Measurement 129 (2018) 489–498

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

# Acceleration measurements inside vehicles: Passengers' comfort mapping on railways

Pablo Zoccali, Giuseppe Loprencipe*, Robert Cristian Lupascu

*Department of Civil, Constructional and Environmental Engineering, Sapienza University of Rome, Via Eudossiana 18, 00184 Rome, Italy*

ARTICLE INFO

*Keywords:*
Transport monitoring
Ride comfort
Vertical acceleration
ISO 2631

ABSTRACT

Monitoring the status of infrastructural networks along their service life is fundamental to ensure a safe and good service quality. Due to the length and extension of infrastructures, it is fundamental to develop effective and low cost approaches that can allow a continuous monitoring. In this paper, an assessment method based on the ride comfort evaluation inside vehicles according to ISO 2631 (i.e. frequency weighted acceleration) was developed and tested on an Italian railway. In particular, the frequency weighted acceleration was calculated along the whole trip between two consecutive stops. In order to identify and localize the most critical areas along the traveling path, the vertical frequency weighted acceleration was also calculated for sub-sections of fixed lengths (i.e. 10 m) and then mapped on geographic information systems (GIS). In this way, it is also possible to determine, for example considering a railway infrastructure, whether the eventual discomfort may be due to localized irregularities or due to the passage on worn switches. Once proper threshold limit values are defined, early interventions can be planned in order to restore adequate comfort and safety levels. To test the proposed procedure, it was applied to a surface metropolitan railway characterized by an automatic guide, which granted the chance of evaluating the repeatability of the present approach. During the in-situ measurements, an inertial measurement unit (IMU) integrated together with a GPS receiver was used.

## 1. Introduction

Ensuring a good service quality to the passengers is one of the main tasks and purposes of a transport operator. Several approaches have been investigated and proposed in order to estimate the service and ride quality of public transports perceived by passengers [1–4]. In the aforementioned works, it was underlined that passengers' perception of the service quality depends on several characteristics, such as accessibility, safety, comfort and service. In addition, passengers' age, behavior and position inside the vehicle can significantly influence the service quality perception.

Ride comfort, in particular, includes different aspects such as: air-condition on board, inside vehicle temperature, seat comfort, noise and vibration exposure. About the latter issue, many researchers dealt with this topic with regard to both railway and road transport systems [5]. Johanning et al. [6] evaluated whole-body vibration exposure inside railroad locomotives according to ISO 2631 [7]. In [8] the correlation between different ride comfort evaluation methods (i.e. Statistical [9–11], Root mean square – r.m.s. [7] and Sperling's methods) for railway vehicles was investigated. The main difference in each method concerns the frequency weighting adopted to take account of human sensation. In this study [8], a correlation factor (R2) greater than 0.88 was found in all cases. Kim et al. [12] performed an experimental study on the ride comfort of the high-speed train using the statistical method. In particular, they decided to use the UIC 513R approach rather than the ISO 10056 one because the first emphasizes the low-frequency vibration of the train. In [13], the ISO 2631 evaluating method was used to assess whole-body vibration exposure in trains, considering different measurement location: seat pan, seat back and floor.

Similar studies, related to the evaluation of whole-body vibration exposure, were also carried out for road vehicles using the ISO 2631 approach [14–17]. With regard to ride comfort evaluation on road infrastructures, many authors investigated the chance of using the frequency weighted vertical acceleration ($a_{wz}$) described in the ISO 2631 to assess and estimate road pavement condition in terms of distresses [18] and/or longitudinal roughness [19–21]. In addition, many studies assessed the capability of performing such acceleration measurements by means of smartphones [22–26], in order to reduce monitoring costs of road pavement condition.

In the last years, many researchers investigated the chance of using Inertial Navigation System (INS) to measure and analyze road and railway track geometry condition from in-service vehicles [27–30].

* Corresponding author.
*E-mail addresses:* pablo.zoccali@uniroma1.it (P. Zoccali), giuseppe.loprencipe@uniroma1.it (G. Loprencipe), robertcristian@live.it (R.C. Lupascu).

https://doi.org/10.1016/j.measurement.2018.07.079
Received 18 September 2017; Received in revised form 30 May 2018; Accepted 25 July 2018
Available online 26 July 2018

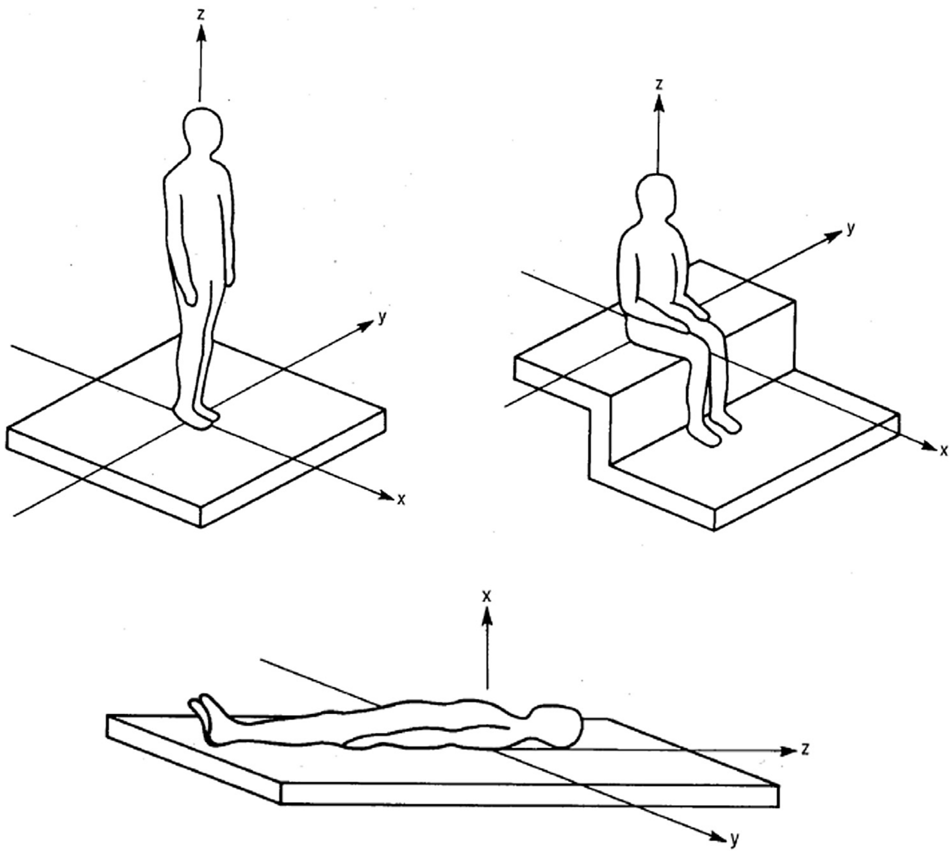


**Fig. 1.** Basicentric axes of the human body for the different position during vibration exposure.

**Table 1**
Guide for the application of frequency-weighting curves provided by ISO 2631.

| *Frequency weighting* | *Health* | *Comfort* | *Perception* | *Motion sickness* |
|---|---|---|---|---|
| $W_k$ | z-axis, seat surface | z-axis, seat surface<br>z-axis, standing vertical recumbent (except head)<br>x-, y-, z-axes, feet (sitting) | z-axis, seat surface<br>z-axis, standing vertical recumbent (except head) | – |
| $W_d$ | x-axis, seat surface<br>y-axis, seat surface | x-axis, seat surface<br>y-axis, seat surface<br>x-, y-axes, standing horizontal recumbent<br>y-,z-axes, seat-back | x-axis, seat surface<br>y-axis, seat surface<br>x-, y-axes, standing horizontal recumbent | – |
| $W_f$ | – | – | – | vertical |

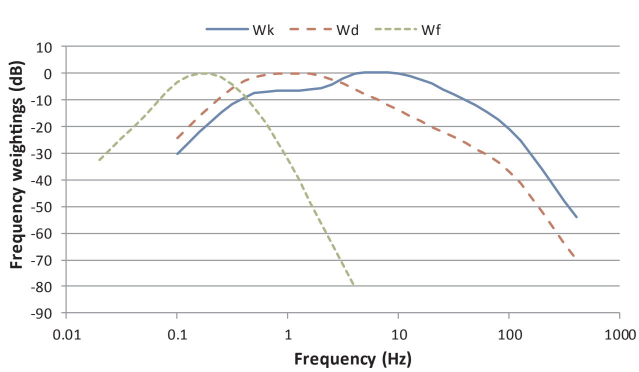


**Fig. 2.** Frequency weighting curves.

In the field of rail transportation, the quality of rail track can be checked by means of inertial measurement unit (IMU) integrated together with a GPS receiver to prevent the generation of noise and vibration [31–34], but also acceleration measurements can be used to properly identify track singularities [35].

**Table 2**
Comfort levels related to $a_{wz}$ threshold values proposed by ISO 2631 for public transport.

| $a_{wz}$ values (m/s$^2$) | Comfort level |
|---|---|
| < 0.315 | Not uncomfortable |
| 0.315–0.63 | A little uncomfortable |
| 0.5–1 | Fairly uncomfortable |
| 0.8–1.6 | Uncomfortable |
| 1.25–2.5 | Very uncomfortable |
| > 2 | Extremely uncomfortable |

In this paper, the use of an IMU integrated together with a GPS receiver was investigated to evaluate ride comfort on railway vehicles adopting the ISO 2631 approach. In particular, the ride quality assessment was carried out considering the whole path between two following stations, but also dividing it in several shorter segments. In this way, the most critical areas can be detected (e.g. presence of a