A Numerical Model to Estimate Road Roughness Condition from Sensor Data Collected by Android Smartphones

Viengnam DOUANGPHACHANH[1] and Hiroyuki ONEYAMA[2]

[1]Member of JSCE, Ph.D. Student, Dept. of Civil and Environmental Eng., Tokyo Metropolitan University
(1-1 Minami Osawa, Hachioji-shi, Tokyo 192-0397, Japan)
Email: douangphachanh-viengnam@ed.tmu.ac.jp
[2]Member of JSCE, Professor, Dept. of Civil and Environmental Eng., Tokyo Metropolitan University
(1-1 Minami Osawa, Hachioji-shi, Tokyo 192-0397, Japan)
Email: oneyama@tmu.ac.jp

Road roughness condition information is useful for road users, and very important for road authorities, which are responsible to carry out the maintenance and management of road infrastructure. Collecting such information is time and resource consuming because it usually requires either, if not all, skillful manpower, a lot of budget, and sophisticated equipment. Therefore, collecting and updating road roughness condition is viewed as a big challenge for many road authorities. The final goal of our research is to explore a low cost and easy to use approach for continuous road condition monitoring by using Android smartphones to estimate road roughness and traffic conditions. In this study we develop a model based on the relationship of smartphone sensor data (acceleration and speed) and road roughness condition, in which in our experiment in Vientiane, Laos, we have found that the acceleration data from smartphones has linear relationship with road roughness condition and the significant of the relationship depends on speed. Preliminary numerical examples and simulation have been carried out whereas the performance of the model and results are very promising.

Key Words: *Road roughness, roughness condition estimation, smartphone sensor data, numerical model*

1. INTRODUCTION

Road roughness condition is the irregularity in the road surface that usually occurs due to the deterioration of the road surface over time, the type of the surface material, and quality of the pavement work. Bad roughness condition may cause uncomfortable ride, extra fuel consumption, unexpected vehicle maintenance costs and safety. Road infrastructure maintenance and management is very important to keep the infrastructure in good condition so that it does not affect road users especially in terms of vehicle maintenance, fuel consumption and ride quality. In developing nations, particularly, maintaining a good quality road infrastructure is a big challenge for almost all road authorities. To obtaining road surface condition data, which is crucial for the maintenance and management planning, there are 2 main approaches listing from visual inspection and the use of sophisticated profilers. The former approach, though quite accurate, is labor intensive and very time consuming because it relies mainly on manual inspection of the inspectors. The later approach relies on the use of one or many of various road profilers available on the market. This approach takes less time, but requires considerably investment especially to obtain, operate and maintain such profilers. Skillful operators are also recommended. Additionally, in order to properly use such profilers, majority of them would require cumbersome calibration before deployment.

The final goal of our research is to explore a low cost and easier way for continuous road condition monitoring by obtaining road surface (roughness) and traffic conditions data using Android smartphones. We believe smartphones would help road authorities in overcoming some difficulties relating to road surface (roughness) and traffic condition data collection and updating. Basic concept of our approach is shown in Fig.1 below:

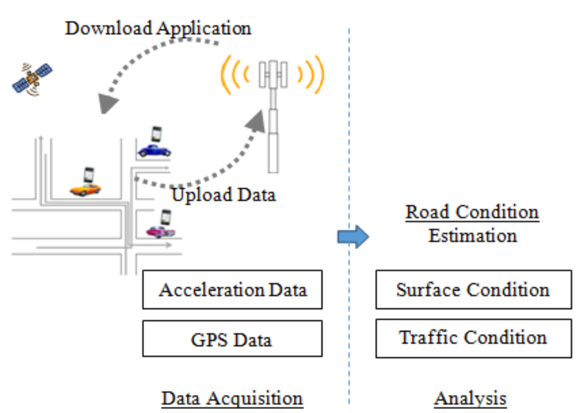

Fig.1 Conceptual image of continuous road condition monitoring system

This paper focuses on the development of a simple model to estimate road roughness condition from acceleration and speed data.

2. RELATED WORKS

Recently, there are some groups of researchers that are interested in detecting road bumps and anomalies using mobile sensors. However, majority of these researchers put a lot of their focuses on identifying and locating road bump and anomalies instead of estimating road surface condition. Gonzalez *et al.*[1] use a standalone accelerometer to fit in a simulation car and use it to assess road roughness condition. Their simulations conclude that roughness of the road can be estimated from acceleration data obtained from the sensor. Similarly, in another study, a system has been developed to utilize standalone accelerometers to successfully detect road anomalies[2]. In India, a group of researchers use many sensing component from mobile phone such as accelerometer, microphone, GSM radio, and GPS to monitor road and traffic condition[3]. By analyzing data from the sensors, potholes, bumps, braking and honking can be detected. The information is then used to assess road and traffic conditions. Mednis *et al.*[4] and Strazdins *et al.*[5] use Android smartphone devices with accelerometer to detect location of potholes. Their approach includes many simple algorithms to detect events in the acceleration vibration data. Tai *et al.*[6] and Perttunen *et al.*[7] analyze data obtained by smartphone accelerometers in frequency domain to extract features that are corresponding to road bumps. In Japan, a group of researchers has developed an Android smartphone application called BumpRecorder to detect the location and severity of road bump on road network that have been affected by the March 11 earthquake in Tohoku region, Japan[8].

3. EXPERIMENT

To realize our model formulation, first, the relationship between road roughness condition and smartphone sensor data must be studied. An experiment has been conducted in Vientiane, Laos in November, 2012; where we use 4 smartphones to place at different location inside 4 experiment vehicles (one vehicle at a time). All 4 smartphones are pre-installed with an application called AndroSensor[9]. For this experiment, only acceleration data (x, y, z) from accelerometer and location data (including speed) from GPS are needed. Data recording is done at an interval of 0.01 second or at a frequency rate of 100Hz.

Referenced pavement condition data for this study is also obtained using Vehicular Intelligent Monitoring System (VIMS)[10]. The system calculates the International Roughness Index (IRI)[11] for every 10 meter road section.

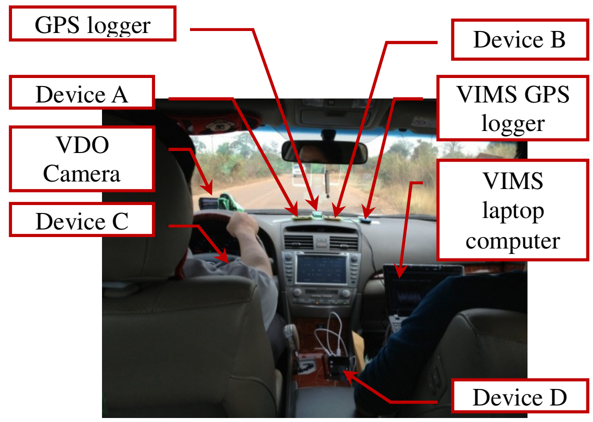

Fig.2 Equipment setting

The 4 devices (smartphones) are placed at different locations inside the vehicles. Device A and Device B are glued closed to each other on the dashboard of the experiment vehicles with strong and thin adhesive tapes. Device C is placed inside the driver's shirt pocket and Device D is placed at a box near the vehicles' gear handle. Other equipment such as GPS and video camera are also placed on the dash board. VIMS components are also installed in accordance to the VIMS manual[12].

The data, collected from smartphones, is checked and matched with referenced data. Analysis is carried out in frequency domain to calculate magnitudes of acceleration data.

From the analysis, it has been found that acceleration data from smartphones has linear relationship with road roughness condition (Fig.1).

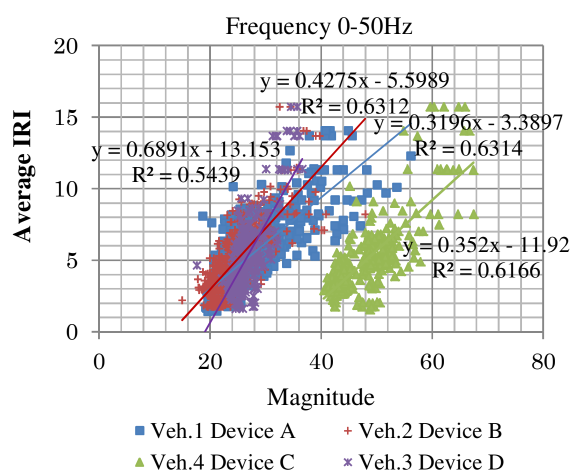

Fig.3 Relationship between road roughness condition (avg. IRI) and acceleration data (magnitude)

However, the significant of relationship depends on speed, vehicle type and device setting.

Table 1 Summary of multiple regression analysis

	Vehicle 4							
	Device A		Device B		Device C		Device D	
Observations	408		411		382		450	
Multiple R	0.836		0.786		0.857		0.786	
R^2	0.699		0.618		0.735		0.617	
Adjusted R^2	0.698		0.617		0.734		0.616	
F Stat	471.376		330.560		525.460		360.712	
	Coeff	t Stat	Coeff	t Stat	Coeff	t Stat	Coeff	t Stat
Intercept	1.798	4.811	2.745	6.940	0.373	0.903	0.796	1.703
Magnitude	0.989	22.779	0.832	18.492	1.172	24.621	3.823	19.854
Avg. Speed	-0.017	-3.277	-0.022	-3.920	0.003	0.582	-0.021	-3.503

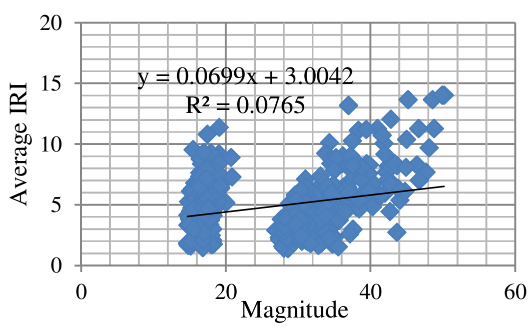

Fig.4 Relationship of Avg. IRI and Magnitude at freq. 0-10Hz (Veh.1 Device C)

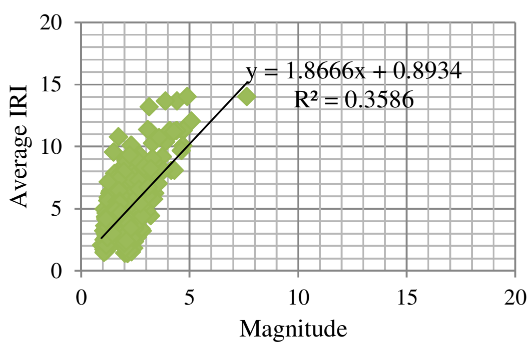

Fig.5 Relationship of Avg. IRI and Magnitude at freq. 20-30Hz (Veh.1 Device C)

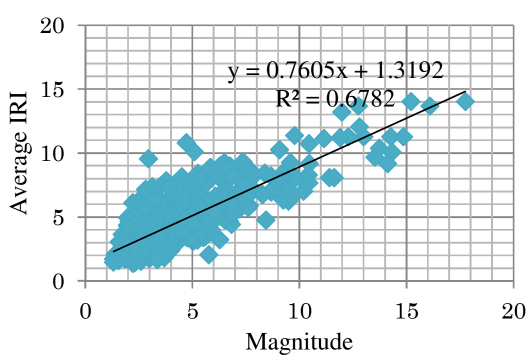

Fig.6 Relationship of Avg. IRI and Magnitude at freq. 40-50Hz (Veh.1 Device C)

Another important finding is that, at the frequency range of 40-50hz, the magnitude of acceleration data (derived from frequency domain analysis) is the most useful in reflecting the vibration caused by road roughness condition. Additionally, based on the condition indexes, that we have adopted[13)], similar tendency of the classification of the sum of magnitudes of acceleration vibration is observed.

In conclusion, a simple linear model can be used to estimate IRI from acceleration and speed data. However, if the smartphone setting and vehicle type are different; model coefficient parameters may also be different.

4. MODEL FORMULATION

Assuming we would like to estimate road roughness condition of road sections, within a road network, from a lot of data (acceleration and average speed data) collected by different smartphones, which are placed inside different vehicles (presumably running on the network randomly). From the conclusion that we have found in our experiment as mentioned in the previous section above, the model to estimate road roughness condition could be written as:

$$C_k = A_{0i} + A_{1i} M_{ik} + A_{2i} v_{ik} \qquad (1)$$

Where:

C_k : Road roughness condition (IRI) at section k,

M_{ik} : Magnitude of acceleration in frequency domain for vehicle i at section k,

v_{ik} : Average speed of vehicle i at section k,

A_{0i}, A_{1i} , A_{2i} : Coefficients of road roughness condition function for vehicle i at section k.

Note that the parameter A_{0i}, A_{1i} , A_{2i} may vary depending on vehicle type, smartphone type and smartphone setting.

The problem here is estimate the unknown variables (C_k, A_{0i}, A_{1i}, and A_{2i}) minimize the error of the model (least squared error method), the equation (1) can be written as:

$$C_k, A_{0i}, A_{1i}, A_{2i} = \arg\min F = \sum_i \sum_j \sum_k \delta_{ijk} \left\{ C_k - \left(A_{0i} + A_{1i} \hat{M}_{ij} + A_{2i} \hat{v}_{ij} \right) \right\}^2 \qquad (2)$$

Under this formulation, C_k, A_{0i}, A_{1i}, and A_{2i} can be estimated provided that we have observed IRI data ($\hat{C}_k$) at several sections (k_{obs}) obtaining from a more precise method (such as VIMS in our study).

In equation (2), j is the sequential data of vehicle i; and δ_{ijk} equals to 1 if the data j of vehicle i has passed through section k, while δ_{ijk} equals to 0 if the data j of vehicle i has not passed through section k.

To solve equation (2), first we solve the following optimization problem to estimate relative road roughness index:

$$c_k, a_{0i}, a_{1i}, a_{2i} = \arg\min F = \sum_i \sum_j \sum_k \delta_{ijk} \left\{ c_k - \left(a_{0i} + a_{1i} \hat{M}_{ij} + a_{2i} \hat{v}_{ij} \right) \right\}^2 \quad (3)$$

$$\text{s.t. } \frac{1}{N} \sum_i a_{1i} = 1$$

Where, c_k is relative road roughness condition at section k, while C_k in equation (1) and (2) is the final road roughness index (IRI) we want to estimate. N is the number of vehicles. a_{0i}, a_{1i}, a_{2i} are coefficients of relative road roughness condition function for vehicle i at section k.

We assume that $\overline{C}_k = b_0 + b_1 \overline{c}_k$, where b_0 and b_1 are parameters that would be derived from solving the regression of $\hat{C}_k = b_0 + b_1 \overline{c}_k$ ($k \in k_{obs}$).

Then, we estimate A_{0i}, A_{1i}, and A_{2i} by solving the following equation:

$$A_{0i}, A_{1i}, A_{2i} = \arg\min F = \sum_i \sum_j \sum_k \delta_{ijk} \left\{ \overline{C}_k - \left(A_{0i} + A_{1i} \hat{M}_{ij} + A_{2i} \hat{v}_{ij} \right) \right\}^2 \quad (4)$$

5. NUMERICAL EXAMPLES

The aim of the numerical examples is to validate the model performance in some simple cases.

(1) Setting:

In our setting, we assume the road network that consists of 18 links (same length) and each link is set to have 20 sections (same length), see Fig.3. Road roughness condition is set to be good for all sections in link 8 and 11; fair for all section in link 3, 4, 5, 6, 13, 14, 15 and 16; poor for all sections in link 1, 2, 7, 10, 17 and 18; and finally, bad for all sections in link 9 and 12. In other words, IRI for each section is assigned randomly within an average IRI range corresponding to its condition index (good, fair, poor, and bad). See Table 2.

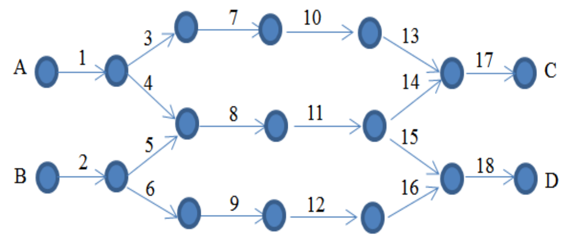

Fig.7 Road network

Table 2 Road condition index

Index	Average IRI
Good	$0 \leq IRI < 4$
Fair	$4 \leq IRI < 7$
Poor	$7 \leq IRI < 10$
Bad	$IRI \geq 10$

Other settings include:

6 running routes:

Route A: via link 1, 4, 8, 11, 14, and 17
Route B: via link 1, 3, 7, 10, 13, and 17
Route C: via link 2, 5, 8, 11, 15, and 18
Route D: via link 2, 6, 9, 12, 16, and 18
Route E: via link 1, 4, 8, 11, 15, and 18
Route F: via link 2, 5, 8, 11, 14, and 17

10 vehicles:

Vehicle 1: Route A x 15 trips + Route B x 5 trips = 20 trips
Vehicle 2: Route C x 15 trips + Route D x 5 trips = 20 trips
Vehicle 3: Route A x 7 trips + Route B x 3 trips = 10 trips
Vehicle 4: Route C x 7 trips + Route D x 3 trips = 10 trips
Vehicle 5: Route A x 5 trips + Route E x 5 trips = 10 trips
Vehicle 6: Route C x 5 trips + Route F x 5 trips = 10 trips
Vehicle 7: Route B x 5 trips = 5 trips
Vehicle 8: Route A x 5 trips = 5 trips
Vehicle 9: Route D x 5 trips = 5 trips
Vehicle 10: Route C x 5 trips = 5 trips

(2) Methodology:

a) Set each section's real road roughness condition (IRI) C_k.
b) Set each vehicle's average speed and standard deviation of model coefficients A_{0i}, A_{1i}, and A_{2i}.
c) Generate A_{0i}, A_{1i}, and A_{2i}.
d) Generate M_{ik} for each vehicle i and section k

randomly.

e) Set each section's pre-observed condition $\hat{C}_k$ randomly. 5 cases are considered:
   i. Only link 8 and 11 (all good condition) are observed precisely, the remaining links are observed roughly with errors;
   ii. Only link 9 and 12 (all bad condition) are observed precisely, the remaining links are observed roughly with errors;
   iii. Only link 8 and 9 (one good condition and one bad condition) are observed precisely, the remaining links are observed roughly with errors;
   iv. Only link 7, 8, 9 and 14 (good, fair, poor and bad; one link each) are observed precisely, the remaining links are observed roughly with errors;
   v. Only link 1, 5, 11 and 12 (good, fair, poor and bad; one link each) are observed precisely, the remaining links are observed roughly with errors.

f) Solve the optimization problem and obtain the solutions. Compare them with real value.

(3) Results:

After running the simulations for 5 cases as mentioned above, the performance of the model can be summarized in the following figures:

a) Only link 8 and 11 (all good condition links) are observed precisely.

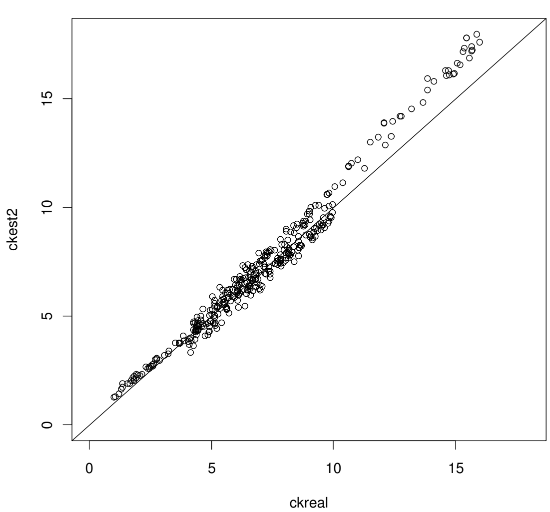

Fig.8 Observed and estimated IRI (case 1)

b) Only link 9 and 12 (all bad condition links) are observed precisely.

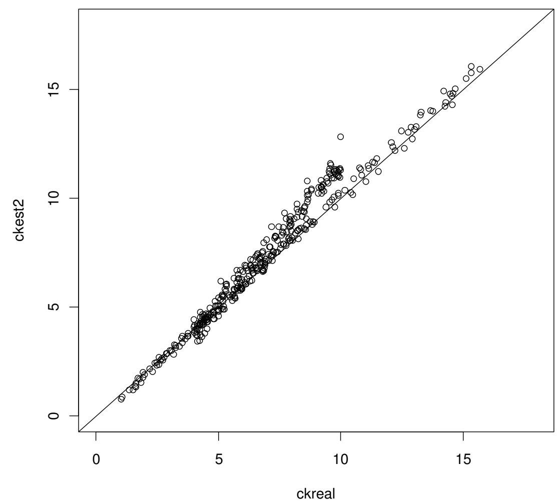

Fig.9 Observed and estimated IRI (Case 2)

c) Only link 8 and 9 (one good condition link and one bad condition link) are observed precisely.

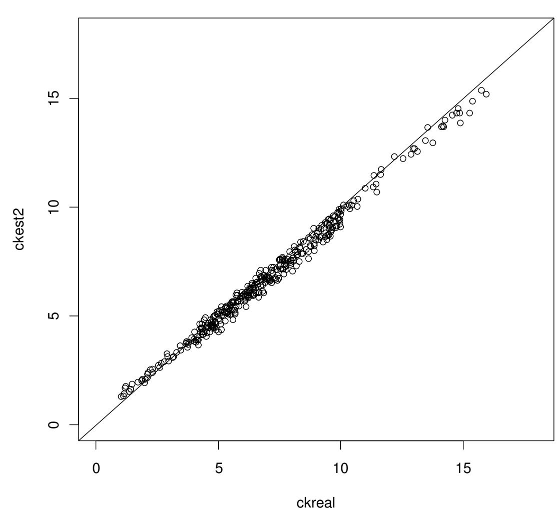

Fig.10 Observed and estimated IRI (Case 3)

d) Only link 7, 8, 9 and 13 (good, fair, poor and bad; one link each) are observed precisely.

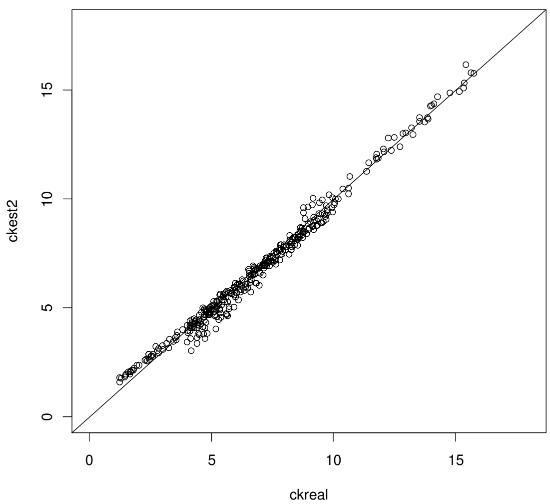

Fig.11 Observed and estimated IRI (Case 4)

e) Only link 9 and 12 (all bad condition links) are observed precisely.

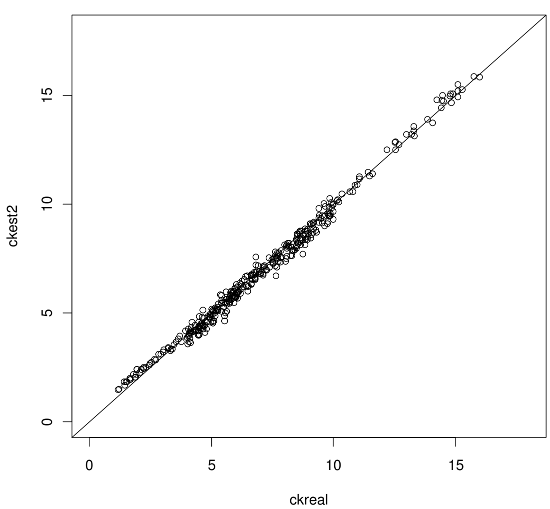

Fig.12 Observed and estimated IRI (Case 5)

(4) Discussion

In general, the model performs considerably good as it yields very good fitting for all the example cases. However, the model obviously perform better, as shown in Fig.10, 11 and 12, if 2 or more different type of road roughness conditions, i.e. a mix of good, fair, poor and bad, are considered as the observed road roughness condition (IRI).

6. CONCLUSION

In this study, we develop a model to estimate road roughness condition (IRI). In order to realize the model, it is necessary to understand the relationship between road roughness condition and the data to be obtained using smartphone devices. We have carried out an experiment to collect the data (acceleration and speed) using Android smartphones. The analysis, which includes matching of data with reference data and investigation in frequency domain, proofs that road roughness condition is a linear function of magnitude of acceleration and average speed.

After model formulation, numerical examples have been simulated. The simulation results show that the model performs promisingly, particularly in cases, where observed road roughness condition consists of different IRI values spreading across different road condition indexes.

In our future works, more focus will be put into improving the model, data collection piloting and practical application.

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