# Comfort Analysis Comparison Between Alfapendular and Intercity Portuguese Trains at the North Rail

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**Abstract**
Nowadays, trains are one of the most used public transportation modes. Comfort is the key to keeping and attracting new users. Vibration highly influences comfort levels and, once it is derived from the train motion it is stated as a primary concern. Due to contact with the seat and floor, passengers are subjected to whole-body vibration. ISO 2631 standard is fully dedicated to the evaluation of this type of vibration. Following its approach, the present research evaluates the comfort levels of Alfapendular and Intercity trains operating in Portugal at the Porto Campanhã – Lisbon Oriente connection. Measurements were performed at the beginning, middle, and end of the train, allowing a comparison between seat types within the same train and the same types from different trains. Results showed higher comfort levels for the Alfapendular trains, while for the Intercity train, both middle and end of train locations were ranked as "Little uncomfortable". As a complementary analysis, it was observed the vibration transmission of the seat based on the Seat Effective Amplitude Transmissibility (SEAT). Results were above 100%, showing vibration amplification by all tested seats. Higher SEAT values were found for the Intercity train seat. This was the first study conducted on Portuguese trains regarding comfort analysis and vibration transmission.

**Keywords**
Railways, Whole-body vibration, Vibration transmission, SEAT.

## 1. Introduction

Trains are becoming competitive transportation over air travel. Its low environmental impact and high transportation capacity took governments to incite its use for connecting distances up to 850 km [1]. Comfort, safety, and user conditions are the key to keeping customers satisfied and attracting new ones. These parameters are influenced by vibration. Once it is derived from the train motion, passengers are subjected to it throughout the entire journey especially due to the contact with the floor and the seat. Vibration types are characterized depending on the transmission path as whole-body vibration (WBV) or hand-arm vibration. If the vibration transmission into the body occurs through a supporting surface, then it is classified as WBV. In opposition, hand-arm vibration is defined by a localized transmission to the hands and arms. Once vibration transmission happens mostly due to the contact of the user with the floor, seat surface, and seatback, this is classified as WBV. This type of vibration can cause discomfort, fatigue, and, in some extreme cases diseases. The human body possesses its natural vibration mode; when these modes coincide with an externally induced vibration, resonance may occur, which, if absorbed, can lead to tissue and organs' physical stress. This way, studying the vibration transmission in a rail environment is crucial not only to quantify the passenger's comfort levels but also to assess the harmful consequences of vibration on users. ISO 2631 standard is fully dedicated to the WBV evaluation related to comfort, health, and motion

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sickness, and, thus, its methodology will be followed in the present study [2–9].

A seat can also mitigate or amplify the vibration transmission and, this way, decrease or increase discomfort caused by vibration. Seat Effective Amplitude Transmissibility (SEAT) is a method dedicated to evaluating this dynamic discomfort caused by vertical vibration. Therefore, this method will be used as a complement vibration analysis to ISO 2631 [10].

The objectives of this study are (1) to evaluate the vibration discomfort levels, concerning the comfort approach, on the Alfapendular and Intercity trains on the same track, (2) to evaluate the vibration transmission on different seat types (comfort and standard classes) within the same train and (3) compare the WBV levels on the same trains as (1).

## 2. Materials and Methods

The present study was conducted on 2 different types of trains, the Alfapendular tilting train, and the Intercity train. Both trains were running at the North line connecting Porto Campanhã and Lisbon Oriente train stations. Vibration measurements were executed at 3 different train locations (beginning, middle, and end) within 3 different measurement places (floor, seat surface, and seatback) following the ISO 2631 standard specification.

### 2.1. ISO 2631

ISO 2631 is a standard specially designed to quantify WBV about comfort, human health, and motion sickness. Concerning motion sickness, it is defined as an interest in the frequencies comprehended within the range of 0.1 – 0.5 Hz. Once comfort and health are related in many ways, the analysis should consider the frequencies between 0.5 – 80 Hz as the interesting ones. At this specific range, vibration affects the body as a whole, causing WBV which can lead to discomfort and fatigue.

Measurements should take place at the interface surfaces between the user and the vibration source, particularly the floor, seat surface, and seatback. The method consists of taking 3-axial acceleration measurements and calculating the root mean square (RMS) acceleration for each axis. Since the human body has its natural vibration mode, vibrations with identical intensities but different spectral content will induce different dynamic responses, thus, this effect needs to be quantified. To do it, the standard stated the application of weighting curves, that, depending on the impact of the RMS acceleration assign different weights to it. Depending on the measurement place and purpose different weighting curves are applied [9, 11]. The weighting process is calculated according to Equation (1)

$$a_w = [\sum(W_i a_i)^2]^{1/2} \quad (1)$$

Where $Wi$ represents the weighting frequencies and $ai$ the RMS accelerations.

The measurement position defines the application of multiplying factors, $k$. Weighting curves and multiplying factors concerning comfort analysis can be found in table 1.

**Table 1**

Frequency weighting curves and multiplying factors defined by ISO 2631 for comfort analysis of a seated passenger

| | X - axis | Y - axis | Z - axis |
|---|---|---|---|
| Floor | $W_k$ and $k_x = 0.25$ | $W_k$ and $k_y = 0.25$ | $W_k$ and $k_z = 0.40$ |
| Seat surface | $W_d$ and $k_x = 1.0$ | $W_d$ and $k_y = 1.0$ | $W_k$ and $k_z = 1.0$ |
| Seatback | $W_c$ and $k_x = 0.80$ | $W_d$ and $k_y = 0.50$ | $W_d$ and $k_z = 0.40$ |

Lastly, the total vibration (av) is obtained following the Equation (2)

$$a_v = \left(k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2\right)^{1/2} \quad (2)$$

Where $a_w$ are the RMS accelerations for each axis. The comfort level is evaluated based on a defined scale, table 2.

ISO 2631 also suggests the use of the Vibration Dose Value (VDV), calculated as follows at Equation (3)

$$VDV = \left[\int_{t1}^{t2} [a_w(t)]^4 \, dt\right]^{1/4} \quad (3)$$

This parameter uses the fourth power of acceleration instead of the second power, this way it is used when the goal is to emphasize acceleration peaks [11].

**Table 2**
ISO 2631 comfort evaluation scale. Adapted from [11]

| $a_v(m/s^2)$ | Ride comfort |
|---|---|
| ≤ 0.315 | Not uncomfortable |
| 0.5 – 0.63 | Little uncomfortable |
| 0.63 – 0.8 | Little uncomfortable to fairly uncomfortable |
| 0.8 – 1.0 | Fairly uncomfortable to uncomfortable |
| 1.0 – 1.25 | Uncomfortable |
| 1.25 – 1.6 | Uncomfortable to very uncomfortable |
| 1.6 – 2.0 | Very uncomfortable |
| 2.0 – 2.5 | Very uncomfortable to extremely uncomfortable |
| ≥ 2.5 | Extremely uncomfortable |

## 2.2. SEAT

SEAT value is a complementary method to evaluate comfort that shows the extent to which a seat is increasing or decreasing vibration transmission; thus, this is an indicator of seat isolation efficiency. To do it, the SEAT compares the vibration discomfort when sitting on a rigid seat to the discomfort feeling on a non-rigid seat [10]. Thus, the SEAT is calculated as the ratio between the VDV measured on the seat and the VDV measured on a rigid support beneath the seat surface, Equation 4

$$SEAT\ \% = \frac{VDV_{seat}}{VDV_{floor}} \times 100 \qquad (4)$$

If the SEAT result is equal to 100% the seat does not influence the vibration transmission. In opposition, if this value is higher than 100% the seat is amplifying the vibration transmission and, thus, the seat is increasing discomfort levels, on the other side, for SEAT values lower than 100% the seat is mitigating the vibration transmission to the passenger.

SEAT can also be calculated with the $a_{RMS}$, however, once the considered journeys are long and the VDV calculation takes more into consideration the acceleration peaks than the RMS acceleration, it was decided to use the VDV to perform the SEAT calculations.

Concerning the rail environment, the vertical SEAT is expected to be greater than 100% because seat foams cannot mitigate the low frequencies vibration dominant in the vertical direction [12].

## 2.3. Alfapendular train

The Alfapendular (AP) tilting train of the 4000 series, was introduced in 1999 in Portugal and it was renovated in 2017. This electric train has a total length of 159m, is operated as a single unit, and is a train with an active titling system consisting of 6 cars, where four are engines and two are trailers. The cars are classified based on two classes and bar facilities; the 1st and 2nd cars are designated as comfort class, figure 1a, on the 3rd car is placed the bar and, the 4th,5th, and 6th cars are categorized as the standard class, figure 1b. Following the train motion, the 1st car corresponds to the begging of the train while the 6th car, located at the opposite end, matches the end of the train [13].


**Figure 1:**
a) Comfort class seat; b) Standard class seat

As noted in figure 1, the seats from the comfort and standard class are different, being the seat of the former larger and with higher foam thickness.

## 2.4. Intercity train

Intercity (IC) train service, introduced in 1980 in Portugal, is currently run by 5600 series locomotives with Corail coaches which, were renovated in 2002. The electric locomotive trails 5 coaches, the 1st and 2nd representing the comfort class and the bar, and the 3rd, 4th, and 5th classified as a standard class. As on the Alfapendular train, according to the train motion, the 1st car corresponds to the start of the train and, consequently, the 6th car, placed at the opposite extremity, means the end of the train [14].

Corail coaches are characterized by having 2 seats per row. However, for the comfort class, besides matching this parameter the seats are arranged individually and, thus, the seat support frame is not shared by 2 seats. In opposition, the touristic seat frame is shared by 2 seats, representing a more similar structure to Alfapendular seats. Depending on the class, the seats show different dimensions and foam thicknesses. Figure 2 illustrates the seats from both classes.


**Figure 2:**
Intercity train seats: a) Comfort class; b) Standard class

## 2.5. Procedures and equipment

The experimental procedure consisted in taking 15 full journeys for the trains (9 for the Alfapendular and 6 for the Intercity train). Measurements occurred at the beginning of the train (1st coach), middle of the train (4th car for the Alfapendular train and 3rd coach for the Intercity), and end of the train (last car).

For each location, following ISO 2631 standard, 3 measurement places were considered, namely the floor, seat surface, and seat back. Vibration measurements were realized using 3-axial accelerometers (PCE-VDL-24I ±16g) fixed into a disc format, flexible, silicone seat pad attached to the vibration transmission source [15].

Matlab scripts, following ISO 2631 guidelines, were developed and validated, in order to calculate the RMS acceleration, total acceleration, VDV and SEAT %.

The track presents a total length of 275 km, divided into 5 stations and 2h50m to complete for the Alfapendular journey and 12 stops and 3h15m to complete for the Intercity trip. It should be noted that a maximum velocity of 220km/h is achieved by the Alfapendular train, while the Intercity achieves a lower maximum speed, around 200km/h. The journeys run under regular operation conditions and passenger transportation [13, 14].

## 3. Results

Following ISO 2631 the $a_{RMS}$, $a_v$ ,and VDVZ were calculated, additionally, the SEAT % was obtained based on VDV values. This way, the journeys were ranked according to their ride comfort and complementary with the seat vibration transmission. The results concerning the full experimental campaign can be observed in table 3.

The AP trips were all ranked as "Not uncomfortable". However, for the IC train, only the journey at the beginning of the train (comfort class) presented this rank. For the middle and end of the train journeys, the ride comfort was classified as "Little uncomfortable". Regarding SEAT %, the results also found the same trend, as the ones for the AP were lower than the ones for

**Table 3**
Experimental testes results

| Measurement position | $a_{RMS}$ $(m/s^2)$ IC | $a_{RMS}$ $(m/s^2)$ AP | $a_v$ $(m/s^2)$ IC | $a_v$ $(m/s^2)$ AP | VDVz $(m/s^{1.75})$ IC | VDVz $(m/s^{1.75})$ AP | SEAT % IC | SEAT % AP |
|---|---|---|---|---|---|---|---|---|
| **Results for the beginning of the train** | | | | | | | | |
| Floor | 0.19 | 0.18 | 0.06 | 0.06 | 3.49 | 3.50 | | |
| Seat Surface | 0.27 | 0.27 | 0.27 | 0.27 | 4.47 | 4.08 | 128.19 | 116.41 |
| Seatback | 0.26 | 0.26 | 0.18 | 0.17 | 3.85 | 3.85 | | |
| **Results for the middle of the train** | | | | | | | | |
| Floor | 0.21 | 0.15 | 0.07 | 0.05 | 3.87 | 3.43 | | |
| Seat Surface | 0.34 | 0.26 | 0.34 | 0.26 | 5.65 | 4.30 | 145.96 | 125.25 |
| Seatback | 0.28 | 0.25 | 0.19 | 0.16 | 4.04 | 4.03 | | |
| **Results for the end of the train** | | | | | | | | |
| Floor | 0.18 | 0.17 | 0.06 | 0.06 | 3.50 | 3.47 | | |
| Seat Surface | 0.34 | 0.28 | 0.34 | 0.28 | 5.55 | 4.40 | 158.54 | 126.81 |
| Seatback | 0.27 | 0.25 | 0.18 | 0.16 | 4.12 | 4.06 | | |

the IC train. This parameter was expected once the seats from the AP train are newer than the IC seats.

Furthermore, concerning the middle and end of the train measurements for the AP train, similar results were obtained for the ISO 2631 and SEAT % analysis. The same did not occur for the IC trains, besides the ride comfort values were similar, the SEAT values increased by 12.58% in the last car.

As anticipated, the SEAT values are higher than 100% for all journeys on both types of trains.

## 4. Discussion

To the authors' knowledge, this is the first test conducted in Portuguese trains during regular service conditions, examining the WBV parameters and vibration transmission.

Concerning the beginning of the train, results were equal or quite similar (0.01 m/s$^2$ difference) for AP and IC on both RMS and total acceleration. It should be highlighted that the highest total acceleration value (0.27 m/s$^2$) was found for both trains on the seat surface measuring location, still 14.3% under the reference value for the "Not uncomfortable" level. SEAT results show an approximately 12% higher value for the IC train (128.19%) than the one for the AP (116.41%). These results are justified based on the higher VDV value presented by the IC seat surface, which traduces its increased susceptibility to transmit and amplify vertical vibration when compared with the AP. As expected, the SEAT values are above 100%, which complies with findings from Gong and Griffin [12].

While seats for the begging of the train are classified as comfort seats, the seats from the middle and end train measurement locations are touristic seats. As evidenced in sections 2.3 and 2.4, this type of seat presents different dimensions and characteristics, so it is expected that this seat does not perform dynamically as well as the comfort ones but present similar results for both locations.

Relatively to the middle of train results, in opposition to what was expected, the AP results for $a_{RMS}$ and $a_V$ decreased when compared with the comfort class, keeping the "Not uncomfortable" level. However, the same did not occur for the IC results as this increased and, the seat surface achieved the "Little uncomfortable" rank. As the seat structure (and dimensions) are different from the first class, dynamic comfort is expected to be different. This is evidenced by the VDV value, which increases at the seat surface and, consequently, leads to an increase of the SEAT in relation to the comfort seats.

For the last car of the train, measurements show similar RMS and total acceleration results with the ones for the middle of the train for both AP and IC trains. It was observed that the worst $a_{RMS}$ result (0.21 m/s$^2$) for the IC train on the floor measurements was 155% lower than the one presented by Indian IC trains, which is also an indicator of the comfort at the Portuguese IC train [16]. Regarding the AP train, comparing the av values found for the seat and backrest with those obtained, in the same locations, in Chinese high-speed trains (0.12 m/s$^2$), the Portuguese trains show 116.67% more total acceleration in the seat and, 33% more in the backrest [17]. However, it should be pointed out that AP passengers do not experience discomfort in any carriage and, all journeys are ranked as "Not uncomfortable". Regarding the VDV and SEAT for the AP train, these remained close to the values of the middle carriage. Since the seats in these locations are equal, these would be the expected results as equal seats should present the same dynamic comfort. The same did not happen for the IC train where, despite the seats being the same as in the previous location, the VDV values increased and consequently the SEAT increased by 12.58%. Thus, this proved to be the worst location to travel and the most susceptible to acceleration peaks and vibration transmission/amplification.

## 5. Conclusion

Multiple interactions between rails, wheels, acceleration, braking, and seats made the vibrating environment of trains very complex. Due to the contact with the seat and floor, vibration is transmitted to the passengers. This can affect not only the ride comfort by also the dynamic seat comfort. To evaluate these parameters, ISO 2631 and the SEAT method were applied to AP and IC Portuguese trains on the Porto Campanhã – Lisbon Oriente connection.

Measurements took place at the beginning, middle, and end of the trains. Results demonstrated the comfort presented in all trains and locations. Different seat types were also evaluated and, as expected, the comfort class seats performed better relative to the dynamic comfort. For the IC train, the worst travelling location was obtained at the end of the train. However, for the

AP train, the middle and end of the train presented similar results.

This is a pioneer study in Portugal, once, to the authors' knowledge, it is the first study to evaluate passengers' ride and dynamic comfort. The present results can provide precious feedback for the operator to improve the passenger's comfort.

Finally, the present study concluded that the passengers of the Alfapendular and Intercity trains are travelling in a comfortable situation considering vibration, with some space for improvements in dynamic comfort, regarding the Porto Campanhã – Lisbon Oriente connection.

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