehicles. Between vehicles, the ORV of the vehicle 1 was higher and the ORV of the vehicle 6 was lower. As explained earlier highest ORV represents the most uncomfortable seat. Vehicle 6 (luxury car) showed the best result while the vehicle 1 (small car) showed the worst ORV. Therefore, luxury car has most comfortable seat than small car.

The ORV for the two subjects and vehicles is presented

(Figure 5), which was obtained in an uneven road. On the uneven road the ORV were similar to those of highway but the levels were increased by 75~98%. Between vehicles, the vehicle 6 showed the smallest increase about 75% on the uneven road. Similar like driving on the highway, the luxury car showed the best result while the small car showed the worst ORV.
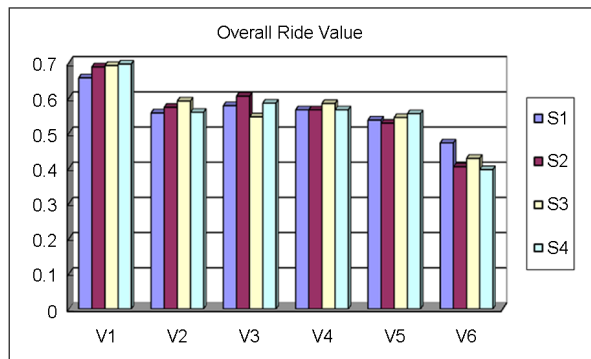

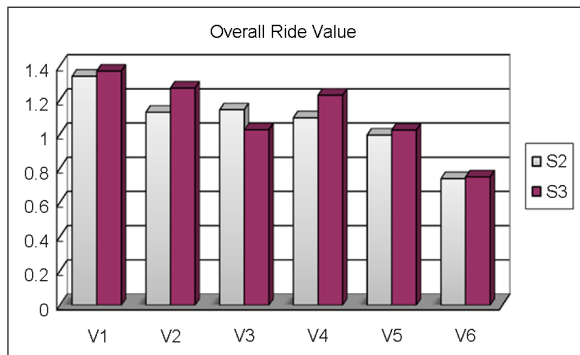**Figure 4.** Overall ride values for 4 subjects and 6 vehicles on the highway

Figure 5. Overall ride value for 2 subjects and 6 vehicles on the uneven road

3.3 SEAT value

The SEAT values were evaluated using Eqn. (3) and represented in Figure 6 for the vehicles and subjects. From the Figure 6 we can't find the effect of the difference of subjects on SEAT value. Though so many other factors can influence the SEAT value, we can say that the seat of vehicle 6 had a best vibration reduction quality and the seat of vehicle 4 had the worst with the results of F-test with 5%

significance level. All vehicles had the SEAT value less than 1, so vibration was reduced by the seats.
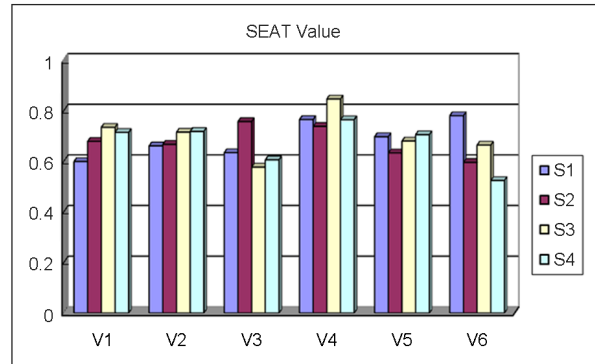

Figure 6. SEAT value for 4 subjects and 6 vehicles

3.4 Relation between driving velocity and vibration

The relation between driving velocity and vehicles vibration level were tested with different vehicle speed on the highway. The ORV and SEAT values were estimated to understand the effects of driving velocity on vibration level and the results are presented in Figure 7 and Figure 8, respectively. The ORV's of the vehicles were increased in proportion to the driving velocity. In terms of SEAT value, the values were decreased for the vehicles when the driving velocity increased. This was because the velocity affects the higher frequency more than the lower frequency and the seat easily damps the high frequency vibration.

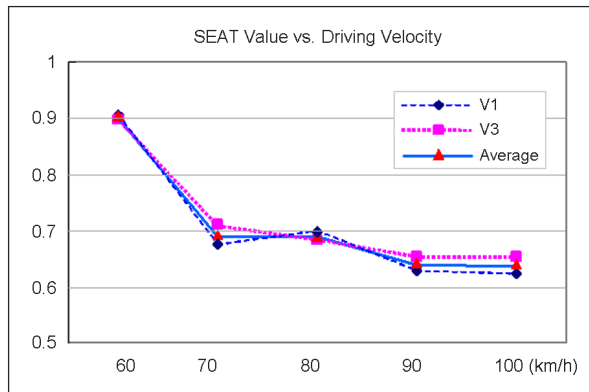**Figure 7.** Overall ride value with respect to driving velocity
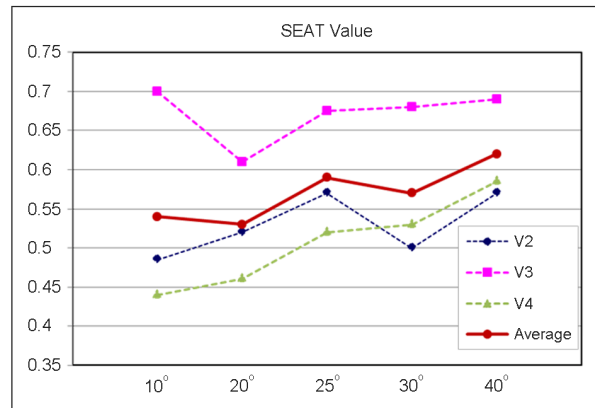
Figure 8. SEAT value with respect to driving velocity

3.5 Relation between posture and vibration

The relation between sitting posture and vehicles vibration level were tested with different backrest angles. The ORV and SEAT values were estimated to understand the effects and the results are shown in Figure 9 and Figure 10, respectively with the backrest angle varied from $10 \sim 40^{\circ}$ in 5 steps. The ORV and the SEAT values were somewhat increased with the increase of the backrest angle. These results clearly indicate that while driving with vibration most comfortable posture was sitting with smaller backrest angle. Even though people feel comfortable when they lean to the backrest with larger angle, in terms of vibration the case was different.

When the backrest angle increased the ride quality in terms of the vibration get worse. This effect represented in
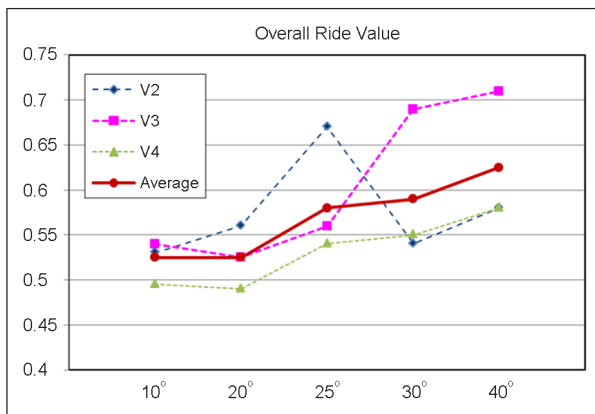

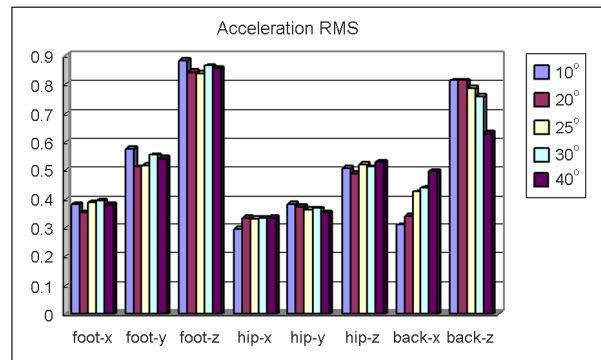**Figure 9.** Overall ride value with respect to backrest angle

Figure 10. SEAT value with respect to backrest angle

Figure 11. Overall ride value with respect to backrest an Acceleration RMS with respect to backrest angle gle
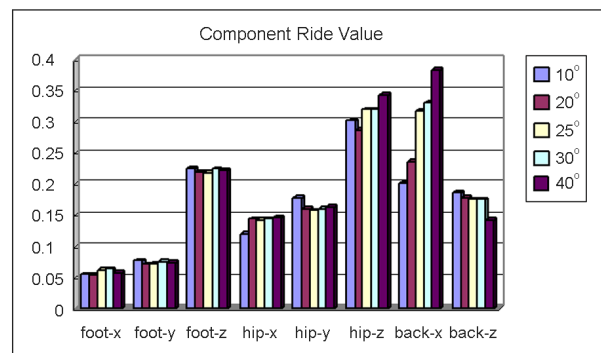

Figure 12. Component ride value with respect to backrest angle

Figure 11 and Figure 12. In Figure 11, the backrest angle increases the back x-direction acceleration level and decreases the back z-direction acceleration level. But the back x-direction acceleration contributes to ride value

significantly than the back z-direction. In Figure 12, the CRV of the back x-direction increases largely and decreases in the back z- direction with the backrest angle. We can see that back x-direction is more significant to the ride quality than hip z-direction when the angle was 40°.

4. Discussion

This study evaluated the ride qualities of the six passenger cars in 4 subjects on the highway and uneven road. The effects variation of driving velocity and driving posture on vibration were also investigated. Seat dynamics were investigated for the transmissibility in the seats and SEAT value. In the present experimental study, the ORV's of the vehicles were smaller while driving on the highway comparing with uneven road. On the uneven road the ORV's were similar to those of highway but the levels were increased by 75~98%. The road surface unevenness is the main vibration source of vehicle dynamic response. The present finding was supported by the previous findings. Lin et al. 2006 observed that, where the asphalt uneven road surface had the worst ride quality and the long wave road surface had the best one. Fouladi et al. 2011 found that seat vibration will have more contribution from bumpy road comparing with smooth road. Paddan and Griffin, 2002 evaluated SEAT values of the 100 work vehicles in 14 categories and found that for most categories of vehicle, the average SEAT value was less than 100%. In the present study all the vehicles had the SEAT value less than 1 or less than 100%, so vibration was reduced by the seat. In terms of driving velocity, the present study showed that faster velocity lowers the SEAT value. This was because the velocity affected the higher frequency more than the lower frequency and the seat easily damps the high frequency vibration. At Lin et al. 2006, the subjects felt uncomfortable when the driving speed reaches 60km/h comparing with lower speed 30~40km/h. The SEAT value is affected by the so many factors. The ORV and SEAT values were somewhat increased with the increase of the backrest angle. So when the backrest angle increases the ride quality in terms of the vibration get worse.

5. Conclusion

This study evaluated the ride qualities of six passenger cars with four subjects on the highway and uneven road. We evaluated the ride values (component ride value, overall ride value, SEAT value) and ranked the vehicles with the ride quality in terms of vibration exposed to the human. The smaller car had a first mode at the higher frequency and showed higher vibration level. SEAT values were mostly affected by the seat property not by vehicle. Based on SEAT values obtained, we ranked the luxury car seat had a best vibration reduction quality than other. The overall ride values increased proportionally and SEAT values somewhat decreased, when the driving velocity increased. When the backrest angle increased the overall ride value increased so the ride qualities get worse in view of vibration exposed to the human.

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