Civil Engineering and Architecture 12(3): 1386-1394, 2024 http://www.hrpub.org
DOI: 10.13189/cea.2024.120308

Rigid Pavement Acceleration-Velocity Dynamic Behavior Induced by Traffic Load

Untoro Nugroho[1,2,*], Sri Prabandiyani Retno Wardani[1], Bagus Hario Setiadji[1]

[1]Department of Civil Engineering, Diponegoro University, Indonesia
[2]Department of Civil Engineering, Universitas Negeri Semarang, Indonesia

Received September 22, 2023; Revised December 4, 2023; Accepted February 17, 2024

Cite This Paper in the Following Citation Styles

(a): *[1] Untoro Nugroho, Sri Prabandiyani Retno Wardani, Bagus Hario Setiadji , "Rigid Pavement Acceleration-Velocity Dynamic Behavior Induced by Traffic Load," Civil Engineering and Architecture, Vol. 12, No. 3, pp. 1386 - 1394, 2024. DOI: 10.13189/cea.2024.120308.*

(b): *Untoro Nugroho, Sri Prabandiyani Retno Wardani, Bagus Hario Setiadji (2024). Rigid Pavement Acceleration-Velocity Dynamic Behavior Induced by Traffic Load. Civil Engineering and Architecture, 12(3), 1386 - 1394. DOI: 10.13189/cea.2024.120308.*

Abstract Identification of highway performance along with service life is very important. The complexity of highway pavement process design requires a better understanding related to physical parameter of the velocity-acceleration process of material caused by the traffic. Vibration monitoring was conducted by using an accelerometer sensor-based equipment. An accelerometer application as a vibration monitoring sensor is non-destructive testing of structural health monitoring system (SHMS). The purpose of this paper is to study the actual acceleration-velocity pavement dynamic behavior triggered by traffic load on the rigid pavement type. The testing was conducted by using a set of acceleration sensors installed on the pavement. All types of vehicle passes were recorded to find the understanding of the acceleration-velocity pavement dynamic behavior in real time. In this paper, the properties of acceleration-velocity were established and the important parameters including vehicle speed of vehicle and axle load, were defined. The results have shown that the acceleration-velocity pavement dynamic behavior was most affected by vehicle speed and the type of vehicle which related to axle load. Motorcycle with velocity 33.80 km/h has frequency 17.57 Hz and heavy vehicle has frequency 205.07 Hz with velocity 16.14 km/h. The results depicted that parameter dynamics of pavement have a positive correlation to the speed and axle loads. The acceleration magnitude for motorcycle, car and heavy vehicle are 30 cm/s^2, 500 cm/s^2, and 700 cm/s^2 respectively. The factors of weight and speed of vehicles contribute to pavement vibration behavior.

Keywords Velocity, Accelerometer, Pavement, Traffic Load

1. Introduction

The highway pavement design is a process which has high complexity. The performance of the pavement structure should be considered by the designers who attempt to characterize all parameters, the effect of the performance of the structure including material properties and potential traffic loading in the most realistic manner possible. For years, most designers have recognized that the loading subject to pavement by traffic is dynamic in nature but in the design mostly still utilized the static loading criterion. In pavement process design procedure, this concept is still acceptable despite not matching to the field. The dynamic loading due to traffic loading has caused engineers to be considerate in their analyses due to their complexity [1-3]. Nowadays, the researcher has created innovation by producing hardware and techniques which could characterize dynamic loading due to traffic loading in the field in real time related to specific engineering terms [4,5]. The data were collected then using for escalating the innovation of highway pavement analysis which have traffic loading experience and predicting the loading which trigger the damaged condition for pavement. This article also discussed the materials testing related to dynamic vehicular loading. The behavior of pavement material due to traffic loading of various vehicles was measured accurately by using a series of accelerometer sensors. The response of pavements provides an important information which required for improving the pavement design procedures with the aim to sustain the pavement serviceability.

Vibration monitoring could be conducted by using an accelerometer sensor-based equipment. An accelerometer application as a vibration monitoring sensor is a non-destructive testing of structural health monitoring system (SHMS). The SHMS method has been widely used in the fields of mechanical engineering, civil engineering, and aerospace. In recent years, the technology of SHMS methods is widely used in structure and bridge engineering. Meesit [6] had an investigation for railway failures which revealed there may need an improvement method for the maintenance system. But for pavement technology, the SHMS methods could be considered as the best choice to predict pavement degradation [7-11]. The function of using the SHMS method is to monitor in real-time the response of a structure due to dynamic loads on it [12]. Apart from supervising structural response in real-time, SHMS also has another function, namely identifying and evaluating the health condition of a structure earlier [13-21]. Traffic loads in the form of loads from vehicles are moving or dynamic loads that occur repeatedly during the service life of the road. Often in planning pavement thickness, vehicle loads are considered as stationary or static loads [22,23]. Vehicle load is a dynamic load which has an influence on the acceleration of soil particles [24-26]. The vertical strain on the top of the subgrade is used as a fundamental criterion for assessing the rutting life of pavement [27]. The type of vehicle that triggers the acceleration rate of soil particles the most is the vehicle that has the greatest load. The greater the load of a vehicle, the greater the level of influence of acceleration of soil particles and vice versa.

The vehicle passing on a pavement produces wheel forces in the pavement surface continuously. These forces could be classified as dynamic loads. The dynamic forces which result from the complex interaction between a vehicle and pavement could be recorded and analyzed to obtain parameter acceleration and velocity of pavement particles. Several vehicles are selected as dynamic loading inputs to estimate the dynamic behavior of pavement. In this article, it is desirable to use experimentally measured vehicle and roadway characteristics which are expected to predict the response of pavement dynamic behavior due to traffic loading. The originality of this study is to predict the dynamic parameters to decide rigid pavement serviceability life.

2. Materials and Methods

2.1. Study Area

The study area in the research is a rigid pavement and is chosen as a road with classification as a two-way undivided road type (2/2 UD) with a rigid pavement structure. Data collection was conducted by using a set accelerometer placed on the pavement protected by a speed bump to reduce the disturbance factor during the collection data. This study aims to determine the maximum, minimum and average vibration values generated from each type of vehicle that crosses the road. Details of equipment used in the field can be seen in Figure 1.

(a)

(b)

(c)

Figure 1. A set of acceleration sensors for field investigations

2.2. Parameter of Research

Before the field experiment was conducted, three types of parameters were considered as basic data for analysis, i.e. acceleration, frequency, and vehicle type. The investigation was only conducted on one type of pavement, i.e., rigid pavement. Data was obtained by measuring the actual field conditions by recording the camera during investigation. The velocity as a considered parameter was classified in the specific range at the study site. Therefore, for purpose of this article is to assess the acceleration-velocity of pavement behavior by using acceleration sensor. This acceleration sensor could predict and measure dynamic forces. Installation of a set of accelerometer sensors during investigation could be seen in Figure 2. The condition in the study area during the measurement could be seen in Figure 3. The vehicles in the figure are a car and a motorcycle that were passing the rumble strip where a series of accelerometers placed inside. In time being, during the measurement, the data were obtained in real-time condition which was connected with Jupiter notebook. For preliminary research, the traffic volume of the study area was evaluated to obtain the peak hour in the study area. Number of vehicles were counting and recording by video camera. The verification of data obtained was also an important factor considered to find an accurate results analysis.

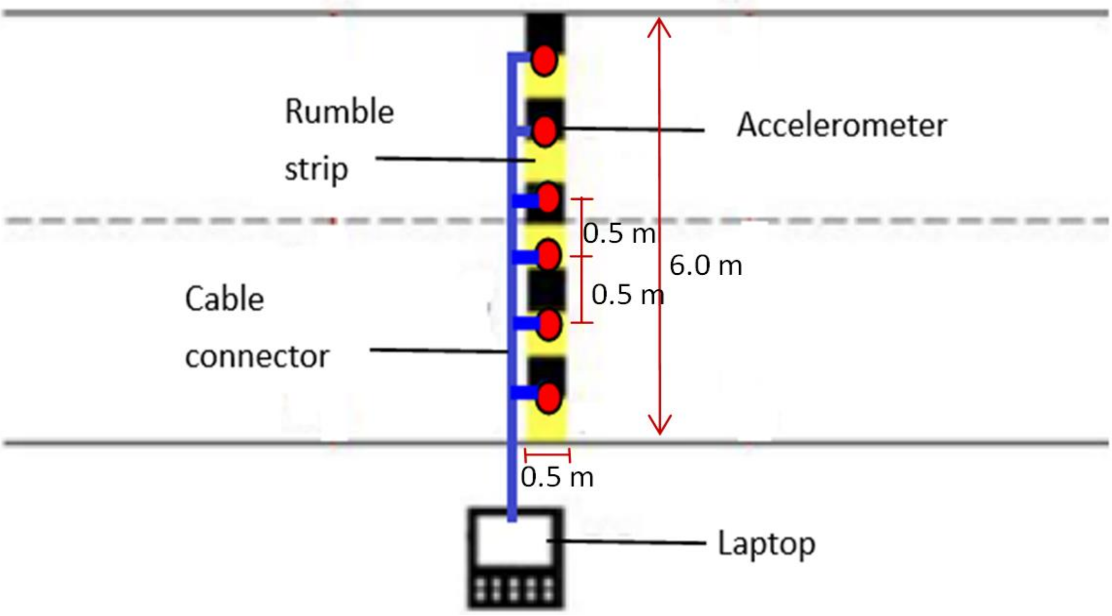


Figure 2. Detail installation of a set acceleration during data collecting

Figure 3. Field measurement of study

2.3. Collecting Data Technique

The data used in this research is secondary and primary data. Secondary data is in the form of inventory data road. This data is needed to provide initial information regarding road conditions in the study area. Road inventory data is obtained from the Semarang City Public Works Office. This data includes the length and width of the road of a rigid pavement. The primary data of this study is total data vehicles based on each type of vehicle, vibration and acceleration of particles and vehicle speed data. This data set was collected by field investigations, literature studies and documentation. Field investigation aims to obtain primary data from variables related to subject and object of the research including the number of vehicles based on each type, vehicle speed, magnitude of vibration acceleration, vibration frequency and displacement amplitude caused by a specific type of vehicle passed. Other supporting data were obtained from photos and recorded video during field investigation. The number of vehicles data was taken by counting the number of vehicles passed directly on the field on July 7, 2022 at 3.49 pm to 3.59 pm for 10 minutes' duration and used as cross-check data video during data collection. Vehicle numbers data is calculated manually with the help of the application multi counter and timestamp recording according to the type of vehicles. Vehicle speed data is calculated manually with starting and ending guideline assistance (distance of 6 meters) and timestamp recording application assistance. Vibration acceleration data is obtained from accelerometer sensor recordings with the help of the Geovibration application. Vibration frequency data and the displacement amplitude data are obtained from processing using the Jupyter notebook application and Matlab R2015a.

2.4. Collecting Vehicle Speed Data

For collecting vehicle speed data, multi counter and timestamp applications are used. The time for each vehicle passed was noticed by timestamp application. In order to obtain the vehicle speed, the formula is used to calculate. [12]:

$$v = \frac{s}{\Delta t} = \frac{s}{(t_2 - t_1)} \tag{1}$$

where, v is vehicle speed (m/s), s is distance traveled (m), Δt is difference in travel time (s), t_2 is final travel time (s) and t_1 is initial travel time (s). Thus, the recapitulation of the acceleration of vibration data / acceleration (cm/s^2) which has been obtained from accelerometer sensor recordings with the assistance of the computer application displays the value along with the vibration graph. This equipment recorded the displacement parameter in real time when the vehicle passed the sensor. Vibration acceleration data must be adjusted to the data of passing vehicles.

In order to determine the frequency value based on spectrum analysis by using Fourier transform formula as follows [13],

$$F(\omega) = \int_{-\infty}^{\infty} f(t)e^{(-i\omega t)}dt \tag{2}$$

where, $F(\omega)$ is transformation function, $f(t)$ is original signal, ω is frequency, and i is imaginary unit. Figure 4 illustrates an example of results recording of generated frequency spectrogram plot from a motorcycle. This figure describes about representation of the frequency spectrum of a signal as it varies with time.

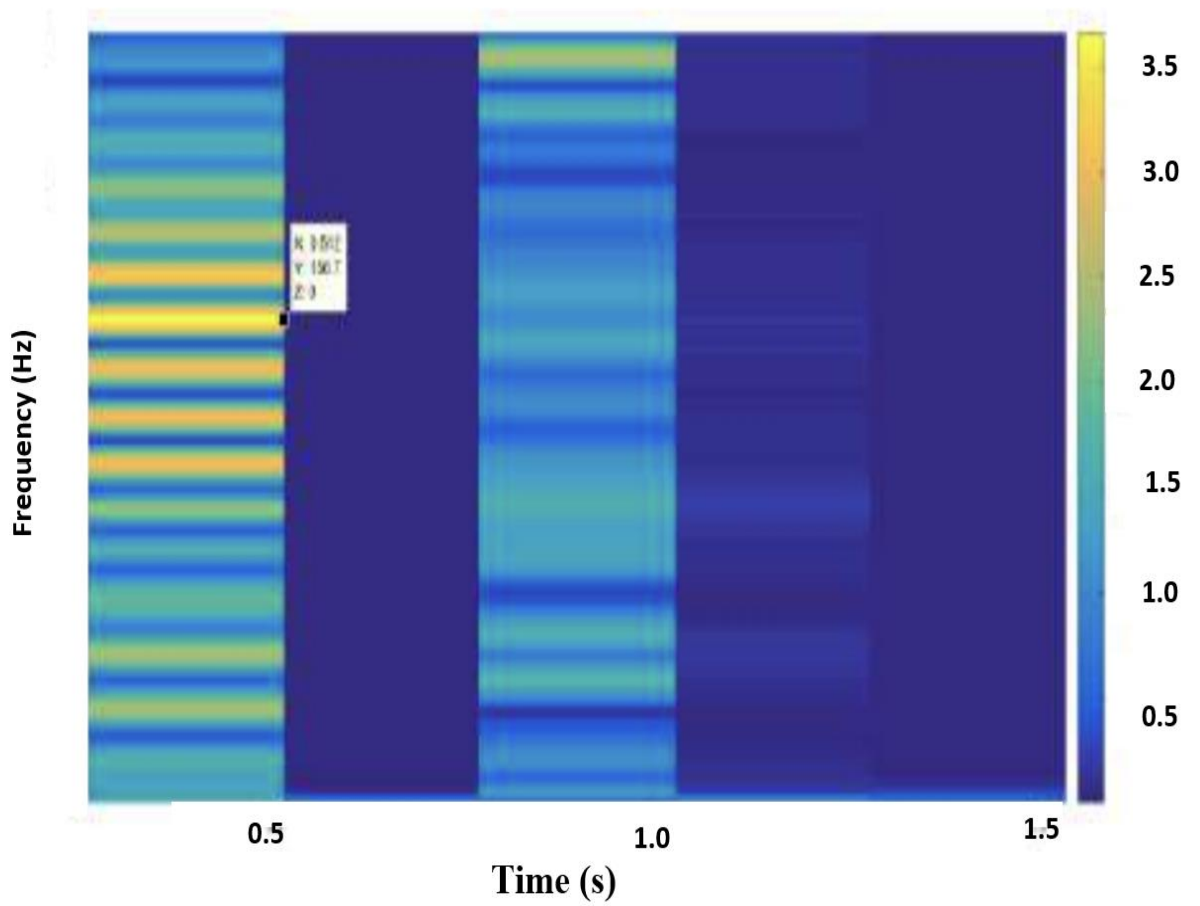


Figure 4. Spectogram frequency plot (Hz)

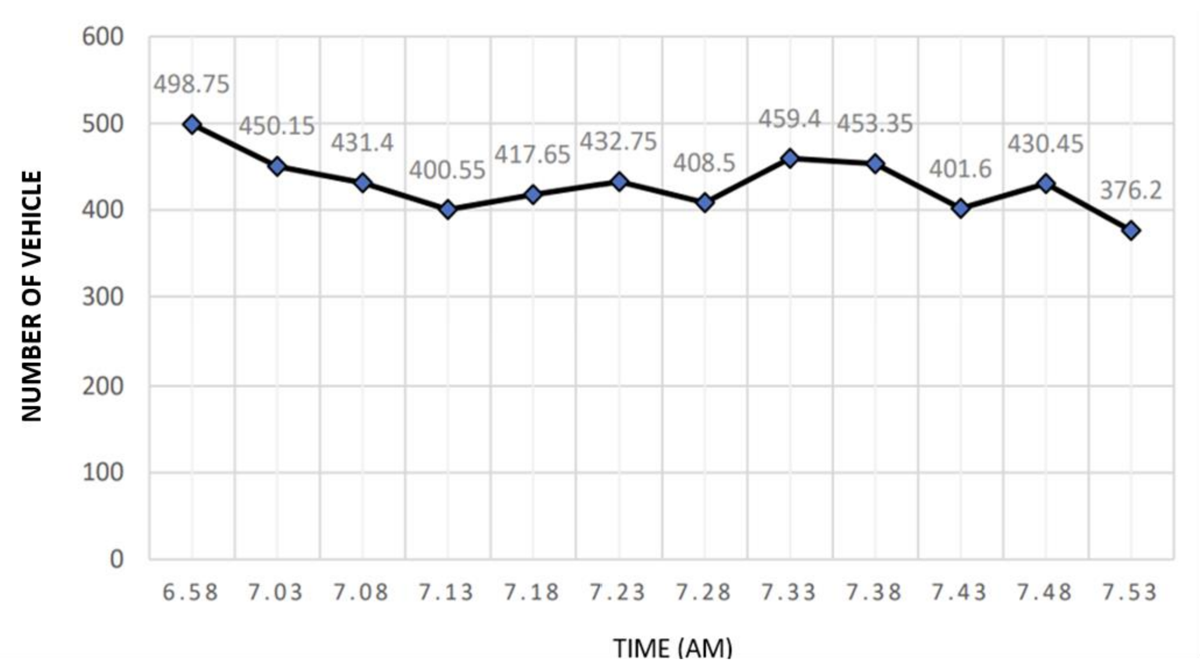


Figure 5. Traffic volume during field measurement from 6.59 am to 7.53 am

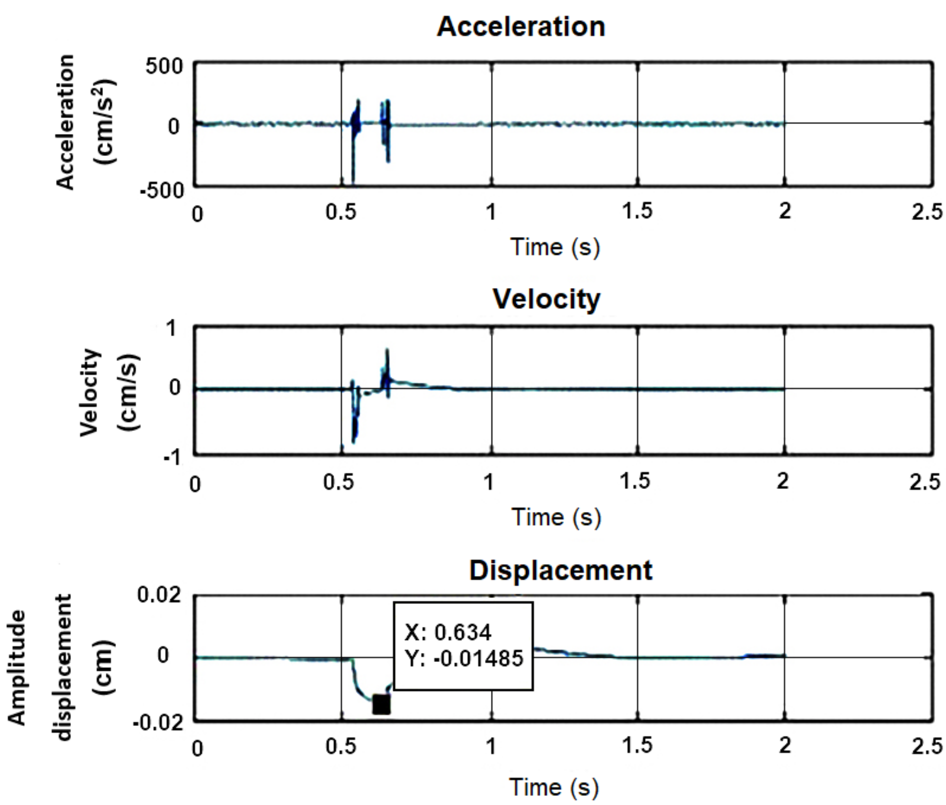
3. Results and Discussion

3.1. Traffic Volume at Study Area

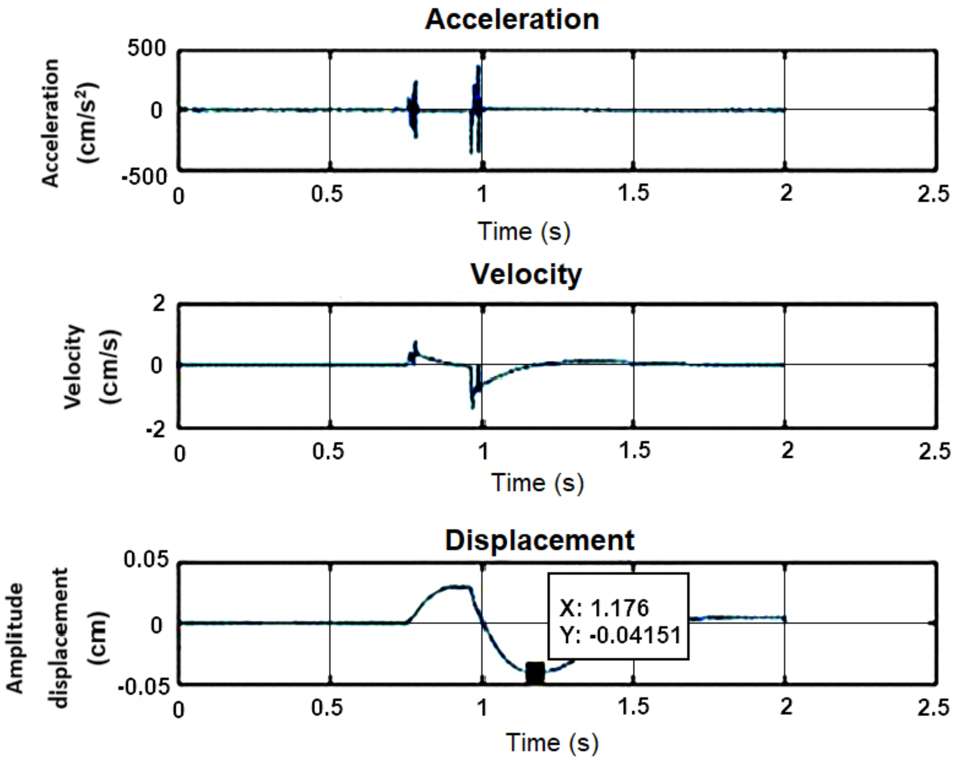
For preliminary investigation, the team decided to analyze the traffic from 6.58 am to 7.53 am to identify the number of vehicles in peak hour. Traffic data collection was carried out at peak hours of workday for one hour. Traffic volume was counted every five minutes by using the passenger car equivalent method based on the Indonesian Road Capacity Manual (MKJI). The results of traffic data measurements could be seen in Figure 5. The figure depicts the peak number of traffic volume that occurred at 6.59 am with total vehicle passed reaching 500 and after that hour the traffic volume tends to be constant. Detail results regarding the number of vehicles every 5 minutes during field investigation could be seen in Figure 5.

3.2. Velocity-Acceleration Analysis

Vibration data generated from the accelerometer sensor is in the form of the magnitude of the vibration acceleration (cm/s^2), with the support of a set of notebook apps and Matlab R2015a software, then obtained the frequency in Hz unity and the displacement amplitude in cm. In general, the accelerometer sensor has three axes movements considered as the X, Y and Z axes direction that have been adjusted with the point of gravity of the earth. The results during field investigation, generated by accelerometer as vibrations particle parameter, were then displayed into particle movement towards z axis (vertical) and the number of sensors used in this research was six sensors. Figure 6 shows graphs of vehicle speed and vibration data generated from each vehicle (motorcycle and car) as a sample crossing road. This figure illustrates when the vehicle passed, it would trigger the acceleration and velocity of particles. These parameters induced the displacement of pavement. Figure 6(a) depicted the maximum of acceleration which reached 500 cm/s^2 then induced the displacement 0.01485 cm in the downward direction Identical analysis for car. As shown in Figure 6(b), it depicted the maximum acceleration reached up to 500 cm/s^2 which induced the displacement 0.04151 cm. Field measurement results related to the velocity and acceleration parameter could be seen in Table 1.



(a) Motorcycle



(b) car

Figure 6. Pavement particle vibration due to vehicle passed

Table 1. Resume of velocity and acceleration parameter based on vehicle passes.

No	Type of vehicle	Velocity (km/h)	Acceleration (cm/s^2)
1	Motorcycle	33.80	30
2	Car	27.73	500
3	Heavy vehicle	16.14	700

From these results, it could be said the increasing of vehicle weight will decrease the velocity. In other hand, the acceleration value has a positive relationship to the weight of vehicle. The value of particle acceleration is increasing toward to the increasing of vehicle weight.

3.3. Frequency Analysis

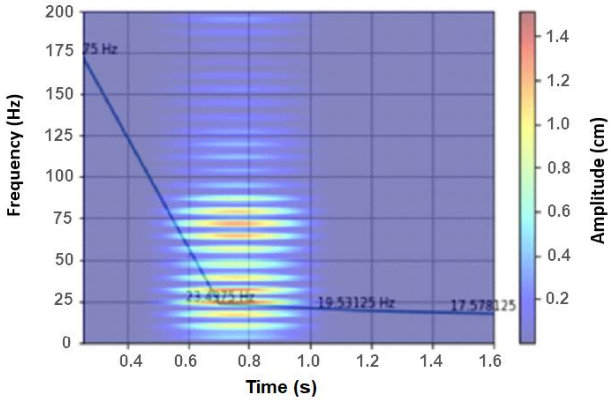
During the investigation, a series of accelerometers were utilized to obtain suitable measurement data for frequency analysis. The accelerometer was laid down on the rigid pavement by using white mortar to ensure accelerometer and pavement became one system to measure the vibration. The vibration due to traffic loading was transmitted to accelerometer which measured the parameter acceleration versus time. From the vibrations which an accelerometer is subjected to, a force is created, which acts on the piezoelectric elements and is defined as the product of the acceleration of the seismic masses and the mass of the accelerometer. When the element inside the accelerometer is subjected by these forces, then it produces a charge which is proportional to the applied force. The results from accelerometer measurements should be verified by comparing the acceleration of the pavement surface and the base of an accelerometer which is connected by using white mortar.

During the field measurements, the accelerometer was indicating the results of frequency as shown in Figure 7. The data is as well obtained from along the width of pavement from three different types of vehicles, i.e. motorcycle, car and heavy car. The average speed of the measured vehicles is considered as well since the speed of the vehicles can affect the results.

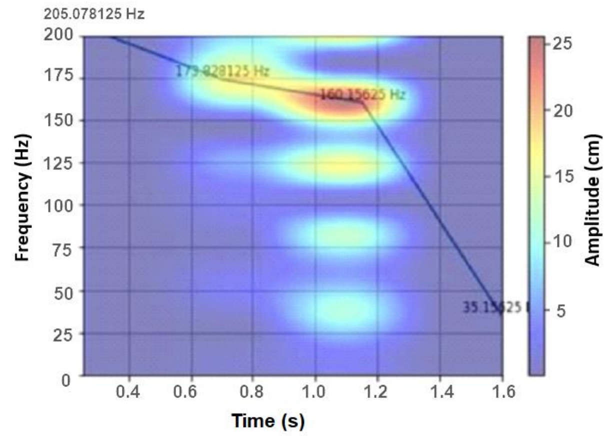
Therefore, by calculation, the average speed is obtained for measurements when it passes with an average speed of 16.14 km/h to 33.80 km/h. The summary of analysis for parameter amplitude and vehicle could be seen in Table 2.

Table 2. Resume of amplitude and frequency analysis based on vehicle passes.

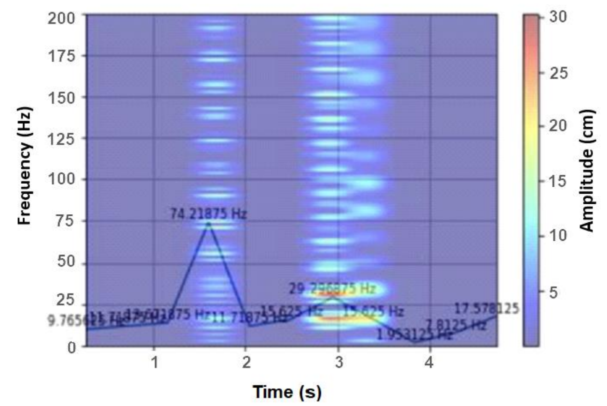
No	Type of vehicle	Velocity (km/h)	Amplitudo (cm)	Frequency (Hz)
1	Motorcycle	33.80	0.0093	17.57
2	Car	27.73	0.0539	74.21
3	Heavy vehicle	16.14	0.1949	205.07



A. motorcycle



B. car



C. heavy vehicle

Figure 7. Illustration relationship frequency-time and amplitude-time from various vehicle

From the point of view speed parameters and type of vehicle, Table 2 depicts that the weight of vehicle passes has reverse relationship to the speed of vehicle. When the weight of vehicle passes increases, the speed of vehicle decreases. For amplitude and frequency parameter, it shows the positive relationship to the weight of vehicle passes.

The purpose of this paper is to study the actual acceleration-velocity pavement dynamic behavior triggered by traffic load on the two types of pavements. Please highlight the effect of the velocity and the weight of the vehicles on the amplitude and frequency of pavement vibration. Another thing, the test was only conducted on one type of pavement, i.e., rigid pavement.

4. Conclusions

In this paper, an innovative real-time field measurement of pavement for acceleration-velocity pavement dynamic behavior induced by traffic load was presented. The factors of weight and speed of vehicles contribute to the pavement vibration behavior. Motorcycle with velocity 33.80 km/h has frequency 17.57 Hz and for heavy vehicle has frequency 205.07 Hz with velocity 16.14 km/h. When the pavement is subjected to traffic loading with large vehicle load, it could increase the particle acceleration and frequency of pavement. The acceleration magnitude for motorcycle, car and heavy vehicle are 30 cm/s^2, 500 cm/s^2, and 700 cm/s^2 respectively. The vehicle speed parameter shows the reverse condition. Frequency and acceleration parameter reached a higher value when the vehicle speed parameter is decreased.

Acknowledgements

The authors acknowledge the Laboratory Soil Mechanics Universitas Negeri Semarang for supporting during the field investigation.

REFERENCES

[1] T.A. dos Santos, C.A.P. da Silva Júnior, H.B. Fontenele. The effect of axle load spectra from AASHTO method on flexible pavement performance, Acta Sci.- Technol. 41 e35117, 2019.

[2] Kusumawardani, R., Nugroho, U., Fansuri, M. H., Mindiastiwi, T., Yuniarti, W., & Hilmi, A. S. The Impact of Vehicle Load Inducing Vibrations on the Subgrade Soil Particle Acceleration. In Journal of Engineering Science and Technology (Vol. 13, Issue 6), 2018.

[3] D.H. Timm, A.L. Priest, T.V. McEwen. Design and instrumentation of the structural pavement experiment at the NCAT test track, NCAT Report 04-01, Auburn, AL., 2004.

[4] I.L. Al-Qadi, A. Loulizi, M. Elseifi, S. Labouar, The Virginia smart road: the impact of pavement instrumentation on understanding pavement performance, Technical Sessions of the Association-of-Asphalt-Paving-Technologists, Baton Rouge, LA. 427-465. 2004,

[5] Z. Ye, H. Xiong, L. Wang, Collecting comprehensive

traffic information using pavement vibration monitoring data, Comput-aided Civ. Inf. 35 (2), 134–149, 2020.

[6] Meesit, R, Phornthepkasemsant, P, Rattanawan, R, & Ruamsab, T, Risk Assessment of Railway Switch and Crossing Failures: Case Study of an Urban Rail Transit in Thailand, Civil Engineering and Architecture 10(2): 557-566, 2022. DOI: 10.13189/cea.2022.100214.

[7] Y. Yang, M. Chadha, Z. Hu, M.D. Todd, An optimal sensor placement design framework for structural health monitoring using Bayes risk, Mech. Syst. Signal Pr. 168, 108618, 2022.

[8] W. Ostachowicz, R. Soman, P. Malinowski, Optimization of sensor placement for structural health monitoring: A review, Struct. Health Monit. 18 (3), 963–988, 2019.

[9] Y. Tan, L. Zhang, Computational methodologies for optimal sensor placement in structural health monitoring: a review, Struct. Health Monit. 19 (4), 1287–1308, 2020.

[10] C. Yang, An adaptive sensor placement algorithm for structural health monitoring based on multi-objective iterative optimization using weight factor updating, Mech. Syst. Signal Pr. 151, 10736, 3, 2021,

[11] Kusumawardani, R., Nugroho, U., Handayani, S., & Fananda, M. A. The analysis of liquefaction phenomenon of the flexible pavement using seismic monitoring equipment. IIUM Engineering Journal, 20(1), 70–78, 2019.

[12] Setiawan, A. Estimation of Sound Source Direction Using Fourier Transformation Method with Arduino. JTECS: Jurnal Sistem Telekomunikasi Elektronika Sistem Kontrol Power Sistem Dan Komputer, 2(2), 111–122, 2022.

[13] Berrar, D. (2018). Cross-validation. Encyclopedia of Bioinformatics and Computational Biology: ABC of Bioinformatics, 1–3(April), 542–545. 12, 2018.

[14] Ying, X. An Overview of Overfitting and its Solutions. Journal of Physics: Conference Series, 1168(2), 2019.

[15] Z. Dong, X. Ma, X. Shao, Airport pavement responses obtained from wireless sensing network upon digital signal processing, Int. J. Pavement Eng. 19 (5), 381–390, 2018.

[16] W. Xue, L. Wang, D. Wang, A prototype integrated monitoring system for pavement and traffic based on an embedded sensing network, IEEE T. Intell. Transp. 16 (3), 1380–1390. 2014.

[17] H. Zhao, D. Wu, M. Zeng, S. Zhong, A vibration-based vehicle classification system using distributed optical sensing technology, Transport. Res. Rec. 2672 (43), 12–23, 2018.

[18] A.H. Alavi, H. Hasni, N. Lajnef, K. Chatti. Continuous health monitoring of pavement systems using smart sensing technology, Constr. Build. Mater, 114, 719–736, 2016, https://doi.org/10.1016/j.conbuildmat.2016.03.128.

[19] N. Wang, T. Han, H. Cheng, T. Li, J. Fu, T. Ma, Y. Fu, F. Chen, Y. Zhang. Monitoring structural health status of asphalt pavement using intelligent sensing technology. Construction and Building Materials, Volume 352, 2022, https://doi.org/10.1016/j.conbuildmat.2022.129025

[20] X. Ma, Z. Dong, Y. Dong, Stiffness identification method for asphalt pavement layers and interfaces using monitoring data from built-in sensors, Struct. Health Monit. 14759217221077612, 2022.

[21] C. Han, T. Ma, J. Huyan, X. Huang, Y. Zhang. CrackW-Net: A novel pavement crack image segmentation convolutional neural network, IEEE Trans. Intell. Transp. Syst, 1–10, 2021, https://doi.org/10.1109/TITS.2021.3095507

[22] W.U. Jin-ting, Y. Fen. Strain behavior of asphalt pavement in accelerated pavement testing with MLS66 under heavy-load and high-frequency. Journal of Highway and Transport, 27 (10), 2014.

[23] C. Han, T. Ma, G. Xu, S. Chen, R. Huang. Intelligent decision model of road maintenance based on improved weight random forest algorithm. Int. J. Pavement Eng., 23 (4), 985–997, 2022, https://doi.org/10.1080/10298436.2020.1784418

[24] R.G. Regis, C.A. Shoemaker, A stochastic radial basis function method for the global optimization of expensive functions, INFORMS J. Comput. 19 (4), 497–509, 2007.

[25] H.M. Gutmann, A radial basis function method for global optimization, J. Global Optim. 19 (3), 201–227, 2001.

[26] Z. Dong, X. Ma, Analytical solutions of asphalt pavement responses under moving loads with arbitrary non-uniform tire contact pressure and irregular tire imprint, Road Mater. Pavement 19 (8), 1887–1903, 2018.

[27] Banerji, A.K., Topdar, P., Datta, A., Effect of Axle Overloading on Pavement Structural Behaviour with Improved Clayey Subgrade Using PET Fibres. Civil Engineering and Architecture 10(6): 2410-2425, 2022. DOI: 10.13189/cea.2022.100614.