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Allowable Limit of Human Annoyance Towards Ground-Borne Vibration Velocity Induced by Rail Traffic: A Review

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Abstract. Many industrialized nations have created their own standards for determining and grading the dangers posed by ground-borne vibration, notably in terms of human irritation. Excessive vibrations created by trains have an impact not only on individuals, but also on sensitive machinery and buildings. The authority as well as practitioners have critical responsibilities in managing and accessing vibrations. This study discusses the differences between the standard and the limit of vibrations caused by trains that can irritate people. The local standard guideline was compared to the standards used by the US, Norway, Sweden, California, Germany, and the Netherlands. This study was mainly interested in the limitations of vibration velocity in residential settings.

1. Introduction

Rail operation causes vibration with a wide range of amplitude and frequency. Large-amplitude vibrations have the potential to harm nearby structures as well as to induce foundation settling, track component damage, and embankment collapse. In their research, [1] discovered that with the growth of the railway network, the number of complaints from the people living close to the rail lines have also increased.

Many regulatory authorities, including the Union of International Railways (UIC), have recently urged the creation of common prediction models that can foretell the effects of vibration on human perception [2]. Malaysia must establish its own regulations on vibration limits and control depending on the regional circumstances given the country's rapid expansion of its rail network. [3]. In their research, [4][5] also emphasized that Malaysia should have its own standards based on the local geological condition, particularly in the design of public transportation infrastructure.

The wave propagation through the ground and structures can be used to characterize the vibrations caused by railroad traffic. Both sensitive equipment and people who reside near the vibration source could be aggravated, uncomfortable, or irritated by the energy that is communicated. Railway vibrations begin at the point where the wheel and rail meet, then travel through the tracks and surrounding earth as "ground-borne vibrations" before they are felt [6][7].

Due to the potentially disastrous effects on the comfort of the local population, the long-term preservation of historic structures, and the operation of precision devices, the topics relating to train-induced vibrations are getting increased attention [8]. Additionally, as part of environmental quality control, the problems associated with train-induced vibrations must be addressed with the rise in overall living standards. The term "vibration pollution" refers to the harmful effects that ground vibrations caused by people, railroads, and other transportation activities have on the comfort and mental health of those who reside nearby. The ground-borne vibrations would have an impact on the safety of buildings, the performance of delicate equipment, and the working environment in the impacted locations.

A ground vibration prediction model will be helpful at various stages of the railway design process, including when getting ready for environmental impact assessments [9]. Most developing nations have their own standards for monitoring and assessing the ground-borne vibration issue, including Germany and the United Kingdom. The existing recommendations and standards for the evaluation and measurement of the effects of ground vibration on structures and people, such as the BS 6472-1 (2008), ISO 2631 (1999), and DIN 4150-3 (1999), are reviewed and assessed in this study. The "Vibration Limits and Control in the Environment," a 2007 document, is Malaysia's own set of guidelines for ground vibration. This guideline was developed to aid in the quantitative evaluation of the requirements for accepting ground vibration.

2. State-of-the-Arts

2.1. Ground-borne Vibration due to Rail Traffic

The phenomena of railway-induced vibration can be explained by wave propagation via the ground and structures. People who live close to the railway tracks could feel uncomfortable as a result of the energy produced, and fragile and sensitive equipment might get hurt. Residents who live near the railroad tracks could encounter some inconvenience and annoyance [9] [10]. Once the railway is running, the moving trains will cause ground vibration. The strength of vibrations in neighboring structures or buildings depends on the force applied by the trains to the rails and the attenuation between the buildings and the rails. To achieve the allowed vibration limit levels for buildings, this attenuation can be computed, and the level of mitigation can be designed [11].

In general, excessive ground-borne vibration generated by train activities has three interrelated links, which are represented in figure 1. The first component is the vibration source, then comes the way the vibrations are transmitted through propagation, and finally there is the receiver, which is typically a person or a structure. The settings and characteristics of each link have an impact on the overall vibration levels. Even though the link functions sequentially, it might occasionally be helpful to analyze each one separately when thinking about how to lessen vibrations [12].

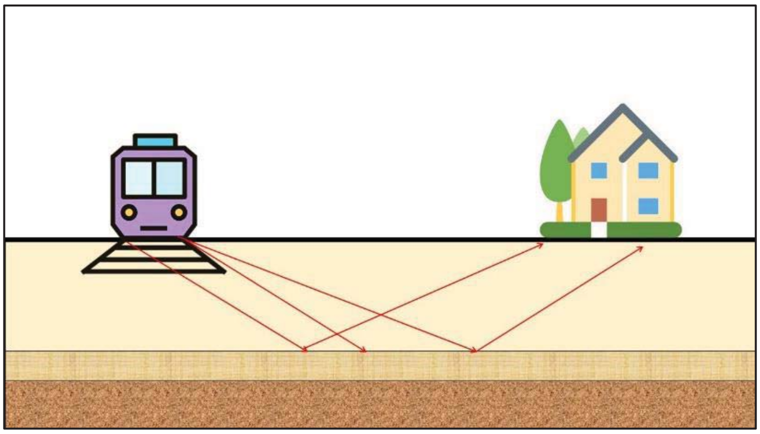

Figure 1. The three links problems of the ground-borne vibration.

2.2 Sources of Vibration

Most of the time, vibration is brought on by the interaction between the motion of the train and the track, which is positioned on the subsurface dirt. The source regions include the various train kinds, the surrounding soil, the supporting structures, and the track structure, and these components work together to produce the initial vibration. Vibrations are transmitted through the tracks' structure after source construction [12]. The four crucial parts of a typical structural track are the track, the sleeper, the rail pad, and the ballast. In some railway systems, in addition to these four elements, external dampers are used. The tracks are set on neatly constructed sleepers made of concrete blocks, and the train travels on steel bars. The ballast floor, primarily up of tiny stones, is partially buried beneath the sleepers. The rail pads are put in place after the sleeper to ensure proper track contact. The sleeper acts as an outer dampening structure and vibration-absorbing dampers are fitted on the track. The main elements that can influence variations in the vibration characteristics are the ballast, sleeper, and dampers [13].

2.3. Propagation

The soil media acts as a transmission medium for vibrations to the surrounding areas. The soil characteristics, other conditions, and the separation between the source and the receiver have the biggest effects on propagation characteristics. The effect of ground vibration attenuation decreases with soil stiffness. The attenuation of ground vibrations would become more noticeable as the length of the ground transmission channel increased. A stiff or hard soil may attenuate and absorb ground vibration considerably more quickly over time than a soft soil. There are several terrains with soft soil, however they are less typical than rigid or hard terrain. The soft ground profile zone has a 5 to 10 Hz ground vibration frequency. The range of low-frequency subsurface vibrations is potentially greater. People who reside 100 to 200 meters away from train lines may experience discomfort because of the large ground vibration impacts caused by the formation of soft soil like silt or soft clay [14].

Extracted from a study by [15], figure 2 shows how the frequency of soil absorption influenced the ground vibration attenuation, indicating a strong impact of the soil profile on the propagation of the ground vibration. The features of various types of soil in terms of vibration velocity and distance from the pavement edge had been amply demonstrated, even though this was a result of road traffic research. In contrast to peat or soft clay, gravel soils and dry sand have the highest vibration absorption capacity [16]. As the distance along the ground transmission line grows, ground vibration tends to rapidly reduce [17]. In comparison to soft soil, ground vibration in a stiff or hard soil could be reduced and absorbed faster with distance.

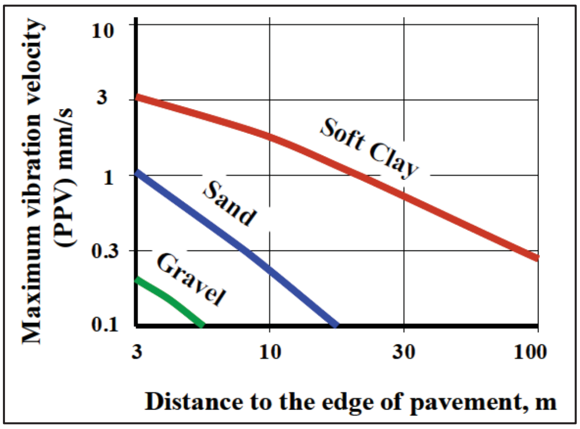

Figure 2. Ground Vibration Propagation in Different Type of Soil [15].

The second element in the process of vibration transmission brought on by railway vehicles is the propagation zone. The soil and bedrock layers between and beneath the rail track and the receiving object, as well as the ground's contour, make up the propagation region. The ground motion is established after the vibrations are produced. According to [12], the ground soil characteristics determine the propagation velocity of each type of wave (see Fig. 3).

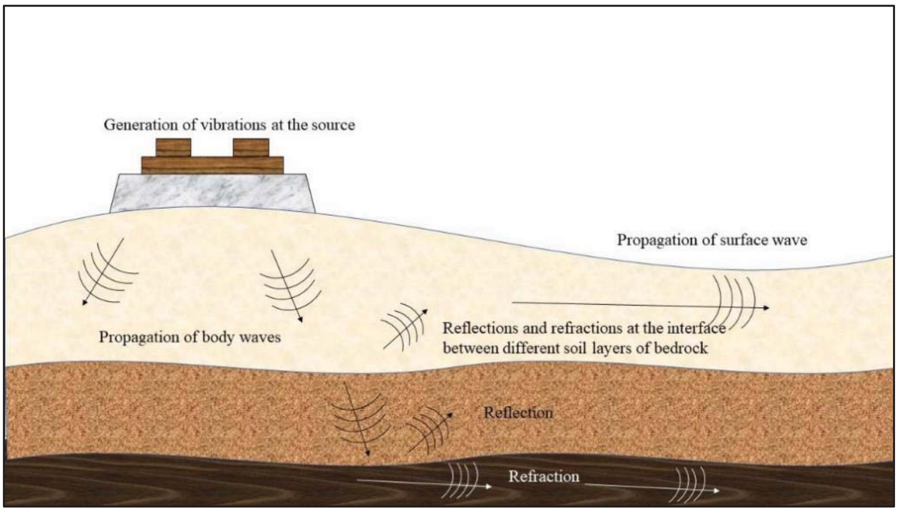

Figure 3. Propagation movement for ground vibration [12].

2.4. Receiver

The receiver completes the process of vibration transmission. The receiver region includes the structure, the ground beneath it, and any nearby soil [18]. The entire structure is then subjected to the vibrations that move from the soil to the foundation. They could be amplified and cause vibrations in the floors and walls. The reaction of the building will be influenced by the soil's quality, the building's geometry, the foundation's design, and the materials used in its construction. The type and layout of the furnishings in the building may also have an impact on the vibration's effects.

In research by [18], it was claimed that the building's size and the vibration's wavelength are related. This is important to the interaction between soil and structure. The vibrations will move the structure translationally if the building's breadth is less than the wavelength. On the other hand, shorter wavelength vibrations may result in structural bending in the building. The other factors that need to be considered are the individual framework and the natural frequencies of the structure.

3. Review of Established Standard and Guidelines

3.1. International Standards

The International Standards Organization (ISO) published the Guide to the Evaluation of Human Exposure to Vibration and Shock in Buildings (1 Hz to 80 Hz) (ISO 2631) in 1981. This document contains the conclusions of most researchers that stated that humans are sensitive to particle velocity between 8 and 80 Hz. This shows that a given velocity at several discrete frequencies causes the same response, such as discomfort or detection. The human body reacts to acceleration more evenly because it is less sensitive to vibrations below 8 Hz [19]. The vibration criteria from ISO 2631 for vibration sources are summarized in Table 1.

Table 1. Response of human to continuous vibration from traffic [19].

Vibration velocity (mm/s)	Building Use
0.8128	Workshop
0.4064	Office
0.2032	Residence
0.1016	Hospital operating room

Many nations utilize the ISO as a guide when developing their own standards. There are various limitations on vibrations depending on the nation. In their research, [20] were able to enumerate the variations in human irritability thresholds between global norms, such those in table 2. Most standards divide human irritability into multiple categories, ranging from "not annoyed" to "extremely annoyed." All these standards have a maximum vibration rate of 0.8 mm/s, which is regarded as being extremely disruptive.

Table 2. Level of annoyance between standards [20].

Standard	Human Annoyance Vibration Value (mm/s)	Human annoyance Response	
Building Research Foundation (SBR) - The Netherlands	<0.1	Not annoyed	
	0.1-0.2	A little annoyed	
	0.2-0.8	Moderately annoyed	
	0.8-3.2	Significant Annoyed	
Swedish Standard (SS 460 38 61:1992) - Sweden	0.4-1.0	Moderate disturbance	
	>1	Probable disturbance	
British Standard (BS 6472) – United Kingdom	0.2-0.4	Adverse comment is in low probability	Day Time
	0.4-0.8	Adverse comment is possible	Day Time
	0.8-1.6	Adverse comment probable	Day Time
	0.1-0.2	Adverse comment is in low probability	Night Time
	0.2-0.4	Adverse comment possible	Night Time
	0.4-0.8	Adverse comment probable	Night Time
Norwegian standard (NS 8178) - Norway	0.1	Class A – very good condition	
	0.15	Class B – Good conditions	
	0.3	Class C- limit value recommended for vibration	
	0.6	Class D – conditions that should be achieved in existing residential buildings	

In research by [21], according to the United States Department of Transportation, the allowed particle velocity for humans is 0.04 mm/s (65 dB with reference to 1e-6 inch/sec). Most people will begin to feel irritated when the ground-borne vibrations increase in intensity. Ground-borne vibration can still be upsetting even if the levels are within the range of human perception. According to the US Department of Transportation, tables 3 and 4 contain the impact requirements for ground-borne vibration for special buildings and conventional buildings, respectively.

Table 3. Criteria of ground-borne vibration (r.m.s. particle velocity) impact according to U.S. Department of Transportation [21].

Land Use Category	Ground-borne vibration impact levels (mm/s)	
	Frequent events	Infrequent events
Category 1: building where vibration would interfere with interior operations	0.045	0.045
Category 2: buildings and residence where tenant normally sleep	0.101	0.254
Category 3: Institutional land uses with primarily daytime uses.	0.143	0.359

Notes:
a.) Frequent events are derived as more than 70 events of vibration per day.
b.) Infrequent events are derived as less than 70 events of vibration per day.
c.) r.m.s is a root mean square

Table 4. Criteria of ground-borne vibration (r.m.s. particle velocity) impact for special buildings according to U.S. Department of Transportation [21].

Type of Room or Building	Ground-borne vibration impact levels (mm/s)	
	Infrequent events	Frequent events
Auditoriums	0.25	0.10
Theaters	0.25	0.10
TV Studios	0.05	0.05
Concert halls	0.05	0.05
Recording Studios	0.05	0.05

Notes:
a.) Frequent events are derived as more than 70 events of vibration per day.
b.) Infrequent events are derived as less than 70 events of vibration per day.

As can be seen in Table 5, a standard released by the US Department of Transportation also lists the human reactions to various levels of ground borne vibrations. According to this regulation, a vibration's maximum permissible speed is 0.452 mm/s.

Table 5. Human response on ground borne vibration [19].

Vibration Level	Ground-borne vibration impact levels (mm/s)
0.452 mm/s	Vibration acceptable only if the events of vibration are infrequent number per day.
0.143 mm/s	Approximate between distinctly perceptible and barely perceptible. Most of the humans find transit vibration at this level are annoying.
0.045 mm/s	Approximate threshold of perception among many humans.

The environmental effect requirements for ground-borne vibrations caused by train activity were created in cooperation by the Swedish Environmental Protection Agency (Naturvardsverket) and the Swedish Railway Administration (Banverket), as indicated in table 6. The Swedish agency has determined that 0.4 mm/s is the maximum allowable vibration level. [22]. Moderate disturbance is defined as a speed of more than 0.4 mm/s, as mentioned in Table 2.

Table 6. Environmental impact from ground borne vibration criterion according to guidelines in Sweden by Banverket and Naturvarsverket [22].

Vibration level (1-80 Hz)	Particle Acceleration	Particle velocity
	14 mm/s	0.4 mm/s

The [23] cited several earlier studies that assessed the ranges of vibration sensitivity in people. Table 7 displays the findings about how people react to continuous (steady state) vibration. The authorities decided that 0.3048 mm/s would be the threshold for human comfort in terms of vibration.

Table 7. Response of human to steady state vibration [23].

Human response	Vibration impact levels (mm/s)
Very disturbing	91.44 – 10.16
Disturbing	17.78 - 4.318
Strongly perceptible	2.54
Distinctly perceptible	0.889
Slightly perceptible	0.3048

Table 8 which was extracted from [23] describes the human responses towards traffic vibration (continuous vibration). It claims that the threshold of perception for irritation is 0.4826 mm/s, and that vibrations of 2.54 mm/s would cause individuals to feel bothered.

Table 8. Response of human to continuous vibration from traffic [23].

Human response	Vibration velocity (mm/s)
Unpleasant	10.16 - 15.24
Annoying	5.08
Begins to annoy	2.54
Readily perceptible	2.032
Threshold of perception	0.1524 – 0.4826

The Netherlands has been able to pinpoint the annoyance level of ground vibrations brought on by rail and road traffic. According to table 9, both vibrational sources vibrate at the same frequency. This table shows that vibrations of 0.8 mm/s or more bother people, while vibrations of less than 0.1 mm/s are the ideal level at which vibrations have no annoying or uncomfortable effects.

Table 9. Level of annoyance for maximum vibration for railway and road traffic in The Netherlands [24].

Reaction	Maximum Vibration
Not annoyed	<0.1
A little annoyed	0.1-0.2
Moderately annoyed	0.2 - 0.8
Annoyed	0.8 – 3.2
Significant annoyed	>3.2

Table 10 shows the classification of the response to vibration used in Germany according to one of its standards, Deutsches Institut für Normung (DIN).

Table 10. Human response to vibrations based on German standard [25].

Perception	Maximum vibration velocity
Threshold of perception, just noticeable	0.1
Weakly noticeable	0.2
Noticeable	0.4
Awakening threshold, clearly noticeable	0.8
Strongly noticeable	1.6
Very strongly noticeable	6.3

Furthermore, according to the DIN standard, a safe value is defined as 0.1 mm/s. However, it is anticipated that humans will be able to detect vibration at 0.4 mm/s.

3.2. Comparison between Malaysia Standard and International Standards

In Malaysia, the Department of Environment (DOE) published a regulation in 2007 called "The Planning Guidelines for Vibration Limits and Control in the Environment" that outlined the proper vibration levels for both the operating and construction phases (long term and steady state vibrations). Tables 11 and 12 display the suggested limits for annoyance and human reaction to both vibrations.

Table 11. Recommended Limits for Human Annoyance and Response due to Steady State Vibrations [26].

Receiver: Land Use category	Day Time 7.00 am – 10.00 pm	Night Time 10.00 pm – 7.00 am
Industrial	Curve 8 - Curve 16	Curve 8 - Curve 16
Vibration sensitive areas	Curve 1	Curve 1
Commercial, Business	Curve 4 - Curve 8	Curve 4
Residential	Curve 2 - Curve 4	Curve 2

Table 12. Recommended Limits for Human Annoyance and Response due to Short Term Vibrations [26].

Receiver: Land Use category	Day Time 7.00 am – 10.00 pm	Night Time 10.00 pm – 7.00 am
Industrial	Curve 32	Curve 32
Vibration sensitive areas	Curve 1	Curve 1
Commercial, Business	Curve 16 - Curve 20	Curve 16 - Curve 20
Residential	Curve 8 - Curve 16	Curve 4

Figure 4 shows the curves indicated in Table 12 in graphical form. Based on ISO 2631 and BS 6472:1992, which are standards for the vibration perception threshold for human reaction, Curve 1 was created. The base curve's multiplication factors are represented by the numbers assigned to the curves [26].

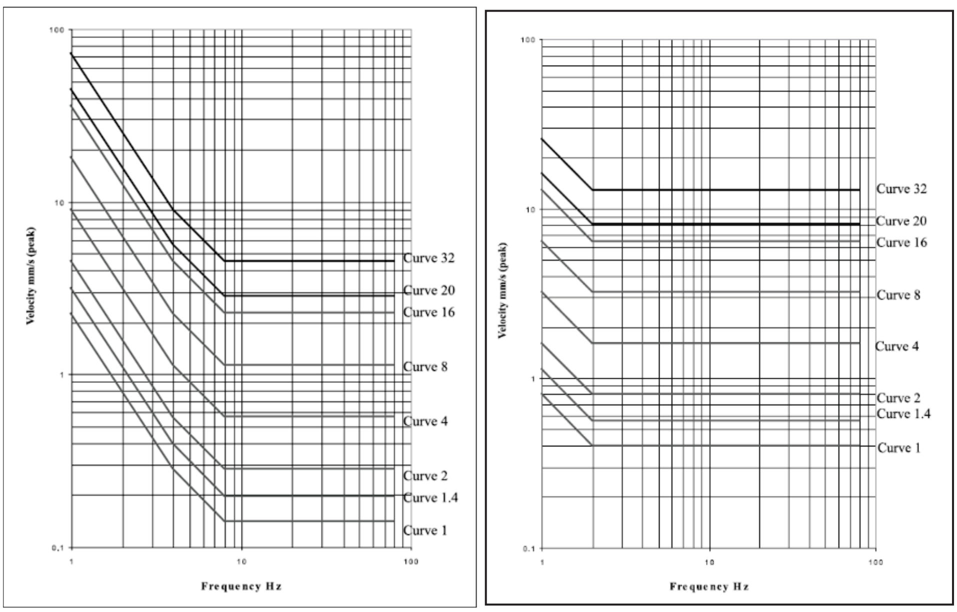

Figure 4. X-Y and Z axis curves of building vibration for peak velocity [26].

As shown in table 13, this standard uses combined-direction base curves in conjunction with multiplication factors to define the allowable level of vibrations for the considered building location.

Table 13. Ranges of multiplying factors for vibrations with respect to human response.

Area	Reaction	
	Night	Day
Workshop		8
Office		4
Residential	2 to 4	1.4
Critical working area		1

Based on the combined-direction base curves with multiplication factors, the local guideline essentially states that the vibration limit is 4 mm/s. There are a few significant distinctions that may be seen between the Malaysian recommendations and those from other countries. The local standard states that 0.567 mm/s, measured from the vertical velocity of the z-axis, is the upper limit of vibration that can irritate people. The vertical velocity is the highest speed attained by the running trains [3]. To determine the permitted limit of human response and annoyance using local recommendations, human perceptibility thresholds of vibrations for a standing person were taken into consideration [27]. The frequencies (Hz) that were used to calculate velocities (mm/s) were between 10 and 100 Hz. The same standard was used in a report by [28] and many other researchers to investigate train-induced ground vibration. According to this research, people are sensitive to particle velocities between 8 and 80 Hertz.

To establish the maximum allowable level of human irritation based on the Malaysian guideline, the Z-axis curve was applied with 8Hz as the lowest frequency and Curve 4 for residential areas criteria. Using this criterion, the maximum vibration velocity permitted in Malaysia was established. The recommended tolerated limit of vibrations for human perceived annoyance is less than 0.8 mm/s, which is in line with the recommendations of most nations. The recommended limit for evoking a human reaction and causing annoyance in commercial zones in Malaysia is 1.176 mm/s, which is higher than the standard for residential zones. The vibration limit for each nation is summarized in table 14. The limitations were chosen based on the human response in residential regions because this study focuses on the residential areas.

Table 14. Different limit of vibrations among the countries.

Country/Standard	Vibration limits (mm/s)
The International Standards Organization (ISO) 2631	0.2032
United State	0.2540
California	0.3048
Sweden	0.4000
Norway	0.6000
German	0.4000
The Netherlands	0.8000
Malaysia	**0.5670**

4. Conclusion

The government's commitment to increase investment in public infrastructure, particularly railway transportation, has helped Malaysia's railway system advance to a higher level. This includes the current construction of MRT Phase 2 (costing RM 32 billion), which was opened to the public on July 17, 2017, following the completion of MRT Phase 1 [29]. Additionally, as part of the Klang Valley Double Track (KDVT) project, the Light Rail Transit (LRT) Phase 3 is also being built with an RM 6 billion investment and an additional RM 5.9 billion for the improvement of KTMB services. The East Coast Rail Link (ECRL) project also received RM 55 billion in investment. The High-Speed Rail network, which will link Singapore and Kuala Lumpur, is another potential megaproject [30]. Malaysia must raise its operation requirements, notably for the limit of vibration caused by train traffic, so that it can serve as a model for other nations to sustainably build and run this expanding railway network. To make sure that the limitations established are appropriate, it is crucial to carefully consider the perceived level of aggravation and pain among those who are impacted by the vibrations while determining the limit.

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