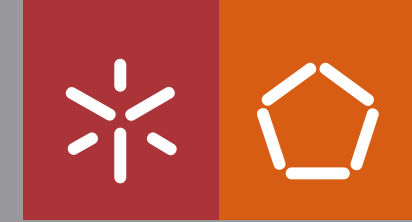




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**Study, analysis and improvement of the
comfort index levels on railways**

Universidade do Minho
Escola de Engenharia





Universidade do Minho
Escola de Engenharia

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Study, analysis and improvement of the comfort index levels on railways

Doctoral Thesis
Doctoral Program in Mechanical Engineer

Work developed under the supervision of:
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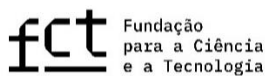
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STATEMENT OF INTEGRITY

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Estudo, análise e melhoramento dos níveis de conforto de comboios de passageiros

Os futuros meios de transporte baseiam-se em soluções amigas do ambiente. A redução do impacto ambiental, congestionamento do tráfego, e a promoção de baixas emissões de CO₂, são passos cruciais para alcançar a neutralidade carbónica. A indústria ferroviária encontra-se classificada como a solução mais proeminente neste objetivo. Especialmente nos países europeus e asiáticos, a maioria dos serviços ferroviários é operada por comboios eletrificados. Deste modo, as suas emissões de CO₂ são residuais ao nível do utilizador final. Para manter a atual tendência e aumentar continuamente o número de passageiros dos comboios, é fundamental proporcionar viagens agradáveis. A sua avaliação baseia-se numa análise extremamente complexa da segurança e do conforto, dependendo da interação de múltiplos fatores. Independentemente da dificuldade mencionada, os fatores de conforto dependentes do funcionamento do comboio são o foco desta tese. Para quantificar adequadamente o conforto, é necessário quantificar parâmetros estáticos e dinâmicos. A análise da influência de parâmetros dinâmicos no conforto, levou à caracterização do mesmo nas viagens de longas distâncias realizadas nos comboios portugueses através da aplicação da norma ISO 2631. Com base nessa avaliação, foi sugerida uma nova metodologia para identificar anomalias na infraestrutura ferroviária e detetar possíveis necessidades de manutenção da mesma. Deste estudo resultou a identificação de doze zonas críticas. Além disso, com base numa abordagem inovadora, a identificação modal permitiu distinguir as vibrações estruturais dos assentos dos movimentos que dependem das frequências naturais da estrutura do veículo. A identificação dessas frequências está dependente do tipo de banco estudado. Foi ainda avaliada a influência da espessura da espuma na transmissão de vibrações, sendo que, espumas mais espessas são mais eficazes na mitigação de vibrações. Relativamente ao conforto estático, este foi caracterizado por metodologias subjetivas e objetivas. A influência das propriedades mecânicas da espuma, assim como, da pressão e temperaturas induzidas na interface passageiro-banco, conduziu à identificação dos elementos mais adequados para aplicações ferroviárias. O sistema identificado como a solução mais promissora para elevar os níveis de conforto em viagens de comboio é composto por uma espuma de poliuretano (80 kg/m³) e uma capa de tecido. Os resultados do presente estudo podem ajudar na conceção de novos bancos capazes de oferecer níveis de conforto elevados e, assim, promover a utilização do comboio como o principal meio de transporte.

Palavras-chave: Comboios de passageiros; Conforto; Conforto dinâmico; Conforto estático; Manutenção.

Study, analysis and improvement of the comfort index levels on railways

Future transportation will be based on environmentally friendly solutions, reducing environmental impact and traffic congestion, and promoting low CO₂ emissions targeting to achieve carbon neutrality. The railway industry is positioned as the most prominent solution to this goal. Especially in European and Asiatic countries, a predominant proportion of rail services are operated by electrified trains. Thus, its CO₂ emissions are residual at the end user. To keep the positive trend and continuously increase rail passengers, it is fundamental to deliver comfortable journeys, which requires a rather complex analysis based on safety and comfort, and depends on the interaction of multiple factors. Regardless of the mentioned difficulty, the comfort factors dependent on the rail motion are the focus of this thesis. To properly quantify comfort, dynamic and static parameters need to be accessed. The analysis of the influence of dynamic parameters when sitting allowed to characterise the ride comfort of the Portuguese rail train journeys, applying ISO 2631. Based on that evaluation, a novel methodology was suggested to identify abnormalities in the rail track infrastructure and detect possible maintenance requirements. A total of twelve critical sections were identified. Moreover, based on an innovative experimental setup and analysis methodology, a modal identification may properly distinguish seat structural vibrations from those dependent on carbody natural frequencies. The identification of these frequencies depends on the seat type, being that of Alfa Pendular and Intercity trains different. The influence of foam thickness in vibration transmission was also evaluated, with thicker foams being more effective in mitigating vibrations. Static comfort was accessed by both, subjective and objective, methodologies. Foam mechanical properties, induced interface pressure, and temperature at the cover-passenger interface led to the identification of the most suitable seating system for railway applications. That identified as the most promising solution to raise comfort levels on train journeys consists of a polyurethane foam (80 kg/m³) and a fabric cover. The results of the present study may help design new railway seats capable of offering increased comfort levels and, thus, promoting rail usage.

Keywords: Comfort; Dynamic comfort; Maintenance; Railways passengers; Static comfort.

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List of Acronyms

a_{p95}^w	95 th percentile of the weighted accelerations (m/s^2)
AP	Alfa pendular
$A_{0-75\%}$	Area under the loading compression cycle (mm^2)
$A_{75-0\%}$	Area under the unloading compression cycle (mm^2)
P_{avg}	Average pressure ($mmHg$)
f	Average value of each natural frequency
BMI	Body mass index
$F_{25\%}$	Compressive load at 25% deformation (N)
$F_{65\%}$	Compressive load at 65% deformation (N)
CBM	Condition-based maintenance
CF	Crest factor
DAQ	Data acquisition
DOF	Degree-of-freedom
G_i	Double-side square acceleration (cm/s^2) ²
EFDD	Enhanced frequency domain decomposition
FEA	Finite element analysis
FSR	Force sensitive resistor
FDD	Frequency domain decomposition
B_i	Frequency weighting curve
GPS	Global positioning system
HAV	Hand-arm vibration
f_{max}	Highest frequency componente (Hz)
ILD	Indentation load deflection (N)
IP	Infraestruturas de Portugal
$G_i(f)$	Input acceleration spectrum at the floor level (Hz)
IC	Intercities
IFFT	Inverse fourier transform
JND	Just Noticeable Difference scale
P_{max}	Maximum peak pressure ($mmHg$)
N_{MV}	Mean comfort index
MAC	Model assurance criterion
k	Multiplying factor
NRS	Numerical rating scale
f_{Nyqu}	Nyquist frequency (Hz)
$G_o(f)$	Output acceleration spectrum at the seat–user interface (Hz)
PU	Polyurethane
PSD	Power spectral density
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses
p_i	Pressure on its cells ($mmHg$)
a_i	Rms accelerations (m/s^2)
SEAT	Seat effective amplitude transmissibility
SPD %	Seat pressure distribution

SVD	Singular value decomposition
W_z	Sperling's ride index
SAG factor	Supportive factor
$S_{yy}(w)$	SVD decomposition of the PSD matrix
p_m	The mean pressure of the n elements ($mmHg$)
n	Total number of nonzero cell elements
a_v	Total vibration (m/s^2)
$H(f)$	Transmissibility function (Hz)
ϕ_j^*	Vector containing the coordinates from the comfort seat mode j
ϕ_i^*	Vector containing the standard seat information of mode i .
VDV	Vibration dose value ($m/s^{1.75}$)
a_w	Weighted acceleration (m/s^2)
W_i	Weighting curves
WBV	Whole-body vibration

Chapter I - Introduction

This document presents the thesis for the Doctoral Program in Mechanical Engineering entitled “Study, analysis and improvement of the comfort index levels on railways”. It aims to address the passenger’s comfort levels and the main influence parameters on railway journeys. The developed concepts are envisioned to be submitted as proof of the candidate's suitability to be considered for a Doctor of Philosophy degree.

The work was designed and developed primarily on three research groups, namely the Mechanical Engineering and Resource Sustainability Center (MEtRICs) from the University of Minho, the Institute of Science and Innovation in Mechanical and Industrial Engineering (INEGI) from the University of Porto and the CONSTRUCT-LESE from the University of Porto. Experimental tests were performed on-board Pendulino and Intercities trains, in the maintenance facilities of Comboios de Portugal (CP) and at FEUP laboratories.

1.1 Motivation and context

Transportation modes are pointed out as one of the most significant challenges for future generations. Due to an era of climate change, urban modernisation and its evolution are mostly defined by the development and bid of public transportation. Increased traffic congestion and, consequently, high CO₂ release and its impact on environmental pollution led multiple governments to implement sustainable transport modes [1,2]. In this context, the European Union has established a goal to achieve climate neutrality by 2050. Thus, a reduction of carbon emissions in transportation modes by 60% is required [3].

Railways are one of the most efficient and widely used mass transportation systems for mid-range distances, also pointed out as the best strategy to reach European Union decarbonisation goals. Compared with air and car transportation, railways present superior efficiency, transportation capacity and safety, and lower environmental impact [4–8]. Moreover, since its development and service introduction, the railway industry has been linked with social development in both social and economic aspects [9].

The railway transportation importance has been sustained by a steady increase in passengers during the last decade, which will continue in the next future [7,8,10–12]. The quality of public transportation services influences the traveller's choices. Passengers with previous good experiences will probably use the same travel transportation mode again, whereas those that experienced service problems may change to a different transportation mode for their next trip. Thus, to keep the increasing trend that leads passengers to shift to railway transportation, it is crucial to identify the currently dissuading factors, raise the trains' attractiveness, and provide safer and more comfortable journeys [13,14]. Journey quality is defined based on safety, comfort and user conditions [7,8].

The analysis of the passengers' comfort is rather complex, as it involves the interaction of multiple factors, such as vibration, noise, temperature, visual stimuli, illumination, smell, humidity, seat design and materials [15–20]. Although all parameters are equally essential and significantly impact the user's comfort levels due to their high complexity and the large number of tests required for their evaluation, the present work focuses on evaluating discomfort parameters induced by the vibration resulting from the train motion. Both static and dynamic properties that interfere with the perceived comfort will be analysed: ride comfort, seat effective amplitude transmissibility (SEAT) and seat transmissibility, interface pressure and foam properties, such as supportive factor (SAG factor) and hysteresis loss [8,21].

Passengers spend most of their time seated; thus, the seat affects passengers' comfort among other interior facilities. A combination of optimum dynamic properties (to minimise unwanted vibration) and the finest static performance (to decrease interface pressure) define the ideal seat [8,22]. Therefore, passengers' comfort is only properly quantified by performing static and dynamic evaluations.

This thesis was motivated by the need and challenge to properly quantify and improve railway passengers' comfort levels in order to promote its use as the main daily public transportation mode. Inspired by the presently applied methodologies, new approaches were developed to fulfil the current research gaps and limitations and provide new insights on this topic.

1.2 Research questions

As highlighted in sub-chapter 1.1, nowadays, when travelling by public transportation, passengers do not only expect to move from one place to another but also demand comfortable journeys. Therefore, balancing transportation's primary function and high comfort levels is needed [23].

Derived from the train motion and the railway track-wheel interaction, vibration is particularly problematic and the leading cause of passengers' discomfort. Human vibration is defined as the physical factor effect on the human body induced by mechanical energy transmission from oscillation sources [24,25]. Regarding a train journey, vibration is transmitted to the users due to contact with the seat and floor [8,26,27]. Besides affecting comfort, vibration reduces the passenger's ability to perform simple tasks, like reading or watching a movie; therefore, investigating the seat's ability to mitigate unwanted vibration is fundamental [28–30]. Moreover, dynamic discomfort may be raised by improperly railway track infrastructure conditions or maintenance requirements, as those may increase vibration levels at the rail vehicle carbody [31–35]. Static parameters mainly influence perceived comfort in the absence of vibration. Those parameters are primarily related to the user's feelings and the surface quality [21,22,36].

Static and dynamic comfort are firmly linked, as the influence of one depends on the other. This way, it is essential to consider both comfort approaches when evaluating comfort levels. Based on the referenced trend, some questions are imposed:

- What are the current comfort levels on Portuguese railway trains?
- How do dynamic and static factors influence the current comfort levels?
- Can we predict maintenance needs based on comfort indexes?

These are stated as the broad research questions of this study. To achieve their answers, a study on static and dynamic parameters influencing discomfort in railway journeys was performed.

Multiple trains (Alfa Pendular (AP) and Intercities (IC)) were instrumented to rate ride comfort, SEAT, seat transmissibility and modal identification, foam properties and interface pressure. Moreover, a methodology capable of identifying railway track infrastructure maintenance needs was developed based on ride comfort evaluation. This way, methodologies were developed and applied to assess both railway vehicles and infrastructures' current condition.

1.3 Thesis organization

The present thesis outlines the phases taken to approach the main research questions. Each chapter is presented in research paper format and addresses the description of the developed study. Therefore, it is organised into seven chapters accordingly:

- **Chapter I** presented a global introduction of this thesis, introducing the theme, the motivation and the research questions.

- **Chapter II** details a systematic review regarding the evaluation of motion parameters influencing passengers' comfort and discomfort.

- **Chapter III** intends to characterise the comfort of Portuguese AP and IC trains passengers. Initially, a vibration measurement system was validated. Then, a case study is presented regarding the ride comfort evaluation of Portuguese rail users at the Northern Line in both AP and IC trains. Moreover, the SEAT is also calculated as a complementary comfort evaluation. ISO 2631 standard methodology was employed, assessing the passenger's comfort levels in the time domain.

- **Chapter IV** shows a railway track infrastructure maintenance requirements identification methodology based on comfort levels. As stated in Chapter III, multiple trains were instrumented. Using floor vibration measurements and the global positioning system (GPS) location of those trains, it was possible to investigate the railway track infrastructure maintenance needs due to its influence on passengers' comfort levels.

- **Chapter V** evidences a modal identification of comfort and standard seats of AP and IC trains, corresponding to the analysis of seating behaviour in the frequency domain. That was based on output-only techniques, namely transmissibility and enhanced frequency domain decomposition (EFDD). Results highlighted the influence of seat structural frame movements, those derived from carbody natural frequencies, and the importance of foam's ability to absorb vibration.

- **Chapter VI** describes the analysis of static comfort by combining the influence of interface pressure and foam properties, i.e. SAG factor and hysteresis loss. Moreover, the effect of interface pressure distribution and temperature on the seat foam was estimated by employing an array of force sensitive resistor (FSR) sensors and a thermographic analysis. This way, a complete analysis of dynamic and static factors influencing passengers' comfort was performed.

- **Chapter VII** presents the overall study conclusions and intends to answer the research questions mentioned in Chapter I. Future work and disseminated scientific articles and oral presentations are also introduced.

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Chapter II - Railways passenger's comfort evaluation through motion parameters

Railways are one of the most broadly used mass transportation systems. Its superior transportation capacity, low environmental impact, high safety, and comfort have been leading to a continuous increase in passengers. To keep this trend, it is crucial to improve railways' attractiveness and comfort levels. A rail journey comfort performance is rather complex, involving the analysis of multiple factors. Those raised by the vehicle motion and seat performance are the focus of vehicle designer concerns. Therefore, only a combination of static and dynamic comfort methodologies can accurately characterise passengers' comfort. This chapter aims to perform a systematic review concerning the comfort evaluation of train passengers. The bibliographic search yielded 62 studies on static and dynamic comfort evaluation methods. Results show a lack of experiments conducted on real rail environments, leading to weak conclusions regarding the real in-service conditions that train users face. Moreover, an investigation gap was observed concerning the simultaneous application of static and dynamic methodologies. Therefore, more investigations are needed to evaluate and increase passengers' comfort and promote rail usage as a daily transportation system.

2.1 Introduction

Rail trains are one of the most broadly used public transportation systems. During the last decade, a continuous increase in passenger numbers was reported. Thus, to keep this trend, improving the users' satisfaction and delivering comfortable journeys is crucial. Those are defined based on user conditions, safety and comfort [1,2]. Based on that assumption, rail design nowadays focuses on comfort performance.

The comfort concept is not consensual, as multiple interpretations can be found in the literature. Perceived comfort is divided into two dimensions, comfort and discomfort, which are processed through different neural perspectives. Comfort is associated with feelings of well-being and relaxation, and the aesthetic impression of a product or environment influences it. This is a hard-to-measure subjective concept [3,4]. On the contrary, discomfort is related to pain, soreness, numbness, and stiffness resulting from the biomechanical load imposed on the musculoskeletal structure. Therefore, discomfort feelings are affected by the product's physical constraints and are easier to quantify [3,5,6]. The most accepted model, used as the base of the present work, is the theoretical sitting model of comfort and discomfort developed by De Looze et al. [7]. This model illustrates the relationship between comfort and discomfort and its relationship with the product. Potential influences are distinguished by three levels: the human, the product, and the environment [4,7,8]. The model is divided into two sides; the right is associated with comfort, whereas the left is linked to discomfort. The user's emotions and expectations highly influence comfort. Discomfort levels are related to the interaction of the human's physical capacity, like weight, physiological processes, muscle activation, body temperature, intradiscal pressure or nerve conduction. This way, comfort and discomfort are defined as a combination of psychological and physical factors. Also, De Looze model concludes with the dominant effect of discomfort on comfort. Therefore, it is more reliable to assess perceived comfort based on discomfort measurements [4,7,8].

Passengers' comfort is rather complex, involving multiple factors, such as vibration, noise, temperature, visual stimuli, illumination, smell, humidity, and seat design. However, due to its high complexity and the significant number of tests required, it is impossible to consider all factors for the evaluation. Therefore, the attention is focused on the parameters related to "motion". Those, dependent on the vehicle, should be evaluated based on both static and dynamic properties. The former concerns surface quality and the sitting impressions of the passenger when there is no vibration, and the latter relates to vibration characteristics and the user sitting impressions while being exposed to vibration [2,9].

Regarding seat cushion quality, the interface pressure, density, hysteresis loss and SAG factor behaviour are usually measured as static properties. As dynamic properties, vibration transmission should be assessed through ride comfort, SEAT and seat transmissibility. Passengers spend most of their time seated, so the seat affects passenger comfort among other interior facilities of the vehicle. Seats may present good dynamic behaviour but poor static performance. The ideal seat presents optimum dynamic properties (to minimise unwanted vibration) combined with the best static behaviour (to equally distribute pressure at the seat surface and, this way, reduce the interface pressure) [2,10].

The objective of this chapter is to study the evaluation methodologies currently applied to assess railways passengers' comfort. A systematic review was performed, along with an evaluation of the presently applied techniques and the identification of research gaps.

2.2 Materials and Methods

The systematic review was conducted following the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) guidelines [11]. Relevant studies concerning the evaluation of motion factors affecting passengers' comfort were carefully selected and reviewed.

2.2.1 Information sources

The bibliographic search was performed over the reference sources Scopus, ISI Web of Science, PubMed and IEEE Xplore with the syntax (TITLE-ABS-KEY(dynamic AND seating AND comfort) OR TITLE-ABS-KEY(static AND seating AND comfort) OR TITLE-ABS-KEY(railways AND passenger AND comfort) OR TITLE-ABS-KEY(railways AND ride AND comfort AND analysis) OR TITLE-ABS-KEY(railways AND passenger AND objective AND comfort) OR TITLE-ABS-KEY(comfort AND evaluation AND train AND passenger) OR TITLE-ABS-KEY(sitting AND comfort AND factors)). Google Scholar database was also searched with the same keyword combination to ensure a wide band with the largest possible number of articles. No time restriction was imposed, and publications were included from the first available date to February 2023. A duplicate deletion was made after the bibliographic search.

2.2.2 Eligibility Criteria and Screening

After article selection, all titles and abstracts were scrutinised, and publications that did not refer to dynamic or static comfort evaluation methods were excluded. Five eligibility criteria were defined: (1) articles need to deal with static or dynamic comfort evaluation methods, (2) articles should report a

comfort assessment, (3) articles should be written in English, (4) review articles were excluded, and (5) articles without full text available online and that still unavailable upon contact with authors are omitted. The introduction and methodology sections were additionally checked if it is unclear to determine about the papers.

2.3 Results

A total of 1823 articles were retrieved from the literature search, 1799 from the four databases, and 16 papers and nine standards, which were identified through other sources. The bibliographic research yielded 1069 records after the removal of duplicates. The third criterion excluded 300 publications, whereas 49 articles were excluded due to criterion 4 and 43 papers were unavailable online (criterion 5). Additionally, from the remaining 677 publications, the title and abstract screening excluded 314 articles that did not mention the application of comfort analysis methods. Finally, 301 papers were excluded once no comfort assessment was reported. The remaining 62 publications were divided according to the comfort type evaluation method (static, dynamic or both). Static comfort was evaluated in 12 studies, whereas the dynamic evaluation produced 46 articles divided into ride comfort, SEAT and transmissibility analysis and four papers assessed both static and dynamic comfort. A flow diagram depicting the steps of this systematic review is shown in Figure 2.1 [11].

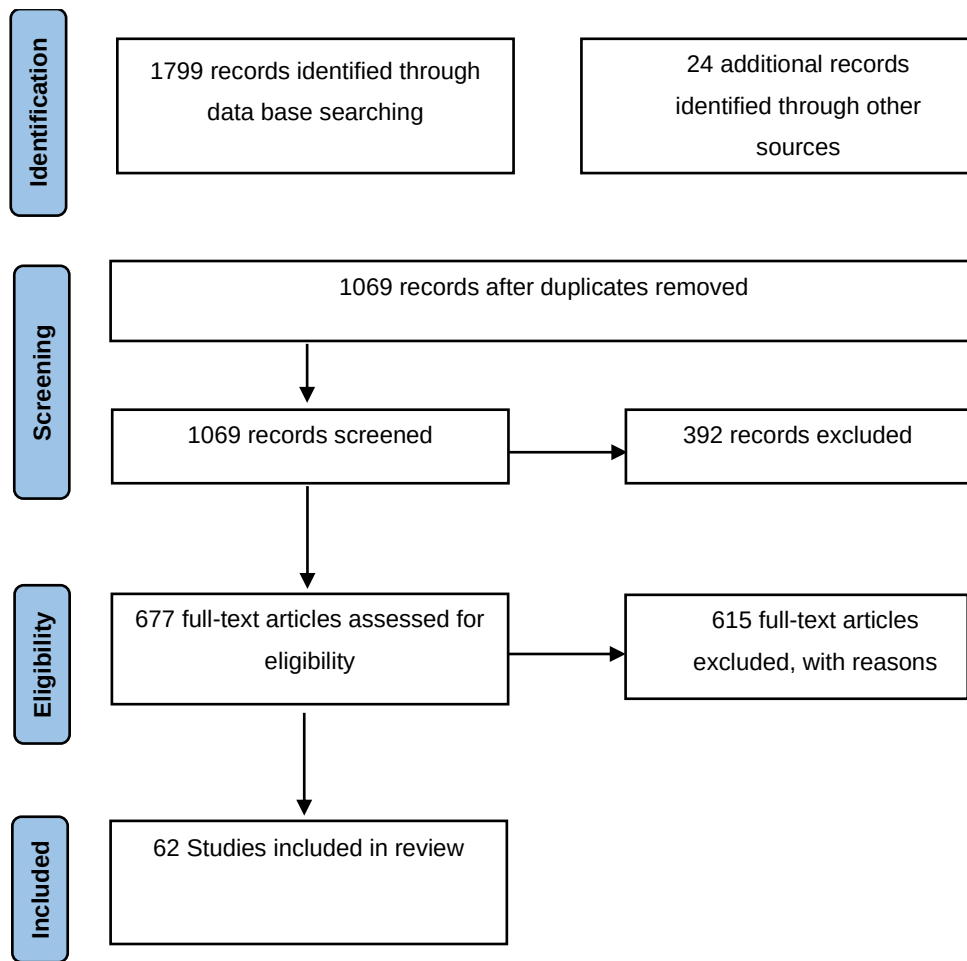


Figure 2.1. Information flow diagram through the steps of the systematic review process. (Adapted from [11]).

2.3.1 Dynamic comfort evaluation

Dynamic comfort is evaluated based on the ride comfort analysis, SEAT and transmissibility. Therefore, the dynamic comfort evaluation section is divided into those three sub-sections.

2.3.1.1 Ride Comfort Analysis

Vibration, derived from wheel-track interaction and rail motion, generates a more complex operating environment on trains than on other transportation systems. That is the critical factor affecting passengers' comfort and health, limiting their performance. Therefore, evaluating the vibration transmission in a rail environment is fundamental for quantifying passengers' comfort levels and assessing the harmful consequences of vibration [1,2,12,13].

Ride comfort, or long-term comfort, defines human tolerance to vibration exposure over time. Several countries use their national standards to evaluate ride comfort, for example, the United Kingdom uses BS ISO 2631 [14] or BS EN 12299 [15], in Japan, it is applied the Japanese National Railway Riding

Comfort Standard [16], in the USA the American ANSI/ASCE 21-13 [17], while in China the GB/T 5599-2019 [18] is the reference standard. Applying different standards worldwide leads to multiple ride comfort interpretations and evaluations, which explains the difficulties of having a comprehensive evaluation methodology. Nevertheless, three main methods are accepted worldwide and widely applied. Those are the base of the previously mentioned standards and are fully dedicated to evaluate passengers' comfort based on vibration analysis: ISO 2631, EN 12299 and Sperling ride index [1]. Additionally to be affected by the exposure time and carbody vibration, ride comfort depends on the human-sensitive frequency bands. The human body has its natural vibration modes, which affect the human vibration feeling. When this mode matches an externally induced vibration, resonance may occur, which, if absorbed, can lead to the physical stress of tissues and organs [1,2,12,13,19–21]. Furthermore, depending on the human tissue's characteristics, vibration with similar intensities but different spectral content will induce different dynamic responses in the human body. Thus, acceleration must be weighted based on human body sensitivity to obtain an index reflecting the vibration feeling. Although different methodologies exist, the three methods mentioned above share the application of frequency weighting curves. Those capable of producing the highest effect are ranked with the highest weight, and other frequencies are attenuated based on their relative importance [2,22–24].

Long-term comfort evaluation methodologies are based on acceleration measurements. Nevertheless, it should be highlighted that besides sharing the same assumptions and goals, the methods use different calculation techniques to evaluate comfort. Therefore, one method cannot be converted into another only by analysing its results. Instead, a complete analysis and correlation among indexes need to be performed. This way, it is crucial to properly understand the relationship between these indices and the advantages and limitations of the different methods [1,2].

ISO 2631, introduced by the International Organization for Standardization, defines the procedures to evaluate human exposure to whole-body vibration (WBV). This standard quantifies WBV regarding comfort, human health, and motion sickness. Comfort and health are strongly linked in several ways; therefore, frequencies between 0.5-80 Hz are defined as the interesting ones; once at this interval, vibration affects the body as a whole, which can lead to discomfort and fatigue. Acceleration measurements should occur on the vibration transmission interfaces: floor, seat surface and seatback, as illustrated in Figure 2.2.

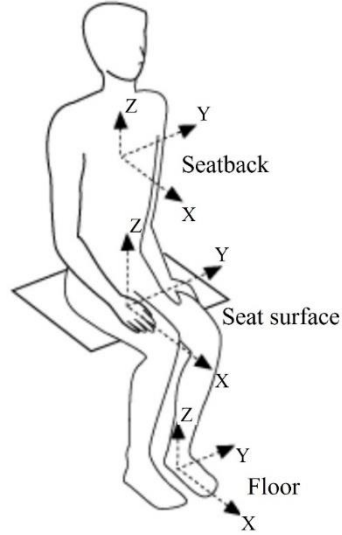


Figure 2.2. Acceleration measurement locations defined by ISO 2631 and respective axis orientation. (Adapted from [24]).

The root-mean-square (rms) acceleration is calculated for each axis, and the corresponding weighting curve is applied [2,19–21,24]. The weighting process is calculated following Equation (2.1):

$$a_w = \left[\sum (W_i a_i)^2 \right]^{1/2} \quad (2.1)$$

where W_i represents the weighting frequencies and a_i the rms accelerations, weighting curves application depends on the measurement location and purpose. The total vibration (a_v) is calculated according to Equation (2.2):

$$a_v = (k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2)^{1/2} \quad (2.2)$$

where a_w are the rms accelerations for each axis, and k represents the multiplying factor dependent on the measuring position, presented in Table 2.1 regarding the comfort approach.

Table 2.1. Weighting curves and multiplying factors applied following the comfort approach for a seated passenger defined by ISO 2631.

	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_e and $k_x = 0.80$	W_d and $k_y = 0.50$	W_d and $k_z = 0.40$

Finally, based on a_v , the discomfort is assessed by a defined scale (see Table 2.2) where accelerations higher than 0.315 m/s^2 are ranked as uncomfortable.

Table 2.2. ISO 2631 comfort evaluation scale.

$a_v(m/s^2)$	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

Large fluctuations in acceleration and frequency levels may arise throughout a train ride due to the track section's condition, rail irregularities, braking or speed restrictions. ISO 2631 is suitable for evaluating WBV when minor frequency-level variations occur. To overcome the standard major limitation, the vibration dose value (VDV) was introduced. This method uses the fourth power of acceleration instead of the second power; thus, it emphasises acceleration peaks [1,2,24]. The VDV is calculated as follows in Equation (2.3):

$$VDV = \left[\int_{t_1}^{t_2} [a_w(t)]^4 dt \right]^{1/4} \quad (2.3)$$

The statistical analysis introduced by the EN 12299 standard was developed based on the rms methodology. EN 12299 standard defines ride comfort based on two methods, the standard and the complete. The former considers only floor vibration (three directions). In contrast, the latter uses both floor (vertical acceleration) and seat locations (vertical and lateral at the seat surface and longitudinal at the backrest). Thus, the standard method can be classified as a simplification of the complete one [25]. Moreover, although this standard presents several methods to calculate different passenger comfort indices, the Mean Comfort Index (N_{MV}) is the one often used.

N_{MV} quantifies the passenger mean comfort during a continuous 5-minute run. This way, the measurement duration shall be a multiple of five, and a minimum of four travelled zones at constant speed must be accomplished to apply the method [1,26,27]. In contrast to the ISO 2631 method, weighting curves are applied initially. Then the rms acceleration over 5 seconds is calculated for each direction (longitudinal, lateral, and vertical) throughout the tested track. Finally, the 95th percentile (i.e. the 4th highest value) is determined for periods of 5 minutes, allowing the achievement of the index for each axis [1,26]. The partial N_{MV} are calculated as follows,

$$N_{MVX} = 6 (a_{XP95}^{W_d}) \quad (\text{Longitudinal}) \quad (2.4)$$

$$N_{MYY} = 6 (a_{YP95}^{W_d}) \quad (\text{Lateral}) \quad (2.5)$$

$$N_{MVZ} = 6 (a_{ZP95}^{W_k}) \quad (\text{Vertical}) \quad (2.6)$$

where, a_{P95}^W represents the 95th percentile of the weighted accelerations in the three directions, x, y and z. By combining the acceleration in the three directions, a global comfort index is obtained, as follows in Equation (2.7),

$$N_{MV} = 6 \sqrt{(a_{XP95}^{W_d})^2 + (a_{YP95}^{W_d})^2 + (a_{ZP95}^{W_k})^2} \quad (2.7)$$

The evaluation of N_{MV} is defined by an established scale, Table 2.3, which considers values between 1 and 5. Values under 1 are considered a "very comfortable ride", and for results above 5 the journey is ranked as "very uncomfortable ride" [27].

Table 2.3. EN 12299 evaluation scale.

N_{MV}	Ride comfort
≤ 1	Very comfortable
1 – 2	Comfortable
2 – 4	Medium
4 – 5	Uncomfortable
≥ 5	Very uncomfortable

The main advantage of this method is that it avoids sensitivity to artefactual extremes. On the other hand, the use of the 95th percentile may lead to data exclusion (loss of information) and some doubtful analysis [1]. Kufver et al. [27] considered three different hypothetical 5-minute vibration patterns. In opposition to what was expected, the three patterns were demonstrated to be equally comfortable. Moreover, the lack of possibility to correspond the track irregularity's location with the N_{MV} values (the highest N_{MV} values can occur during three different 5 seconds time intervals) represents another significant limitation [27]. Finally, the test defines that it should be executed during four blocks of 5 minutes while keeping a constant speed. These conditions are difficult to achieve during passenger service and do not reflect the natural in-service circumstances [25,27].

Sperling proposed an alternative ride comfort evaluation method, fundamentally distinct from the methods based on rms analysis. The Sperling's ride index (W_z) is evaluated individually for longitudinal, lateral and vertical directions. Moreover, W_z is calculated for defined time intervals or track sections [1,22] according to the following Equation (2.8):

$$W_{zi} = \left[\int_{0.5}^{30} G_i(f) B_i^2(f) df \right]^{1/6.67} \quad (2.8)$$

where G_i corresponds to the double-side square acceleration $[(\text{cm/s}^2)^2]$ and B_i represents the frequency weighting curve. As with the previous methods, passenger comfort is evaluated by a scale, Table 2.4, where passengers will not feel discomfort for values below 3 and will feel extreme discomfort for results higher than 3.5 [2].

Table 2.4. Sperling's method comfort evaluation scale.

W_z	Ride comfort
1	Just noticeable
2	Clearly noticeable
2.5	More pronounced but not unpleasant
3	Strong, irregular but still tolerable
3.25	Very irregular
3.5	Extremely irregular, unpleasant, annoying; prolonged exposure intolerable
4	Extremely unpleasant; prolonged exposure harmful

The particularity of being evaluated based on a fixed number makes Sperling's method the most convenient for comparing different conditions or trains. Multiple authors agree with that statement and highlight that when compared with ISO 2631 methodology, Sperling's method is easier to apply and understand. However, the ISO methodology is highly superior in accuracy and results quality. Additionally, this method assesses vibration individually for all directions, being generally employed to evaluate the carriage's vibration level instead of the passenger's comfort. Sperling's method's primary limitation is that vibration influences in distinct frequency bands and directions in sitting comfort are neglected [22,23,28,29].

Multiple authors apply the three ride comfort analysis methodologies around the world. Liu et al. [25] applied ISO 2631 to investigate the effect of train speed and track geometry on ride comfort in high-speed trains (speed up to 400km/h). Initially, the authors take real measurements at a high-speed train (steady speed of about 210 km/h) on the floor, seat surface and backrest. The data showed a total acceleration of 0.358 m/s^2 , corresponding to a "little uncomfortable" ride. Then, using the three-dimensional multi-body vehicle model developed by Wickens and Huang, Liu et al. expanded its conclusion for speed up to 400 km/h. The authors stated that the track's vertical irregularities are the predominant source of vibration discomfort, even though the lateral irregularities also develop to be essential as speed increases. Moreover, it was concluded that as speed increases from 200 to 300 km/h, the total acceleration increases by a factor of 2. That factor rises to 3.5 when the speed rises from 200 km/h to 400 km/h [25]. Similar conclusions were drawn by Peng et al. [23] when studying the ride

comfort on high-speed (300 km/h) railways connecting Shanghai-Kunming in China. The authors applied three-axial accelerometers on the seat surface and seatback. Maximum total accelerations of 0.12 m/s^2 were obtained. Results demonstrated higher discomfort provoked by the vertical acceleration on both seat surface and seatback. Therefore, vertical vibration had the most significant impact among the three directions (vertical, lateral, and longitudinal). Furthermore, Peng et al. [23] also demonstrated the significant influence of tunnels and running speed on passengers' ride comfort [23]. In the research developed by Johanning et al. [30], when evaluating the WBV exposure of locomotive engineers under normal operating conditions, the same conclusions as Liu et al. [25] and Peng et al. [23] were obtained. By placing three-axial accelerometers at both floor and seat surface, higher weighted accelerations were found for the vertical axis, again demonstrating this direction's significant influence on ride comfort [30].

Cheng and Hsu [31] numerically evaluated the effect of the vehicle speed and tilting angles based on a tilting railway vehicle modelled by a 27-degree-of-freedom (DOF) car system. Regarding the tilting vehicle, as the speed rises, the ride comfort also rises. On the contrary, the non-tilting train ride comfort initially rises, decreasing subsequently when vehicle speed increases. Concerning the tilting angles, higher discomfort was found for higher angles. Ride comfort also appears to be sensitive to rail irregularities, as it increases when those are introduced [31]. To ascertain the vibration limit levels that affect sedentary activities, Khan and Sundstrom [22] instrumented second-class seats of three different Inter-regional Swedish trains, particularly the IR-train, Y2-train and X50-train. The authors conducted a survey questionnaire and calculated both a_v and W_z . While a_v results noticed "not uncomfortable" rides, the same measurements but evaluated with W_z ranked the journeys as "more pronounced but not unpleasant". The results highlighted the differences between both standards' applications. Regarding the vibration effect on sedentary activities, even with the low levels of vibration demonstrated by the ride comfort methodologies, 47% of the passengers described that shocks and vibration were their leading causes of disturbances. Moreover, 60% of passengers reported moderate difficulties in performing a short writing test, and 12% noticed great difficulty in performing that test. Those results show that even low vibration levels can cause substantial limitations for rail users [22].

Jiang et al. [1] tried to establish a relationship between N_{MV} and W_z indices. For that purpose, the authors installed three-axial accelerometers on the floor of Australian N-series passenger carriages. As in the studies mentioned above, both methods agreed on the vertical direction vibration effect on passengers' comfort caused by track irregularities. However, the vibration ranking did not agree as the vibration evaluated based on W_z revealed higher discomfort levels than those of N_{MV} [1]. Dimitriu and Leu [32] compare similarly to Jiang et al. [1] but on a mechanical model travelling on a track with

vertical irregularities. The vehicle consisted of a rigid-flexible coupled model, including an elastic beam for the carbody and six rigid bodies for bogies and axles. Initially, the authors observed that ride comfort indices increase in non-uniform growth when speed increases. The non-uniform growth is justified by the geometric filtering effect, which is a critical feature regarding the vertical vibration behaviour in railway vehicles. Then, the critical comfort points were identified. Indeed, at high speed (250 km/h), both bogies and carbody centre are comparable when applying EN 12299 standard, demonstrating results of 1.91 N_{MV} at the carbody centre, 1.82 N_{MV} above bogie 1 (front), and 1.99 N_{MV} above bogie 2 (rear). As in the other mentioned studies, Sperling's method results are slightly higher than those of Mean Comfort, presenting 2.0 W_Z at the carbody centre, 2.7 W_Z above bogie 1 and 3.1 W_Z above bogie 2 [32]. Munawir et al. [33] also developed a study to compare Sperling's method and the EN 12299 ride comfort indices on the Ampang line route in Malaysia. Similar evaluations were found for both EN 12299 and Sperling's method. Mostly, the journey was considered as comfortable. The highest discomfort levels were 3.34 for N_{MV} and 2.63 for W_Z , respectively [33]. Also, investigating the comparison between Sperling's method and Mean Comfort, Dimitriu and Stanica [34] predicted, through a numerical simulation, the effects of speed and train suspension on the ride comfort index. The vehicle model consisted of a rigid-flexible coupled model, Figure 2.3. The carbody was represented by an equivalent Euler-Bernoulli beam, and the bogies and wheelsets were modelled through rigid bodies. Utilising a speed interval between 0-240 km/h, the authors found a relationship between increasing speed and low comfort levels, exposing lower comfort levels when speed increases. Additionally, when analysing the three reference points (one at the carbody centre and two above each bogie) for speed until 80 km/h, the three points demonstrated similar comfort levels on both methods. As speed increases above this threshold, the discomfort levels are higher at bogies (1.72 N_{MV} above bogie 1 and 1.86 N_{MV} above bogie 2 for 240 km/h) than at the carbody centre (1.68 N_{MV} at 240 km/h). Under the same running conditions, higher W_Z were noticed, as the carbody centre demonstrated 1.9 W_Z discomfort, bogie 1 discomfort equal to 3.0, and 2.7 W_Z regarding bogie 2. Therefore, significant differences between both ride comfort assessment methods were reported, being that of W_Z producing a weaker ride comfort than the N_{MV} . For the suspension effect, employing values of damping ratio within the range of 0.10 to 0.40, it was found that lower levels of damping will result in a lower ride comfort index, corresponding to higher comfort levels [34].

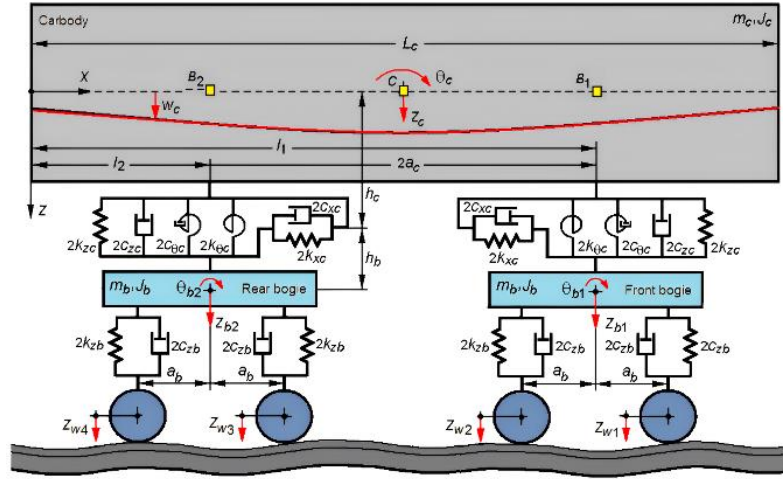


Figure 2.3. Vehicle model used by Dimitriu and Stanica. (Adapted from [34]).

Kim et al. [2] tried to compare ISO 2631, EN 12299 and Sperling's method comfort levels. To achieve this goal, the authors recorded acceleration measurements on Korean high-speed trains, which were used as vibration models of railway vehicles. Based on those models, equations of fitted curves between two ride comfort indices were obtained, namely $W_z - a_v$, $W_z - N_{MV}$ and $N_{MV} - a_v$. However, the authors did not report values of ride comfort indices [2].

Although all three ride comfort analysis methodologies present some advantages and limitations, the ISO 2631 standard seems to be the most employed one. The methods share the application of frequency-dependent filters and acceleration records at the passenger-seat-car body interfaces. That approach involves a set of dedicated accelerometers installed in multiple locations, which may be challenging. Indeed, the passengers' involuntary movements may modify the accelerometers' positioning, compromising the measurements' quality. Nevertheless, when performed adequately, this approach constitutes the more adequate one to evaluate passenger comfort because it considers a more realistic model of seat structure dynamics [35–37].

Tables 2.5, 2.6 and 2.7, respectively, resume the a_v , N_{MV} and W_z results reported in the aforementioned studies.

Table 2.5. ISO 2631 results resumed from the retrieved literature, with respective measurement position (floor, seat surface and seatback), total acceleration and discomfort level and the type of experiment (experimental or numerical simulation).

Ref.	Measurement position	$a_v(m/s^2)$	Discomfort level	Type of experiment
[17]	Floor	0.06	Not uncomfortable	Experimental (IR-train)
	Seat surface	0.24	Not uncomfortable	
	Seatback	0.18	Not uncomfortable	
	Floor	0.16	Not uncomfortable	Experimental (Y2-train)
	Seat surface	0.41	Little uncomfortable	
	Seatback	0.28	Not uncomfortable	
	Floor	0.07	Not uncomfortable	Experimental (X50-train)
	Seat surface	0.28	Not uncomfortable	
	Seatback\k	0.17	Not uncomfortable	
[23]	Seat surface	0.12	Not uncomfortable	Experimental (high-speed train)
	Seatback	0.12	Not uncomfortable	
[25]	Seat surface	0.358	Little uncomfortable	Experimental (high-speed train)
[30]	Seat surface	0.59	Little uncomfortable	Experimental (Locomotives)

Table 2.6. EN 12299 yielded literature resume, with respective measurement position (floor, seat surface and seatback or carbody centre, front bogie and rear bogie), total acceleration and discomfort level and the type of experiment (experimental or numerical simulation).

Ref.	Measurement position	N_{MV}	Discomfort level	Type of experiment
[1]	Floor	0.5	Very comfortable	Experimental (N-series passenger carriage)
[32]	Carbody centre	1.91	Comfortable	Numerical simulation
	Front bogie	1.82	Comfortable	
	Rear bogie	1.99	Comfortable	
[33]	Seat surface	3.34	Medium	Experimental (Light rapid train)
[34]	Carbody centre	1.68	Comfortable	Numerical simulation
	Front bogie	1.72	Comfortable	
	Rear bogie	1.86	Comfortable	

Table 2.7. Sperling's method presented literature resume, with respective measurement position (floor, seat surface and seatback or carbody centre, front bogie and rear bogie), total acceleration and discomfort level and the type of experiment (experimental or numerical simulation).

Ref.	Measurement position	W_z	Discomfort level	Type of experiment
[1]	Floor	1.5	Clearly noticeable	Experimental (N-series passenger carriage)
[32]	Carbody centre	2.0	Clearly noticeable	Numerical simulation
	Front bogie	2.7	Strong, irregular but still tolerable	
	Rear bogie	3.1	Strong, irregular but still tolerable	
[33]	Seat surface	2.63	Strong, irregular but still tolerable	Experimental (Light rapid train)
[34]	Carbody centre	1.9	Clearly noticeable	Numerical simulation
	Front bogie	3.0	Strong, irregular but still tolerable	
	Rear bogie	2.7	Strong, irregular but still tolerable	

2.3.1.2 Seat Effective Amplitude Transmissibility

On a rail journey, passengers spend the majority of their time seated. Thus, the vibration felt by users depends on the seat's dynamic behaviour, namely its vibration isolation performance. Seats with poor dynamic behaviour will lead to unpleasant ride comfort [38]. SEAT value is a complementary method used to estimate dynamic seat comfort. This indicator of seat isolation efficiency reflects the extent to which a seat amplifies or attenuates vibration transmission [39]. The extent to which a seat can provide vibration attenuation relies on three factors: the spectrum of vibration (characterised by the vehicle motion), how the seat modifies the vibration spectrum (seat vibration transmissibility) and the sensitivity of the human body to the vibration range causing discomfort. This way, SEAT reports how those three parameters fluctuate with the frequency and vibration direction to estimate the seat's vibration isolation [38,40,41].

SEAT compares the vibration discomfort when sitting on a rigid seat to discomfort on a non-rigid seat [41]. Thus, SEAT is specified as the ratio between the VDV measured on the seat and the VDV assessed on a rigid support beneath the seat surface, according to Equation 2.9:

$$SEAT \% = \frac{VDV_{seat}}{VDV_{floor}} \times 100 \quad (2.9)$$

where VDV_{seat} represents the vibration dose value measured at the seat, and VDV_{floor} means those vibration dose values obtained at the floor. Depending on vibration characteristics, it is possible to calculate SEAT by either VDV or weighted rms acceleration (a_w). The vibration Crest Factor (CF) determines how impulsive a measure is by calculating the ratio of the peak weighted acceleration ($\max |a_w|$) to its rms value (a_w), as in Equation (2.10):

$$CF = \frac{\max |a_w|}{a_w} \quad (2.10)$$

Data with crest factors under nine (low crest factors) can be evaluated with a_w , while data with higher crest factors must be evaluated based on VDV. Nevertheless, SEAT evaluation is rather performed using VDV once this highlights the vibration peaks effect [42].

A SEAT value greater than 100% implies that the seat magnifies vibration transmission; thus, the discomfort the user feels on the seat is higher than that of a rigid seat. On the other side, SEAT values lower than 100% indicate vibration mitigation by the seat, and therefore, the seat provides proper vibration attenuation and increases passengers' comfort. The seat does not influence vibration transmission if a SEAT result equals 100%. Due to the foam cushion's inability to absorb low-frequency vibrations, typically dominant in the vertical direction of railways, the vertical SEAT of those vehicle seats is generally higher than 100% [38].

Seats are designed to have the lowest SEAT value, yet this must fit other constraints. Reducing the SEAT value may lead to a too-soft or hard seat, resulting in poor static comfort for the passengers [38]. Therefore, the optimum SEAT value will not eliminate the vibration transmission to the user but will minimise vibration exposure [38,40].

SEAT values can be achieved by direct acceleration measurements at rail seats and floor, laboratory experiments where the railway environment is mimicked, or even by estimation using vibration records and transmissibility functions of the seat/user combination [39,42].

Multiple authors applied SEAT to measure or predict dynamic seat behaviour. Gong and Griffin [38] used SEAT to understand vibration transmission through railway passenger seats, specifically in each direction. Based on a laboratory experiment, a double train seat unit (similar to subway seats) was fixed to a six-axis motion simulator and instrumented with two three-axial accelerometers at both the seat surface and seatback. Three types of stimuli were applied: simulated train vibration, three-axial random vibration, and single random vibration. The authors calculated, measured, and predicted SEAT values for each direction (longitudinal, lateral and fore-and-aft). Results were similar for the three axes when applying three-axial and single-axis random vibration. For the same stimulus, the SEAT at the backrest

presented 10% higher SEAT values for the three-axis vibration at the fore-and-aft direction than for the single-axis vibration. The values obtained using the simulated train vibration were higher than those using the other two stimuli on both seat surface and seatback conditions. The authors concluded that a real vibration should be applied when studying the SEAT; otherwise, the conclusions are invalid for the conditions that passengers and seats face in service [38].

Patelli and Griffin [41] conducted a study to realise the transmission of vertical shocks across a seat cushion. In order to achieve it, a rigid seat (with approximately 1000 kg) was attached to an electrohydraulic vibrator. The subjects were seated in three conditions: the rigid seat, 40 mm seat foam and 80 mm seat foam. The stimuli consisted of 13 different vertical mechanical shocks with frequencies comprehended between 1-16 Hz. SEAT results demonstrated discomfort differences when sitting on the rigid seat and the foam cushions. Both foams increased discomfort by frequencies between 1-4 Hz and decreased discomfort caused by shocks within the 8-16 Hz range. The 80 mm foam originated greater discomfort, i.e., higher foam thickness increased user vibration discomfort [41]. Van Niekerk et al. [42] conducted a laboratory experiment to investigate using SEAT values to predict dynamic comfort and the correlation between subjective and objective data. Sixteen seats were fixed to a six-DOF hydraulic actuator, which vertically excited the seats. The seats were instrumented with two three-axial accelerometers placed at the seat surface and backrest. Besides measuring data objectively, six subjects also ranked the discomfort based on the Just Noticeable Difference (JND) scale. Seat surface results indicated a good correlation between SEAT values and dynamic vertical comfort. The correlation between SEAT objective and subjective results revealed promising results as the preferences of the six subjects were similar to the objective data measurements. This way, the authors assumed that it is feasible to set levels for vertical vibration transmission utilising SEAT values [42]. In a complementary study regarding the same objective as the previous one but on the seatback, Westhuizen and Van Niekerk [39] implemented the same methodology and used the same seats and subjects. However, the authors failed to identify the seatback influence on dynamic seat comfort, as no correlation was found between subjective and objective data results [39].

2.3.1.3 Transmissibility

Seat dynamics is mostly quantified regarding transmissibility, which corroborates seat efficiency in handling vibration discomfort. The seat and human body constitute a coupled complex dynamic system; thus, train seats are fundamental for reducing vibration transmission from the carbody to the passenger [20,41,43]. A substantial difference may be noted when comparing the transmissibility of subjects with

identical characteristics, namely identical mass. Seat transmissibility can be highly affected by the biodynamics of the human body and its noticeable non-linearity [44]. The human body has its natural resonance frequencies. When matched, that resonance can result in physiological responses. The frequency range between 4 Hz and 8 Hz conducts to resonance in the abdominal region; those like the head and neck muscles are affected by a superior frequency range within 20-30 Hz. Finally, the ocular system perceives resonance in the frequency interval between 30 and 80 Hz [21,45–47].

The biodynamic response of the human body is cross-axis-coupled, i.e., inducing vibration in one axis may lead to a response in another axis. Westhuizen and Van Niekerk [39] demonstrated the cross-axis characteristic of transmissibility by reporting significant body movements in the fore-and-aft direction at the seatback when only vertical excitation was induced at the seat base [39]. This way, it was proven the cross-axis-coupled characteristic of seat transmissibility.

Moreover, various authors assessed the influence of subjects' physical characteristics, such as weight, on the resonance frequency and seat transmissibility. Several studies conducted employing subjects with varying mass ranges stated unaffected results. The foam's behaviour justifies the absence of the subject's weight's effect on seat transmissibility once, raising the loading imposed by the subject's weight tends to raise the foam's dynamic stiffness. Therefore, inter-subject variability does not affect vibration transmissibility [48–52].

Transmissibility varies in direction, specifically in the vertical, fore-and-aft, and lateral directions, and location, for example, the seat surface and seatback. Multiple laboratory experiments have exhibited a vertical transmissibility peak at around 4–6 Hz when sitting upright with backrest support [38,40,48,52]. The seat surface generally presents lateral and longitudinal transmissibility around 25 Hz. Those values are reported at the lateral and vertical transmissibility at the seatback, whereas its longitudinal vibration transmissibility reports frequencies around 4–6 Hz [38]. However, these experiments implement transmissibility tests in a seat simplification constituted by a single rigid seat frame with different characteristics from the ones of a traditional train seat. The seat model used in those experiments has frame dimensions and support points distinct from the current train seat designs, as observed in Figure 2.4. Additionally, the foam was freely placed on top of the seat surface without any restricting cover [38,40,48,52]. The foam constraint conditions are fundamental to adequately evaluate the influence of the foam thickness variation on the seat transmissibility, especially on the evaluation of its dynamic stiffness [40].



Figure 2.4. Transmissibility experimental setup used in laboratory experiments with seat simplification. (Adapted from [48]).

Based on a simplified experimental setup, Ribeiro et al. [53] instrumented a standard class AP seat to, experimentally and numerically, investigate its transmissibility in a rail environment. A transmissibility resonance around 4.3 Hz was experimentally obtained. A 1 DOF numerical simulation achieved the same results [53]. Figure 2.5 presents the simplified experimental setup used by Ribeiro et al. [53].

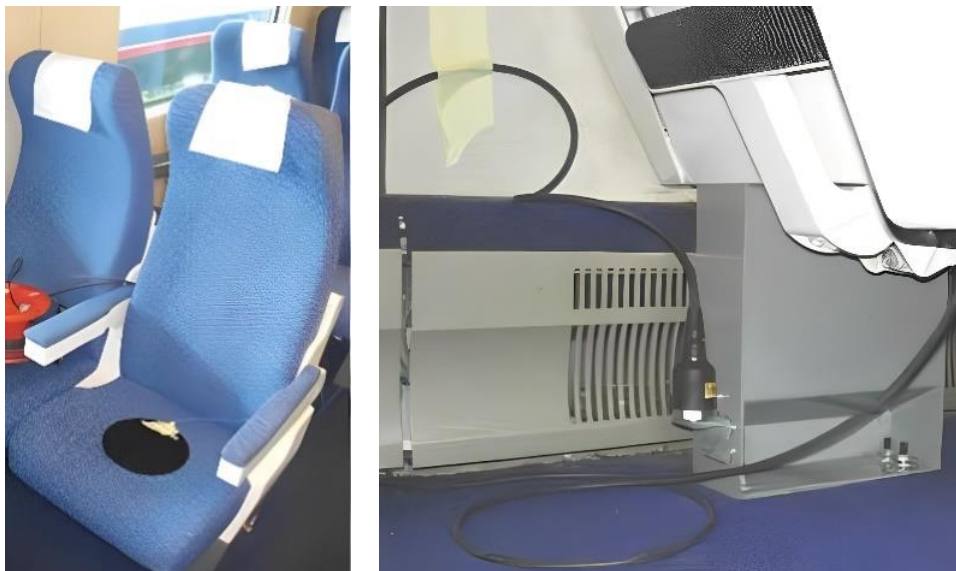


Figure 2.5. Transmissibility experimental setup applied in real train environment experiments by Ribeiro et al.. (Adapted from [53]).

Then, Ribeiro et al. [54] numerically investigated the vertical sitting transmissibility passengers felt when crossing a bridge. A 1 DOF numerical simulation demonstrated vertical transmissibility of 4.3 Hz. The authors also concluded that the identified frequency mode corresponds to isolated vibrations of the passenger-seat system and is unrelated to vehicle carbody natural frequencies [54]. Liu et al. [25] were

the first authors to study the transmissibility of railway seats and its association with carbody natural frequencies in a real train environment. The authors instrumented a standard class seat of a Chinese high-speed train in service. Vertical transmissibility around 5 Hz was noticed regarding the seat cushion. Considering the seatback, the vertical transmissibility revealed peaks at 7, 10, 20 and 30 Hz. Performing the vertical floor input – fore-and-aft seatback output transmissibility, longitudinal transmissibility was obtained at approximately 12 Hz, corresponding to the first-order vertical bending and torsional modes of the carbody. This study evidences the importance of carbody natural frequencies on seat transmissibility [25].

Moreover, the use of a backrest also significantly influences vibration discomfort. Basri and Griffin [40] compared vibration transmissibility when sitting in a rigid back to a seatback with foam. Although foam reduced the vibrations at frequencies superior to around 8 Hz, it intensified those vibrations within the 4-8 Hz range for the x-axis vibration. The discomfort caused by the longitudinal vibration at seatback decreases by 30-40% when the backrest reclining angle increases from 0° to 30°. Thus, seatback inclination decreases vibration discomfort [40].

Concerning seat cushion properties, changing foam thickness has usually been demonstrated to have the most noticeable and predictable impacts on seat transmissibility. Doubling the foam thickness approximately halves its stiffness, increasing transmissibility and discomfort. Patelli and Griffin [41] performed an experimental study to examine the effect of foam thickness on seat transmissibility. The authors increased the foam thickness from 40 mm to 80 mm; consequently, transmissibility was reduced from 4–7 Hz to 3–5 Hz. Resonance frequencies were within the 3–4 Hz range for 40 mm foam, decreasing to 2–3 Hz for 80 mm foam. The experimented subjects did not exert contact with the seatback [41]. Zhang et al. [48] stated a similar tendency. The authors noticed a higher transmissibility resonance when the seat cushion foam thickness increased from 60 mm to 80 mm and posteriorly to 100 mm. Ebe and Griffin [55] and Neal [56] reported the same tendency as those aforementioned studies.

In opposition, varying the foam hardness (composition and density) does not substantially affect seat transmissibility. Indeed, density influences static comfort but not seat transmissibility because of the hysteresis loss. Ebe and Griffin [9] analysed that parameter using four foam cushions with equal dimensions but varying densities (45 to 65 kg/m³). Seat transmissibility did not notice significant alterations, differing from what was observed with the individual's comfort judgments. This way, those judgment variations were connected to the static seat comfort [9]. Choi and Kim [57] conducted a distinct investigation to assess the molecular effect of crosslinking agents on the dynamic comfort of polyurethane foams (traditionally used on railway vehicles). Three crosslinking agents were used, namely DEA, DETA

and BHMTA. Vibrational energy can be transmitted from one side to another of the foam over the cell wall and struts. Regarding cell morphology, thinner cell wall and strut and lower wall area are presumably advantageous in accomplishing lower vibration transmission. Those characteristics were evidenced by the BHMTA crosslinking agent foam, which guaranteed the lowest vibration transmissibility. The DETA foam demonstrated higher cell wall area, which negatively influenced transmissibility. Thus, the crosslinking agent strongly impacts the dynamic comfort properties of polyurethane foams and should be carefully selected to increase the passengers' comfort. The results presented by the authors are demonstrated in Figure 2.6 [57].

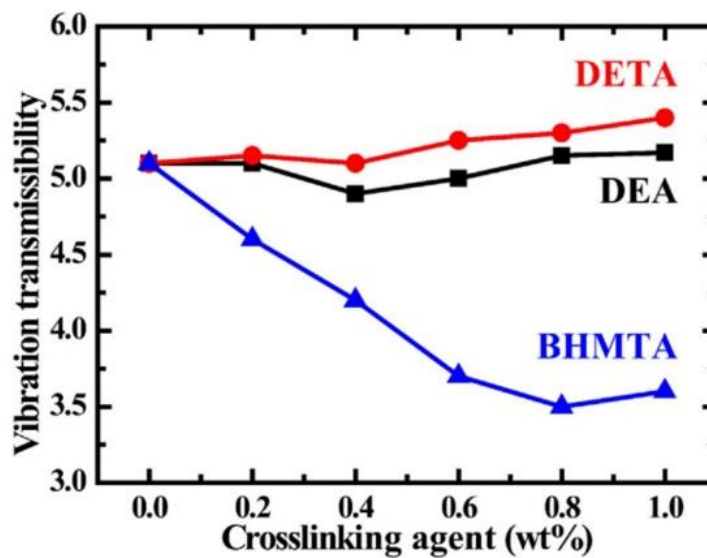


Figure 2.6. Foam vibration transmissibility evaluation due to the influence of crosslinking agents. (Adapted from [57]).

2.3.2 Static evaluation

Static comfort indicates the sitting impressions of seat users when there is no vibration. Both dynamic and static seat characteristics influence overall seat discomfort. These two factors are firmly connected; the importance of one depends on the other influence. In low or absent vibration, discomfort evaluation depends mainly on the static seat characteristics. In opposition, dynamic features dominated discomfort evaluation when vibration magnitude increases. Therefore, it is essential to consider static and dynamic seat characteristics when evaluating passengers' comfort. Interface pressure and foam properties are commonly assessed as a static comfort evaluation technique [10,58].

When a passenger sits, it exerts pressure on the seat cushion due to the biomechanical load imposed by the musculoskeletal structure. The pressure at the seat-user buttocks interface varies over the seat surface area since the human buttocks are not flat. Local pressure variation is generally defined

as pressure distribution, which can be affected by multiple factors, like the user's anatomical characteristics and seat foam features, such as hardness and shape. Pressure distribution provides information, such as specific pressure points, contact area and peak pressure. Moreover, pressure distribution directly correlates with seat comfort and subjective comfort evaluation once it is obtained with a person sitting. This way, pressure measurements evaluate the biomechanics factor of sitting discomfort by evaluating and correlating objective measurements with subjective rankings [3,9,59,60].

More than 70% of the human body is supported by the seat cushion when a passenger is seated. This way, a significant pressure concentration occurs, particularly under the ischial tuberosity, leading to pressure peaks. This interface pressure causes low oxygen content in cells, inducing fatigue, pain, and discomfort [10,59,61,62]. However, the literature has no consensus about the maximum pressure threshold. Multiple authors defend that 32 mmHg should not be exceeded. That pressure corresponds to the capillary pressure value. An above pressure can be considered harmful once it can obstruct the capillaries, restricting blood circulation and, consequently, resulting in a deprivation of oxygen in the tissues, causing discomfort [58,59,63–65]. In opposition, other authors state that a seat is considered comfortable if it presents a maximum 43.50 mmHg pressure under ischial tuberosities and 21.75 mmHg elsewhere, highlighting that mean pressure should never be above 37.75 mmHg once at this pressure, skin capillaries close [60,62]. Although no studies define the ideal body pressure distribution, it seems a consensus that a widely dispersed distribution, without local concentration peaks, represents the ideal foam [3,58,60,62–66].

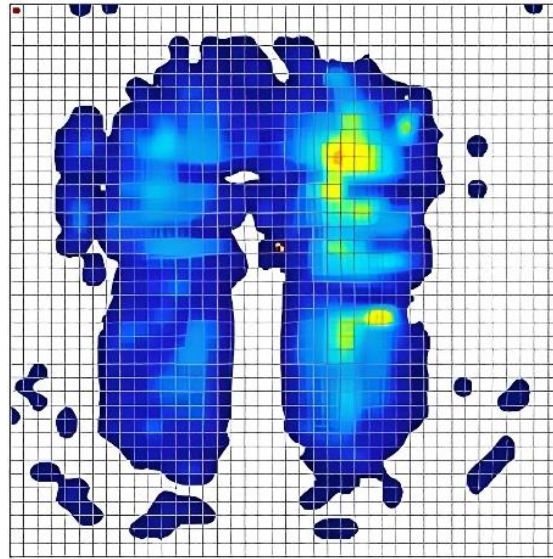
Using in conjunction with a pressure map sensor, the Seat Pressure Distribution (SPD %) indicates the seat cushion's ability to distribute pressure uniformly [60]. It is calculated according to Equation (2.11),

$$SPD\% = \frac{\sum_{i=1}^n (p_i - p_m)^2}{4np_m^2} \times 100 \quad (2.11)$$

where n represents the total number of nonzero cell elements, p_i the pressure on its cells and p_m the mean pressure of the n elements. Lower SPD % corresponds to uniform pressure distribution on the seat cushion, whereas zero represents the total equilibrium of pressure distribution.

User anthropometric characteristics, like weight, height, body mass index (BMI), body part or knee angle, influence pressure distribution. Heavy subjects tend to induce lower pressure due to their higher contact area with the seat surface, while thinner subjects present higher pressure around the ischial tuberosities area [60]. Hu et al. [60] evaluated the effect of BMI on sitting pressure distribution. Three individuals with different BMI (underweight, normal, and obese) were tested. Normal users presented

lower pressure magnitudes (maximum and mean pressures) and lower contact areas. In opposition, the obese subject generates the highest contact area. Results demonstrated that contact area would linearly increase when subjects' weight and height increased. Due to its larger contact area, the obese subject also had the lowest SPD % of all subjects. Therefore, larger contact areas represent a more distributed pressure and, consequently, lower discomfort levels [60]. Akgunduz et al. [66] examined the influence of knee angle on seat interface pressure. Results suggested that increasing the angle from 95° to 115° and up to 135° decreases the pressure around ischial tuberosities and increases pressure beneath the thighs. This way, pressure is distributed along the seat surface, reducing pressure magnitudes. The increased contact area also supports this fact [66]. Xu et al. [59] discussed the association between local comfort and whole-body comfort. Four body parts were defined: back, waist, hips, and thighs. Pressure measurements and a subjective ranking assessed discomfort. Results highlighted the hips as the most significant body part affecting whole-body discomfort, followed by the back, waist and thighs, Figure 2.7 (a) [59]. A similar study by Peng et al. [62] revealed the passengers sitting local and overall comfort degradation mechanism in high-speed railways. Pressure map sensors measure the interface pressure between the user and the seat on a second-class Chinese high-speed rail seat, Figure 2.7 (b). At every 10 minutes of the experiment, passengers evaluated discomfort based on a subjective ranking. Local comfort was divided into eight parts: shoulders, mid-back, side back, waist, buttocks, upper, side and lower thigh. Results demonstrated that the comfort of the shoulders, waist and buttocks mainly influence overall comfort. In contrast, the side back, upper thigh and lower thigh noticed the lowest correlation with overall comfort. Comfort degradation was defined based on sitting time. During the initial 20 minutes of sitting, the seat negatively influences the comfort degradation rate, with fatigue appearing after this time [62]. Yuxie et al. [3] also analysed sitting duration's influence on overall comfort on high-speed railways. By evaluating comfort with both objective (Tekscan body pressure measurement system) and subjective (numerical rating scale (NRS)) methods, the authors concluded that higher sitting duration leads to higher discomfort levels [3].



(a)



(b)

Figure 2.7. Interface pressure experiments (a) typical body pressure distribution (adapted from [59]); (b) experimental setup employed by Peng et al. on a Chinese high-speed rail 2nd class seat (adapted from [62]).

Regarding foam characteristics, the hardness, hysteresis loss, SAG factor and foam shape may interfere with pressure distribution and are generally presented as static comfort properties. Seat hardness seems to be the factor that mainly affects pressure distribution comfort. Multiple authors stated that softer seats lead to higher comfort levels. Indeed, a soft seat contact area is considerably larger than that on a rigid seat; this way, pressure peaks are minimised by the soft seat. Moreover, a more rigid foam is less flexible than a soft one, which induces higher pressure around the ischial tuberosities. Therefore, while on a rigid seat, the contact area is caused by the subject's buttocks' deformation; on a soft seat, both seat and buttocks deformations contribute to enlarging the contact area [9, 60, 66].

Commonly, the foam hardness is obtained following ISO 2439 standard specifications, particularly the 25% indentation load deflection (ILD) hardness. That standard also defines the calculation of the SAG factor, while ISO 3386 defines the foam hysteresis loss. Seat materials require a high SAG factor and low hysteresis values [9,57,67]. The SAG factor represents comfort while seated and is determined as the ratio of the stress value at 65% strain with that of 25%. A higher than 2.8 SAG factor is proposed for seating applications. At lower values, bottoming may occur as the passengers feel the seat pad bottom [9,57]. Hysteresis loss is calculated as the percentage ratio in energies between loading (0% - 75%) and unloading (75% - 0%) compression cycles. Energy is obtained based on the area under the stress-strain curve. This way, hysteresis loss represents the passengers' comfort during de-seating [57]. This property is highly influenced by the cellular foam structure, particularly the cell wall area ratio, once energy loss occurs mainly due to the buckling affecting the unrecovered cell walls and struts. Therefore, low cell wall area ratios are required to obtain low hysteresis values [57]. Figure 2.8 illustrates the influence of crosslinking agent found by Choi and Kim [57] on hysteresis loss evaluation, where the BHMTA agent promoted the lowest cell wall area ratio.

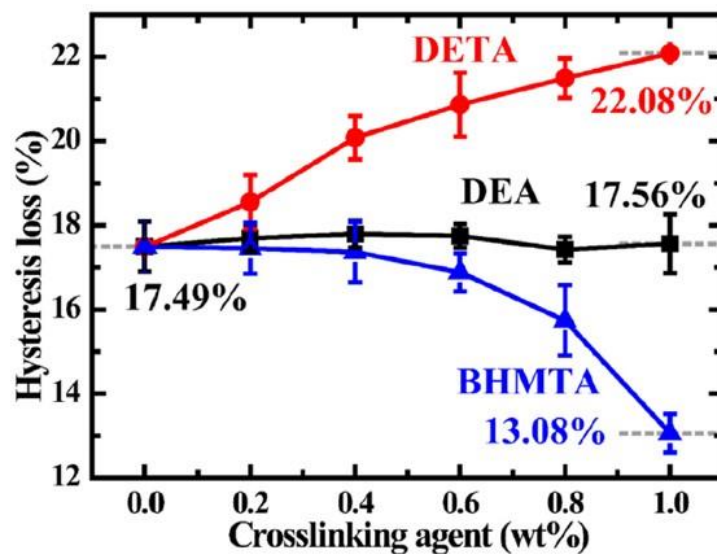


Figure 2.8. Influence of crosslinking agent on hysteresis loss evaluation. (Adapted from [57]).

Ebe and Griffin [9] related multiple static physical foam characteristics to subjects' impressions of sitting comfort. Based on four foams with equal hardness but different densities (45, 52, 55 and 65 kg/m³), the influence of density, hysteresis loss and SAG factor on sitting comfort was investigated. The low-density foam (45 kg/m³) was judged as the least comfortable foam, whereas a high-durability foam (55 kg/m³) was ranked as the most comfortable seat. The same foams presented 34.3% and 29% hysteresis loss, respectively. This way, as expected, it was observed that the foam with the lowest

hysteresis loss was classified as the most comfortable. Moreover, from the investigated factors, the hysteresis loss revealed the lowest correlation with comfort evaluations, whereas a higher correlation between seat comfort and SAG factor was obtained [9].

Tang et al. [68] developed an experiment to indicate which seat cushion foam shape model is preferred based on discomfort analysis. Three surface shape models were produced with equal thickness and material: (1) bilateral protruding cushion, (2) front protruding cushion and (3) flat cushion. A pressure sensor system and a subjective body region discomfort questionnaire quantified discomfort. Static pressure distribution among the three cushions showed a significant difference, where foam (2) presented the highest-pressure peaks, followed by (1), whereas cushion (3) presented the lowest peaks. On the subjective questionnaire, the highest overall comfort was achieved by foam (3) and the lowest by (1). Thus, the flat cushion shape was considered the most suitable foam shape for high-speed railways seats [68].

2.4 Discussion

Multiple factors influence railways passengers' comfort; being those dependent on the vehicle and its motion the primary research concern. Passengers' comfort relies on the static and dynamic vehicle and seat characteristics, depending on the presence or absence of vibration. The influence of both comfort types depends on the environmental conditions. For low vibration magnitudes, comfort relies on static characteristics, while in opposite conditions, when vibration magnitude increases, discomfort is dominated by dynamic characteristics [10]. Dynamic comfort is evaluated by ride comfort indexes, SEAT and transmissibility, whereas static comfort is mainly assessed by measuring the seat-user interface pressure, which highly depends on the user's anthropometric characteristics and foam properties.

Ride comfort defines the human tolerance to vibration exposure over time. Besides several countries applying their own comfort evaluation standards, those were developed based on three principal methodologies/standards specially developed for that purpose, ISO 2631, EN 12299 and Sperling's method. Evaluations following the different methods agree that vertical direction induces higher discomfort than longitudinal or lateral accelerations. Moreover, the track's vertical irregularities are the dominant cause of vibration discomfort [23,25,30]. However, besides sharing the same assumptions, frequency dependence and goals, each method has its calculation formulation and evaluation scale. Thus, one method cannot be directly converted into another without performing a complete analysis [1]. Although several authors tried to establish a comparison methodology between the ride comfort methods,

that goal was still unachieved. Experimental campaigns must be performed and evaluated based on the three methods to fill this research gap. Moreover, the lack of a consensus methodology capable of being applied worldwide and in multiple conditions leads to misevaluation when comparing results.

Based on the ride comfort analysis, notably the ISO 2631 methodology, SEAT values should be calculated as a complementary comfort examination for an accurate passenger comfort evaluation. The SEAT reflects seat isolation efficiency [39]. Due to the low-frequency vibrations, dominant in the vertical direction of railways, and foam's incapacity to absorb that, a vertical SEAT higher than 100% is expected [38]. Currently, SEAT evaluations are primarily performed in laboratory experiments, which do not correctly traduce the seat behaviour under service conditions. Gong and Griffin [38] concluded that SEAT values should be obtained based on real vibration conditions; otherwise, the conclusions are not valid for service conditions.

Seat transmissibility quantifies seat dynamics and verifies its efficiency in handling vibration discomfort. Seat efficiency depends on human body biodynamics, vibration excitation and foam properties. The human body produces nonlinear physiological responses to vibration. Thus, vibration frequency range influences more some body regions than others; for example, frequencies comprehended between 4-8 Hz led to resonance in the abdominal region [20,41,44]. Moreover, once the biodynamic response of the human body is cross-axis-coupled, vibration transmissibility presents the same characteristic. The cross-axis-coupled transmissibility is a crucial factor once, this way, vibration induced in one axis induces responses in other axes [39]. Seat users' anthropometric characteristics do not influence vibration transmissibility [48–52]. Additionally to being cross-axis-coupled, transmissibility differs in direction and location. Therefore, transmissibility peaks in vertical, longitudinal, and lateral directions in both seat surface and seatback present different trends. Whereas the vertical seat surface transmissibility reveals a peak between 4-6 Hz, that transmissibility increases to approximately 25 Hz for both lateral and longitudinal directions. The seatback transmissibility peaks are a rotation of those of the seat surface. This way, while the vertical and lateral transmissibilities have peaked around 25 Hz, the longitudinal direction ones are comprehended between 4-6 Hz [38]. The most referenced bibliography studies' major limitation concerns its performance on a seat simplification instead of a train seat. Seat dimensions, support points, foam coupling, real train vibration inducing and the influence of carbody natural frequencies on seat transmissibility are crucial parameters not evaluated in that studies. Transmissibility tests should be conducted on real train environments instead of laboratory analysis. This way, tests can be adapted to perform a modal identification and analysis of the seat structure. Particularly, natural frequencies related to the seat frame structure can be distinguished from those dependent on

the carbody, increasing the ability to perform a more robust comfort evaluation. Regarding foam properties, the thickness was demonstrated to influence seat transmissibility. Doubling the foam thickness approximately halves its stiffness, increasing transmissibility and discomfort [41,46,48,55,56]. Foam hardness, composition and density do not significantly affect seat transmissibility [9].

The biomechanical load the human body's musculoskeletal structure imposes on a seat surface defines its interface pressure. That depends on the users' anatomical characteristics and foam properties, such as hardness, hysteresis loss and SAG factor. The human buttocks are not flat; this way, local pressure varies over the seating contact area, achieving higher values under the ischial tuberosities. Those local pressure peaks are highly related to discomfort and should be avoided [3,9,59,60]. The maximum interface pressure threshold is not consensus in the literature. Some authors defend that a 32 mmHg pressure should not be exceeded once it represents the capillary pressure value, while others accept a higher 37.75 mmHg pressure. However, although the lack of consensus defines a maximum pressure threshold, it seems unanimous that the ideal seat will avoid pressure peaks, leading to a widely dispersed distribution [58,60,62–66,69].

Regarding passengers' anthropometric characteristics influencing interface pressure, subjects' weight induces the most substantial impact. Heavier subjects report higher contact areas with the seat surface, leading to lower pressure and increased comfort. In opposition, thinner subjects tend to produce a higher pressure around the ischial tuberosities, conducting higher discomfort levels [60]. Additionally, the waist and buttocks are the most remarkable body parts influencing whole-body discomfort [59,62]. Currently, to the author's knowledge and research, only experiments conducted with adults were performed. Since the interface pressure depends on the subject's weight, conducting an interface pressure experiment in children would be interesting since they are typically shorter and lighter than adults.

Foam properties, i.e., hardness, hysteresis loss and SAG factor, also significantly impact pressure distribution. Softer seats reach higher comfort levels due to increased contact area than rigid seats [9,60,66]. The SAG factor, which represents comfort while seated, should present higher than 2.8 values for seating applications. Lower values induce bottoming and, consequently, passenger discomfort [9,57]. In its turn, hysteresis loss represents the passenger's comfort during de-seating. Thus, theoretically, low hysteresis loss values are required to increase passengers' comfort [9,57]. Moreover, Ebe and Griffin [9] concluded that the SAG factor highly correlates with passenger comfort. In resume, the ideal foam presents low hysteresis loss, high SAG factor and low vibration transmissibility.

To the author's knowledge and appraised research, there is a lack of interface pressure tests conducted on real train seats under static and dynamic conditions. To accurately characterise static foam comfort, foams evaluation should be performed in a complement between interface pressure analysis and foam properties laboratory analysis, namely density, hardness, hysteresis loss and SAG factor. This way, the foam behaviour under static conditions could be thoroughly evaluated. Most authors agree on the performance of combined static and dynamic comfort evaluation. However, to the authors' knowledge, only four published studies evaluate both comfort types simultaneously, representing an investigation gap.

2.5 Conclusions

Railways are currently one of the most used public transportation systems. Therefore, its comfort performance is now a central theme regarding rail design. Depending on multiple factors, rail comfort is evaluated by both static and dynamic behaviour of motion parameters. Interface pressure, density, hysteresis loss and SAG factor define static comfort, whereas dynamic comfort is assessed employing ride comfort, SEAT and seat transmissibility.

Ride comfort is evaluated by three main methods, ISO 2631, EN 12299 and Sperling's method. Besides sharing similar assumptions and goals, the methodologies vary in comfort calculations, and no correlation has been found between methods, invalidating a universal analysis methodology. It also should be highlighted that the lack of a consensus methodology to evaluate passengers' ride comfort possibly leads to misevaluation when comparing results. This way, a research gap can be identified, and more efforts must be made to accomplish a global and consensus ride comfort evaluation methodology. SEAT and transmissibility agree in determining the importance of vertical vibrations in passengers' discomfort. Nevertheless, the main bibliographic research conducted on these topics is performed under laboratory conditions, which do not consider the influence of the seat frame structure and carbody natural frequencies. Therefore, those experiments may not correctly reproduce the railway in service conditions and how those parameters affect passengers' comfort.

When applied together, interface pressure analysis and foam properties accurately define the foam's static behaviour. However, only one study reported the combined use of static comfort analysis methods, and more work needs to be performed. Furthermore, multiple studies demonstrated that the subject's weight influences the interface pressure. Since children are typically shorter and lighter than adults, conducting experimental research on children's interface pressure in rail seats would be relevant.

A generalised lack of experiments conducted on real rail vehicles and seats exists. Laboratory experiments allow comfort predictions but do not represent actual in-service conditions. Moreover, comfort is only thoroughly evaluated if static and dynamic evaluations are performed. The present research revealed an investigation gap once only four studies were obtained regarding that type of evaluation. More work is needed to evaluate and increase passengers' comfort and promote rail usage as a daily transportation system.

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Chapter III - Ride comfort evaluation of the Portuguese Railways Northern Line

Measurements of whole-body vibration are fundamental for accessing and evaluating comfort levels and possible injury development in the human being. The International Standard ISO 2631 is fully dedicated for measuring and assessing vibration levels. The present chapter focuses on characterising the vibration comfort of long-distance Portuguese railway trains, namely AP and IC trains.

Initially, an alternative WBV measurement system was validated. Then, several AP and IC trains were instrumented to evaluate the passenger's ride comfort regarding those trains' performance at the Portuguese Railways Northern Line. Measurements ran under regular passenger service operation. Complementary to ISO 2631 recommendations, SEAT value was calculated for a complete seat dynamic performance evaluation. AP seats were revealed to perform better than the IC ones. Nevertheless, both AP and IC seats present an intermedium dynamic performance compared to other experiments on similar trains worldwide.

3.1 Introduction

The quality of public transportation services influences the travellers' choices. Passengers with previous good travel experiences will probably use the same travel transportation mode again. In opposition, customers that experienced problems with the journey service may change to a different transportation mode for their next trip. Therefore, to keep up the increasing trend in passenger numbers, it is crucial to raise trains' attractiveness and provide comfortable journeys [1,2]. Those are defined based on safety, comfort, and user conditions [3,4]. In particular, the seat and vibration are strongly linked with discomfort. Passengers spend most of their travel time seated; thus, vibration, derived from train motion and train-track interaction, is transmitted to the user through this surface, being classified as WBV. This way, the ideal seat can reduce that vibration, presenting good dynamic behaviour and, consequently, leading to low fatigue levels and a general sense of comfort for the passengers [5].

As mentioned in Chapter II, it is fundamental to study railway journey ride comfort to ascertain the passengers' comfort levels regarding vibrational comfort. Multiple methods were introduced to fulfil that achievement [4,6,7]. Based on the previously described ride comfort analysis methods' major limitations and advantages, ISO 2631 standard methodology was employed in the present work once it was considered the most suitable to accomplish its aims. Moreover, that standard seems to be one most applied worldwide.

The present chapter intends to characterise the AP and IC trains passengers' comfort levels regarding the Portuguese Railways Northern Line, specifically the section connecting Porto (Campanhã) to Lisbon (Oriente) stations. Furthermore, results will be compared with others observed in similar trains but in different countries when applying the same standard. Liu et al. [8] studied the passengers' comfort in a Chinese high-speed train. The authors reported a seat surface discomfort of 0.358 m/s^2 , corresponding to the second discomfort level, which is stated as "Little uncomfortable" [8]. A similar study was conducted by Peng et al. [9], where users' comfort levels were assessed by employing ISO 2631 in a Chinese high-speed train on the Shanghai-Kunming high-speed railway line. Comfort levels within the first evaluation level were noticed for both seat surface and seatback, as both seat measurements revealed a total acceleration equal to 0.12 m/s^2 . Additionally, regarding the seat surface measurements, it was observed a stronger influence of the z-axis, whereas, for the seatback, that prominent influence was associated with the x-axis. At the latter measurement location, the z-axis demonstrated a similar but slightly inferior influence than the x-axis [9]. A similar tendency was noticed by Johanning et al. [10] while studying WBV discomfort on American locomotives. A significant influence

of the vertical axis was found for both seat surface and seatback [10]. In order to investigate the extent to which vibration affects the performance of sedentary activities while travelling by train, Khan and Sundstrom [11] instrumented three Swedish IC trains at the floor, seat surface and seatback. Results highlighted higher discomfort levels at the seat cushion [11]. Table 3.1 presents a resume of the mentioned studies concerning ride comfort evaluation.

Table 3.1. Multiple authors reported discomfort levels.

Ref.	Measurement location	a_v (m/s^2)	Railway type
[8]	Seat surface	0.358	High-speed
[9]	Seat surface	0.12	High-speed
	Seatback	0.12	
[10]	Floor	-	Locomotives
	Seat surface	0.59	
[11]	Floor	0.06	IR-train
	Seat surface	0.24	
	Seatback	0.18	
	Floor	0.16	Y2-train
	Seat surface	0.41	
	Seatback	0.28	
	Floor	0.07	X50-train
	Seat surface	0.28	
	Seatback	0.17	

ISO 2631 standard recommended measuring WBV at the interface superficies where vibration transmission occurs, namely floor, seat surface and seatback [6]. The traditional WBV measurement equipment currently comprises three units: measurement, acquisition, and record. Those units traduce a system composed of a seat pad (measurement unit) connected to a data acquisition (DAQ) system (acquisition unit – the DAQ system comprises the chassis and modules, the number of modules depends on the number of seat pads) linked with a computer (record unit). Moreover, there is a need for a power supply, which can be done by electricity or battery. Due to the many components that constitute the WBV measurement system, this tends to become bulky, hard to adjust and adapt, and expensive. This equipment's major advantage is the possibility of using multiple seat pads simultaneously, which only depends on the number of available modules. A second option is presented at the market, which connects the seat pad with reading equipment. That equipment can act as a data logger and analyser, displaying the results immediately after finishing the experiments. However, this option only allows using

a maximum of two seat pads simultaneously, restricting the measurement positions. To use multiple seat pads simultaneously, extra data logger equipment must be added, increasing the number of equipment and the system cost. This equipment is mainly employed for measuring hand-arm vibration (HAV). Both types of equipment have a high capability of sample frequency and guarantee synchronised data measurement [8,9,12–16].

Due to the impossibility of gathering the aforementioned equipment, it was necessary to find an alternative solution. The identified one comprises three components: a 3-axial accelerometer, a protective metal case, and a semi-rigid rubber disc. The device can record data on a μ SD card, is easily moved and adapted, is autonomous and low-cost. The 3-axial accelerometer was already calibrated and programmed; thus, it was only necessary to validate that there was no or minimum influence of the two remaining elements. Then, after validating the equipment, it was employed to measure acceleration in multiple AP and IC train journeys during regular passenger service conditions. Following ISO 2631 recommendations (measurement location, interesting frequency range, weighting curves, and multiplying factors), the weighted acceleration per axis, the total acceleration and SEAT were calculated. This way, it was possible to characterise the AP and IC passengers' vibration comfort levels regarding the Porto (Campanhã) – Lisbon (Oriente) train stations.

3.2 WBV alternative measurement equipment validation

According to ISO 2631, a couple of rules must be accomplished to measure WBV properly. The standard defines 3-axial measurements, and a rigid and protective setting should shield the accelerometer. This protector case should be housed in a semi-rigid rubber disc [6]. Thus, three steps were taken to find an alternative equipment capable of measuring WBV. The first one consisted of selecting the accelerometer. Secondly, a metal case was designed, simulated and produced. Finally, a silicone rubber disc was produced.

3.2.1 Equipment selection and production

As stated, ISO 2631 defines the evaluation method to quantify WBV. That states a vibration frequency range between 0.5-80 Hz as the interesting interval to measure and record for health, comfort, and perception analysis. To fulfil the enunciated requirement, as calculated in Equation (3.1), vibration measurements should be recorded using a sample rate equal to or higher than 160 Hz, respecting the Nyquist theorem and preventing aliasing, which leads to data loss [17].

$$f_{Nyqu} \geq 2f_{max}$$

$$f_{Nyqu} \geq 2 \times 80 \geq 160 \text{ Hz}$$
(3.1)

where f_{Nyqu} represents the Nyquist frequency and f_{max} indicates the highest frequency component of the signal [17]. Moreover, due to the need to access vibration on three axes, only 3-axial accelerometers were considered [6,8].

PCE Instruments company, a current project partner, kindly provided the PCE-VDL-24I accelerometer. This 3-axes accelerometer presented the following technical characteristics, scale range: ± 16 g, sample rating between 0 – 2400 Hz, precision: ± 0.24 g, resolution: 0.004 g, autonomous recording (32 GB μ SD – at 200 Hz sample rate records during 1d08h32min), Li-Ion 3.7 V/500 mAh integrated battery and, allows post-analysis due to data export (CSV file). The accelerometer was programmed and calibrated, being selected as the measurement unit [15].

Moreover, a metallic box was designed and validated to set the accelerometer and protect it from external disturbances [6]. Two pieces were thought to form a metallic box. Also provided by PCE Instruments, a mounting plate guaranteed the accelerometer's rigid fixation. Figure 3.1 illustrates the accelerometer and its coupling with the mounting plate.



Figure 3.1. 3-axial accelerometer attached on the mounting plate where (a) top view and (b) bottom view.

The top of the protector metal case needs to support and sustain a user's weight without damaging the accelerometer or influencing the vibration measurements. The proposed solution involved the development of an aluminium 6061 box, reinforced at the top and laterally, as represented in Figure 3.2.

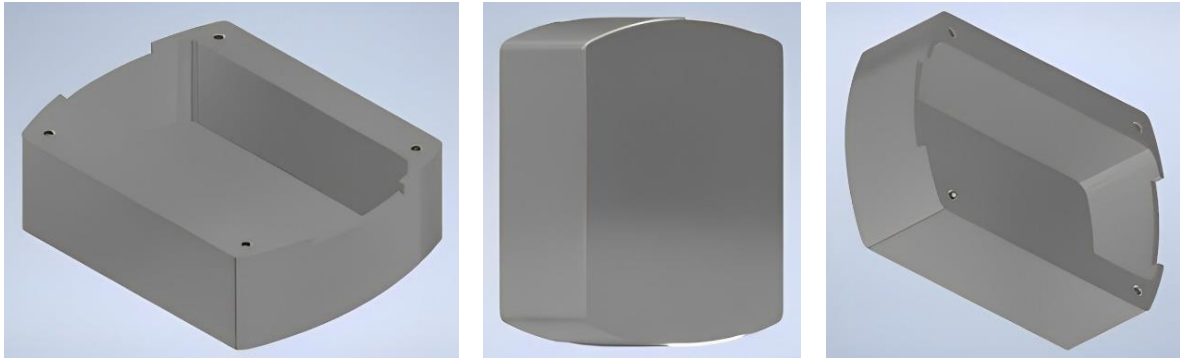
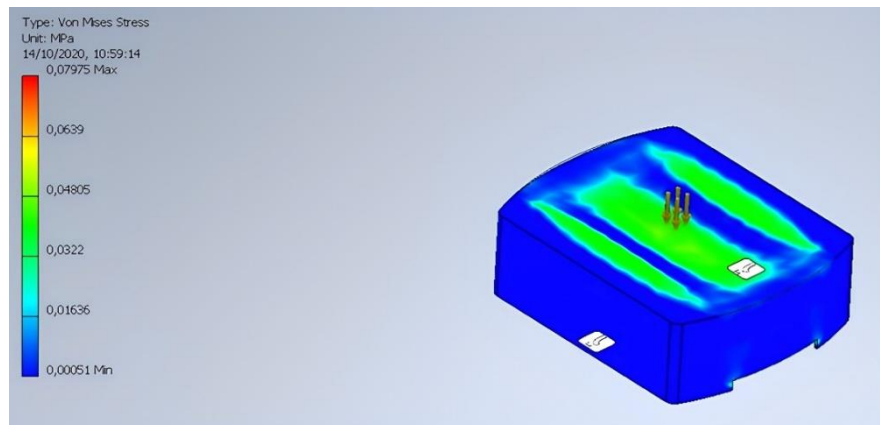
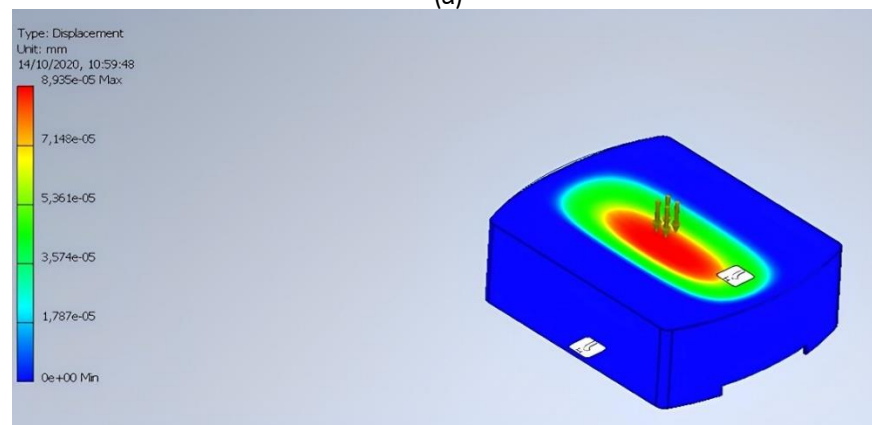


Figure 3.2. Multiple views of the box designed in Autodesk Inventor [19].

To validate the top box element, a pressure test was conducted using a finite element analysis (FEA) on Autodesk Inventor software [18]. According to SAE J1384 [19], a 75 kg mass should be used in place of a human when testing vibration equipment. To obtain a more elevated test margin and the correspondent representation of people with a higher weight, the pressure test was performed with 1kPa, representing the exerted pressure of a 100 kg person seated on the box. Results, presented in Figure 3.3, showed a maximum Von Misses stress of 0.08 MPa, a maximum displacement of $8.94 \times 10^{-2} \mu\text{m}$, and 15 safety factor, demonstrating the box's reliability and security [20].



(a)



(b)

Figure 3.3. FEA pressure tests results where (a) Von Misses stress and (b) displacement analysis.

Finally, a silicone disc having a 235 mm diameter was designed. A fit with the metal box dimensions was withdrawn from the centre of the disc to couple the metal box. Figure 3.4 shows the developed system, composed of the metallic box housed in the silicone disc.



Figure 3.4. Developed system, metallic box coupled with a silicone rubber 80 Shore A disc.

3.2.4 System elements validation

As described, three elements compose the alternative WBV measurement system. Although the accelerometer was factory calibrated, it was necessary to experimentally ascertain the minimum or non-influence of the new elements in vibration measurements.

A vibration measurement test was performed using a Brovind vibration equipment connected to a CB controller [21–23]. Initially, the equipment was fixed on the vibrating container; then, the vibration was set at level 0 for 75 seconds, increased to level 1 for another 75 seconds and, finally, returned to level 0 for the last 75 seconds. The accelerometer axes (x, y, and z) were fixed in the same position for all experiments. Each experiment was repeated three times for each configuration (accelerometer, mounting plate, metallic box, and complete system). Figure 3.5 shows the experiments and axis configuration.

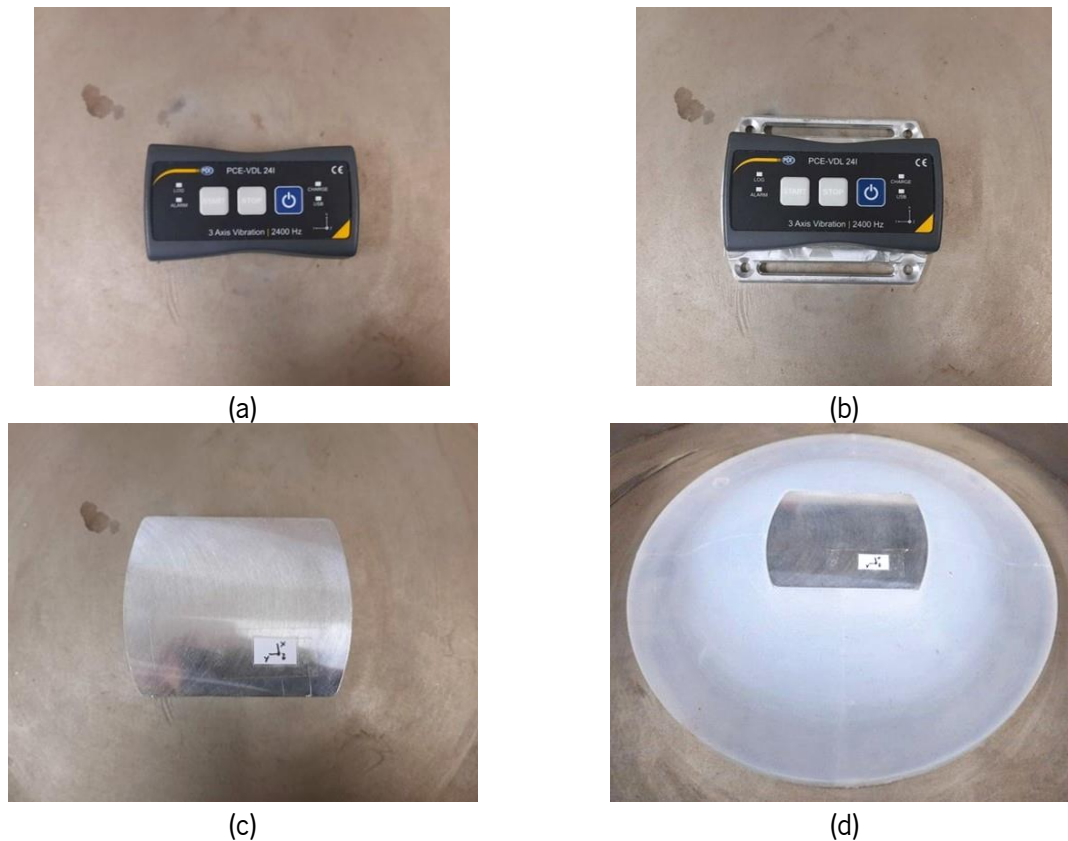


Figure 3.5. Experimental setup: (a) accelerometer; (b) mounting plate; (c) metallic box; (s) rubber disc/complete equipment.

The results were obtained and analysed using MATLAB software [24]. Although the accelerometer measurements are in g's, they were posteriorly converted in m/s^2 . An ANOVA test was used to validate the complete equipment. This test determines the probability of whether the means of the different datasets are equal. Four ANOVA tests were performed. The influence of each piece of equipment was observed when compared with the accelerometer, namely the accelerometer/mounting plate, accelerometer/metallic box, and accelerometer/complete equipment, which studied the influence of the three components as a complete WBV measurement equipment. The null hypothesis was that the equipment's presented the same mean. If the p-value returns higher than 0.05, the means are equal; otherwise, they are considered different [25–27].

The results exhibited the highest acceleration values for the accelerometer, with a mean of 3.136 m/s^2 , a maximum of 18.013 m/s^2 , and a minimum value of -3.373 m/s^2 . The other configurations presented similar results, and no significant differences were reported. The outcomes are presented in Table 3.2.

Table 3.2. Experimental results according to system configuration.

	Accelerometer	Mounting plate	Metallic box	Complete equipment
Mean (m/s ²)	3.136	3.134	3.133	3.134
Maximum (m/s ²)	18.013	18.009	18.012	18.012
Minimum (m/s ²)	-3.373	-3.374	-3.374	-3.374

An ANOVA statistical analysis was performed for the interaction between the primary element (accelerometer) and the other configurations. This way, differences in mean values for each test were statistically tested and further analysed (see Table 3.3).

Table 3.3. ANOVA statistical analysis results.

Comparison	p-value
Accelerometer/ Mounting plate	0.3295
Accelerometer/ Metallic box	0.652
Accelerometer/ Complete equipment	0.8025

Likewise, an analysis comprehended the comparison between all configurations and the accelerometer was performed. As the results were all above 0.05, it can be assumed that they have similar average outputs. Thus, the null hypothesis was not rejected, and therefore, the results showed significance. Once the accelerometer, main element of the measurement system, was previously calibrated, these were the expected outcomes, representing the system's suitability to be used as an alternative WBV measurement system.

3.3 Case study: Portuguese Railways Northern Line ride comfort

Vibration is the critical factor affecting passengers' comfort, performance and health, and it can limit the user's ability to carry out simple tasks, such as reading and writing [28–30]. Therefore, assessing the harmful consequences of vibration on train users is crucial. That can be accomplished following ISO 2631 standard comfort approach recommendations [6]. In order to characterise the passenger's comfort levels at the Portuguese Railways Northern Line, experimental tests were conducted on several AP and IC trains. Then, the standard methodology was applied to properly quantify users' discomfort levels. Moreover, vibration transmission can be mitigated or amplified by the seat and, consequently, vibration discomfort may decrease or increase. In order to quantify that influence, the SEAT calculation was applied as a complementary analysis method [31].

3.3.1 Procedures and equipment

ISO 2631 approach was followed to perform the WBV evaluation during Porto (Campanhã) – Lisbon (Oriente) connection on AP and IC trains. As mentioned, according to this standard, 3-axes acceleration measurements should occur at the interface surfaces where vibration is transmitted to the user, namely: floor, seat surface and seatback. Therefore, the previously developed measurement equipment was attached to those interface surfaces at both AP and IC seats. A sample rate of 200 Hz, preventing aliasing and obeying the Nyquist theorem, was set. Moreover, it should be highlighted that the human feeling while exposed to vibration depends on those frequencies. To quantify the effect of sensitive vibration ranges, the ISO 2631 weighting curves amplify the effect of those frequencies most influencing passenger's discomfort and reduce the impact of those frequencies less affecting passenger's discomfort [3].

Experiments run at the Portuguese CPA 4000 series Pendolino, traditionally named AP. This train achieves a maximum 220 km/h speed and is operated as a single unit, divided into six cars. Those are organised according to two classes and bar facilities. The first and second cars are classified as comfort class, whereas the others are named as standard. Moreover, the bar is placed on the third car, reducing the available seats. Belonging to different classes, comfort and standard seats are visually and dimensionally different. Those of the comfort class present higher dimensions than the standard class [32,33]. According to the train motion, the first car corresponds to the beginning of the train; consequently, the sixth car is placed at the opposite extremity, meaning the end of the train. The procedure at AP trains comprised nine complete journeys following the location and class; thus, three journeys took place on the first car, three on the fourth car, representing the middle of the train, and three on the sixth car. Figure 3.6 presents the AP measurement location and the experimental setup.

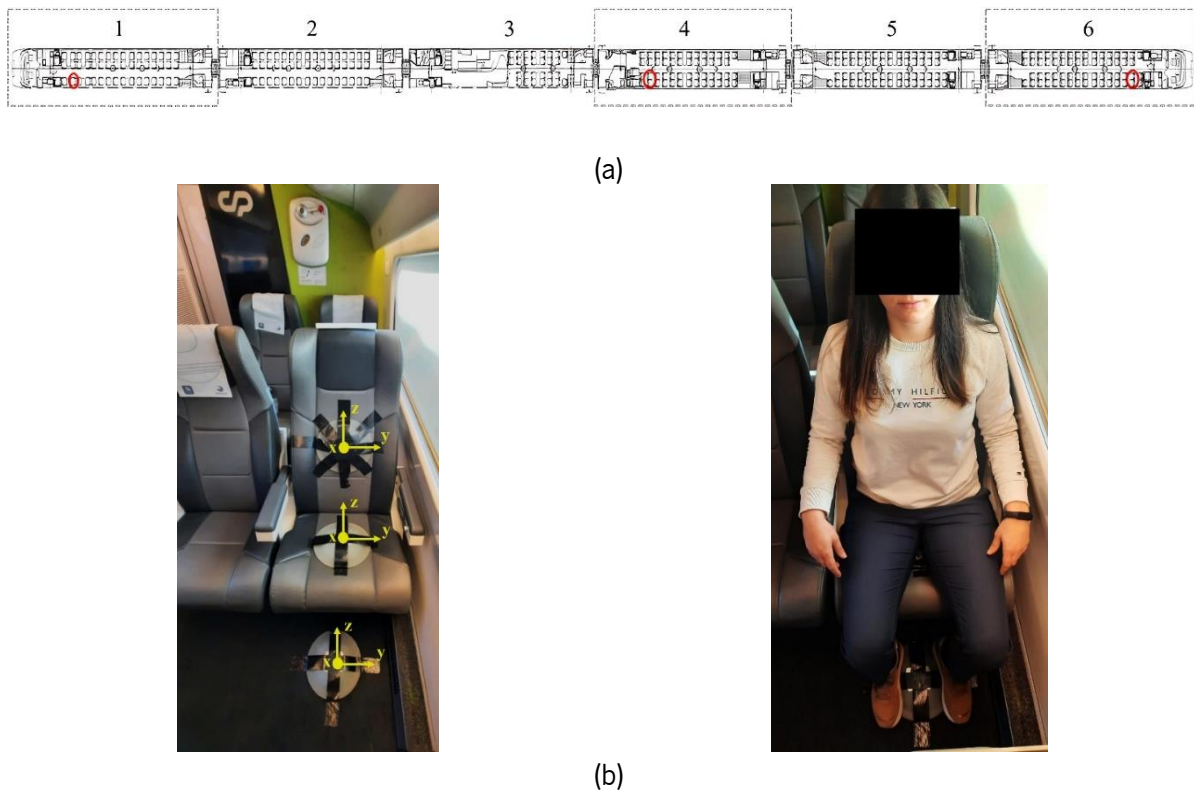


Figure 3.6. (a) AP interior layout and measurement points and (b) experimental setup, right side standard class and left side standard class with the subject.

IC train service, introduced in 1980 in Portugal, runs at a maximum 200 km/h speed. This train is run by 5600 series locomotives with Corail coaches, renovated in 2002. The electric locomotive trails five coaches, the first and second representing the comfort class and the bar, and the third, fourth, and fifth classified as a standard class. Depending on the class, the seats show different dimensions and foam thicknesses. Furthermore, Corail coaches are characterised by having two seats per row. However, for the comfort class, besides matching this parameter, the seats are arranged individually; thus, the seat support frame is not shared by two seats. In opposition, the touristic seat frame is shared by two seats, representing a more similar structure to AP seats [34]. IC instrumented seats were localised at the first, third and fifth carriages, corresponding to the train start, mid and end points. Figure 3.7 illustrates the comfort class seat measurement location and experimental setup.

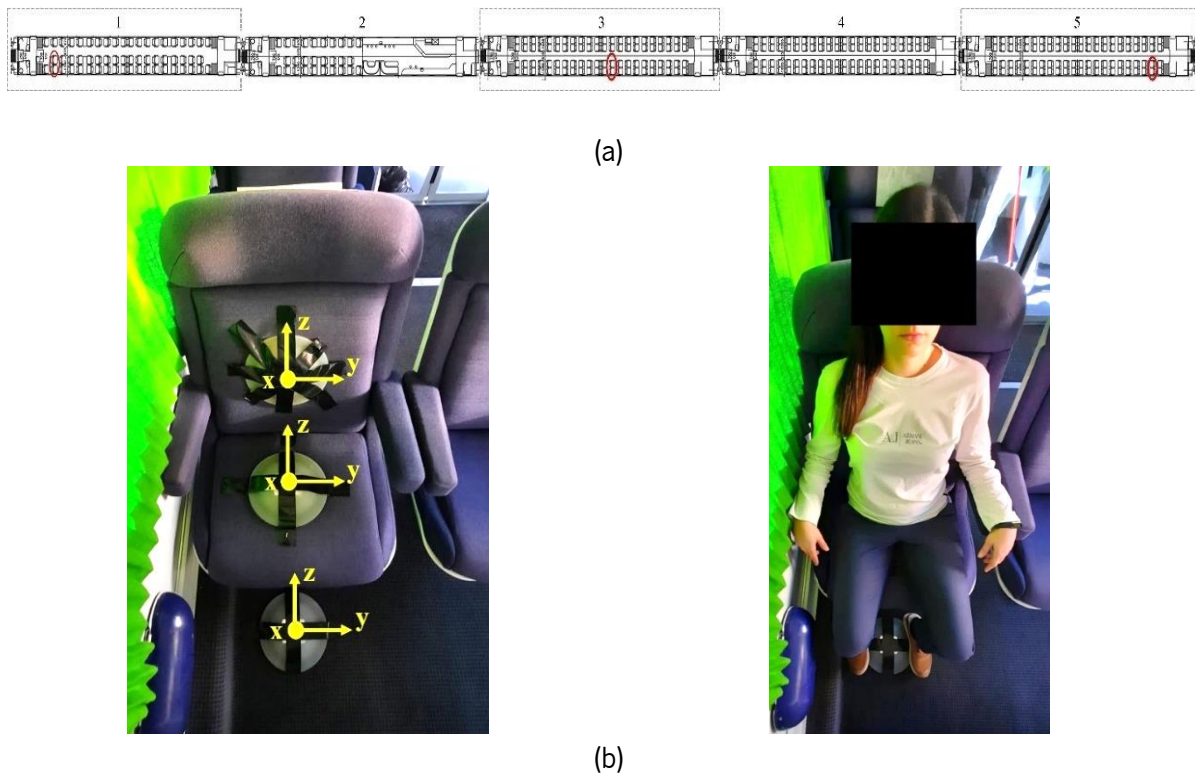


Figure 3.7. (a) IC train interior layout and measurement points; (b) experimental setup, right side comfort class and left side comfort class setup with the subject.

As on the AP train, according to the train motion, the first car corresponds to the start of the train; consequently, the sixth car, placed at the opposite extremity, means the end of the train.

Regarding the Northern Line, it presents a total length of 275 km. When travelled by AP, it takes around 2h50m to complete, comprising five station stops. For the IC train, approximately 3h15m are needed to complete the journey, been that divided into twelve train station breaks. All journeys run under regular operation conditions and passenger transportation.

3.3.2 Ride comfort analysis: results and discussion

Following the ISO 2631 recommendations, weighted acceleration (a_w) per axis and total acceleration (a_v) were calculated to evaluate AP and IC passengers' discomfort levels. Table 3.4 presents the results regarding the nine AP journeys, demonstrating the measurement car (1, 4 or 6) and location (floor, seat surface and seatback), as well as the train identification (Train ID). The train identification number was replaced to keep the train's ID anonymous.

Table 3.4. Weighted acceleration per axis and total acceleration results regarding the AP trains.

Car	Train ID	Measurement location	$a_w(m/s^2)$			$a_v (m/s^2)$	Discomfort level
			x	y	z		
1	A	Floor	0.07	0.08	0.15	0.06	Not uncomfortable
		Seat surface	0.06	0.09	0.26	0.28	Not uncomfortable
		Seatback	0.16	0.11	0.15	0.15	Not uncomfortable
	B	Floor	0.07	0.08	0.14	0.06	Not uncomfortable
		Seat surface	0.06	0.10	0.24	0.26	Not uncomfortable
		Seatback	0.21	0.11	0.15	0.19	Not uncomfortable
	B	Floor	0.07	0.09	0.15	0.07	Not uncomfortable
		Seat surface	0.06	0.10	0.23	0.26	Not uncomfortable
		Seatback	0.19	0.11	0.16	0.17	Not uncomfortable
4	C	Floor	0.07	0.07	0.12	0.06	Not uncomfortable
		Seat surface	0.05	0.09	0.26	0.28	Not uncomfortable
		Seatback	0.19	0.09	0.15	0.17	Not uncomfortable
	D	Floor	0.05	0.06	0.12	0.05	Not uncomfortable
		Seat surface	0.05	0.08	0.24	0.26	Not uncomfortable
		Seatback	0.14	0.08	0.13	0.13	Not uncomfortable
	A	Floor	0.08	0.07	0.13	0.06	Not uncomfortable
		Seat surface	0.05	0.08	0.21	0.23	Not uncomfortable
		Seatback	0.21	0.09	0.15	0.19	Not uncomfortable
6	C	Floor	0.07	0.07	0.13	0.06	Not uncomfortable
		Seat surface	0.05	0.11	0.23	0.26	Not uncomfortable
		Seatback	0.16	0.11	0.15	0.15	Not uncomfortable
	C	Floor	0.08	0.09	0.14	0.06	Not uncomfortable
		Seat surface	0.05	0.13	0.27	0.30	Not uncomfortable
		Seatback	0.18	0.14	0.15	0.17	Not uncomfortable
	E	Floor	0.07	0.08	0.14	0.06	Not uncomfortable
		Seat surface	0.05	0.10	0.25	0.27	Not uncomfortable
		Seatback	0.15	0.11	0.15	0.15	Not uncomfortable

Observing the results, it was possible to conclude that regarding the floor and seat surface a_w the vertical axis is the most prominent influencing discomfort, whereas, on the seatback, the x and z axes present a similar influence complying with Peng et al. [9] and Johanning et al. [10]. Moreover, as in the investigation developed by Khan and Sundstrom [11], when observing the vibration evolution from the floor to the seat surface and seatback, an increased discomfort level was noticed for the seat surface. These results highlight the seating capacity to modify vibration transmission, being in the present case

amplified [26,35,36]. Figure 3.8 illustrates and highlights the vibration transmission from the floor throughout the seat by comparing a_w at the floor, seat surface and seatback.

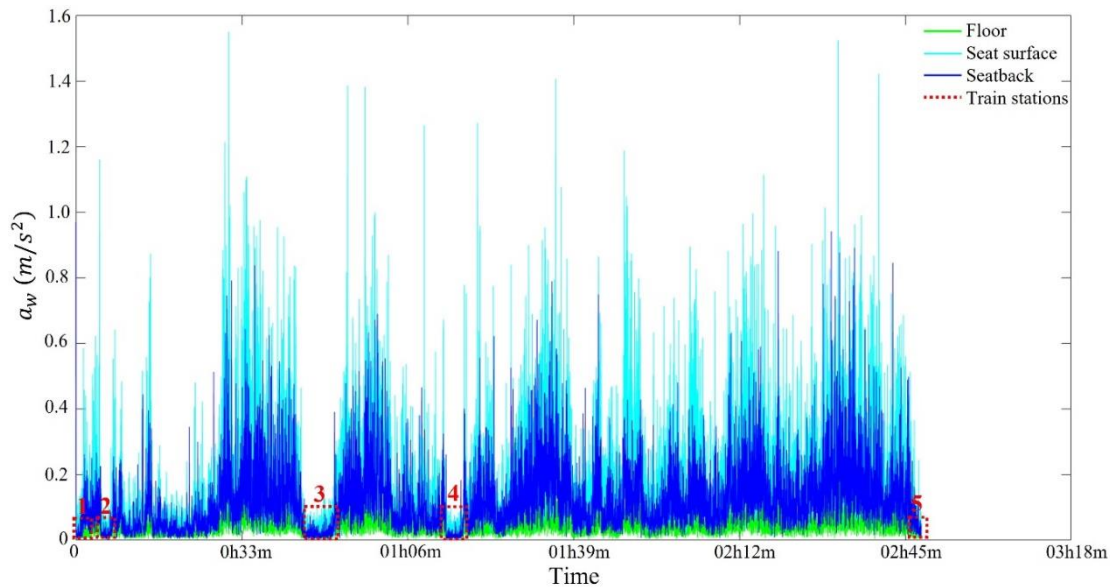


Figure 3.8. Vibration discomfort levels evolution from the floor throughout the seat of AP trains.

Additionally, based on Figure 3.8, the seat's tendency to increase vibration peaks recorded on the floor can be observed. The seating capacity to amplify or mitigate vibration shocks will be further analysed through SEAT calculations. Moreover, the location of the train stations is also identified based on the low a_w presented at those locations.

Focusing on each measurement location, independently of the car, comparable results were found for the floor vibrations. The same trend was noticed regarding the seat surface and seatback results, where both a_w and a_v have demonstrated similar values in the three cars. This way, results may indicate that seat discomfort induced by vibration does not depend on the seat location nor on the seat type.

Globally comparing the AP discomfort results with those reported by Liu et al. [8] and Peng et al. [9] on Chinese high-speed railways, AP trains presented an intermedium value for the seat surface measurements. Revealing better performance than the seats evaluated by Liu et al. [8] and worst than those instrumented by Peng et al. [9]. Regarding seatback, only one comparison can be conducted; the AP seats have a poor dynamic behaviour than those evidenced in the seats evaluated by Peng et al. [9]. Nevertheless, all AP journeys were ranked as "Not uncomfortable". Furthermore, it should be highlighted that the AP is not a high-speed train but the most similar train owned by Portugal.

Complementarily, vertical SEAT was calculated based on the VDV obtained for the same direction. VDV highlights vibration peaks; thus, it was used instead of a_w to evidence the seat behaviour regarding vibration shocks. Table 3.5 presents VDV_z , SEAT and the mean SEAT by car.

Table 3.5. Vertical SEAT values regarding the AP train.

Car	Train ID	Measurement location	$VDV_z \left(m/s^{1.75}\right)$	SEAT (%)	Mean SEAT (%)
1	A	Floor	3.49	120.16	116.38
		Seat surface	4.20		
	B	Floor	3.51	114.19	
		Seat surface	4.01		
	B	Floor	3.51	114.81	
		Seat surface	4.03		
4	C	Floor	3.43	136.23	125.26
		Seat surface	4.67		
	D	Floor	3.44	123.94	
		Seat surface	4.26		
	A	Floor	3.44	115.62	
		Seat surface	3.97		
6	C	Floor	3.48	120.43	126.81
		Seat surface	4.19		
	C	Floor	3.48	134.40	
		Seat surface	4.67		
	E	Floor	3.46	125.59	
		Seat surface	4.34		

Comparing SEAT values of the two AP train seat classes, those of the standard class present higher values than that of the comfort class. Therefore, the standard class seats are more susceptible to amplifying vibration peaks. Moreover, the standard seats of cars 4 and 6 present similar SEAT values. Therefore, like on a_v results, vibration transmission does not rely on the seat location. As expected and reported by several authors, AP seats present SEAT values higher than 100% [35–38].

Observing both, a_v and SEAT values of AP trains, it is possible to conclude that both seat classes, comfort and standard, have similar vibration comfort levels, being those of the standard class more propitious to amplify vibration peaks.

In opposition to AP condition, where three trains performed more than one journey, the used carriages are not repeated in IC experiments. Furthermore, AP trains are a single unit; thus, all cars have performed the same journeys and travelled kilometres, leading to similar degradation on all cars, whereas

the IC train is composed of individual carriages. This way, carriage degradation levels are an individual parameter, and different carriages may present different degradation rates [34]. IC train ID's, car and measurement location and ISO 2631, a_w and a_v , results are presented in Table 3.6. As on AP, the IC trains identification numbers were replaced by letters to maintain the train identification anonymous.

Table 3.6. IC trains ID, car and measurement location and ISO 2631 results.

Car	Train ID	Measurement location	$a_w(m/s^2)$			$a_v(m/s^2)$	Discomfort level
			x	y	z		
1	A	Floor	0.11	0.09	0.13	0.06	Not uncomfortable
		Seat surface	0.06	0.11	0.22	0.25	Not uncomfortable
		Seatback	0.22	0.11	0.13	0.19	Not uncomfortable
	B	Floor	0.10	0.09	0.13	0.06	Not uncomfortable
		Seat surface	0.05	0.11	0.26	0.29	Not uncomfortable
		Seatback	0.18	0.11	0.13	0.16	Not uncomfortable
3	C	Floor	0.09	0.09	0.19	0.08	Not uncomfortable
		Seat surface	0.06	0.11	0.28	0.30	Not uncomfortable
		Seatback	0.23	0.12	0.14	0.20	Not uncomfortable
	D	Floor	0.09	0.10	0.14	0.07	Not uncomfortable
		Seat surface	0.05	0.12	0.35	0.37	Little uncomfortable
		Seatback	0.20	0.13	0.14	0.18	Not uncomfortable
5	E	Floor	0.09	0.08	0.13	0.06	Not uncomfortable
		Seat surface	0.05	0.11	0.26	0.29	Not uncomfortable
		Seatback	0.18	0.12	0.14	0.17	Not uncomfortable
	F	Floor	0.10	0.09	0.14	0.06	Not uncomfortable
		Seat surface	0.06	0.11	0.36	0.38	Little uncomfortable
		Seatback	0.22	0.12	0.14	0.20	Not uncomfortable

Floor results reported similar a_v for all journeys, demonstrating the non-influence of the seat location. However, that trend was not observed concerning seat surface and seatback, as standard class seats presented higher discomfort levels on that measurement locations. IC coaches D and F have seat surface discomfort levels within the second discomfort level ("Little uncomfortable"). Once only these two trains present that discomfort level on the seat surface, but their floor discomfort is similar to the one evidenced by the other carriages, it can be concluded that these carriages are probably more degraded and worn than the others. Therefore, carriages D and F require interior maintenance. As on the AP results, the vertical axis is the most influential for floor and seat surface measurements, whereas the longitudinal axis (x) demonstrates the most substantial influence at seatback. Moreover, following the AP train seats trend, vibration increases from the floor throughout the seat, see Figure 3.9.

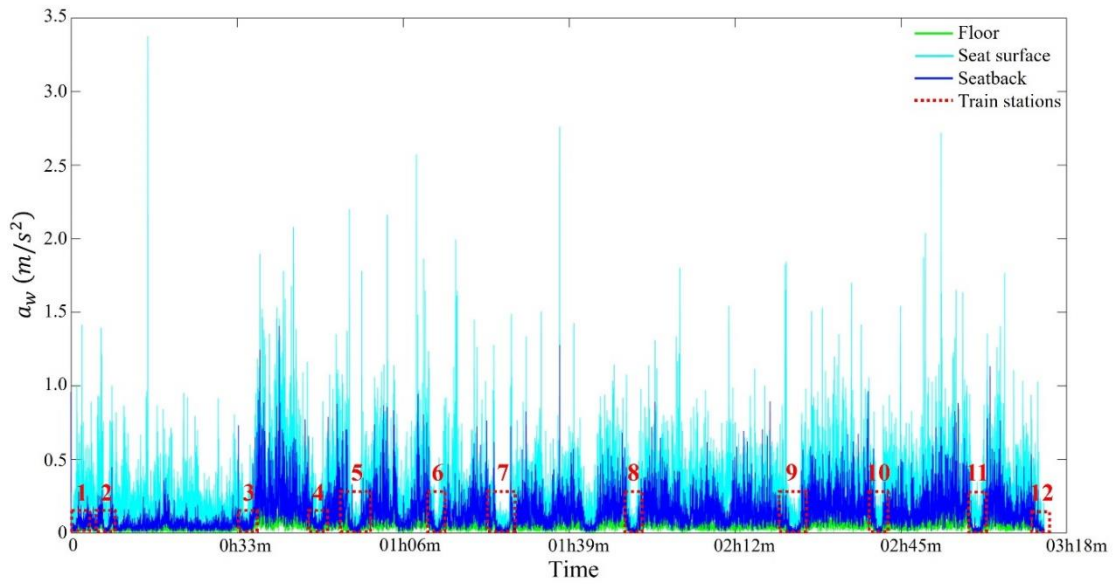


Figure 3.9. Vibration transmission evolution from the floor throughout the seat regarding IC trains.

As in Figure 3.8, it was possible to identify the twelve train station stops and locations based on the low levels of a_w .

Comparing ISO 2631 standard IC results with those reported by Johanning et al. [10] in American locomotives, the Portuguese IC seats are performing better for both floor and seat surfaces. The results of the three Swedish IC trains studied by Khan and Sundstrom [11] are similar to those of the Portuguese trains.

Regarding the vertical VDV, SEAT and mean SEAT results, those are presented in Table 3.7.

Table 3.7. IC train vertical VDV, SEAT and mean SEAT results.

Car	Train ID	Measurement location	$VDV_z \left(m/s^{1.75}\right)$	SEAT (%)	Mean SEAT (%)
1	A	Floor	3.48	118.66	128.17
		Seat surface	4.13		
	B	Floor	3.49	137.68	
		Seat surface	4.81		
3	C	Floor	4.19	119.86	148.32
		Seat surface	5.03		
	D	Floor	3.55	176.78	
		Seat surface	6.28		
5	E	Floor	3.50	137.66	158.50
		Seat surface	4.81		
	F	Floor	3.51	179.34	
		Seat surface	6.29		

Standard seats are more susceptible to increase vibration shocks as they present higher SEAT values than comfort ones. Generally, IC carriage's SEAT results are higher than those of AP trains. It should be highlighted that carriages D and F, which present seat surface a_v superior to 0.315 m/s^2 , are the only coaches demonstrating SEATs above 140, being those values even higher than 170.

Moreover, comparing both a_v and SEAT results of the different seats of AP and IC trains, higher results were obtained for the latter. Therefore, it is possible to conclude that IC carriage seats have worse dynamic behaviour than AP ones. Nevertheless, it should be noted that the present study does not consider the influence of aerodynamic forces. That significantly impacts high-speed trains achieving speeds higher than 300 km/h , which is not the present case [39]. Even so, as AP and IC trains have different structural designs, their dynamic behaviours are expected to be different, which may impact their vibration levels [40].

3.4 Conclusions

During a rail journey, vibration is transmitted to the passengers through contact with the floor and seat. Moreover, since users spend most of their time seated, the seat assumes immense importance when characterising the trains' vibration environments. ISO 2631 standard accesses and evaluates the WBV induced on the passengers and their respective discomfort levels. Thus, that standard was defined as the gold reference of the present chapter.

Due to the impossibility of gathering the traditional WBV measurement equipment, an alternative solution was validated. Multiple trains were instrumented to fulfil the chapter's main objective of characterising the AP and IC trains passengers' comfort levels regarding the Portuguese Railways Northern Line. Measurements occurred at defined places on each train: *start*, *mid* and *end* points. At each of those points, seats were instrumented with accelerometers located at the floor, seat surface and seatback.

Experiments showed better AP seats' dynamic performance than the ones in IC carriages. Similar tendencies were observed on both trains, as floor and seat surfaces were demonstrated to be highly influenced by vertical vibration. In contrast, that discomfort is mainly induced by the longitudinal axis at the seatback. The observations comply with those reported by several authors. A vibration transmission increasing from the floor through the seat was observed in both train types. The vibration tends to rise from the floor to the seat surface and slightly decrease towards the seatback.

Once rail vehicles have different structural designs, which may impact their dynamic behaviour and vibration levels, AP and IC trains were only compared with vehicles presenting similar designs. Finally, it should be highlighted that AP passengers are travelling in a comfortable vibrational environment. Its seats revealed an intermedium dynamic behaviour when compared with those of other similar trains. Regarding the IC users, its ride comfort depends on the carriage degradation and wear, as different carriages of the same class evidenced different ride comfort levels. Compared with similar carriages, such as the AP trains, the IC carriages' seats demonstrated an intermedium dynamic performance. Overall, the IC journeys presented higher acceleration levels than AP trips, demonstrating, this way, a worst dynamic performance.

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Chapter IV - Indirect assessment of railway infrastructure anomalies based on passenger comfort criteria

Railways are among the most efficient and widely used mass transportation systems for mid-range distances. To improve the attractiveness of this type of transport, it is necessary to improve the comfort, which is much influenced by the vibration derived from the train motion and wheel-track interaction, making railway track infrastructure condition and maintenance a main concern. Based on the discomfort level, a methodology capable of detecting railway track infrastructure failures is proposed. During the regular passenger service, acceleration and GPS measurements were taken on AP and IC trains between Porto (Campanhã) and Lisbon (Oriente) stations. ISO 2631 methodology was used to calculate instantaneous floor discomfort levels. By matching results for both trains, using GPS coordinates, twelve track section locations were found to require preventive maintenance actions. The methodology was validated by comparing these results with those obtained by the EM 120 track inspection vehicle for which similar locations were found. The developed system is a complementary condition-based maintenance tool that presents the advantage of being low-cost and not disturbing the regular train operation.

4.1 Introduction

High safety levels are guaranteed through adequate maintenance actions based on corrective or preventive strategies. The corrective action occurs after a fault is recognised and intends to recover the normal working state [1–4]. In contrast, proactive measures intend to prevent and minimise eventual faults that did not yet cause the system to fail, thus anticipating the problems.

Preventive maintenance's main goal is to preserve the system functions and to prevent rail system failure, being performed according to a defined scheduled time. On the other hand, condition-based maintenance (CBM), the typical railway track infrastructure condition monitoring system, is a preventive maintenance strategy that acts when there is evidence of failure. Railway track infrastructure monitoring actions can be performed in two ways, either by human or automatic means, depending on the type and extent of work [5–7]. Human inspection is performed by well-trained inspectors who periodically walk along railway track infrastructure to detect defects. The inspectors can be aided by portable equipment for the auscultation and measurement of geometric parameters of the track infrastructure. However, this maintenance technique results in high costs and can be potentially hazardous for inspectors. Moreover, the human inspection can only be applied by stopping or restraining traffic, and its results highly depend on the observer's capability to detect anomalies and recognise critical situations [1,8]. Due to the problems associated with human inspection and advances in technology, automatic inspection methods have been developed, such as inspection vehicles. These dedicated vehicles can detect railway track infrastructure defects and evaluate the infrastructure performance. Generally, an inspection vehicle uses optical and inertial sensors linked to a GPS, which increases the method's efficiency and decreases the required time [2,3,9,10]. This inspection is periodically performed along the railway track infrastructure. However, in addition to being expensive, these vehicles introduce traffic disruptions during the inspection, affecting the regular service operation. Different types of inspection vehicles are used worldwide. In Portugal, the EM 120 inspection vehicle, owned by Infraestruturas de Portugal (IP), is responsible for identifying maintenance needs and railway track infrastructure failures. After detecting a failure, the defect is fixed, and ideally, the system is restored to its initial state [4,6]. More recently, cargo vehicles are also being used as instrumented inspection vehicles, particularly in the axle box [11–15]. However, implementing the experimental setup is problematic for that approach, limiting its use in passenger trains. These vehicles have the advantage of continuously surveying the track without any traffic interference, thus providing information on a more regular base at a reduced cost. Moreover, railway track infrastructure maintenance also improves the interaction performance of the rail vehicle and the overhead

infrastructures, such as the pantograph-catenary interaction, which leads to a safer, more stable and comfortable journey [16].

It is known that there is a significant difference in the vibration level when comparing a healthy with a defective railway track infrastructure, being the latter characterised by higher peak values. Thus, besides affecting safety, isolated and continuous infrastructure defects lead to poor passenger comfort due to increased vibration levels [3]. Once comfort is mainly affected by vibration, which mainly derives from the train motion and rail track infrastructure irregularities, passengers are subjected to it throughout the journey due to contact with the seat and floor. Therefore, vibration is transmitted through all the passenger-seat and passenger-floor contact surfaces, generally defined as WBV. Besides causing discomfort, this can also lead to fatigue and, in some extreme cases, diseases. Due to its adverse consequences, it is vital to classify vibration levels in the rail environment. One of the reference international documents is ISO 2631 standard, which precisely quantifies WBV regarding comfort, human health, and motion sickness [17–20].

Up to this date, passenger comfort levels have not been used for possible damage detection. Based on the close connection between railway track infrastructure condition, induced vibration, and passengers' discomfort levels, it was possible to develop a new CBM methodology to identify critical railway track infrastructure locations. The goal was to provide a low-cost solution to improve maintenance needs detection and increase infrastructure availability. The present method overcomes the limitations of the traditional railway infrastructure maintenance detection methods, as it does not cause disturbance in the railway operation. This study considers that the railway track infrastructure requires maintenance actions if multiple trains with different dynamic characteristics present floor discomfort on the same GPS location.

Based on the limitations of the previous experiments, this study aims to give clear contributions about some aspects that presently, according to the authors' knowledge, are not sufficiently addressed in the existing literature, particularly:

- Development of methodology capable of detecting rail track infrastructure abnormalities or damages based on measurements on in-service trains. This way, the service runs under regular operation without disruption or interference.
- Development of an easy-to-adapt and implement methodology, capable of being applied in any in-service rail vehicle. This way, overcoming the limitations of the accelerometer installation in the axle box, which imposes difficulties on the processes of installation, maintenance and dismounting.

- The results of the present methodology are not dependent on the vehicle type. Thus, it can be applied to passenger trains with different characteristics. This was stated based on the results of a large extent of measurement campaigns proving the methodology's accuracy and precision.

4.2 Ballasted track

Worldwide, as well as in Portugal, the most common railway system is the ballasted track system, which has lower construction costs and adequate response to static and dynamic forces [21]. This track type is grouped into two main categories: superstructure and substructure. The former consists of rail, sleepers, ballast, and components that connect these elements. In contrast, the latter is associated with the geotechnical system and comprises sub-ballast, embankments and subgrade layers [14,15,22,23]. Figure 4.1 presents a schematic representation of the railway ballasted track system.

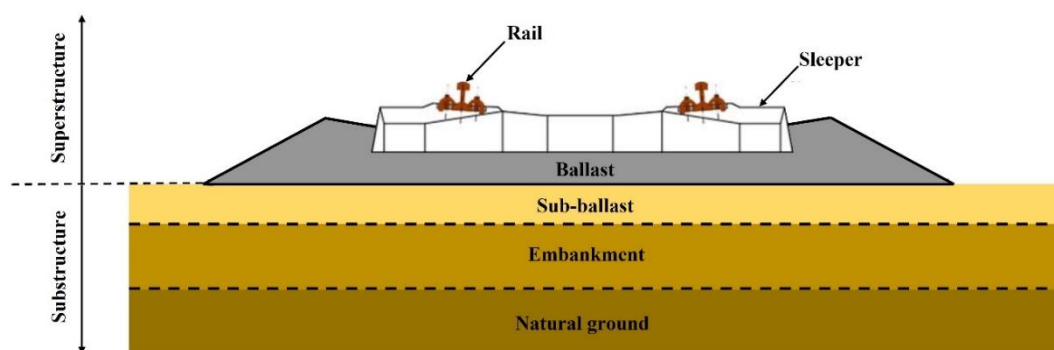


Figure 4.1. Schematic illustration of the railway ballasted infrastructure.

Track integrity problems are dependent on the superstructure and substructure deformation. Both are related, but the health of the track substructure defines the structural performance [15,23].

The main substructure issues are related to sub-ballast and subgrade deterioration, which can induce poor drainage and track settlements. Those issues may also reduce track stability, capacity and safety, leading to misalignments and increased wear [15].

Superstructure track faults can be grouped into three main conditions, those related to geometry (cross-level, alignment, longitudinal levelling, twist and gauge), those dependent on rail surface faults (surface, corrugation, fatigue cracking, squat and creep) and, lastly, those dependent on the ballast condition (fouled ballast, ballast pockets and poor ballast drainage) [14,21].

Track defects and irregularities negatively affect track performance and safety. Wavelengths between 10 – 120 m mainly influence passengers' comfort. EN 13848 [24] defines three wavelength intervals for

the evaluation of vertical and lateral track geometry conditions, D1 (3-25 m), D2 (25-70 m) and D3 (70-150 m). The D1 wavelength range irregularities are mainly associated with running safety conditions, whereas D2 and D3 ranges strongly affect ride comfort [24,25]. Lower wavelengths define rail surface faults; for example, rail corrugation can appear between 0.03-0.08 m wavelength, whereas rail squat comprehends 0.02-0.04 m wavelengths. A discontinuity in the rail caused by a weld or a joint can present 0.01-0.02 m wavelengths [26,27]. It should be highlighted that the aforementioned defects' wavelengths are the most typical ones. Nevertheless, depending on its severity and dimension, the same type of defect can produce higher or lower wavelengths. Figure 4.2 presents the rail track geometry conditions evaluation defined by EN 13848, along with rail surface faults (rail corrugation, squats and discontinuities) and passenger's comfort wavelengths.

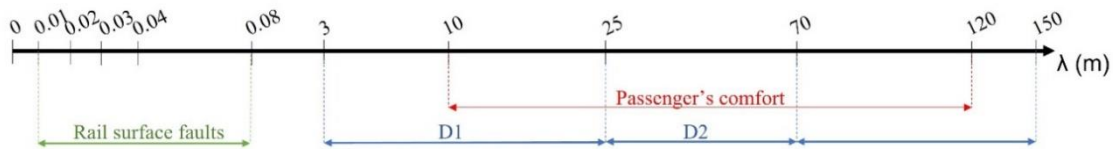


Figure 4.2. Typical rail surface faults and EN 13848 track geometry evaluation wavelengths and those capable of affecting passengers' comfort.

Rail defects and increased speed further amplify the rail vehicle-track dynamic interaction forces [13,14,23,28]. When a rail vehicle and track do not present defects or abnormalities, the vehicle exerts low-frequency forces (under 20 Hz). However, that frequency increases in the presence of faults, leading to dynamic impact wheel-rail forces. Moreover, dynamic loads, which are connected to track irregularities, amplify the rail deterioration rate. Vehicle vibration magnitudes are strongly linked with track irregularities and can be used to assess the general track condition effectively [13,22,23]. Karoumi et al. [29] and Norris [30] noticed that railway track defects could be identified based on acceleration records according to their peak values, as illustrated in the example of Figure 4.3.

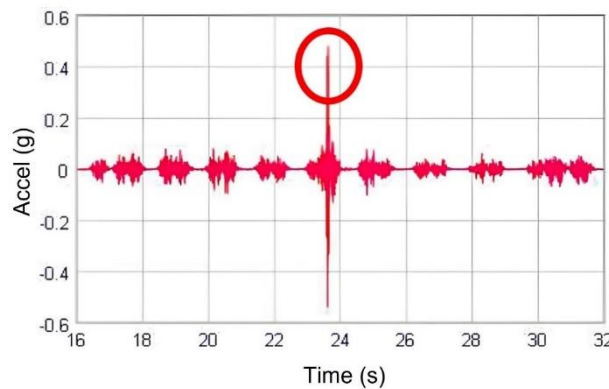


Figure 4.3. Detection of rail irregularities based on acceleration measurements. (Adapted from [29]).

Besides affecting comfort, track irregularities can lead to a derailment, which may have significant consequences [12]. Therefore, promoting scheduled railway infrastructure maintenance is crucial to maintain high safety levels and the comfort of passengers.

When a railway vehicle passes over a railway track, it causes static (weight) and dynamic (inertia and impact) loads. That dynamic load leads the railway track to vibrate for a certain period and, consequently, to deform. Moreover, those loads need to be transmitted to the track subgrade. The dynamic load exerted on the track is the critical parameter causing track deterioration, whereas wear and fatigue are the main consequences. Generally, rail defects are caused by loads applied to the rails in longitudinal, transverse and vertical directions. Additionally, the weather also plays a significant role in railway infrastructure deterioration as it can promote corrosion, thermal expansion and buckling. This way, the railway track experiences different conditions at different points along the track, and, consequently, different track sections show different degradation behaviours and require different maintenance plans [15].

4.3 Suspension systems

The interaction between the wheels and railway track infrastructure, healthy or with defects, generates vibration with varying amplitude and frequency. This vibration can cause damage to both trains and railway track infrastructure; thus, it must be controlled. The train suspension system, constituted by primary and secondary suspension, fulfils this function by enabling the filtering of the vibrations derived from the vehicle-track dynamic interaction (promoting ride comfort) and controlling the kinematic modes of the bogie (promoting stability). Suspension systems are natural low-pass filters, preventing the transmission of high frequencies from the rail track and wheel to the carbody and seats [31].

The primary suspension's main goals are to secure stability and guidance, reduce track forces and wear, and improve curve performance. Regarding the secondary suspensions, it suppresses the vibration transmission from the bogie to the carbody and attenuate vehicle vibrations derived from railway track irregularities, improving ride comfort and controlling the quasi-static motion [31–33].

Although with the same goal, different trains present different suspension systems, which interfere with the filtered ranges of frequencies. The present research conducts experimental tests on AP and IC trains. Due to their model series and tilting mechanisms, these trains present different suspension systems. Therefore, characterising those trains' suspension systems is essential.

4.3.1 Alfa Pendular vehicles suspension

AP train, composed of six cars, has an active tilting system, which reduces the lateral acceleration perceived by the passengers and, consequently, allows the performance of curves at higher speeds than the balanced one while maintaining high passenger comfort levels [31]. Two bogies support each car distanced by 19 m, and are 6 m far from the bogies of consecutive cars.

Figure 4.4 (a) illustrates the primary AP suspension, while Figure 4.4 (b) shows its secondary suspension system. Primary suspension is composed of four helicoidal springs (sets of two plus two) (1) and a vertical damper (2), both filtering the vibration derived from the vehicle-track interaction in each wheel. Thus, each bogie of the AP tilting train has twelve flexi-coil springs combined with six dampers acting as secondary suspension and sixteen springs coupled to four vertical hydraulic dampers performing as primary suspension [34–36].

The mechanical elements of the secondary suspension ensure the carbody-bogie connection. The secondary suspension (see Figure 4.4 (b)) is constituted of twelve flexi-coil springs grouped within four units of three (3). Between spring units, on each side of the bogie, there are a vertical (4), a transversal (5) and an anti-yaw (6) hydraulic damper.

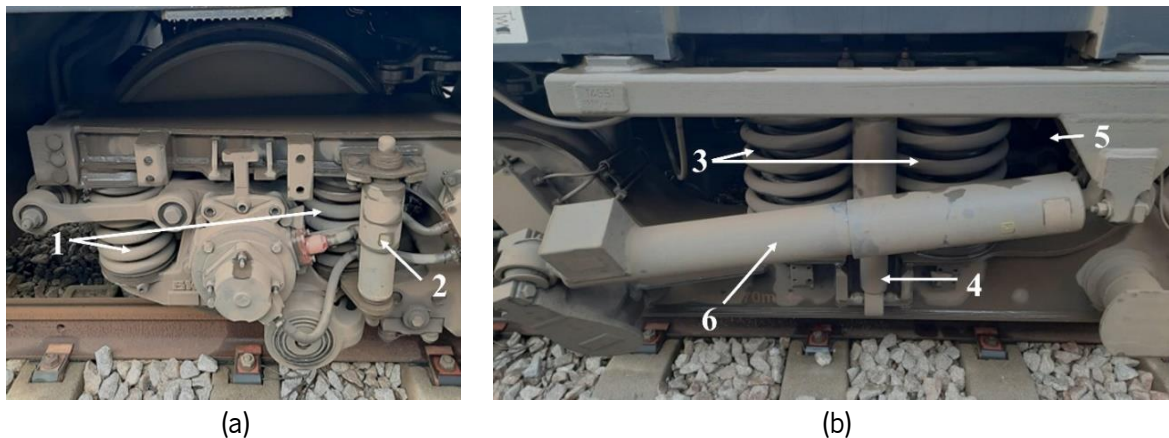


Figure 4.4. AP train bogie: (a) primary suspension; (b) secondary suspension.

4.3.2 Intercity vehicles suspension

IC train service is currently run by 5600 series locomotives with hauled Corail coaches. The electric locomotive trails five Corail coaches, each with a length of 26.4 m. As on the AP train, each carriage has two bogies, separated by 18.4 m distance within the same vehicle and 8 m between consecutive carriages.

Figure 4.5 presents both, primary and secondary, suspension systems of IC vehicles [37]. The primary suspension (see Figure 4.5 (a)) comprises eight helicoidal springs and four hydraulic dampers, resulting in two springs (1) and one damper (2) per wheel. The bogie-carbody connection, partially performed by the secondary suspension (Figure 4.5 (b)), comprises two grouped helicoidal springs (3) aided by two vertical (4) and two transversal (5) dampers, one on each side of the bogie.

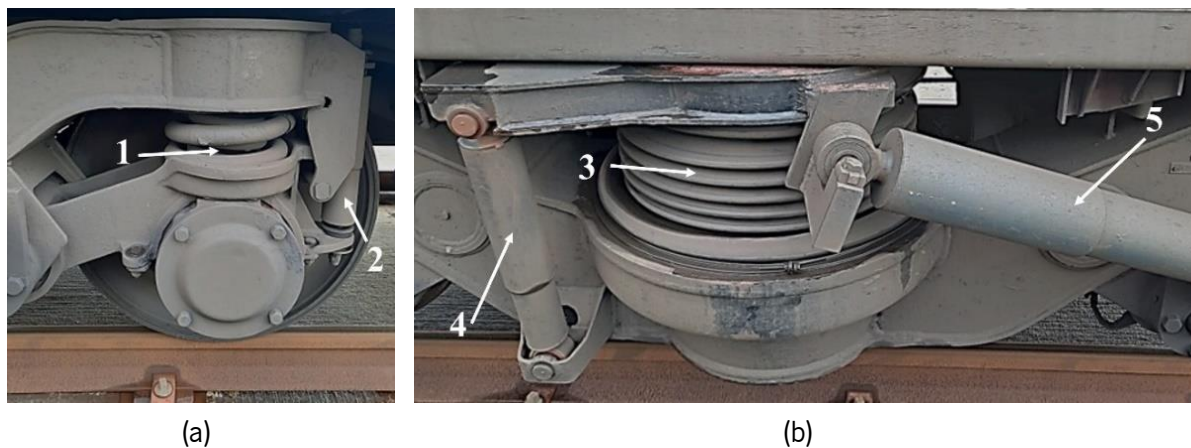


Figure 4.5. IC bogie: (a) primary suspension; (b) secondary suspension.

Table 4.1 resumes the primary and secondary elements of both types of trains (AP and IC).

Table 4.1. Primary and secondary elements of AP and IC trains suspension systems.

Train	Primary suspension	Secondary suspension
AP	16 helicoidal springs + 4 vertical hydraulic dampers	12 flexi-coil springs + 6 hydraulic dampers (2 vertical, 2 transversals, 2 anti-yaw)
IC	8 helicoidal springs + 4 vertical hydraulic dampers	4 helicoidal springs + 4 hydraulic dampers (2 vertical, 2 transversal)

4.4 Indirect method for infrastructure condition assessment based on comfort criteria

Railway track infrastructure maintenance interventions are commonly decided based on measurements obtained by inspection vehicles and not on the dynamic response of in-service railway vehicles.

Passenger comfort is affected by the vibration that the carbody experiences due to motion and railway track infrastructure irregularities. As aforementioned, railway track irregularities can be identified based on acceleration records according to visible peaks in those measurements. Passenger comfort levels are also assessed through acceleration measurements. Thus, a strong link between isolated railway track irregularities and passenger comfort levels can be identified. The present method relies on that connection. Based on the natural excitation created by the passage of railway vehicles over the track and the fact that a defective railway track system induces higher vibration, it is expected that high discomfort levels will be accomplished when in the presence of an abnormality on the railway track infrastructure. Thus, it was hypothesised that the railway track infrastructure needed maintenance if multiple trains with different suspension mechanisms reported instantaneous floor discomfort levels at the same geographic location.

Therefore, a CBM identification methodology was developed to investigate the defined hypothesis. The proposed methodology includes two stages, the experimental data measurement and acquisition and the data analysis. Acceleration measurements were performed based on a 3-axial accelerometer aided by a GPS to determine the vehicle's location. ISO 2631 standard provided the reference evaluation method for assessing passenger comfort. Then, a MATLAB algorithm was developed to match multiple railway vehicles' discomfort locations and identify the maintenance needs locations. It should be highlighted that the methodology was applied on ballasted tracks once, that is, the track type of the Northern Line of the Portuguese railways. Nevertheless, there are no expected assessment differences when applying the present method to ballastless tracks.

4.4.1 Whole-body vibration evaluation

WBV evaluation was performed based on the aforementioned ISO 2631 standard, following its requirements and recommendations [38-41].

As mentioned, the standard determines acceleration measurements at interface surfaces where vibration is transmitted to the user. However, it is well known that the seat modifies the vibration transmission [42–45]. Additionally, the floor represents the closer location between the users and the carbody. This way, the calculation of instantaneous floor discomfort by performing the standard analysis per second and applying the recommendations concerning floor measurement location (W_k as weighting curve and multiplying factors $k_x = k_y = 0.25$ and $k_z = 0.40$) was performed [41].

4.4.2 Condition-based maintenance identification methodology

The developed condition-based maintenance identification methodology comprises two stages: data acquisition and data analysis. The latter, performed in MATLAB, produces a list of locations where high vibration levels were found in all railway vehicles, thus identifying the exact track locations that possibly require maintenance.

4.4.2.1 Data acquisition system

The data acquisition system comprises one three-axial accelerometer and a GPS measurement; both components log data to a μ SD card.

Floor vibration measurements were conducted by the three-axial accelerometer (PCE-VDL-24I $\pm 16g$), which permits data recording and follows ISO 2631 requirements [41]. As aforementioned, the standard defines the frequency range between 0.5 – 80 Hz as the most relevant for comfort evaluation. Thus, a sample rate of 200 Hz was set, respecting the Nyquist theorem and preventing aliasing.

The GPS geographic location is obtained from a system composed of a GPS Logger [46] (position accuracy 2.5 m and velocity accuracy 0.05 m/s) connected with a RedBoard Qwiic [47], programmed to retrieve location, rail vehicle speed, and record data on a μ SD card at 1 Hz. Vibration and geographic measurements occurred synchronously. Figure 4.6 shows the data acquisition system, including the vibration measurement and GPS units.

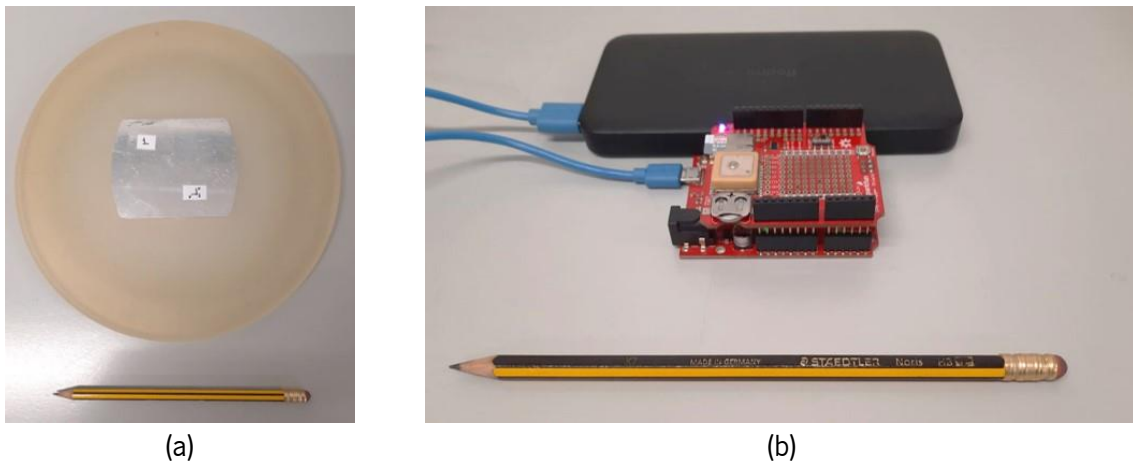


Figure 4.6. Data acquisition system: (a) Three-axial accelerometer pad; (b) GPS system.

4.4.2.2 Data analysis

The data analysis was performed in MATLAB 2022a [48] using an algorithm developed for this purpose. The algorithm starts by calculating the instantaneous floor discomfort (discomfort level at each second) according to ISO 2631 recommendations [41]. A slight adaptation of the standard was conducted, as discomfort levels were only divided into two categories. Those were defined based on the first discomfort threshold the ISO 2631 standard defined. The first category determines that accelerations equal to or under 0.315 m/s^2 are ranked as "Not uncomfortable", whereas, above 0.315 m/s^2 , accelerations were rated as "Uncomfortable". The uncomfortable locations were identified and mapped in all journeys.

To remove the interference of eventual railway vehicle maintenance needs, it was assumed that only the common discomfort sections need maintenance, i.e., segments with the same location and simultaneously reported by different trains.

The GPS signal is perfectly obtained in any location inside the IC train. This way, geographic location and acceleration records are synchronously acquired. However, the same conditions are not presented in AP vehicles, where the best GPS signal is obtained by installing the device into the train driver's cabin. Therefore, considering the AP train length, a maximum distance of 158.9 m between the accelerometer and GPS model can be observed for measurements taken at the opposite end of the train. Moreover, considering the worst-case scenario where the AP travels at 220 km/h, the distance it achieves in 1 second is approximately 61.1 m. Thus, a maximum offset of 220 m ($158.9 \text{ m} + 61.1 \text{ m}$) between AP and IC was used to get the matching segment. Figure 4.7 illustrates the steps comprehended between the measurements and the final report.

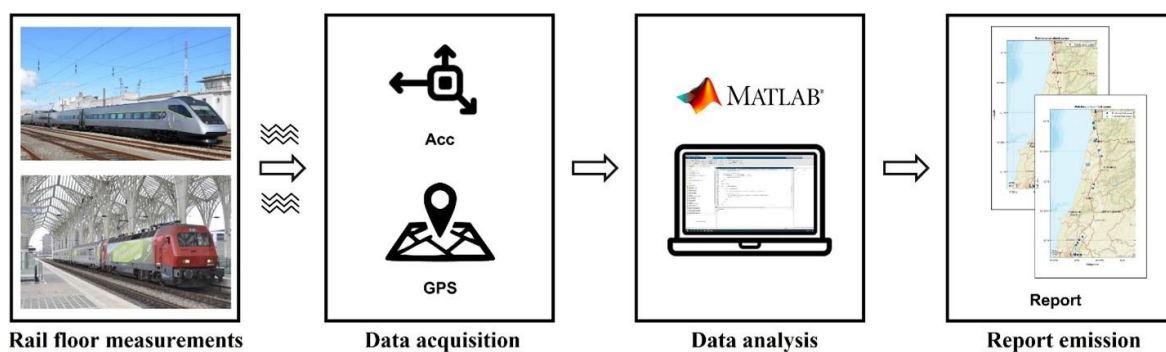


Figure 4.7. Developed methodology illustration.

It should be highlighted that the developed methodology only identifies abnormalities in the railway track infrastructure, and therefore, it does not distinguish the type of abnormality presented. Moreover,

the developed methodology is more accurate for identifying abnormalities within 10 – 120 m wavelength once it is based on the comfort analysis. Lower wavelength irregularities may not be precisely detected.

4.5 Case study: Portuguese Northern Line condition assessment

To validate and verify the accuracy of the developed methodology, vibration records took place at the Portuguese Railways Northern Line, downward direction, connecting Porto (Campanhã) to Lisbon (Oriente) stations. Multiple AP and IC railway vehicles were monitored while performing regular passenger service. Then, its results were compared with those reported by the Portuguese infrastructure manager (IP) obtained by the EM 120 track inspection vehicle.

4.5.1 Measurement campaigns

Floor records took place on nine AP and six IC trains under normal passenger service conditions. Five measurements (three in AP and two in IC) were taken on each position inside the train: start, mid and end cars/carriages.

Figure 4.8 demonstrates both the AP and IC design and the measurement locations. As aforementioned, the AP train is constituted of six cars. This way, three acceleration records were placed at cars 1, 4 and 6, corresponding to the train's beginning, middle and end cars. Moreover, car 1 is classified as a comfort class, whereas cars 4 and 6 are standard classes. This way, cars 4 and 6 present an equal interior layout, unlike car 1. Figure 4.8 (a) presents those interior layouts and the respective measurement locations. The IC train comprises five hauled Corail coaches, whereas carriage 1 is classified as comfort class, and carriages 3 and 5 are standard. These carriages correspond to that type of train's beginning, middle and end carriage. As on the AP train, comfort and standard classes have different interior layouts, as presented in Figure 4.8 (b). Figure 4.8 (c) shows the experimental setup on the AP train (left side) and the IC train (right side).

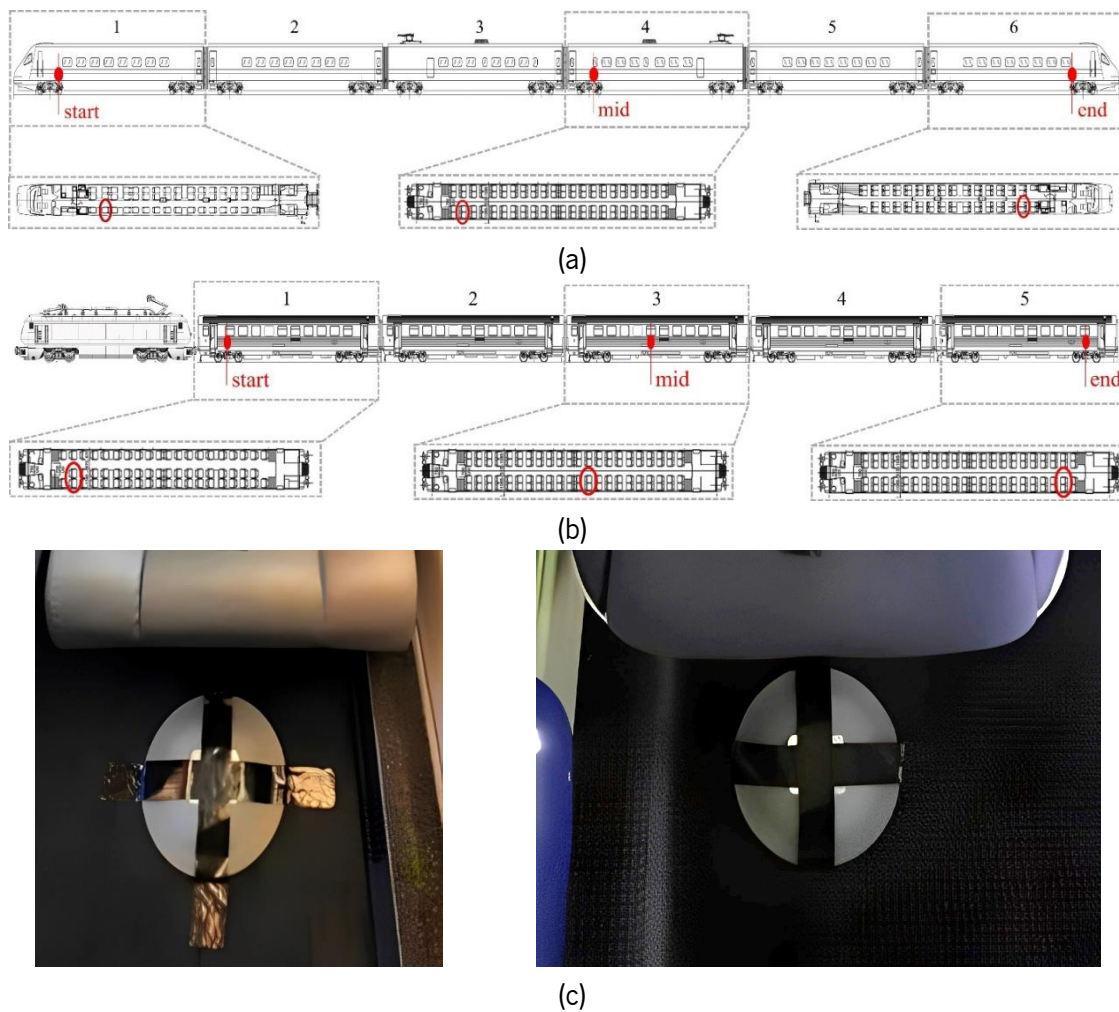


Figure 4.8. Floor measurement locations: (a) AP train and car measurement locations; (b) IC train and car measurement locations; (c) accelerometer placement at AP train (left side) and IC train (right side).

4.5.2 Maintenance needs identified by IP

Nowadays, the Portuguese infrastructure manager IP assesses the railway track infrastructure irregularities through measurements obtained by the passage of the EM 120 track inspection vehicle (Figure 4.9) [49,50]. This vehicle can detect and record track infrastructure faults with high precision.



Figure 4.9. EM 120 track inspection vehicle from IP. (Adapted from [48]).

The lastly released report regarding the Portuguese Northern Line railway track infrastructure evaluation and maintenance needs detection by IP revealed multiple track sections in poor conditions and, consequently, with maintenance needs [50]. A resume of those segments' identification can be found in Table 4.2.

Table 4.2. Track segments' maintenance needs identified by IP through the passage of EM 120 inspection vehicle. (Adapted from [49]).

Track Section		Kilometre interval		Track segment
Start station	End station	Start	End	
Alhandra	Castanheira do Ribatejo	26	27	A
Albergaria dos Doze	Alfarelos	147	199	B
Pampilhosa	Válega	232	297	C
Válega	Espinho	297	316	D

4.5.3 Maintenance needs identified by the indirect method

The data analysis identifies railway track infrastructure maintenance sections by comparing the discomfort zones of the AP versus those of the IC. Karoumi et al. [29] and Norris [30] state that a railway track infrastructure with isolated irregularities presents higher vibration levels at that location than a healthy one. Those higher vibrations will lead to increased discomfort levels.

The developed methodology divided floor discomfort levels into "Not uncomfortable" and "Uncomfortable" categories depending on the instantaneous acceleration evaluation. Those under 0.315 m/s^2 , corresponding to the ISO 2631 first discomfort level threshold, are grouped in the first category, while the second category comprises those above that discomfort threshold. Therefore, an abnormality in the railway track infrastructure was expected to present higher than 0.315 m/s^2 discomfort peaks at that location. In opposition, a healthy infrastructure should have instantaneous floor discomfort levels

lower than that threshold. Ideally, those discomfort levels should present consistent behaviour. The reported trend was observed in the acceleration records and analysis. Figure 4.10 illustrates AP and IC trains' behaviour regarding the same locations (latitude).

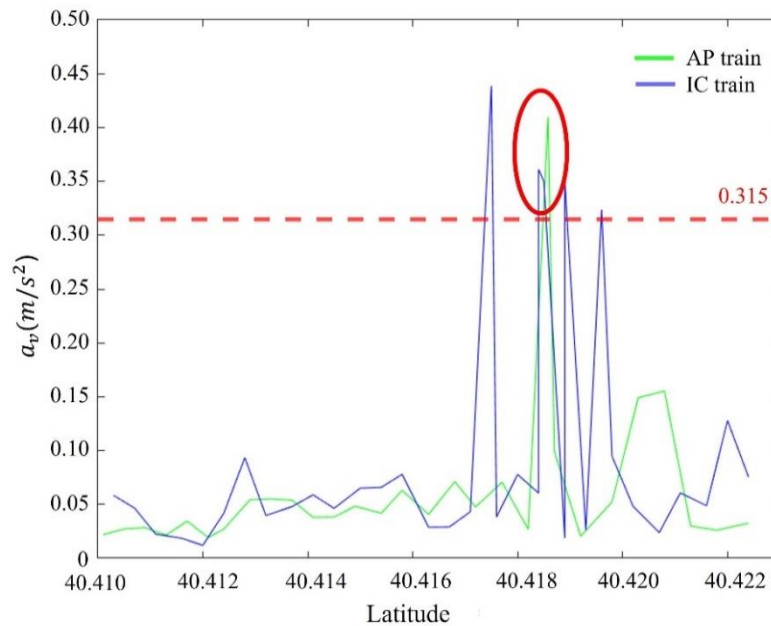


Figure 4.10. Instantaneous floor discomfort levels for AP and IC trains (where the red mark identifies a railway track infrastructure abnormality).

Vibration peaks capable of going through primary and secondary suspension systems cause passenger discomfort. AP and IC trains have different suspension systems and elements, so when the discomfort sections of both trains agree, it can be concluded that the railway track infrastructure needs maintenance. An example of that matching between both train discomfort levels is observed in Figure 4.10. The red mark illustrates the overlapping between the AP and IC discomfort levels. Thus, it can be established that an abnormality is presented at that specific location, and the railway track infrastructure needs maintenance. Figure 4.11 shows all maintenance required sections identified on the railway Northern Line using this algorithm, where AP and IC floor discomfort levels matched. Those below 220 m distance between peak locations correspond to the sections where maintenance is needed and are identified and illustrated.

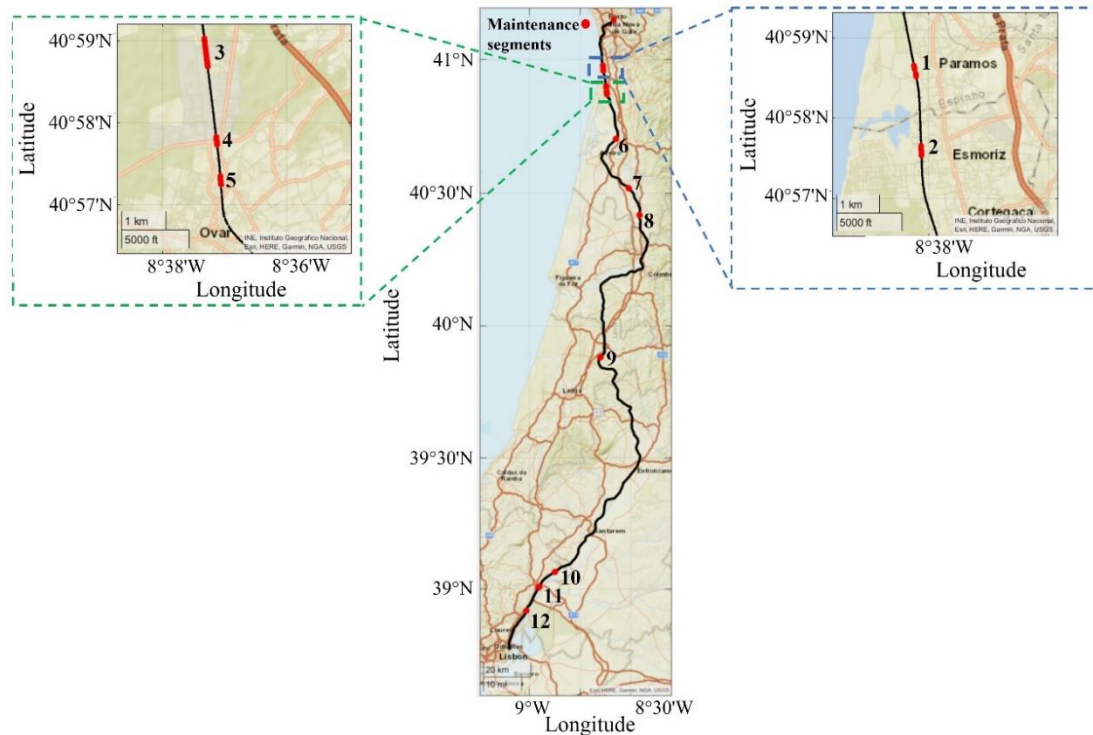


Figure 4.11. Northern Line railway track infrastructure maintenance needs identification; detailed zones (left side and right side) are at the laterals.

According to Figure 4.11, twelve maintenance zones were identified. For each zone, the start and end coordinates and their associated line kilometre were registered in Table 4.3, which also defines the matching with the IP-identified track sections. Due to the map resolution, some close zones appear to be just one. Blue and green markers define two sections that are, indeed, divided into small zones, 1 and 2 for the blue marker and 3, 4 and 5 for the green section. The discomfort location obtained at the Porto (Campanhã) train station is not numbered, as it is due to the acceleration to start the motion and not to a railway infrastructure abnormality.

Table 4.3. Maintenance needs identification segments and comparison with EM 120 inspection vehicle results.

Zone number	Initial coordinates		Final coordinates		Line km	Track segment IP
	Latitude	Longitude	Latitude	Longitude		
1	40.9776	-8.6374	40.9753	-8.6368	315	D
2	40.9609	-8.6354	40.9589	-8.6353	313	D
3	40.9005	-8.6221	40.8948	-8.6212	306	D
4	40.8805	-8.6189	40.8789	-8.6187	304	D
5	40.8725	-8.6178	40.8708	-8.6176	303	D
6	40.7044	-8.5727	40.7038	-8.5735	283	C
7	40.5196	-8.5108	40.5180	-8.5087	255	C
8	40.4198	-8.4564	40.4172	-8.4566	242	C
9	39.8820	-8.6489	39.8807	-8.6507	166	B
10	39.0651	-8.8734	39.0639	-8.8758	46	-
11	39.0081	-8.9518	39.0047	-8.9542	37	-
12	38.9159	-9.0155	38.9149	-9.0160	26	A

Ten listed locations match those the Portuguese infrastructure manager company (IP) pointed out to be subject to maintenance, identified by the EM 120 inspection vehicle [50]. Thus, it confirms that the obtained locations are critical points of the railway track infrastructure, therefore validating this methodology. Moreover, two extra zones were detected, zones 10 and 11. In addition to its proven accuracy, the model demonstrates the ability to be considered a viable alternative to the current methods. It should be highlighted that it is a low-cost method capable of simultaneously identifying railway track infrastructure isolated irregularities and analysing the passenger's comfort levels.

It should be noted that the proposed methodology cannot characterise the abnormality types present on the railway track infrastructure, but it is focused on detecting the critical track sections. Additionally, the present study does not consider the effect of aerodynamic forces. That has a more significant effect on high-speed trains, namely those achieving speeds higher than 300 km/h, which is not the case in this experimental research [51]. Nevertheless, it should be highlighted that since AP and IC trains have different structural designs, their aerodynamic behaviours are different, which may have a distinct influence on their vibration levels [52].

In the future, more work is intended to be developed regarding abnormality identification using more advanced methodologies, such as supervised machine learning procedures. Implementing these procedures will require vehicles to pass through track sections with well-known and characterised abnormalities. This way, it will be possible to learn and identify the typical dynamic response patterns of each abnormality [53].

4.6 Conclusions

Railways are currently one of the most used mass transportation systems worldwide. The increase in railway transportation demands more velocity and load. These two factors and the weather conditions accelerate the railway track infrastructure degradation, which must be assessed more frequently.

The interaction between rail infrastructure, wheels and vehicle motion creates a complex vibration environment, which is filtered by two suspension systems, primary and secondary. The former intends to induce stability and reduce the vibration transmission from the track-wheels interaction, while the latter concerns the bogie-carbody transmission. These systems decrease the vibration transmission to the passenger and thus increase comfort.

The railway track infrastructure, main component of the rail industry, affects both safety and comfort; thus, it needs continuous maintenance. Nowadays, railway track infrastructure evaluation is mainly accomplished by inspection vehicles. However, these vehicles are expensive, and their passage disrupts the programmed timetable. Based on these limitations, a low-cost CBM system was developed to identify railway track infrastructure maintenance needs based on comfort measurements without timetable disruptions.

AP and IC trains ran multiple journeys at the Portuguese Railways Northern Line, where accelerations and GPS measurements were recorded. ISO 2631 standard methodology was followed to obtain floor discomfort levels. Matching the instantaneous floor discomfort for both types of trains, the railway track infrastructure maintenance sections were found. The identified geographic locations are similar to those obtained by the EM 120 inspection vehicle. Therefore, the system was validated and proved its precision. Moreover, compared with previous studies where acceleration measurements were acquired at the axle box, the application of comfort levels to assess maintenance requirements is a novelty.

The developed system provides a complementary, low-cost, CBM railway track infrastructure analysis capable of detecting abnormalities (although not the type of), using in-service passenger trains to get measurements, thus avoiding any service disruption. A future goal of the present research is to identify the abnormality type. Therefore, machine learning procedures will be developed and applied.

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Chapter V - Modal Identification of Train Passenger Seats Based on Dynamic Tests and Output-Only Techniques

This chapter describes the experimental vibration modal identification of train seats based on a dedicated set of dynamic tests performed on AP and IC trains. This work uses two output-only modal identification techniques: the transmissibility functions and the Enhanced Frequency Domain Decomposition (EFDD) method. The last method allows us to clearly distinguish the seat structural movements, particularly those related to torsion and bending of the seat frame, from the local vertical foam vibrations. The natural frequencies and mode shapes are validated by matching the results derived from the transmissibility functions and EFDD method. The identified modal parameters are particularly relevant to characterise the vibration transmissibility provided by the foams (local transmissibility) and the vibration transmissibility derived from the metallic seat frame (global transmissibility).

5.1 Introduction

Trains' attractivity is usually achieved based on three main parameters: safety, comfort, and user conditions [1–4]. Resulting of the rail motion and wheel–track interaction, seat vibration affects users' comfort and health, limiting the attractiveness performance. As passengers spend most of their time seated, vibration will be transmitted to the user through interfaces between the human body, the seat structure, and the vehicle [8]. Thus, evaluating vibration transmission in a rail environment is crucial to assess the vibration frequencies and amplitudes transmitted to the user and evaluate passengers' comfort [4–9].

Several reference standards and guidelines, such as EN 12299 [3], UIC 513 [10], and ISO 2631-1 [11], define methodologies for the assessment of passengers' comfort based on both simplified and complete measurements. The simplified measurements are exclusively based on the accelerations measured at the floor of the carbody. This approach has the advantage of using a simpler measurement layout. However, the transposition of the acceleration from the floor to the passenger seat level requires the application of dedicated weighting frequency-dependent filters [3,10,11]. Otherwise, the complete measurements are based on the acceleration recorded on the passenger–seat–carbody interfaces, such as headrest–neck, armrest–upper arms, seat–hip, seat–back, and floor–seat, as well as on the carbody floor, close to the seat. This approach requires a set of dedicated accelerometers installed on several sites, which may be difficult. Inclusively, involuntary movements of the passengers can change the accelerometers' positioning, compromising the measurements' quality. Nevertheless, if performed adequately, it constitutes the most adequate approach to evaluate passenger comfort as it considers more realistically the complexity of the seat structure dynamics [12–15].

Seat dynamics is quantified regarding transmissibility, which verifies seat efficiency in handling vibration discomfort. Train seats are crucial to decrease vibration transmission from the floor to the user. Together, the seat and human body constitute a coupled, complex dynamic system [9,16–18]. A significant discrepancy can be observed when comparing the transmissibility of subjects with identical characteristics, including identical mass. Moreover, the human body has its own natural resonance frequencies that may lead to physiological responses when matched. The range between 5 and 10 Hz leads to resonance in the chest and abdominal region, and a higher frequency range, comprehended between 20 and 30 Hz, affects the head and neck muscles. Lastly, in the interval between 30 and 60 Hz, the ocular system perceives resonance [19–22]. Therefore, seat transmissibility can be significantly influenced by the biodynamics of the human body and its pronounced nonlinearity [23].

The biodynamic response of the human body is cross-axis-coupled, i.e., inducing vibration in one axis may lead to a response in another axis. Significant body movements in the fore-and-aft direction are produced during vertical excitation. This way, seat transmissibility is cross-axis-coupled. Additionally, the influence of subjects' physical characteristics, such as weight, on the resonance frequency and seat transmissibility has been evaluated by several authors. Multiple studies developed using subjects with varying mass ranges reported unaffected results. Increasing the loading on the seat surface (by the subject's weight) tends to increase the foam's dynamic stiffness. This foam behaviour explains the absence of the subject's weight's effect on seat transmissibility [24–27].

Transmissibility differs in direction, particularly in the vertical, fore-and-aft, and lateral directions, and location, namely the seat surface and seatback. Several laboratory experiments have demonstrated a vertical transmissibility peak at 4–6 Hz when sitting upright with seatback support [18,27–29]. However, these experiments did not implement transmissibility tests in traditional train seats. Instead, a single rigid seat frame with distinct characteristics from the ones of a current train seat, such as frame dimensions and support points, was considered. In addition, the foam was freely placed on top of the seat surface without any restricting cover [18,27–29]. The constraint conditions of the foam are crucial to correctly address the influence of the foam thickness variation on the transmissibility of the seat, particularly on the evaluation of its dynamic stiffness [29].

Regarding seat cushion properties, changing foam thickness has generally been found to have the most prominent and predictable effects on seat transmissibility. Doubling the foam thickness roughly halves its stiffness, leading to increased transmissibility and discomfort. Patelli and Griffin [18] conducted a study to observe the effect of foam thickness on seat transmissibility. Increasing the thickness from 40 to 80 mm reduced the transmissibility from 4–7 Hz to 3–5 Hz. Resonance frequencies were found to be equal to 3–4 Hz, for 40 mm foam, decreasing to 2–3 Hz for 80 mm foam. The experimented individuals did not have contact with the backrest [18]. A similar tendency was reported by Zhang et al. [30], where a higher transmissibility resonance was observed when the seat surface foam increased from 60 mm to 80 mm, and posteriorly to 100 mm.

In turn, changing the foam hardness (composition and density) does not significantly affect seat transmissibility. Due to hysteresis loss, density affects the static comfort instead of the seat transmissibility. Ebe and Griffin [8] examined seat transmissibility by considering four foam cushions with equal dimensions but varying densities (from 45 to 65 kg/m³). Seat transmissibility did not present significative differences, contrary to what was observed with the subjects' comfort judgments. Therefore, those judgment differences were related to the static seat comfort [8].

Based on the limitations of the previous experiments, this chapter aims to give clear contributions about some aspects that presently, according to the authors' knowledge, are not sufficiently addressed in the existing literature, particularly:

- Development of an experimental test setup on a real train environment. This way, the influence of the flexible seat base, instead of the currently rigid base used in laboratory experiments, as well as the influence of the carbody/bogies resonance movements, are considered on the seat dynamic performance. In addition, this dedicated experimental setup can clearly distinguish the seat frame's structural movements from the foam's local vibrations.
- Accurate characterisation of modal parameters of the seat structural frame and surface foam for different types of seats belonging to AP and IC trains, including standard and comfort seats.
- Train seat modal parameters validation based on the application of two distinct output-only techniques, one based on transmissibility functions, which is used by most of the authors in the bibliography, and the other based on the Enhanced Frequency Domain Decomposition (EFDD) method. The latter allows for visualising the modal configurations, which is a novelty in relation to the previous research works.

5.2 Modal identification methodologies

Vibration measurements have been intensively applied to structural health monitoring applications in civil and transportation engineering [31–33]. The output-only modal analysis, also called operational modal analysis, relies on applying modal identification techniques based exclusively on the structural response measurements. Modal identification techniques are divided into two groups, those based on the frequency domain and those based on the time domain. The present chapter considers only frequency domain techniques [34], mainly the transmissibility function and the EFDD.

5.2.1 Transmissibility Function

Seat dynamics is quantified regarding transmissibility, which is an indicator of dynamic comfort [1,2,6,7,16,27]. Transmissibility is defined as the ratio between the response amplitude at a specific seat location under an external forced vibration and the excitation amplitude at the seat base, both expressed in the frequency domain [35]. Therefore, the transmissibility function between the user–seat interface and the floor, $H(f)$, is a non-dimensional parameter calculated by the following Equation (5.1):

$$H(f) = \frac{Go(f)}{Gi(f)} \quad (5.1)$$

where $Go(f)$ is the output acceleration spectrum at the seat–user interface, and $Gi(f)$ represents the input acceleration spectrum at the floor level [18].

As the human body is a highly complex nonlinear biomechanical system, the vibration transmissibility varies with the direction and location of the measurements [36]. Therefore, seat transmissibility can be measured according to the axis (vertical, lateral, or longitudinal) and location (e.g., seat surface, seatback, armrest). Most published research involves the study of vertical transmissibility measured at the floor and seat surface, as these are the axes and locations most affecting passenger comfort [35]. Conventional train seats show a typical seat transmissibility curve, as displayed in Figure 5.1, and resonances are comprehended between 4 and 6 Hz [20].

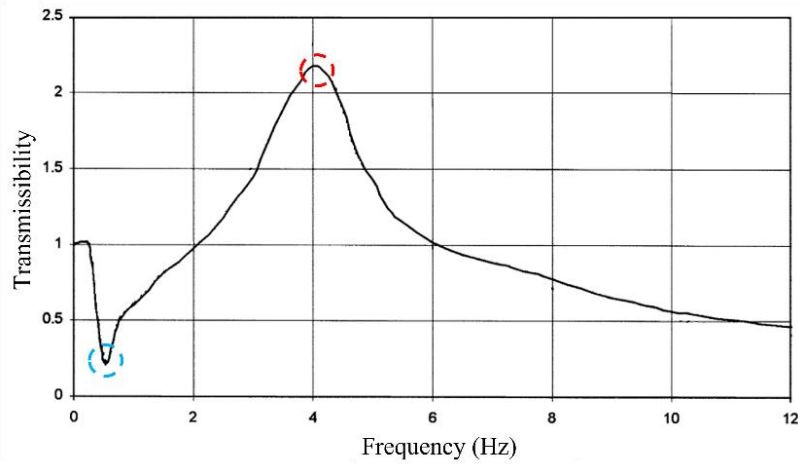


Figure 5.1. Typical transmissibility curve on conventional train seats (red dot represents the resonant frequency and blue dot represents the antiresonance frequency). (Adapted from [37]).

In Figure 5.1, a resonance peak (red dot) is noticed that characterises, in this case, the highest vibration transmission to the user, but in other situations, it can also be associated with a local maximum. In contrast, the antiresonance valley (blue dot) occurs when the responses of certain system components under forced excitation present a local minimum, in most situations, quite close to zero [34,35,37,38].

Regarding the train seat, the resonance frequencies can be associated with the single or combined movements of the foam and structural seat frame, while the antiresonance frequencies may be associated with the transition between the distinct type of seat vibrations.

5.2.2 Enhanced Frequency Domain Decomposition (EFDD)

The EFDD method is an upgrade of the Frequency Domain Decomposition (FDD) method, proposed by Brincker et al. [39], and allows an accurate estimation not only of the natural frequencies but also of mode shapes and damping coefficients. This method is based on the Singular Value Decomposition (SVD) of the Power Spectral Density (PSD) matrix, $S_{yy}(\omega)$, which can be obtained by the Fourier transform of the time-domain autocorrelation functions. Thus, the main diagonal of the PSD matrix is composed of the auto-spectral density functions, and the out-of-diagonal terms represent the cross-spectral density functions. The SVD decomposition of the PSD matrix can be summarised by the following equation:

$$S_{yy}(\omega) = U \Sigma V^H \quad (5.2)$$

where Σ is a diagonal matrix containing the singular values, and U and V are similar matrices containing the singular vectors. Brincker et al. [39] demonstrated that, for structures with low values of damping and subject to white noise excitations, the matrix of singular values corresponds to the power spectral density functions of a set of one DOF oscillators, whose singular values and vectors coincide with those of the real structure. If the white noise excitation assumption is not fulfilled, the method can still be applied, and the obtained results are approximated. Those results are considered reliable and enhanced compared to those obtained on the classical peak-picking method [39,40]. Then, the SVD allows for isolating the contribution of each of the mode vibrations as a 1-DOF system. The main steps (1 to 4) of the EFDD method are summarised in Figure 5.2 and involve mathematical operations first in the time domain and then in the frequency domain.

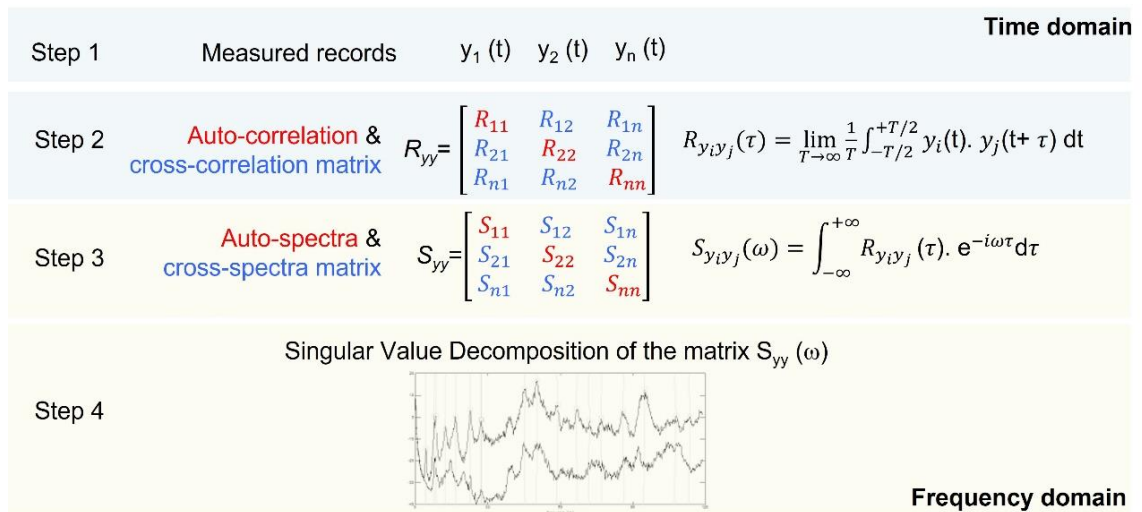


Figure 5.2. Main steps for the application of the Enhanced Frequency Domain Decomposition (EFDD) method.

In the case of well-separated modes, only the first singular value will have significant information. However, in the case of closely spaced modes, one will be identified in the first singular value curve,

while the others will be identified in the second- or higher-order singular values curves. The natural frequencies and damping coefficients are derived from the time domain autocorrelation function, which is calculated by the Inverse Fourier Transform (IFFT) of the singular values around each resonance peak.

The comparison between vectors can be performed employing a scalar index denominated as the Model Assurance Criterion (MAC), which investigates the correlation between two modal configurations [39,40]. The estimation of modal configurations associated with each natural frequency is calculated by averaging the singular vectors of the neighbourhood points of the resonance frequencies with MAC higher than 0.8, and weighting by the value of the corresponding singular values. This way, the selection of the SVD points is based on the similarity between their singular vectors calculated through the MAC parameter. Respecting the assumptions of the method, these functions will be proportional to the free vibration decay of the 1-DOF oscillator. Thus, it is possible to estimate the natural frequency based on a dedicated counting of vibration cycles and damping coefficient, by applying the logarithm decrement method, which involves adjusting the exponential term $e^{-\zeta\omega_n t}$ to the free vibration decay movement [39,41,42].

Regarding the present work, pairing comfort and standard seat modes can be conducted through the MAC parameter, which, as stated, measures the linear correlation between modal vectors through their mean square deviation [43]. The MAC parameter is a scalar, varying between 0 and 1, whose unit value indicates that the modes are coincident or linearly dependent [44,45]. Its value is estimated based on the following expression:

$$MAC_{ij} = MAC(\Phi_i^*, \Phi_j^*) = \frac{\Phi_i^{*T} \Phi_j^*}{(\Phi_i^{*T} \Phi_i^*) (\Phi_j^{*T} \Phi_j^*)} \quad (5.3)$$

where Φ_j^* is the vector containing the coordinates from the comfort seat mode j corresponding to its data, and Φ_i^* is the vector containing the standard seat information of mode i .

5.3 Case study: Alfa Pendular

Figure 5.3 shows the CPA 4000 series, traditionally named AP, on a regular passenger service. The train is a conventional electric train with an active tilting system and a total length of 158.9 m. It is operated as a single unit and comprises six vehicles, four motor and two hauled vehicles [46,47].



Figure 5.3. CPA 4000 series train in operation.

Cars 1 and 2 are classified as comfort classes, while the others are standard class. Despite being visually similar, the seats of the two classes are different in terms of their dimensions. The comfort seat is larger than the standard one. Therefore, comfort class seats present a higher seating area, thicker seat surface and seatback foams, larger seat frame, and higher distance between seats.

In 2017, the AP train was renovated, leading to a significant change in seat design while retaining the same seat structural frame. This renovation introduced several changes to the seat cover and foam design. While the pre-renovation seats presented a free foam covered by fabric, the renovated ones exhibited a restricting leather cover with large hems and new foams [48,49]. Figure 5.4 illustrates the renovated comfort and standard class seats and their respective location. Seats instrumented on this work were positioned in the same location inside vehicles 1 and 6, respectively, for comfort and standard classes, more specifically near the rear bogies.

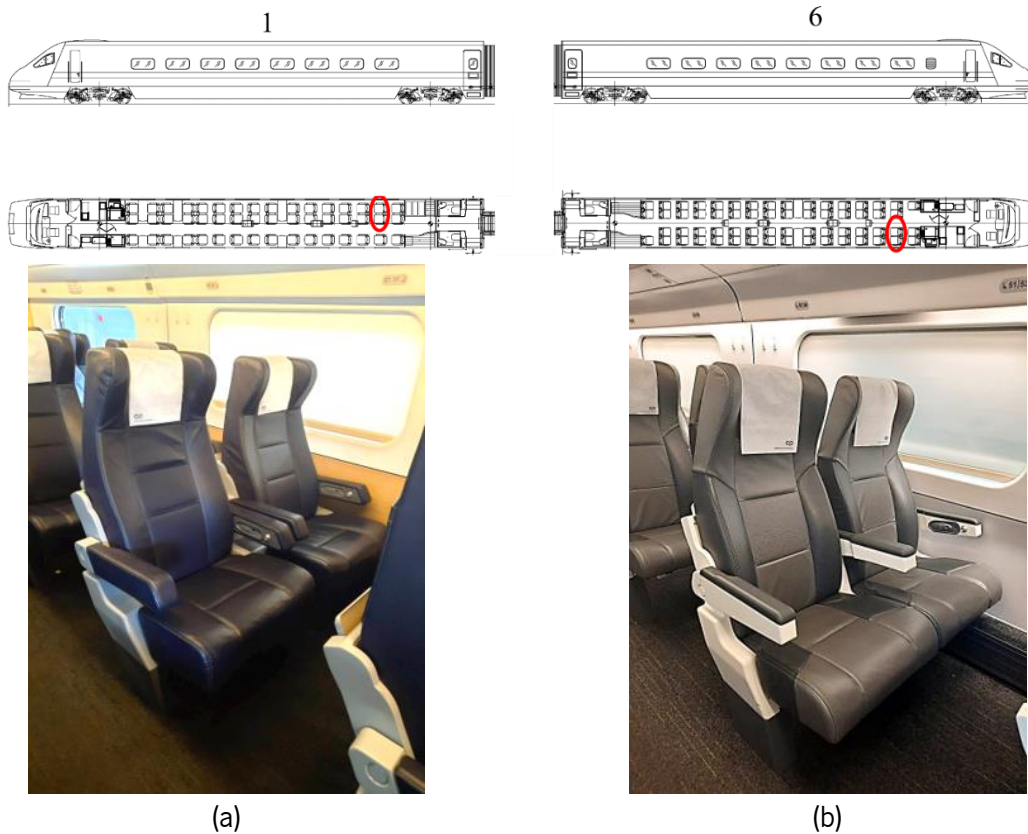


Figure 5.4. Alfa Pendular seats: (a) comfort class seat; (b) standard class seat.

The comfort class seats have a seat surface foam thickness of 190 mm, while for the standard class seats, the same thickness is equal to 130 mm. Regarding the seatback, the foam thickness is 127 mm and 110 mm, respectively, for comfort and standard seats. Moreover, both seats and foams have a 2 mm thick leather cover. The aluminium structural frame underneath that supports the seats is presented in Figure 5.5. The frame comprises two vertical columns and a transversal girder and provides the seat's connection to the carbody platform. These elements compose the structural frame of both seat classes. As the seats differ in dimensions, the elements constituting the comfort seat frame have higher dimensions than those of the standard seat [49].



Figure 5.5. Seat metallic frame.

5.3.1 Dynamic tests

A set of dedicated experimental tests were performed in the Portuguese Train operator–CP maintenance facilities to evaluate the seats' dynamic behaviour. Three volunteers (2 males and 1 female), aged between 25 and 39, weighing 58–115 kg, and 1.70–1.87 m in height, participated in the tests (Table 5.1). The Ethics Committee of the University of Minho approved the experiment (Appendix I). Each experiment was conducted three times for each subject. The subjects were instructed to sit in a normal posture, place both hands on their thighs, and perform complete contact with the seatback.

Table 5.1. Subjects' characteristics.

Subject	Gender	Age (Years)	Weight (kg)	Height (m)
S1	Female	25	58	1.70
S2	Male	26	80	1.87
S3	Male	39	115	1.85

Figure 5.6 illustrates the experimental setup for estimating the AP seats' transmissibility and modal parameters. Two seats, one of each class, were instrumented. It should also be highlighted that the subjects were seated near the window. The acceleration at the seat surface was measured using a 3-axial seat pad accelerometer (PCB model 356B41), as illustrated in Figure 5.6 (a) (left side). On the same Figure 5.6 (a), an ongoing experimental test is demonstrated on the right side. Additionally, uniaxial accelerometers (PCB model 393A03) were placed on the floor (1 unit) and the metallic support frame (4 units) for measuring the acceleration in the z (vertical) direction at the seat frame, as represented in Figure 5.6 (b). It should be highlighted that accelerations on node 2 were derived from the accelerations on node 1. Based on this assumption, when using ARTEMIS software, node 1 was defined as the master while node 2 assumed the slave position. The accelerometers were strategically distributed to properly distinguish the seat frame's vertical torsion and bending modes and the seat foam's local vibrations.

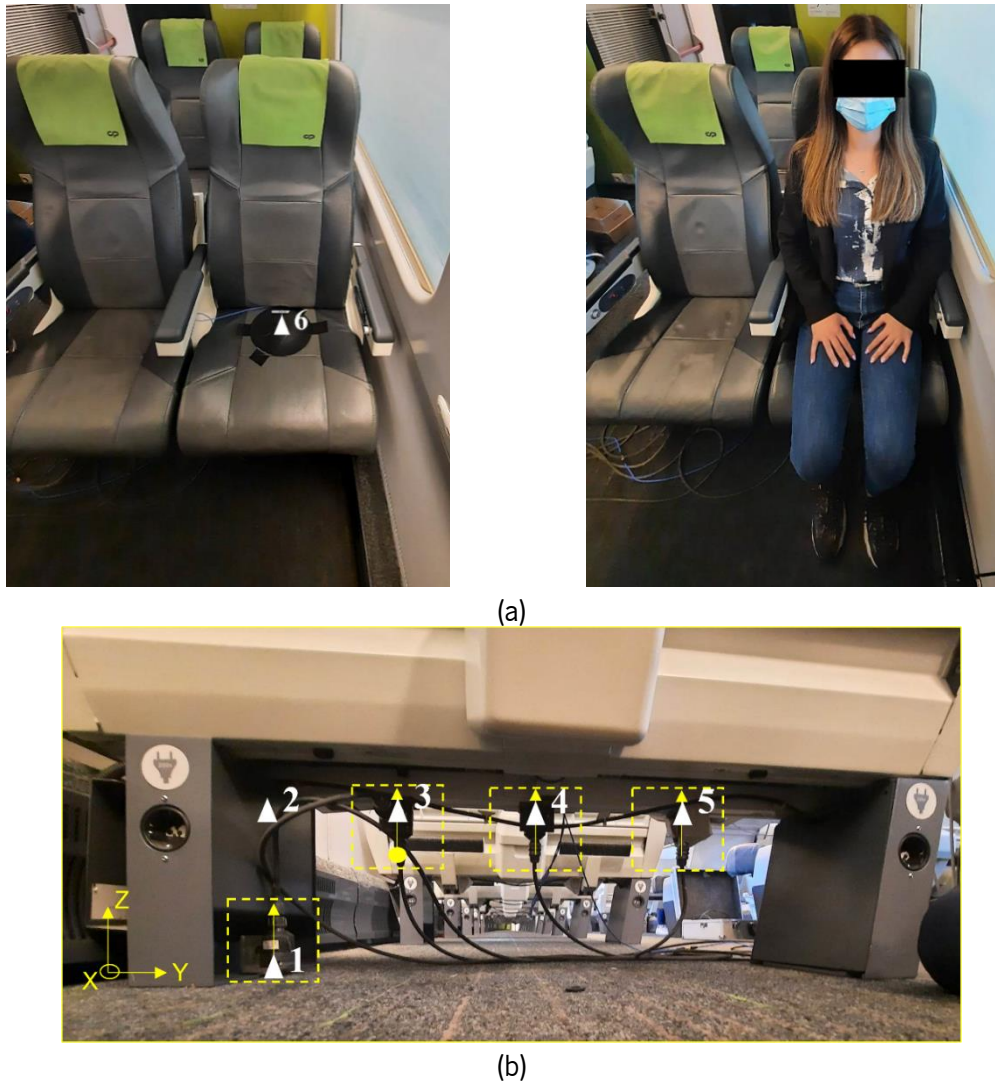


Figure 5.6. Experimental test setup: (a) seat pad location and experimental test; (b) accelerometers distribution along seat frame structure. Each number represents the modal node used on ARTeMIS software.

Time series were acquired in periods of 5 min, with a sampling frequency of 2048 Hz, posteriorly decimated to a frequency of 64 Hz. The down-sample was conducted based on the assumption that the frequencies of interest regarding passengers' comfort are, generally, ranged between DC and 20 Hz. In addition, the data are presented between DC and 12 Hz, which enables a closer view of the frequencies of interest. The data acquisition system was composed of a National Instruments (NI) cDAQ-9172 equipped with IEPE analogue input modules with 24-bit resolution (NI 9234) connected to a PC to acquire and record data measurements. The vibration was induced by a group of people randomly walking and jumping nearby the seat. The experiments were run with an interior train temperature of around 20 °C.

5.3.2 Results

Results are divided according to the modal identification technique used: the transmissibility curves and EFDD method.

5.3.2.1 Transmissibility curves

Transmissibility curves were evaluated using MATLAB scripts validated in previous works [50]. These curves were obtained based on the information from accelerometers 1 and 6, both at the z-axis. Due to the similarity between experiments and to obtain a cleaner presentation, only one experiment per subject is presented. Figure 5.7 shows the transmissibility curves for the three subjects (S1, S2, and S3), considering the comfort (Figure 5.7 (a)) and standard (Figure 5.7 (b)) seats. It is possible to observe the resonance peaks (marked by red circles) and the antiresonance peaks (marked by blue circles).

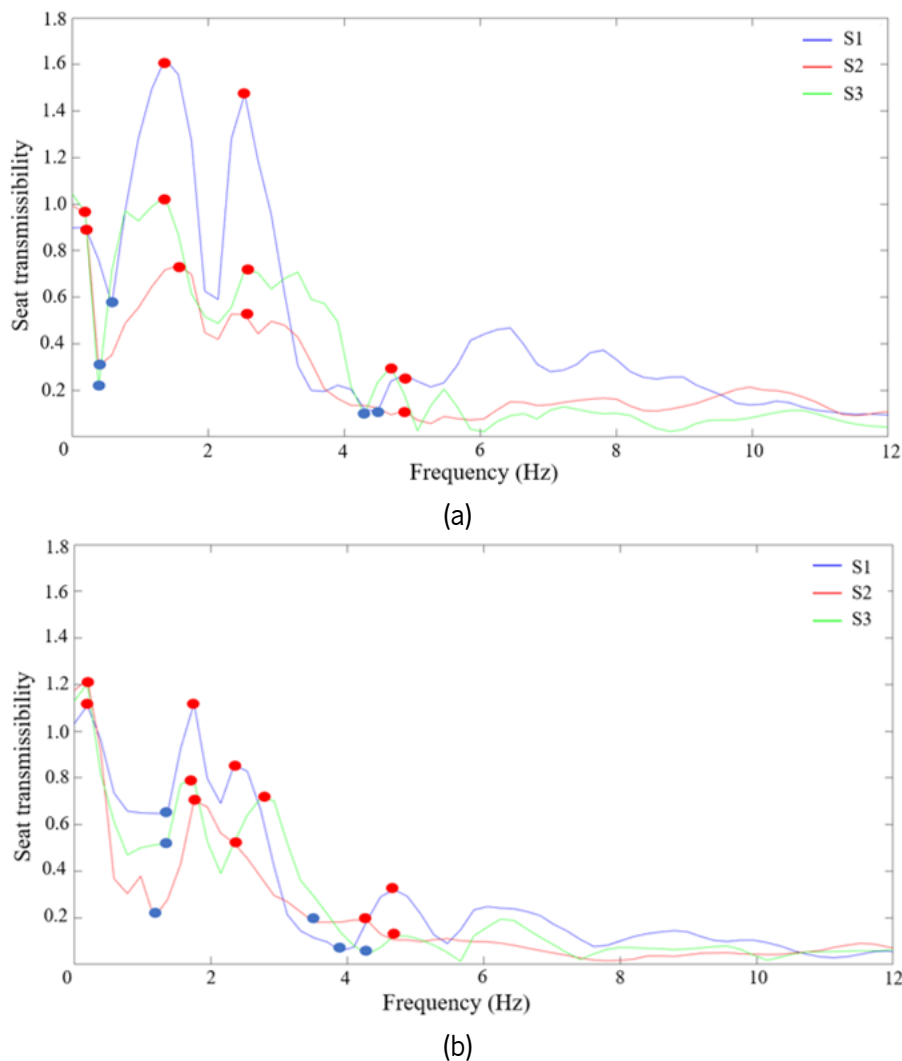


Figure 5.7. Transmissibility curves: (a) comfort seat; (b) standard seat.

Table 5.2 summarises the main resonance and antiresonance peaks for comfort and standard seats. Due to its intensity, it is expected that some of these frequencies cannot induce a different type of movement.

Table 5.2. Main resonance and antiresonance frequency values for comfort and standard seats of AP train.

Subject	Comfort		Standard	
	Resonance (Hz)	Antiresonance (Hz)	Resonance (Hz)	Antiresonance (Hz)
S1	0.20	0.59	0.20	1.37
	1.37	4.49	1.76	3.91
	2.54		2.34	
	4.88		4.69	
S2	0.20	0.39	0.20	1.17
	1.56	4.69	1.76	3.52
	2.54		2.34	
	4.88		4.30	
S3	0.20	0.39	0.20	0.78
	1.37	4.30	1.76	4.30
	2.54		2.73	
	4.69		4.69	

Comfort seat transmissibilities are characterised by resonance frequencies of 0.20, 1.37–1.56, 2.54, and 4.69–4.88 Hz. It should be pointed out that the higher-amplitude transmissibility peaks occur at low frequencies, namely 0.20 and 1.37–1.56 Hz. The antiresonance values are found between 0.39–0.59 and 4.30–4.69 Hz. Despite the inter-subject variability, no significant differences are found between the transmissibility resonances and antiresonances frequency values when comparing all subjects' results. These conclusions comply with the ones found by Toward and Griffin [27].

Regarding standard seat transmissibility, the results are similar for all analysed subjects. Resonances of 0.20, 1.76, 2.34–2.73, and 4.30–4.69 Hz and antiresonances equal to 0.78–1.37 and 3.52–4.30 Hz characterise this class. Higher transmissibility resonances are obtained for 0.20 and 1.76 Hz. Those transmissibility peaks are higher than the ones of the comfort seat. This result agrees with the conclusions derived from the studies performed by Patelli and Griffin [18] and Zhang et al. [30], where the transmissibility peak values decreased for higher foam thicknesses. As aforementioned, the comfort seat has a seat surface thickness of 190 mm, whereas the standard seat thickness is equal to 130 mm. The previously mentioned studies evaluated the effect of foam thickness on thicker foams, namely 40, 60, 80, and 100 mm. Therefore, the AP seat foam thickness is higher than those of the previous studies. Following the reported trend, comparing those results with the present ones, lower transmissibility frequencies in the present results were observed.

The transmissibility frequency resonance peaks presented in this study are lower than those presented by other authors [18,27–29], who found vertical transmissibility frequencies around 4.30 Hz. However, the experiments reported in the bibliography were performed in laboratory conditions instead of using a real railway vehicle. More specifically, those tests considered a single seat with a simplified rigid metallic structure (with a mass of approximately 1000 kg) composed of 4 vertical rigid columns and a free foam on top of the surface without covering it nor restricting its movement. In turn, the train seats instrumented in this study present a leather cover with a large seam hem. The cover significantly modifies the foam vibration transmission by restricting the foam cellular morphology movements. Therefore, the vibration absorption is clearly distinct compared to the laboratory experiments' free foam.

Figure 5.7 also identifies a peak around 3 Hz associated with the rigid body movement of the seat frame over the carbody due to the stiffness provided by the flexible connection elements, particularly screws and rubber pads. These elements act as a spring that flexibilize the seat frame movements.

5.3.2.2 EFDD method

The modal identification was performed using the EFDD method available in the ARTeMIS software [51]. Once the inter-subject variability did not notice any significant alteration in transmissibility analysis, the EFDD method was performed only for subject S1. The natural frequencies estimated from the EFDD method and transmissibility functions are equal once the latter is the base for identifying the natural modes. Figure 5.8 shows the first two curves of the average normalised singular values of the spectral density matrices of subject S1 considering the comfort seat test. In this figure, it is possible to observe the peaks corresponding to the identified frequencies and mode shapes.

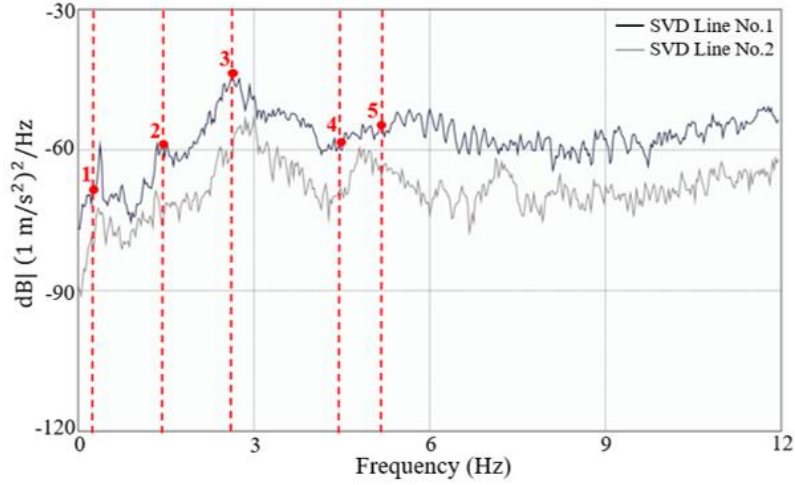


Figure 5.8. EFDD method: average normalised singular values of the spectral density matrices regarding AP comfort seat.

The seat modal parameters, namely the natural frequencies and modal configurations, are depicted in Figure 5.9, where f represents the average value of each natural frequency. The figure represents each modal configuration by the front and lateral views. Moreover, the undeformed structure is represented in blue, while the deformed structure is red-coloured.

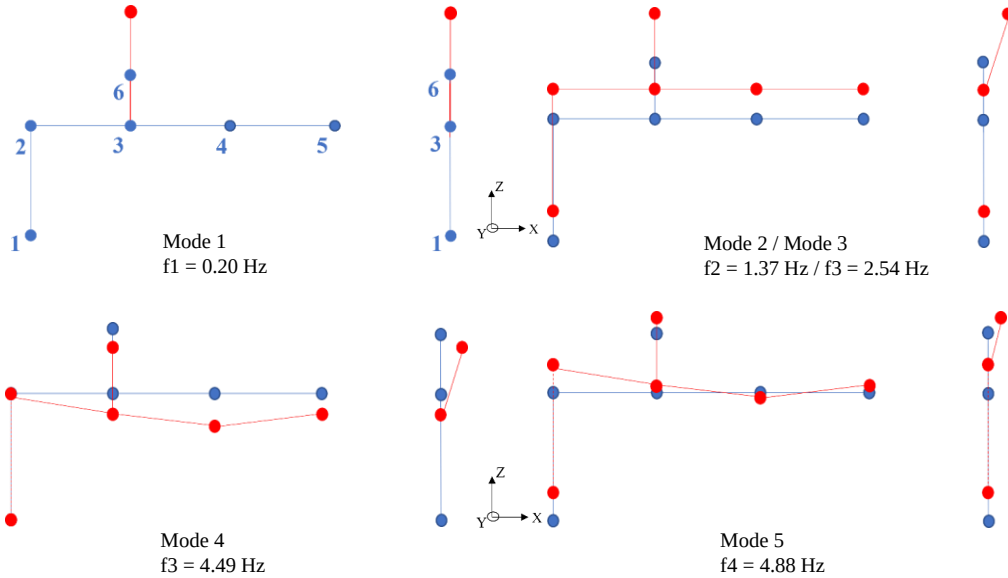


Figure 5.9. Experimental modal parameters for the comfort seat.

As expected, each vibration mode corresponds to a different seat movement. Mode 1, with a frequency of 0.20 Hz is related to the vertical foam local movements.

Mode 2, with a frequency of 1.37 Hz, is possibly associated with a global movement of the vehicle carbody, which induces a rigid body motion on the seat structure, with a slight foam movement in the vertical and longitudinal directions. This longitudinal component is associated with distortional

movements of the foam layer. Concerning the AP train natural frequencies, Ribeiro et al. [50], based on a forced vibration test of the carbody, estimated the frequency values of the three rigid body modes of the carbody, associated with rolling, bouncing, and pitching movements, ranging between 1.0 Hz and 1.6 Hz, which are in full compliance with Mode 2's physical interpretation. It should be highlighted that the 0.59 Hz antiresonance frequency identified on the transmissibility curve matches the same movements as Mode 2.

Mode 3, with a frequency around 3 Hz, is associated with rigid body movements of the seat frame due to the flexibility of the connection elements between the seat and the carbody. This modal configuration has similar movements to the ones of Mode 2.

Mode 4 demonstrates a seat movement transition. Characterised by this antiresonance frequency, the seat frame presents a quite well-defined bending movement coupled with a torsion movement, as stated by the longitudinal movement of the seat foam. The bending of the seat frame is naturally mobilised by the externally induced vibration and the mass of the passenger (Figure 5.10). At this frequency value, the foam layer strictly follows the movement of the seat frame without any type of independent vibration, being comparable to the result obtained by Ribeiro [50], 4.23 Hz, conducted in the same environment but on a pre-renovation seat and with a simplified experimental setup. That comprised an accelerometer placed on the floor and one tri-axial accelerometer on the seat surface. Therefore, the author obtained the transmissibility curves but could not perform the modal identification. The new foams and restricting covers justify the slight difference between results.

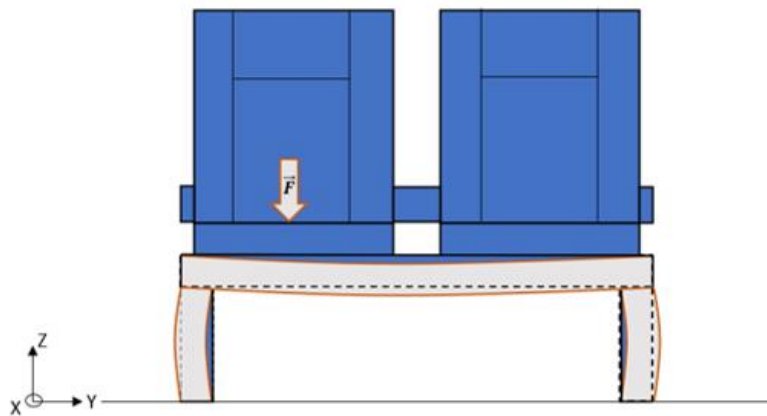


Figure 5.10. Demonstration of seat bending movement.

Mode 5, with a frequency equal to 4.88 Hz, is associated with a coupled mode involving structural movement of the carbody, as stated by the quite visible support vertical movement, structural movement of the seat frame, demonstrated by bending movement, and vertical foam movements.

In conclusion, resonance modes 1 and 5 are connected with the seat frame and foam natural frequencies and, therefore, amplified movements. Mode 2 and the antiresonance valley, Mode 4, are strictly connected with seat frame movements and the generation of those movements transitions.

Figure 5.11 illustrates the first two curves of the average normalised singular values of the spectral density matrices of the S1 standard seat test, where it is possible to observe the peaks corresponding to the identified frequencies and mode shapes.

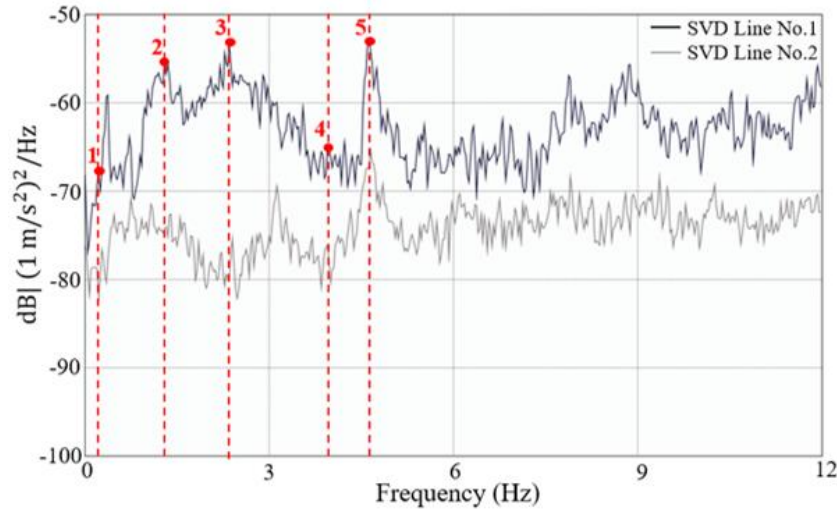


Figure 5.11. EFDD method: average normalised singular values of the spectral density matrices regarding AP standard seat.

The seat movements derived from the vibration modes are demonstrated in Figure 5.12, where f represents the average value of the natural frequency.

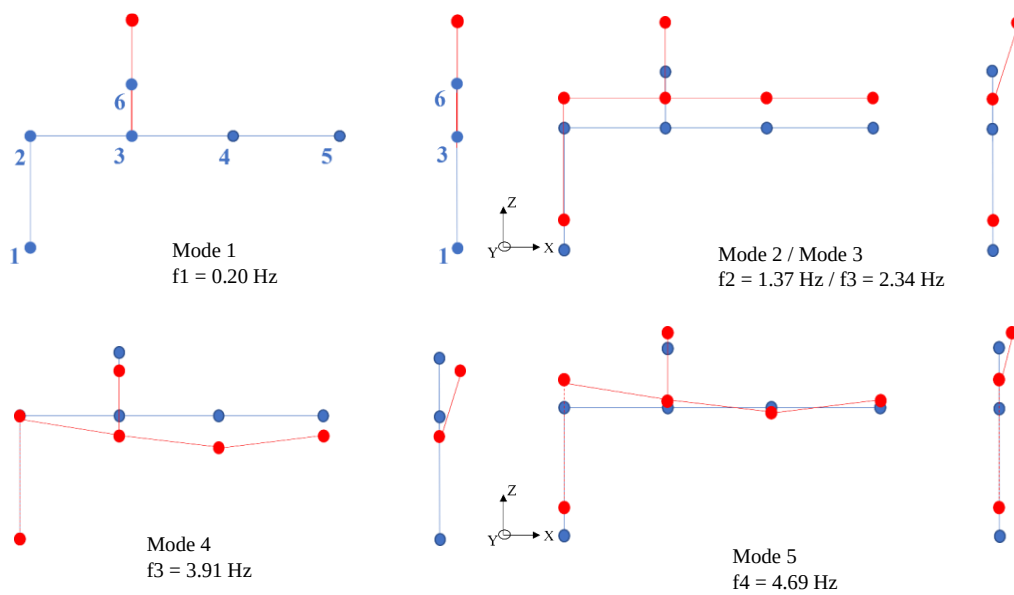


Figure 5.12. AP standard seat experimental modal parameters, where the front and lateral views are presented.

As previously mentioned, standard and comfort seats differ mainly in terms of dimensions. Therefore, it was anticipated that both seats face a similar structural behaviour. Due to the foam thickness difference, a distinct foam vibration range absorption was expected, as observed on transmissibility curves.

To confirm the similar structural behaviour of both seats, mode pairing was conducted through the MAC parameter. Mode 2 presents an MAC value of 0.96, followed by Mode 1 (MAC equal to 0.93) and Mode 5 (0.86).

Indeed, the modal analysis demonstrated that standard and comfort seats present the same seat frame movements occurring at different frequencies. Mode 1 is the exception, as it occurs on the same frequency for both seats. Standard seat Mode 2 matches Mode 2 of the comfort seat. Modes 4 and 5, characterised by higher deformations, occur at slightly, but not significantly, lower frequencies for the standard seat.

The standard seat foam demonstrates the capacity to absorb vibrations within the 1.37–3.91 Hz frequency range. This parameter represents the main difference regarding both seats, as the comfort foam presents a larger vibration range absorption (0.59–4.88 Hz).

5.4 Case study: Intercity train

The IC train service was introduced earlier than the AP in 1980 and was renovated in 2002. Figure 5.13 illustrates the IC train in its regular passenger service. This service is run by 5600 series locomotives with five hauled Corail coaches. Generally, coaches 1 and 2 are comfort classes, while the other cars are designed as standard classes.



Figure 5.13. Intercity train in operation.

Being from different classes, comfort and standard seats are distinct. In opposition to AP train seats, the IC seats differ in terms of dimensions and structural frame. While the comfort seat is a single seat (like those used in laboratory experiments), the standard seat is a classical double seat (Figure 5.14). The figure demonstrates the seat location within the train. As on the AP experimental setup, both seats were positioned in the same location inside vehicles 1 and 5, respectively, for comfort and standard classes, particularly near the rear bogies.

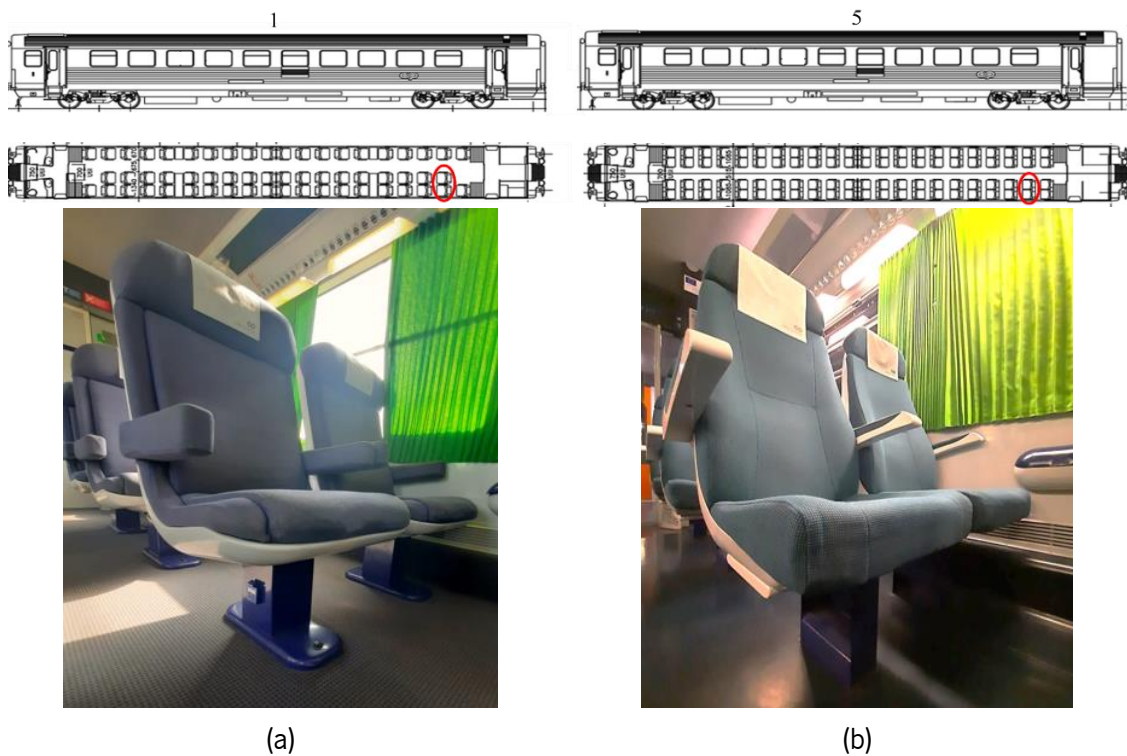


Figure 5.14. Intercity train seats: (a) comfort class; (b) standard class.

Regarding the dimensions, the comfort seat has a foam thickness of 80 mm, and equal to the seatback. For the standard class, the thickness is 60 mm for both seat surface and seatback. Although presenting different foam dimensions, both seats share the fabric cover type. This way, the foam is placed freely on top of the seat's metallic support structure without any movement restriction. This represents a more similar configuration with the laboratory experiments setup in comparison to the one of AP train.

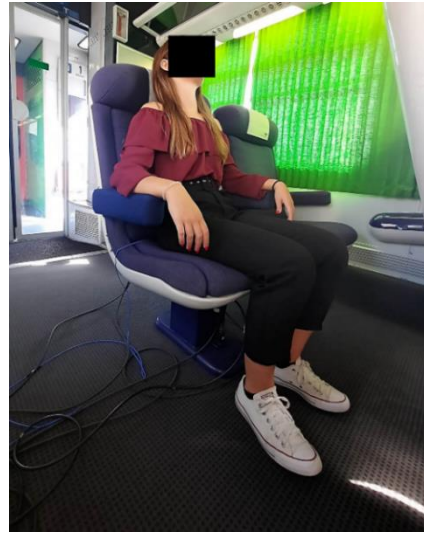
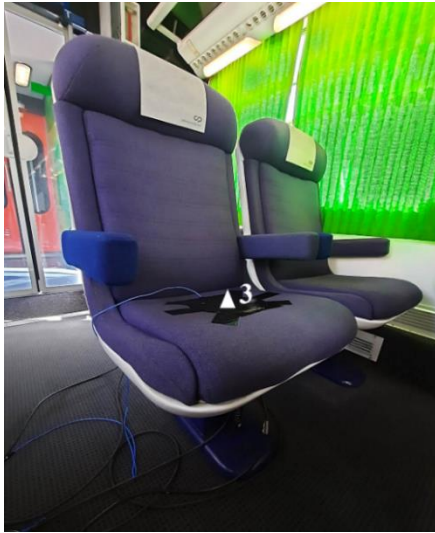
Regarding the structural frame, the comfort seat is composed of a vertical column connected on its base to the floor. The standard seat comprises two circular transversal girders connected at both extremities and linked with two vertical columns located at the centre of each seat. Figure 5.15 illustrates the metallic seat frame concerning both seat types.



Figure 5.15. Seat metallic structural frame: (a) comfort seat structural frame; (b) standard seat structural frame.

5.4.1 Dynamic tests

The experimental tests were accomplished in the CP-maintenance facilities with the same subjects, accelerometers, seat location, and vibration conditions as the AP experiments. One seat of each class was instrumented on the seat surface and support frame. Due to the metallic frame differences, a different experimental setup was designed for each seating class. Regarding the comfort seat, acceleration measurements took place at the floor connection (Figure 5.16 (b), left), beneath the seat surface, at the seat surface (Figure 5.16 (a) represents this configuration with/without subject), and at the seatback (Figure 5.16 (b), right). For the standard seat, accelerometers were placed at the floor connection (z-axis), beneath both seat surfaces (z-axis), at the seat surface (z and x-axes), and at the seatback (z and x-axes). The experiments were performed with an interior train temperature of approximately 20 °C.



(a)



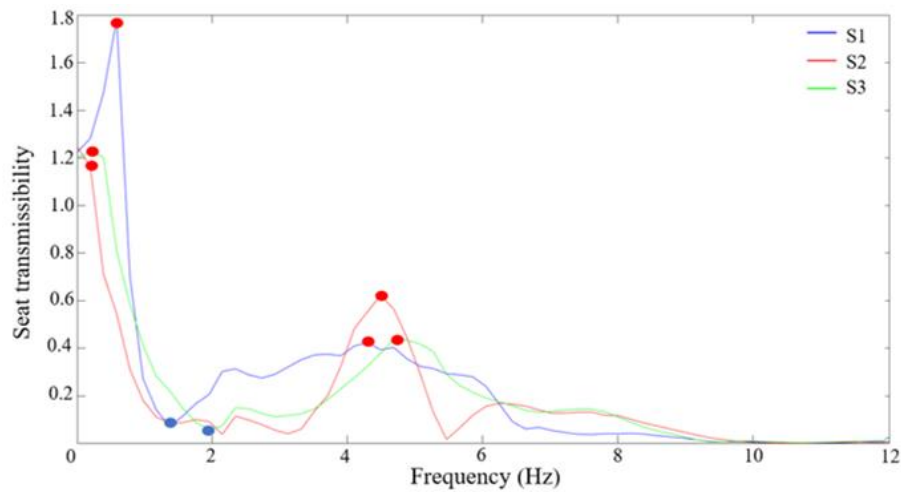
(b)

Figure 5.16. Experimental setup: (a) seat pad location; (b) accelerometers on seat frame structure.

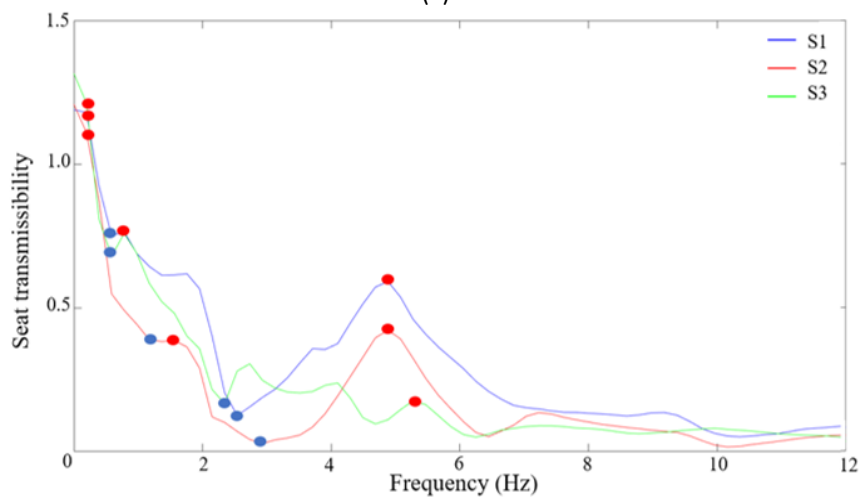
5.4.2 Results

5.4.2.1 Transmissibility curves

Figure 5.17 shows the transmissibility curves of the three subjects within the two seats. It is possible to observe the resonance (red marks) and antiresonance peaks (blue marks).



(a)



(b)

Figure 5.17. Transmissibility curves of Intercity train seat: (a) comfort seat; (b) standard seat.

Table 5.3 presents the resonance and antiresonance peaks regarding both seats. Due to the seat specification, namely seat design and foam restrictions, IC's seat transmissibility is expected to differ from those of AP train seats.

Table 5.3. Main resonance and antiresonance frequency values for comfort and standard seats of Intercity trains.

Subject	Comfort		Standard	
	Resonance (Hz)	Antiresonance (Hz)	Resonance (Hz)	Antiresonance (Hz)
S1	0.59	1.37	0.20	0.59
	4.30		0.78	2.54
			4.88	
S2	0.20	1.37	0.20	1.17
	4.49		1.56	2.93
			4.88	
S3	0.20	1.95	0.20	0.59
	4.69		0.78	2.34
			5.27	

Comfort seat transmissibilities are characterised by resonance frequencies between 0.20–0.59 Hz and 4.30–4.69 Hz. As on AP train seats, the higher transmissibility peaks occur at low frequencies, namely 0.20 and 0.59 Hz, while the antiresonances are found between 1.37 and 1.95 Hz. Resonance and antiresonance frequencies are similar for all subjects, which agrees with the results of Toward and Griffin [27]. The comfort seat is similar to those used in laboratory experiments. Therefore, a vertical resonance transmissibility between 4 and 6 Hz is anticipated, which agrees with the results presented by several authors and reinforces the influence of the movement restriction introduced by the cover leather on the AP train seats [18,27–29].

Standard seat transmissibility results are comparable for all subjects as the comfort seat has resonances of 0.20, 0.78–1.56, and 4.88–5.27 Hz and antiresonances between 0.59–1.17 and 2.34–2.93 Hz. Higher transmissibility peaks are found for this seat compared to the comfort class. Those results match the AP seat observation and comply with the studies conducted by Patelli and Griffin [18] and Zhang et al. [30].

Due to the positioning of accelerometers on the seatback structure of the seats, it was possible to explore the seatback fore-and-aft/floor vertical transmissibility. This transmissibility, illustrated in Figure 5.18, may provide important information about the seatback's local bending movements.

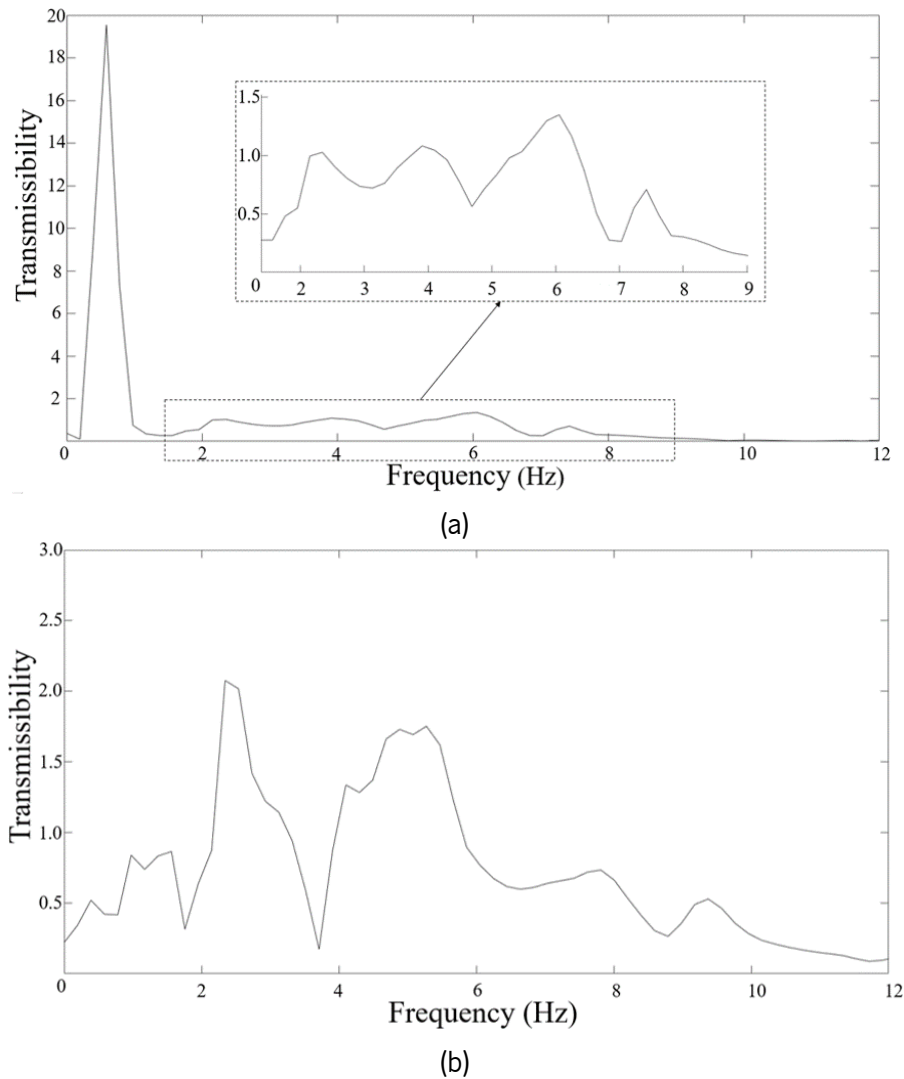


Figure 5.18. Seatback (x-axis)/Floor (z-axis) transmissibility: (a) comfort seat; (b) standard seat.

Prominent resonance equal to 0.59 Hz defines the seatback comfort seat, whereas those of the standard seat demonstrate main peaks of 0.98, 2.34, and 4.88 Hz. The modal identification is expected to prove the influence of seatback local bending movements regarding those frequencies.

5.4.2.2 EFDD method

The EFDD method was applied using ARTeMIS software [51]. Based on the assumption of AP seats, the modal analysis was conducted only for S1. Figure 5.19 shows the first two curves of the average normalised singular values of the spectral density matrices of the S1 comfort seat experiment, where it is possible to observe the peaks corresponding to the identified frequencies and mode shapes.

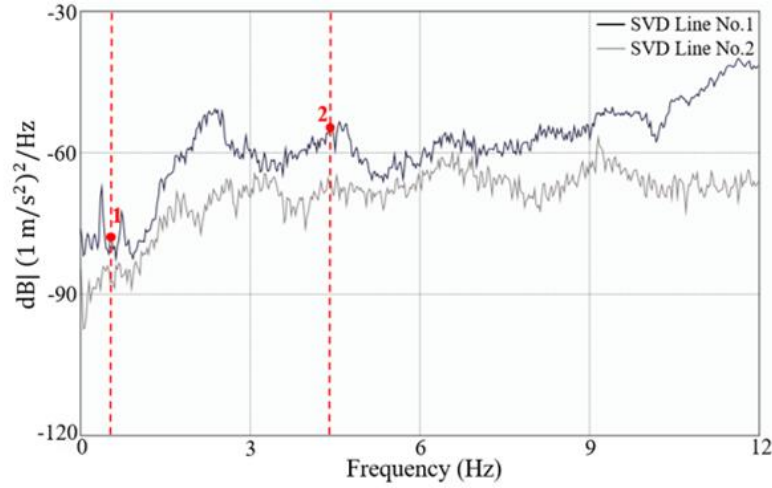


Figure 5.19. EFDD method: average normalised singular values of the spectral density matrices regarding Intercity comfort seat.

The seat movements derived from the vibration modes are represented in Figure 5.20, where f represents the average value of the natural frequency.

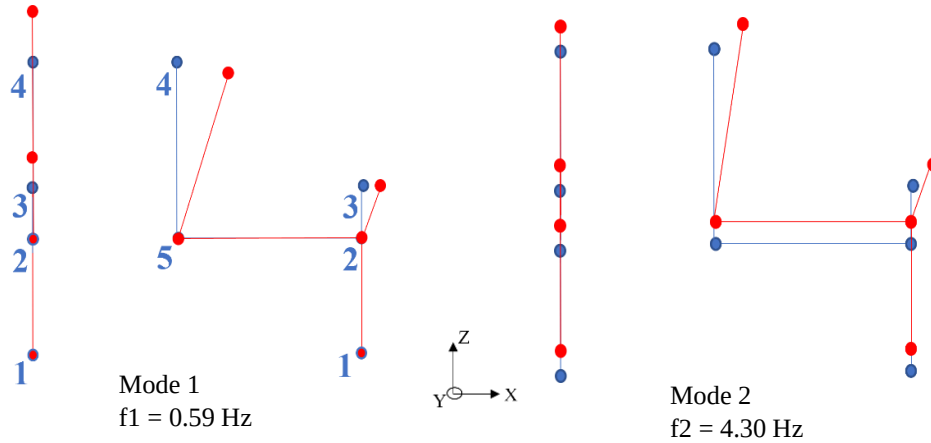


Figure 5.20. Comfort seat experimental modal parameters, where the front and lateral views are presented.

As estimated, each mode corresponds to a different seat movement. Vertical and longitudinal foam movements and seatback local bending movements characterise frequencies lower than 0.59 Hz. This frequency matches the one identified as a prominent resonance on the fore-and-aft seatback transmissibility curve. This factor validates the applied methodology and the experimental setup and reveals a strong connection between the transmissibility curve and the modal identification. Mode 1 is deeply connected with foam movements, which represents a dependency on the foam's capacity to absorb vibration.

Mode 2 is associated with a global movement of the vehicle's carbody. This induces a rigid body movement on the seat frame, coupled with foam distortions in the vertical and longitudinal directions and seatback local bending.

Concerning the standard seat experiment, Figure 5.21 illustrates the first two curves of the average normalised singular values of the spectral density matrices, where it is possible to observe the peaks corresponding to the identified frequencies and mode shapes.

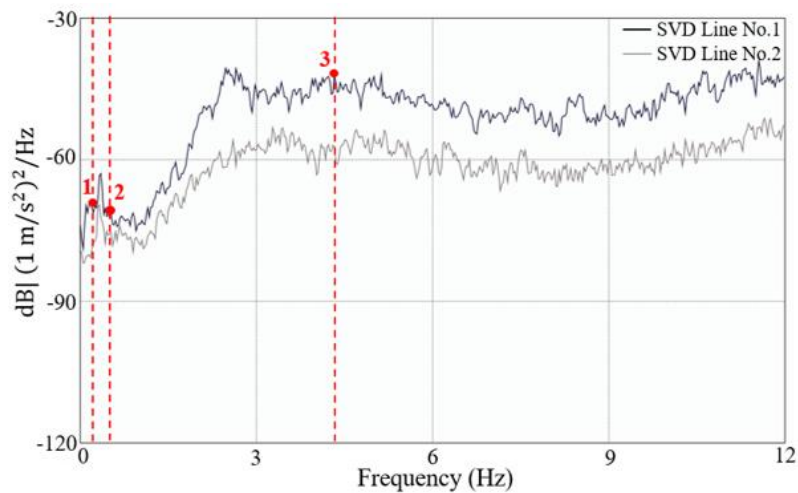


Figure 5.21. EFDD method: average normalised singular values of the spectral density matrices regarding IC standard seat.

Figure 5.22 illustrates the seat movements derived from the vibration modes, where f represents the average value of the natural frequency.

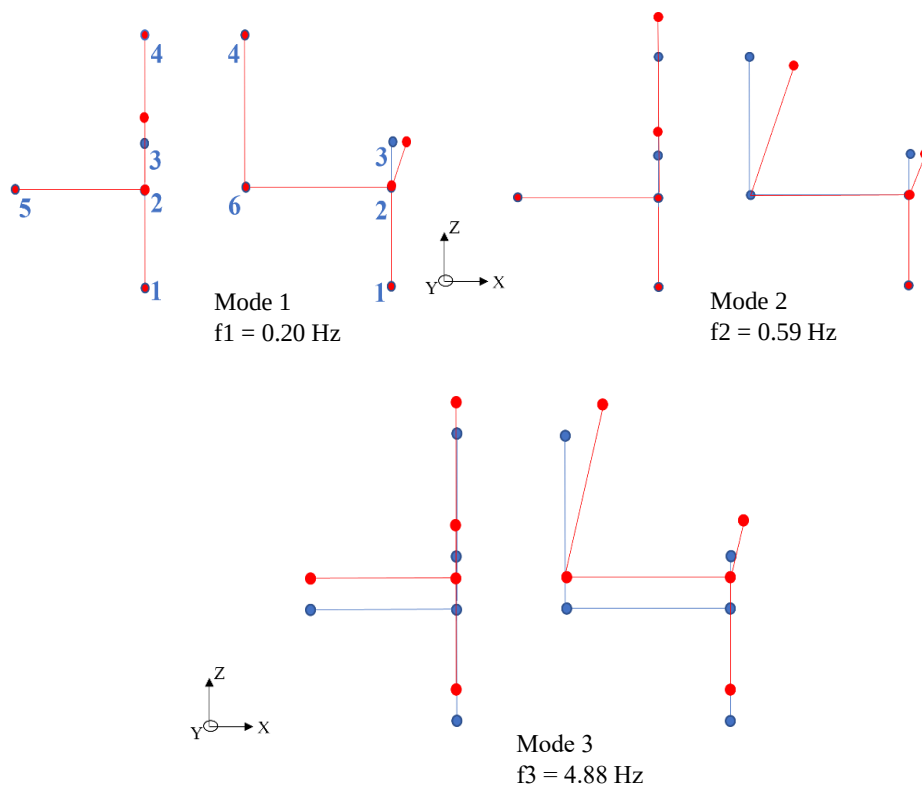


Figure 5.22. Standard seat experimental modal parameters, where the front and lateral views are presented regarding Intercity trains.

Mode 1 is characterised by the foam's incapacity to absorb low-frequency vibrations (<0.20 Hz), while Mode 2 combines that foam incapacity with seatback local bending movements. Mode 3 demonstrates rigid body movements induced by the car-body, associated with seatback local bending movements and foam vertical and longitudinal motion. As on the other analysed seats, the last mode is defined by a combination of the remaining modes.

The fore-and-aft seatback transmissibility results show resonance peaks within the modes presenting seatback local bending movements, complying with comfort seat observations. Modes 1 and 2 are related to vibration transmission associated with vertical and longitudinal foam movements, so these can be designated as local transmissibility. Mode 3 relies on structural and foam movements; thus, it can be classified as global and local transmissibility.

5.5 Conclusions

This chapter presented a dynamic experimental analysis of typical rail seats under a real train in situ environment. This analysis included the modal identification of the seat based on output-only methodologies, namely the transmissibility functions and the EFDD method. The study included the development of dedicated experimental setups that were applied on real train seats, namely the comfort and standard seats of AP and IC trains. Being employed in a real train environment, the experiments can realistically consider all aspects of the seat dynamics, particularly the effect of the flexibility of the seat surfaces and carbody components.

Based on the dynamic testing results, it was possible to draw conclusions about the influence of the seat structural movements and dependence on the foam vibration absorption capacity. Regarding AP train seats, the inter-subject variability did not affect transmissibility resonances and antiresonances. Moreover, the standard seat presented higher transmissibility peaks than the comfort seat. Compared with laboratory experiments, AP seats presented lower transmissibility resonance peaks, which reveals the influence of the seat structural frame and foam leather cover. These factors significantly modify the vibration transmission; particularly, the cover restricts the foam cellular morphology movements, leading to variations in foam absorption capacity, while the seat frame movements may couple with movements of the carbody components. Modal identification depicted seat bending movements and vertical foam movements. By matching transmissibility and modal identification, it was possible to associate the resonance frequencies with seat and foam natural frequencies and the corresponding amplified

movements. In contrast, the antiresonance valleys generated those movement changes on the structural support.

The IC train's comfort seat is similar to that used in laboratory experiments. The foam is freely placed on the seat surface, covered by a non-restricting fabric cover. Its results are close to those of laboratory conditions. The Intercity seats experimental setup allows for concluding about the influence of the seatback local bending movements on the transmissibility response. Seatback transmissibility resonances matched the local bending movement frequencies identified by modal identification. This way, the applied methodology was validated based on the strong correlation between the transmissibility curve and the EFDD method.

The present work demonstrated the influence of seat structural frame movements and foam vibration absorption on user–seat vibration transmissibility. Moreover, this is a pioneer study regarding train seat modal identification, which may be used for further studies concerning seat vibration reduction to increase passengers' comfort.

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Chapter VI - Influence of static factors on sitting comfort

Static comfort is relevant in low or no-vibration situations. The foam mechanical properties and interface pressure mainly evaluates the static comfort parameters. Another critical parameter affecting perceived comfort is the seat-passenger interface temperature. The present chapter presents a complete static evaluation of different foams and seat covers to assess the most suitable solution for railway seating applications.

Based on the evaluation of foam mechanical properties and interface pressure profiles, it was concluded that the foam presenting a higher density (80 kg/m^3) is the most prominent solution. Regarding the foam cover, a thermographic assessment demonstrated that the fabric cover induced lower temperatures at passenger interface contact, promoting higher comfort levels. It should be highlighted that experiments were conducted on real train seat cushions and environments with a thermographic camera and pressure map sensor.

6.1 Introduction

Public transportation users demand faster, safer, and more comfortable journeys. Passengers spend most of their time seated, so the seat assumes a crucial impact on users' comfort [1]. This way, seats should fulfil their primary support function and provide increased comfort. Perceived comfort is divided into static and dynamic categories, dependent on the presence or absence of vibration. Both are strongly connected, as the influence of one relies on the other. Thus, both comfort categories must be evaluated to properly quantify comfort levels. Without vibration, static comfort dominates the overall comfort evaluation [2,3].

When seated, passengers are in close contact with seat cushions, being those considered one of the most critical factors affecting sitting comfort [4,5]. Therefore, evaluating the foam's mechanical properties and its influence on passengers' comfort is critical. Traditionally, seat cushions are made of polyurethane (PU) foams. Those have been universally used in multiple industries due to their versatile physical properties, such as excellent sound absorption and low thermal conductivity, comfort properties, low cost and easy processing. PU foams are cellular polymers, typically produced by reacting an isocyanate with polyols in the presence of blowing and crosslinking agents and additives [6–8].

As mentioned in Chapter II, there is no consensus on comfort definition; thus, comfort quantitate evaluation is still ambiguous [9–12]. Several authors suggest evaluating seat physical characteristics and its relation with sitting comfort as the first approach to overcome the aforementioned limitation. From those physical properties, the hardness, the support factor (SAG factor) and the hysteresis loss were identified as strongly affecting seating comfort, becoming the main focus of most studies. Hardness corresponds to the foam's firmness, the SAG factor indicates the supporting property and the hysteresis loss correlates with resilience [7]. Understanding the influence of the seat's physical characteristics on passengers' sitting impressions is fundamental for designing the ideal foam, which can be accomplished by changing its mechanical properties to achieve high comfort levels [3,13].

According to De Looze et al. [14] comfort model, which is applied as the base comfort model of the present study, comfort and discomfort resulting from the interaction between the product, the user and the environment — being evaluated by a combination of psychological and physical factors. The users' expectations define psychological factors, being assessed based on questionnaires and rating scales (subjective evaluation). In contrast, the physical parameters depend on the human body weight, shape and anthropometric dimensions, being defined by objective measurements [13,15–17]. The passenger's pressure on the seat cushion strongly affects the seating interaction due to the biomechanical load imposed by the user's musculoskeletal structure. That load may lead to skin and tissue deformation,

affecting blood flow and the musculoskeletal system [18]. The skin has thermoreceptors capable of detecting temperature changes and four mechanoreceptors that provide information about touch, pressure, vibration, and cutaneous tension. The Meissner's corpuscles are exceptionally efficient in transducing information regarding tactile and sensitive changes. The Pacinian corpuscles, responsible for detecting vibration, have a lower response threshold than the Meissner ones acting faster than these. Merkel's disks and Ruffini's corpuscles are slowly adapted mechanoreceptors. The former specialises in detecting pressure changes, and the latter can detect stretch and shear stresses. The thermoreceptors and the mechanoreceptors record the stressed surface changes and send the information to the brain, leading to comfort perception [19–21]. Therefore, although the foam's mechanical properties influence comfort, the seat/skin interface pressure and temperature are also essential factors.

The present chapter deals with the evaluation of static parameters and their influence on passengers' discomfort. The foam properties of two samples were initially assessed in the lab. Then, those foams' interface pressure and temperature were evaluated using a pressure map sensor and an infrared thermographic camera. Moreover, it was also possible to draw conclusions about the influence of the seat cover.

6.2 Influence of foam properties in sitting comfort impressions

As previously described, foam cushions represent the primary contact between the user and the seat. Thus, some authors studied the relationship between foam's physical characteristics and sitting comfort. This connection was assessed by means of subjective questionnaires and interface pressure measurements.

Lei et al. [22] related hysteresis loss with seating comfort once it correlates with resilience. Hysteresis loss is defined as the percentage ratio between the area under the loading (0-75%) and unloading (75-0%) compression cycles. Its calculation proceeds as follows (6.1):

$$\text{Hysteresis loss \%} = \frac{A_{0-75\%}}{A_{75-0\%}} \quad (6.1)$$

Ideally, foams should present low hysteresis loss percentages, this value increases as resilience decreases [23,24]. Hysteresis loss is highly influenced by the cellular foam structure, specifically the cell/wall area ratio. During the compression cycle, the energy loss happens primarily due to the buckling affecting unrecovered cell walls and struts. Thus, to obtain low hysteresis, low cell/wall area ratios are required [25].

The SAG factor is another measure of foam's suitability for sitting applications. This is obtained by the ratio of the compressive load at 65% deformation ($F_{65\%}$) and that load at 25% foam deformation ($F_{25\%}$), as demonstrated in Equation (6.2):

$$SAG\ factor = \frac{F_{65\%}}{F_{25\%}} \quad (6.2)$$

Once the SAG factor provides an indication of the foam-supporting property, high values are associated with higher comfort performance. The supportive factor is influenced by the foam's cell structure and density. Regarding seating applications, a SAG value higher than 2.8 is recommended; otherwise, users may feel the seat pad bottom [13,23–26].

Lee and Ferraiuolo [27] identified foam thickness and hardness as significantly affecting sitting comfort. Hardness is defined by the 25% indentation load deflection (ILD). This relates to foam stiffness and defines the foam's resistance to deformation when applying a load. High values correspond to high firmness, whereas low values are associated with lower firmness [28]. Using foam samples with equal density and hardness but varying thicknesses (50, 75 and 100 mm), Neal [29] concluded that foam thickness does not influence hysteresis loss but influences the 25% load, as thicker foams reported higher forces.

Ebe and Griffin [13] conducted a study to relate the influence of foam properties, such as density, SAG factor and hysteresis loss, in sitting comfort impressions. The sitting impressions of twelve subjects were obtained to judge the comfort of four foams with equal hardness (≈ 205 N) but varying density (45–65 kg/m³). The high-durability seat (55 kg/m³) was rated as the most comfortable, whereas the lowest-density foam (45 kg/m³) was stated as the least comfortable. Moreover, the low-density foam presented the highest hysteresis loss (34%). In contrast, the high-durability foam demonstrated a lower hysteresis (29%). A high correlation was observed between the comfort scores and the SAG factor. A second experiment was performed to evaluate the influence of foam's hardness. The same twelve subjects rated the comfort perception of five foams with 25% ILD hardness between 120–285 N. Results suggested that hardness influences static comfort, but the preferred foam varied between subjects. Additionally, it should be highlighted that harder foams noticed the lowest hysteresis loss. Similar conclusions were reported by Moon et al. [23] when studying the production of PU foams with multiple layers. The foam considered the best for seating applications demonstrated a SAG factor around 3, hardness of 150 N and hysteresis loss of approximately 22.5%.

Analysing the aforementioned studies, the ideal foam is characterised by a high SAG factor, low hysteresis loss and intermedium to high density.

6.3. Influence of interface pressure in sitting impressions

While sitting, the human body is in direct contact with the seat cushion, exerting pressure due to the biomechanical load imposed by the user's musculoskeletal structure. Following this assumption, multiple authors explored and defined comfort based on the seat-passenger interface pressure. The pressure profile strongly connects with discomfort, as proved by the correlation obtained between objective and subjective evaluations, being capable of evaluating the biomechanic factors of sitting discomfort. Therefore, the seat static comfort evaluation usually begins by considering body pressure distribution [9,13,14,30].

Indeed, when seated, more than 70% of the human body weight is supported by the seat cushion. Since the human buttocks are not flat, the seat-passenger interface pressure varies over the seat surface. That feature leads to a significant pressure concentration in the ischial tuberosity area, resulting in pressure peaks. Those peaks may provoke low cell oxygen content, prompting fatigue, pain, and discomfort. Although defining a maximum pressure threshold is fundamental for providing high comfort levels and reducing the harmful consequences for passengers, no consensus has been obtained [3,30–32]. Nevertheless, multiple authors stated that 32 mmHg, corresponding to the capillary pressure, should not be exceeded. Higher pressure may obstruct the capillaries, limiting blood circulation and leading to oxygen deprivation in the tissues, causing discomfort [2,16,31,33,34]. In opposition, other authors defended that a seat is still considered comfortable when presenting a maximum pressure of 43.50 mmHg under the ischial tuberosities and 21.75 mmHg elsewhere. However, those authors defined that the maximum mean pressure should never exceed 37.75 mmHg; once the skin capillaries close at this pressure [15,32]. Besides, no consensus on defining the pressure distribution threshold has been reached, it is unanimous that a widely dispersed distribution without local peak concentration represents the ideal foam [2,15,16,32–35].

Pressure distribution profiles provide information regarding multiple parameters. Those more related to discomfort are the contact area, maximum pressure peaks (especially those near the ischial tuberosities) and average pressure [36,37]. Moreover, the pressure profile can be affected by several factors, namely the user's anatomical characteristics (weight, height, BMI, and body part) and foam properties (hardness, SAG factor, hysteresis, thickness, and contour).

Several authors reported lower peak pressure concerning heavier subjects. Those tend to have higher contact areas, leading to lower peak pressures but higher mean pressures. In opposition, thinner subjects present higher peak pressure around the ischial tuberosities [15,38]. Li et al. [38] evaluated

static factors affecting the comfort levels of high-speed trains. The authors group the volunteers' results according to their stature. Those with larger stature reported higher average contact area, higher average pressure (similar to that of medium stature volunteers) and lower average peak pressure than the small stature subjects. Hu et al. [15] evaluated the effect of BMI on sitting pressure distribution. Experiments run with three subjects with varying BMIs: underweight, normal, and obese. The obese subject generated the highest contact area, whereas the normal subject demonstrated lower maximum and mean pressures, and reduced contact areas. Moreover, results showed that the contact area would linearly increase according to increased subjects' weight and height.

The association between local and whole-body comfort was evaluated by Xu et al. [31]. Pressure measurements and subjective rankings were used to assess discomfort. Body parts were divided into four segments: back, waist, hips, and thighs. The hips were the most significant body part influencing whole-body discomfort, followed by the back, waist, and thighs. A similar investigation was conducted by Peng et al. [32]. However, local comfort was divided into eight parts: shoulders, mid-back, side back, waist, buttocks, and upper, side, and lower thigh. The shoulder, waist and buttocks were revealed to be the body parts most affecting overall comfort.

Pressure distribution may also be influenced by foam's physical properties, particularly hardness, SAG factor, hysteresis loss and thickness. In fact, multiple authors strongly link foam's hardness with interface pressure. Softer seats tend to induce higher comfort levels. Those generate a significantly larger contact area than that of a rigid seat, reducing this way pressure peaks. Additionally, higher pressure peaks around the ischial tuberosities are expected for rigid foams once these are less flexible than the soft ones. Thus, both seat and buttock deformations enlarge the contact area regarding a soft seat, whereas the subject's buttocks deformation mainly defines the rigid foams contact area [13,15,35]. As aforementioned, the SAG factor should be higher than 2.8 (to prevent users from feeling bottoming) and the hysteresis loss as reduced as possible [13,23–26]. The foam thickness is another important physical parameter to evaluate. Multiple authors stated that higher foam thicknesses induce higher comfort levels. Ebe and Griffin [13] assessed foam thickness's influence on sitting impressions. Results highlighted that thinner foams had more bottoming and, consequently, higher discomfort levels. Using a finite element model, Kumar et al. [39] investigated the influence of foam thickness (40, 60, 80 and 100 mm) on interface pressure. The authors concluded that increasing the foam thickness significantly reduces contact stress and, consequently, reduces interface pressure.

Foam contour may also influence interface pressure. Different contours affect the seat-user interaction resulting in varying interface pressures [40]. Tang et al. [41] evaluated the contour effect on

sitting impressions. Pressure measurements and local discomfort questionnaires evaluated discomfort. Three contours were produced: flat, bilateral protruding cushion and front protruding cushion. The flat foam was defined as promoting higher comfort levels; subjectively, it was rated with the highest overall comfort and, objectively, it presented the lowest pressure peaks.

Lastly, the foam cover is an essential element of the sitting system, as it directly promotes contact between the user and the seat. Depending on the material, this element also alters the sitting interface pressure. Wagner et al. [40] studied the influence of seat cover properties on perceived comfort. Two identical seats with different seat cover materials (leather and fabric) were evaluated by 30 subjects. Evaluation comprehended both objective (pressure measurements) and subjective (discomfort rating) methods. Moreover, subjects were blindfolded and got no information about the seats. The subjective evaluation noted that neither the leather nor the fabric cover were uncomfortable, as 16 subjects preferred the leather seat and 14 the fabric seat. Regarding the objective evaluation, the leather seat presented a maximum pressure 14 mmHg higher than that of the fabric cover.

6.4. Interface temperature influence on perceived comfort

Thermal comfort is an important parameter to consider when assessing passengers' comfort. Multiple authors stated that there is evidence that the heat exchange at the seat-user interface influences perceived comfort [42–45]. The heat exchanges between the human body and its surroundings in a railway vehicle can be compared to that in a car seat. Those heat exchanges are influenced by four mechanisms of heat transference, convective, radiative, conductive, and evaporative, and it is calculated as follows in Equation (6.3):

$$Q = Q_{cv} + Q_{cd} + Q_r + E_{sk} \quad (6.3)$$

where Q represents the total heat exchanges, Q_{cv} is the convective heat transfer, Q_{cd} relates to the conductive heat transfer, and E_{sk} means the evaporative heat transfer. In a close environment, as in the case of rail vehicles, the human body exchanges more heat with surroundings by radiation and conduction. Additionally, conduction heat exchanges assume a critical significance as a considerable portion of the body surface area is in contact with the seat [46]. This way, the seat cover is a determinant factor in thermal comfort.

When the contact pressure is associated with thermal accumulation, discomfort and harmful consequences may be raised for the users [47]. Current investigations focus more on analysing pressure

distribution comfort than the seat-passenger interface temperature [48]. This way, a research gap was identified.

Infrared thermography is a technique capable of being applied to investigate thermal exchanges. Thermographic cameras operate following the principles of Stefan-Boltzmann, Wien, Planck, and Kirchhoff laws [49]. The Planck law states that all bodies above absolute zero temperature (0 K, 273.15 °C) are constituted by small particles in continuous motion in a random direction that emit electromagnetic radiation [50,51]. Therefore, thermographic cameras detect the infrared radiation emitted by a body and convert it into a thermal image. In conclusion, this non-destructive and non-invasive technique allows the mapping of materials to locate temperature variations [52]. Thus, this methodology can help investigate the existence of microclimates at the seat cushions interaction [24].

Sales et al. [50] employed infrared thermography to evaluate the thermal response of seat cushions and backrests of eight different chairs (with varying designs and materials). Results demonstrated a similar behaviour of leather and fabric covers (main interest cover materials of the present chapter), as they reported final temperatures around 30 °C, promoting a temperature increase of approximately 6-7 °C.

Liu et al. [47] reported that foam thickness interferes with thermal conductivity. The temperature at the body-seat contact surface increases as the foam thickness increases. By applying an infrared thermographic camera on four different wheelchair cushions, Bui et al. [53] concluded that lower temperatures at the seat-user interface promote higher comfort levels.

Stockton and Rithalia [54] investigated the influence of both seating temperature and interface pressure on sitting discomfort levels. Contrary to the results reported by other authors, results suggested that high temperatures were not necessarily associated with discomfort, and low interface pressures may not be linked to comfort. These contradictory results highlighted the need to perform more experimental campaigns regarding static sitting comfort and the parameters capable of affecting it.

6.5. Experimental campaign

The mechanical properties, interface pressure and temperature of four foams were assessed to investigate which foam and seat cover are more suitable for railway seating applications. Foams were characterised based on its density, thickness, SAG factor, hardness and hysteresis loss, and induced interface pressure and temperature. The suitability of the infrared thermography method to perform temperature mapping on the current application should be highlighted. Both leather and fabric have high

emissivity, 0.96 and 0.92, respectively [55]. This parameter induced a reduced influence of the environment on the method. In opposition, if the materials' emissivity were low, the environment would significantly impact the method, limiting its suitability [56].

Long-distance railways generally have two-seat categories defined based on seat performance. Those with higher comfort levels are rated as comfort class seats, whereas those with suitable but less comfortable performance are rated as standard class seats. Seats differ in dimensions and, consequently, cushion thickness. Comfort seats have thicker foam cushions. Currently, the AP comfort seats present a total thickness of 190 mm and a 60 mm thickness under the users' ischial tuberosities. The standard seat's thicknesses decrease to 130 mm and 40 mm for total and local thickness, respectively. The present study uses the current AP train, comfort, and standard seats, as well as two foam samples with mechanical properties equal to those previously employed before the 2017 AP renovation [57,58]. While the current foams have a 40 kg/m³ density, the previous foams have 80 kg/m³. Moreover, the current AP seats have a leather cover, while the older AP seat covers are made of fabric.

6.5.1 Experiment 1: Mechanical properties assessment

Following both ISO 2439 [59] and ISO 3386 [60] recommendations, an experimental setup was developed to measure and calculate foams hardness, SAG factor and hysteresis loss. The setup consists of a hydraulic actuator (1) connected to a 200 kN load cell (2) and a posterior 5 kN load cell (for obtaining accurate and noise-free data) (3). A circular plate (4) was attached to the 5 kN load cell, which performs complete contact with the seat sample (5). The actuator's internal LVDT measured the circular plate displacement. A control and acquisition system was used to control the actuator speed and record and analyse the data. Figure 6.1 illustrates the experimental setup.

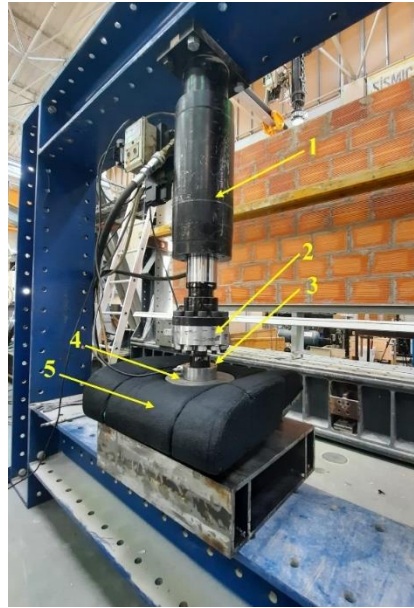


Figure 6.1. Experimental setup specially developed for measuring foam mechanical properties.

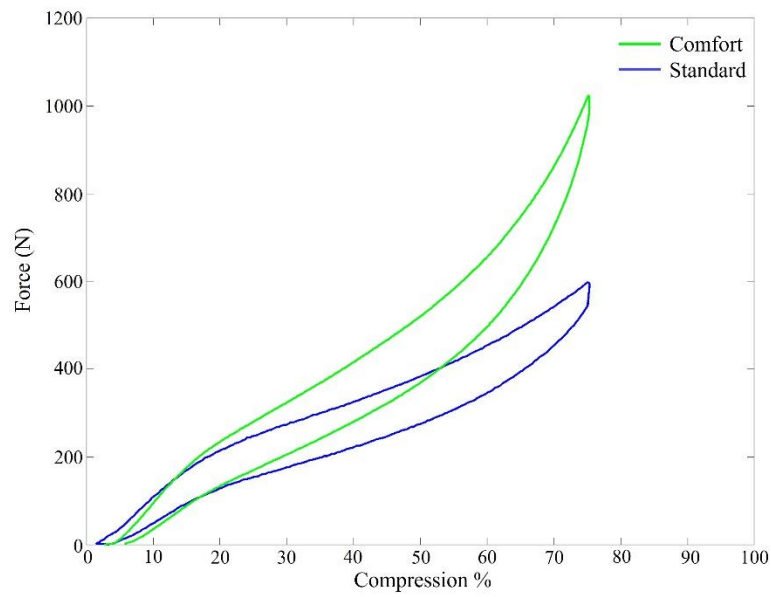
Both ISO 2439 [59] and ISO 3386 [60] experiments elapsed at a 100 mm/min constant speed with a 200 mm diameter circular plate.

Hysteresis loss and SAG factor experiments run only in foams without cover. These were applied to the 25% ILD hardness experiments to avoid damage to the covers. Table 6.1 presents the hysteresis loss percentages and the force achieved at 75% deformation.

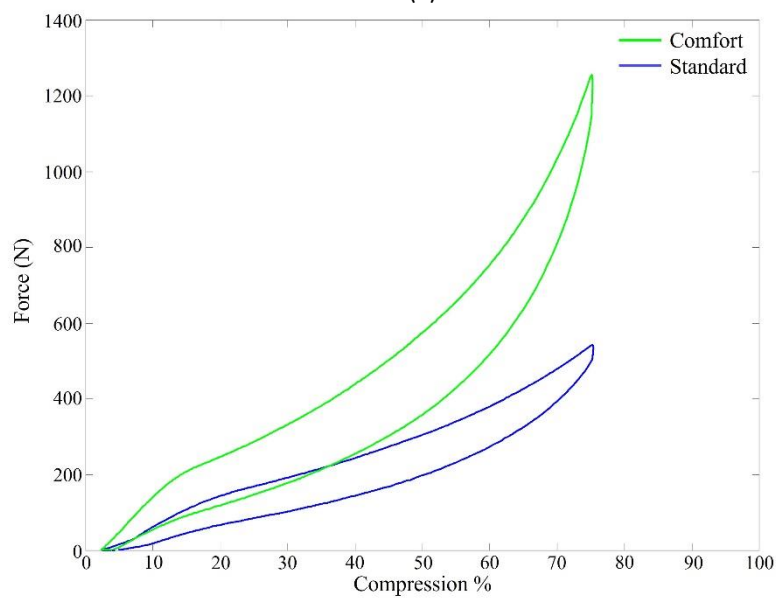
Table 6.1. Hysteresis loss percentage and force at 75% deformation for the four analysed cushions.

Seat cushion	Hysteresis loss %	$F_{75\%}$
Current comfort seat	13.7	1024
Current standard seat	13.8	598
Older comfort seat	15.1	1255
Older standard seat	14.9	542

Similar results were obtained regarding the cushions of the same foam type, which may indicate that the foam thickness does not influence the hysteresis loss percentage, complying with the observations carried out by Neal [29]. Comparing the results of the current and older seats, the latter presented slightly higher, but not significant, hysteresis loss. Therefore, considering only this property, both seats are expected to perform well and similarly. Moreover, the results have demonstrated lower values than those reported by Ebe and Griffin [13] and Moon et al. [23]. Figures 6.2 (a) and (b) illustrate the hysteresis loss of current and older AP seat cushions, respectively.



(a)



(b)

Figure 6.2. Hysteresis loss illustration of (a) current AP seats and (b) older AP seats.

Regarding the SAG factor, as mentioned above, it should be, ideally, superior to 2.8 for seating applications [13,23–26]. Table 6.2 presents the calculated values for both foam types.

Table 6.2. SAG factor results.

Seat cushion	SAG factor
Current comfort seat	2.7
Current standard seat	2.0
Older comfort seat	3.2
Older standard seat	2.6

Observing the results, the older foams demonstrated a higher SAG factor than the new ones. Its results are closer and superior to 2.8 regarding the standard and comfort cushions, respectively. Current and older seat foams are different in terms of density, but equal in dimensions. Therefore, based on the current results, it may be concluded that density is affecting the foam-supporting capacity. Moreover, the current standard seat has the lowest supporting factor of all foams. When comparing both seat types (comfort and standard) SAG factors, an increase is noticed for the thicker seat, which may indicate the influence of foam thickness on this physical property.

The 25% ILD hardness evaluated hardness. To understand the effect of the seat cover, cushions were compressed with and without cover, and the increasing hardness percentage was calculated. Table 6.3 exhibits the 25% ILD cushion hardness with and without seat cover and the increase %.

Table 6.3. Foam hardness results with and without a seat cover.

Seat cushion	25% ILD hardness (foam) (N)	25% ILD hardness with seat cover (N)	Increasing %
Current comfort seat	288	360	26
Current standard seat	250	320	28
Older comfort seat	271	354	44
Older standard seat	167	240	30

By analysing the results of Table 6.3 it can be concluded that current foams have a higher hardness than older ones. Moreover, hardness increases as the foam thickness rises, which is demonstrated by comfort foams that show a higher 25% ILD hardness than the standard ones, in agreement with Neal [29]. Additionally, the seat cover highly influences the system's (foam and cover) hardness. While the leather cover promoted a maximum increase of 28%, the fabric cover corresponded to a 44% hardness increase. It should be highlighted that if a cover is stretchable and loosely connected to the foam, its mechanical properties can be more predominant as the foam can freely deform. In opposition, a stiff cover tightly attached to the foam may limit its deformation behaviour and, consequently, influence its performance [18].

Additionally, an extra experiment assessed the foam and cover capacity for absorbing energy. That consisted of releasing a ball (52 mm diameter and weighing 127 g) and measuring its initial and bump heights, Figure 6.3. That was constituted by the seat (with and without cover) (1), a motion sensor CBR 2 (Texas Instruments) (2) [62] capable of measuring and recording distance, velocity, and acceleration, connected with a computer (3) and the ball (4). The calculation of energy absorption %, follows Equation (6.4):

$$\% E_{abs} = \frac{v_2}{v_1} \times 100 = \left(\frac{h_2}{h_1} \right)^{1/2} \times 100 \quad (6.4)$$

where v_1 and h_1 are corresponding to the ball's initial speed and height and v_2 and h_2 represent the ball's rebound speed and height. It was assumed that the ball acts as a rigid body. This way, the ball did not lose energy, but the seat cushion suffered deformation due to the collision [61].



Figure 6.3. Experimental setup employed to assess the energy absorption.

Measurements were recorded at 50 Hz sample frequency. Experiments run five times for each cushion with and without the seat cover. Table 6.4 presents the experiments' mean energy absorption percentage.

Table 6.4. Mean energy absorption percentage with and without seat cover.

Seat cushion	Energy absorption % (foam)	Energy absorption % with cover
Current comfort seat	68	82
Current standard seat	66	76
Older comfort seat	71	73
Older standard seat	58	69

The cover increases the energy absorption percentage, especially the leather cover. At the current AP seats, energy absorption increases by 14 % and 10%, respectively, for the comfort and standard seats. That absorption % increase is less noticed for the older seats, as the fabric cover only increased 2 % and 11% of the energy absorption for the comfort and standard cushions, respectively. This way, based on the hardness increase and the energy absorption percentage, the leather cover appears to be more

suitable for seating applications. Nevertheless, more experiments need to be performed to properly evaluate the cover influence.

6.5.2. Experiment 2: the influence of seat-passenger interface pressure and temperature

A set of dedicated experimental tests were developed and performed to evaluate interface pressure and temperature influence on sitting comfort. The University of Minho Ethics Committee previously approved the experiment's realisation (Appendix I). Before the beginning of the experiments, the volunteers gave their informed consent (Appendix II). Three volunteers (2 male and 1 female) participated in the experiment. Table 6.5 illustrates the subjects' anthropometric characteristics.

Table 6.5. Volunteers' anthropometric characteristics.

Subject	Gender	Age (Years)	Mass (kg)	Height (m)
S1	Female	25	58	1.70
S2	Male	26	80	1.87
S3	Male	39	115	1.85

The experimental setup was designed to simultaneously assess pressure and temperature at the seat-passenger interface. The pressure was measured using a CONFORMat, developed by Tekscan Inc [63], presenting a sensitive area of 471.4 mm x 471.4 mm. The pressure map was positioned at the seat surface, where the subjects sat. A FLIR A325sc thermal imaging camera was positioned perpendicularly to the seat to evaluate the seat temperature [64]. Both, pressure map and thermographic camera, were connected to individual computers containing specialised software. Figure 6.4 illustrates the complete experimental setup.



Figure 6.4. Experimental setup developed to assess the pressure and temperature at the seat-passenger interface.

The experiment consisted of sitting for 10 minutes, while pressure was measured and recorded during the entire sitting experience at a 1 Hz sample frequency. Maximum peak pressure (P_{max}), average pressure (P_{avg}) and contact area were analysed. Concluded the 10 minutes period, thermal images of the seat were obtained. Moreover, following the aforementioned studies of multiple authors that evidenced the importance of matching objective and subjective static evaluations, volunteers rated their total and local sitting comfort impressions using a 7-point scale (Table 6.6). Local comfort was divided into four body parts, as demonstrated by Figure 6.5.

Table 6.6. Subjective 7-point comfort/discomfort rating scale.

Ranking	Comfort/discomfort level
-3	Very uncomfortable
-2	Uncomfortable
-1	Slightly uncomfortable
0	Neutral
1	Slightly comfortable
2	Comfortable
3	Very comfortable

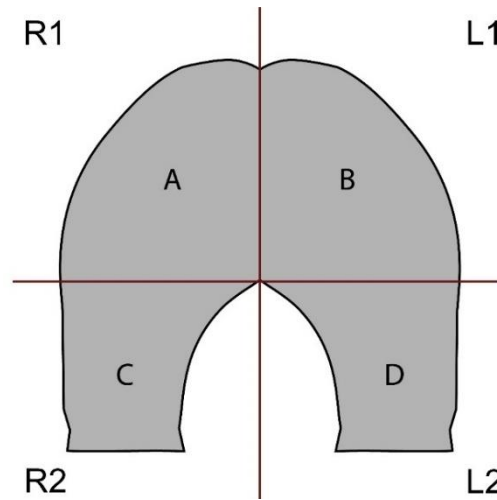


Figure 6.5. Local body parts distribution.

The experiment was performed by the three subjects in the current AP seats to investigate the effects of users' anthropometric characteristics. After assessing the effects, subject S1 experimented with the older seats and fabric cover to compare seats (current and older), matching results with foam's mechanical properties and assessing the best seat configuration (foam and cover).

6.5.2.1 The influence of anthropometric characteristics

The three subjects performed the experiments at the current AP train seats (comfort and standard) to evaluate the influence of users' anthropometric characteristics on perceived comfort. Pressure results regarding the comfort seat can be found in Table 6.7.

Table 6.7. Maximum and mean pressure and contact area regarding the current comfort AP seat.

Sub.	P_{max} (mmHg)				P_{avg} (mmHg)				Contact area (cm ²)
	R1	R2	L1	L2	R1	R2	L1	L2	
S1	37	26	29	20	29	20	23	15	1076
S2	57	18	50	17	46	16	44	14	1060
S3	41	29	65	27	35	22	58	22	1339

By observing the results, both, maximum and mean pressures, demonstrated values above the maximum 32 mmHg. Some authors defined this threshold as the trigger for developing discomfort and increasing the risk of health consequences, particularly for longer sitting exposures [2,16,31,33,34]. Those pressures and contact areas revealed an increasing tendency related to the subject's weight. Moreover, pressure peaks were obtained at the ischial tuberosities regions (R1 and L1). Those measured for subjects S2 (57 mmHg) and S3 (65 mmHg) are even above the pressure threshold (43.50 mmHg) stated for that specific region [15,32]. Additionally, Hu et al. [15] and Peng et al. [32] suggested that the

mean pressure should never exceed 37.75 mmHg elsewhere in the sitting region, which is true for the present case. S1 and S3, lightest and heaviest subject's pressure profiles are illustrated in Figure 6.6.

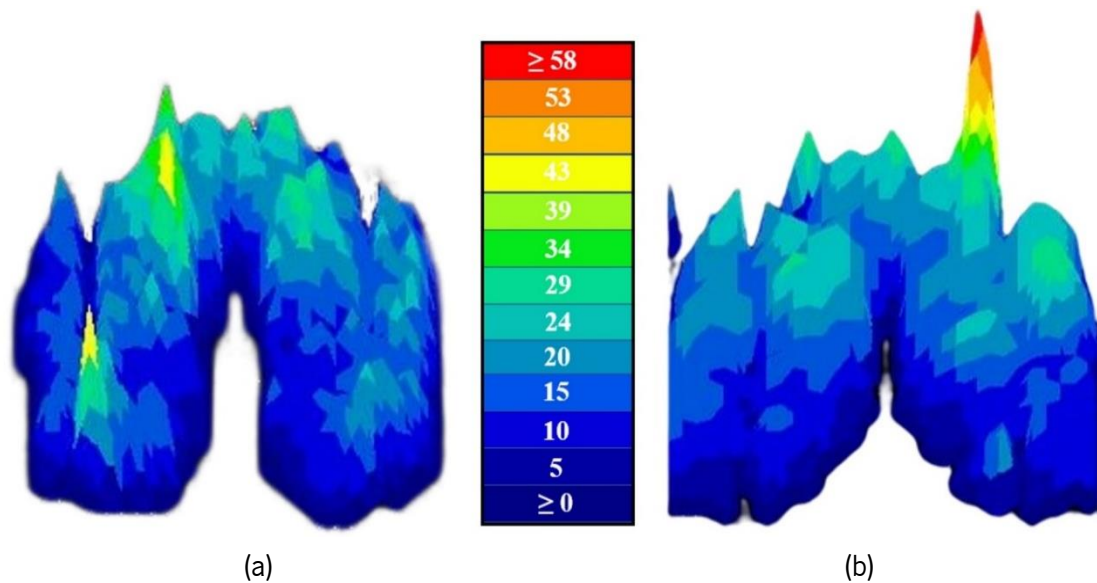


Figure 6.6. Current AP comfort seat pressure profiles where: (a) S1 subject profile and (b) S3 subject profile.

As observed, the two subjects demonstrated different pressure profiles, being the S3 larger and the S1 with a higher length. Comparing both contact areas, as expected, the heaviest subject produced a higher contact area than the lightest individual. Table 6.8 presents the pressure distributions regarding the standard seat.

Table 6.8. Maximum and mean pressure and contact area regarding the current standard AP seat.

Sub.	P_{max} (mmHg)				P_{avg} (mmHg)				Contact area (cm ²)
	R1	R2	L1	L2	R1	R2	L1	L2	
S1	38	21	35	24	28	16	28	19	1100
S2	51	15	46	34	41	13	38	25	1035
S3	50	49	46	35	37	38	40	29	1350

As on the comfort seat, all subjects presented maximum pressures above 32 mmHg for the standard seat as well. Nevertheless, those pressure peak values are slightly inferior to those of the comfort seat. The same decreasing tendency was observed for the mean pressure. This fact can be justified by the highest contact areas promoted by the standard seat.

Regarding the interface temperature, results present the maximum, minimum, and average temperatures, and the difference between maximum and minimum temperatures for the sitting area and for a profile line. Figure 6.7 (a) shows a 3D thermal image in the course of the experiment; Figure 6.7 (b) the region of interest and a profile line, of the seat.

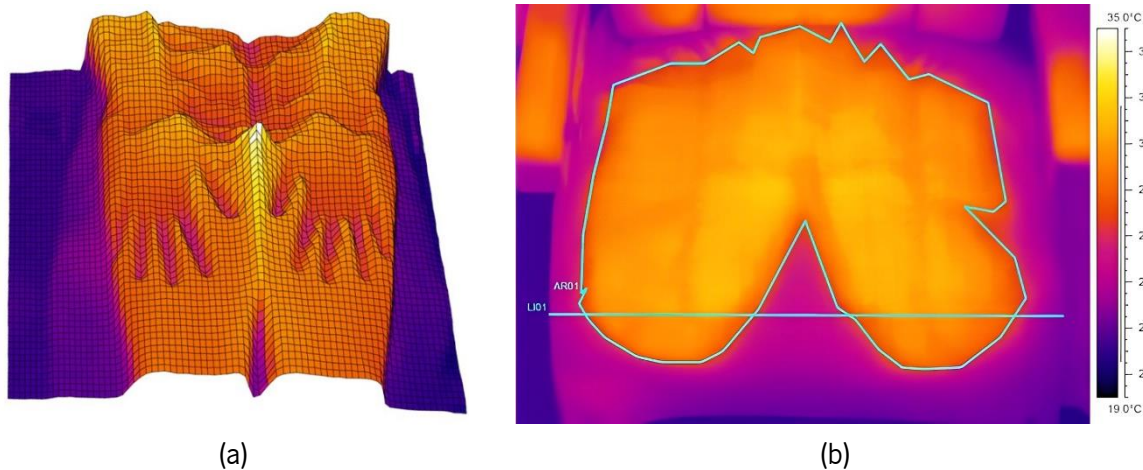


Figure 6.7. Thermographic illustrations where (a) is on course experiment and (b) defined sitting area and analysis line.

Results concerning the comfort seat are presented in Table 6.9.

Table 6.9. Temperature records regarding the comfort seat.

Subject	Sitting area				Sitting profile line			
	Min. (°C)	Max. (°C)	Max-Min (°C)	Avg. (°C)	Min. (°C)	Max. (°C)	Max-Min (°C)	Avg. (°C)
S1	28	34.1	6.1	31.8	25.2	32.9	7.7	31.8
S2	27.1	33.1	6.0	31.3	25.0	31.2	6.1	28.5
S3	24.4	30.2	5.8	27.7	23	28.2	5.3	26.4

Regarding the sitting area, similar temperatures were obtained for the difference between maximum and minimum values. This result may indicate that the user's anthropometric characteristics do not influence the temperature increase. The same parameter of the sitting line revealed that subject S1 induced higher temperature differences when compared to the seat's initial temperature. Moreover, the same subject also induced the highest maximum and average temperatures in the sitting area. This is the only female subject, which may justify the results. Therefore, although the passengers' anthropometric features (weight and height) do not impact the temperature, it may be observed that gender is a cause of influence. Regarding standard seat, results are exhibited in Table 6.10.

Table 6.10. Temperature records regarding the standard seat.

Subject	Sitting area				Sitting profile line			
	Min. (°C)	Max. (°C)	Max-Min (°C)	Avg. (°C)	Min. (°C)	Max. (°C)	Max-Min (°C)	Avg. (°C)
S1	26.2	32.9	6.7	30.5	23.9	31.3	7.4	27.6
S2	25.1	31.7	6.7	29.6	21.8	31	9.2	28.1
S3	24.3	32.1	7.8	29.8	23.3	31.1	7.8	28.5

Results of standard seats revealed a similar tendency to that of comfort, both demonstrated equivalent maximum and average temperatures in the sitting area and profile line.

Subjectively, three subjects unanimously ranked the ischial tuberosity areas (R1 and L1) as "Slightly uncomfortable", which in fact, exhibited the highest-pressure peaks. Therefore, complying with the findings of Xu et al. [31] and Peng et al. [32], the ischial tuberosity area seems to be the one most influencing the perception of sitting comfort. Additionally, based on the mentioned assumption, it is also possible to conclude that pressure profiles were strongly linked to discomfort rankings [9,13,14,30]. Regarding temperature, the similarities between experiment results did not allow to conclude about its impact on sitting impressions. That influence will be further analysed in the following sub-section. It should be highlighted that the small number of volunteers is the main limitation of this experiment.

6.5.2.2. The influence of seat and cover features on sitting comfort

To verify the influence of the seat and the cover on sitting comfort, S1 subject performed experiments with the current and older AP seats. As aforementioned, these seats have foams with similar dimensions, but different densities. Moreover, their covers are produced from different materials. This way, it will be possible to investigate the influence of foam mechanical properties on interface pressure and the impact of interface temperature promoted by the seat cover.

Results regarding the interface pressure of current and older AP comfort seats are depicted in Table 6.11.

Table 6.11. Maximum and mean pressure and contact area regarding the current and older AP comfort seat for subject S1.

Seat type	P_{max} (mmHg)				P_{avg} (mmHg)				Contact area (cm²)
	R1	R2	L1	L2	R1	R2	L1	L2	
Current	37	26	29	20	29	20	23	15	1076
Older	33	16	27	17	28	14	21	14	983

Generally, the older seat presented a lower average and peak pressures. Although the main peak pressure occurs at the same region as current seats (R1), it presents a lower 4 mmHg magnitude. Therefore, based on the previously found correlation between discomfort and pressure distribution, it can be concluded that the older foams induce higher comfort levels. This result is also sustained by the lower hardness presented by the older foams [13,15,35]. Pressure profiles (Figure 6.8) highlighted the differences between both foams. The current foam (Figure 6.8 (a)) induced multiple pressure peaks at the ischial tuberosities regions and a generally higher average pressure. Concerning the older foam

(Figure 6.8 (b)), a reduced number of localised pressure peaks around the ischial tuberosities are observed. Those are coupled with a globally distributed pressure, reducing the average pressure.

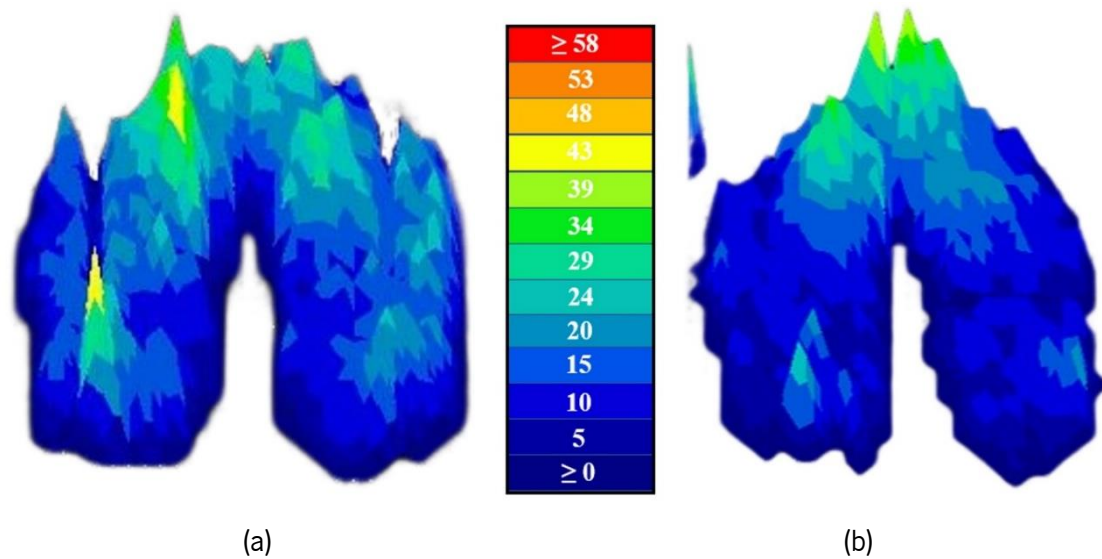


Figure 6.8. Pressure distribution profiles of (a) current AP comfort seats and (b) older AP comfort seats.

As described in Table 6.12, similar pressure tendencies were obtained on the standard seats.

Table 6.12. Maximum and mean pressure and contact area regarding the current and older AP standard seat for subject S1.

Seat type	P_{max} (mmHg)				P_{avg} (mmHg)				Contact area (cm ²)
	R1	R2	L1	L2	R1	R2	L1	L2	
Current	38	21	35	24	28	16	28	19	1100
Older	33	16	19	14	25	13	16	12	981

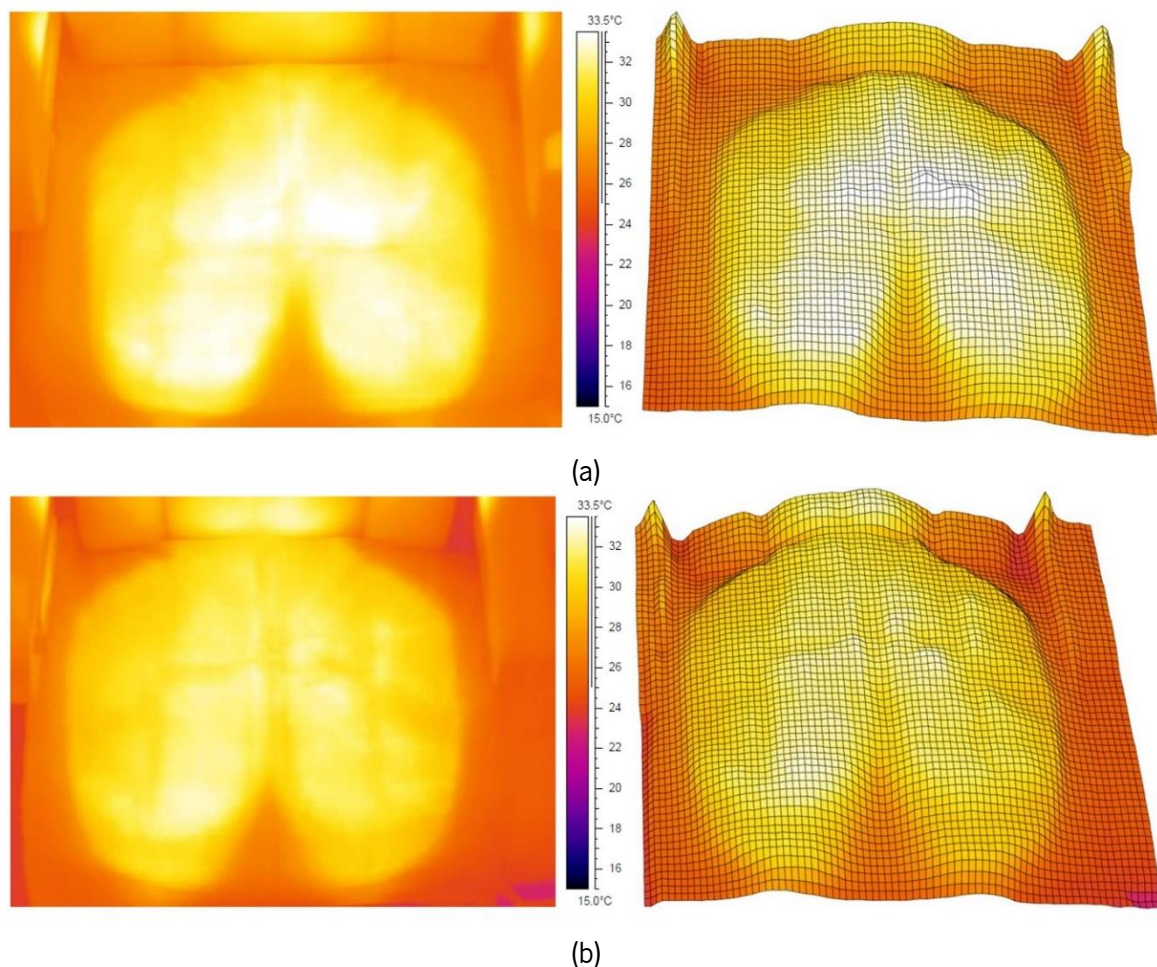
Standard and comfort seats only differ in terms of dimensions, namely thickness. Comparing the similarity of results of those seat types, it can be concluded that thickness is not influencing pressure distribution. These findings contradict Ebe and Griffin [13] and Kumar et al. [39], which stated that increasing foam thickness reduces interface pressures.

Seat cover influence was assessed by the thermographic images. The evaluation methodology was the same as in section 6.5.2.1; a sitting area and a defined profile line were applied. Table 6.13 presents the thermal results of both seat covers.

Table 6.13. Temperature records regarding the different seating covers.

Seat type/Cover	Sitting area				Sitting profile line			
	Min. (°C)	Max. (°C)	Max-Min (°C)	Avg. (°C)	Min. (°C)	Max. (°C)	Max-Min (°C)	Avg. (°C)
Comfort/Leather	28	34.1	6.1	31.8	25.2	32.9	7.7	31.8
Comfort/Fabric	19	27.1	8.1	24.1	17.1	25.1	7.9	20.9
Standard/Leather	26.2	32.9	6.7	30.5	23.9	31.3	7.4	27.6
Standard/Fabric	18.7	27.5	8.8	24.1	16.7	26.3	9.6	23.6

Analysing Table 6.13 results it was noticed that fabric cover seats have a lower minimum, maximum and average temperatures, independently of the seat type. Similar results were found within the same cover seats, meaning the non-influence of seat thickness. For the leather cover, both comfort and standard seats presented minimum temperatures of approximately 28 °C, whereas the maximum temperature was around 33 °C, see Figure 6.9.

**Figure 6.9.** Thermographic profiles of leather cover seats, where (a) is comfort seat and (b) standard seat.

When considering the fabric seats, the temperature results slightly decreased. Likewise, minimum temperatures of around 19 °C and maximum temperatures of 27 °C were found, as illustrated in Figure 6.10.

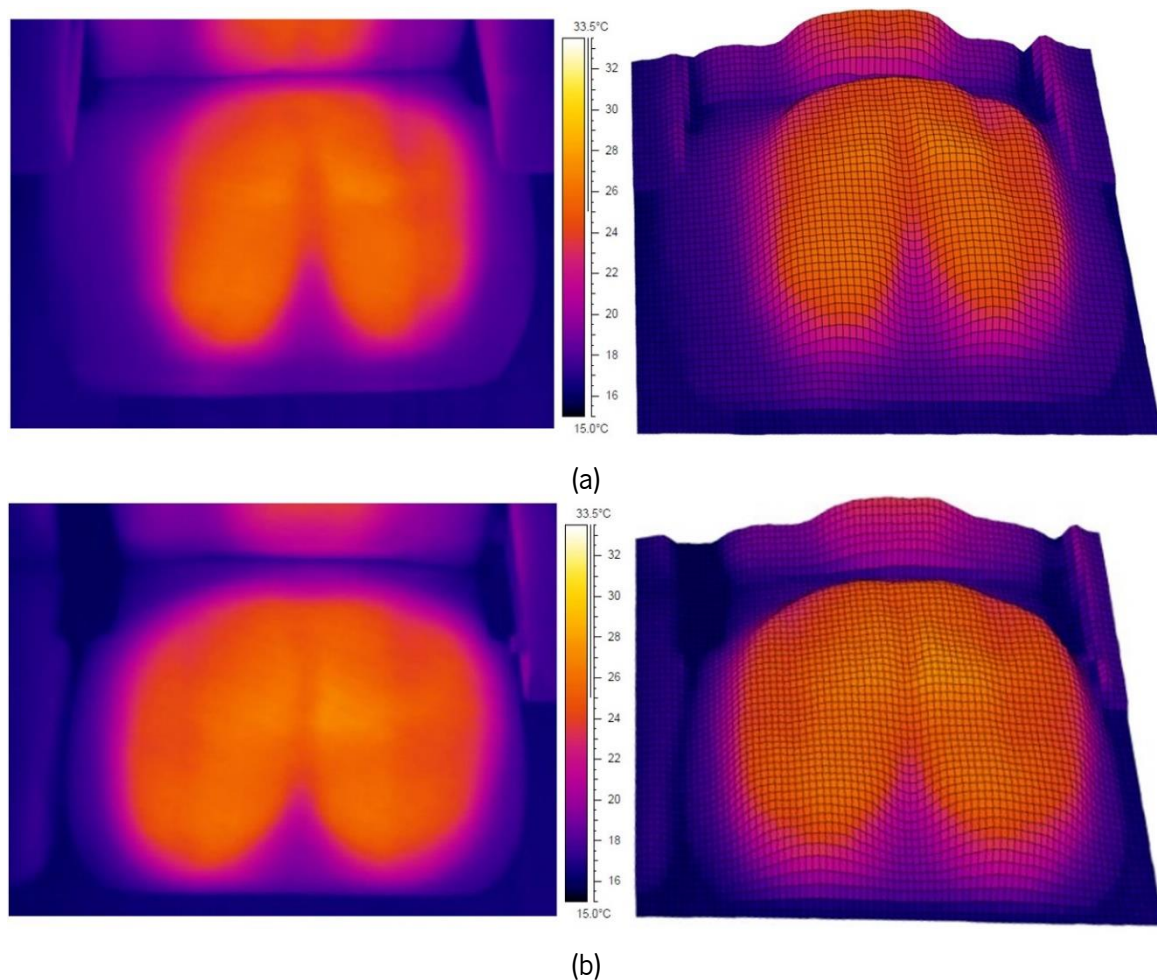


Figure 6.10. Thermographic profiles of fabric cover seats, where (a) is comfort seat and (b) standard seat.

Moreover, it should be noted that regarding the average temperature, fabric covers presented values of 24 °C, whereas that of leather covers was around 31 °C. Results contradict the findings of Sales et al. [50], who reported that leather and fabric covers have similar thermic behaviour, and that of Liu et al. [47], once foam thickness did not influence results when using the same cover material.

Based on the assumption stated by Bui et al. [53] that lower temperatures at the seat-user interface promote higher comfort levels, it can be concluded that fabric covers are more suitable for railway seat applications than leather covers. Results agree with those reported by Bartels [65], Wölfling et al. [66] and Wegner et al. [40], where fabric covers revealed superior seat comfort than leather covers. Nevertheless, it should be highlighted that leather covers demonstrated a higher capacity to absorb

energy and less hardness increase. The latter parameter may be linked to the cover foam connection [18]. Therefore, there is still space for fabric cover improvements and attachment within rail seats.

6.6. Conclusions

In the absence of vibration, static comfort factors mainly influence passengers' perceived comfort. Static comfort is usually assessed using foam mechanical properties and interface pressure experiments. Additionally, the influence of temperature at the seat-passenger interface was also evaluated by employing an infrared thermographic assessment. This methodology revealed its suitability due to the high emissivity of fabric and leather covers.

Interface pressure analysis allows a conclusion regarding the seat's consequences on the user (increased pressure). In contrast, the thermographic analysis permits measuring the opposite effect, i.e., the effect that the passenger induces on the seat (increased temperature). In this way, these two methods can be considered complementary to the sitting comfort analysis.

Initially, an analysis of the influence of users' anthropometric characteristics on interface pressure was performed. The results partially agree with those reported by Li et al. [38], as higher mean pressures and larger contact areas were obtained for heavier people. However, contrary to this author, higher peak pressures were also demonstrated for heavier individuals. Moreover, the pressure profile of the lighter subject and the heavier individual also show significant differences. While the former shows a longer pressure profile, the latter evidence a wider profile. The pressure in the ischial tuberosities area significantly influences the subjective results of discomfort. All pressure peaks were located in this area, which was rated as "Slightly uncomfortable" by all subjects. Thus, it is possible to conclude that the pressure profiles are directly related to discomfort levels.

To assess the best foam and cover for railway seating application, two foams with different densities and two covers made of different materials (leather and fabric) were analysed. The foams have the same properties as the current (lower density) and older (higher density) AP train seats. Older foams exhibited better pressure profiles (lower average and maximum pressures) and distributed the pressure more uniformly over the contact area. Combining these results with the assumption that lower pressure levels are associated with higher comfort levels, it is possible to conclude that the higher-density foams have a better static performance than the lower-density ones. This statement is also sustained by their mechanical characteristics, especially the high SAG factor and the low 25% ILD hardness. Both foams show similar results regarding hysteresis loss and energy absorption capacity, so these are not

considered differentiating factors. Moreover, by comparing comfort and standard seats, it was noticed that foam thickness does not influence pressure measurements, thus contradicting what has been reported by other authors.

Finally, regarding selecting the more appropriate cover, it was observed that the fabric cover promotes maximum, minimum, and average temperatures lower than the leather cover. Thus, this one is the most suitable for application in railway seats since lower interface temperatures promote higher comfort levels.

Moreover, it should be highlighted that the experiments elapsed with real seat foams and not isolated foams, as reported in most bibliographic research. Nevertheless, the reduced number of volunteers participating in the experiment should be noted, representing its main limitation.

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Chapter VII - Conclusions

"The real voyage of discovery consists not in seeking new landscapes, but in having new eyes." - Marcel Proust - La Prisonnière (The Captive, 1923)

7.1 Final remarks

Environmental friendly transportation is denoted as the future of transportation modes. Railways are positioned as the prominent solution, being the most efficient and widely used mass transportation system. Since its introduction, the rail industry has also been associated with social development, sustaining its continuously grow. On the other hand, service quality influences the increase in rail passengers. That relies on users' conditions, safety and comfortable journeys. However, comfort and discomfort are two complex and controversial concepts leading to the existence of multiple and non-consensus definitions. Nevertheless, the most accepted model relates the interaction between the human, the product and the environment with comfort and discomfort feelings.

Regarding railway journeys, passengers' comfort is rather complex, resulting from the interaction of multiple factors. Those dependent on the vehicle motion and, therefore, capable of being controlled, were at the centre of the present work. Moreover, to properly assess and rate perceived comfort, it is necessary to consider both, static and dynamic comfort categories. Additionally, they are related, thus influencing each other. Static comfort is mainly rated to the foam's mechanical properties and seat-passenger interface pressure. Dynamic comfort is usually defined by ride comfort indexes, seat effective amplitude transmissibility and seat transmissibility. Therefore, the present study aimed to assess how dynamic and static factors influence comfort levels.

Initially, taking the Portuguese Railways Northern Line as a case study, particularly the section comprehended between Porto (Campanhã) – Lisbon (Oriente) stations, a ride comfort evaluation was performed by instrumenting multiple AP and IC trains. The analysis allowed to conclude about the vibration comfort levels experienced by users and identify possible maintenance needs. All AP journeys were evaluated as "Not uncomfortable" for floor and seating locations. However, the IC journeys did not observe that trend, and two trains revealed "Little uncomfortable" levels at the seat surface location. The more degraded and worn vibration environment exhibited by these specific carriages permitted to conclude about possible interior maintenance requirements. Moreover, vertical vibration was identified as that most influencing discomfort levels on both, floor and seat surface, whereas, on the seatback, both vertical and longitudinal axes present similar influence. Weighted accelerations and SEAT evaluations revealed the seating capacity to modify vibration, being that, in the present investigation, amplified. Additionally, due to their higher seat values, it was observed that standard seats are more propitious to amplify vibration shocks. Nevertheless, it should be highlighted that Portuguese railway trains present a generally good vibration comfort performance.

Additionally, by applying an instantaneous floor ride comfort analysis based on ISO 2631 standard methodology, it was possible to identify railway track maintenance needs once twelve track sections evidenced abnormalities. This simple methodology proved its robustness and accuracy sustained by the high number of experiments and matched with EM 120 results. Its application may lead to the opportunity of assessing railway track infrastructure maintenance requirements using in-service trains, namely passenger rail vehicles at a very low cost. Therefore, answering one of the research questions defined in Chapter I, it can be affirmed that using comfort indexes makes it possible to assess maintenance requirements on both railway vehicles and track infrastructure.

Following the dynamic comfort research, a modal identification analysis detailed the seat structural movements. Based on output-only modal identification techniques, particularly transmissibility curves and EFDD methods, the movements dependent on the carbody and seat foam can be distinguished. Initially, the non-influence of the inter-subject variability was proved, as no significant differences were found between the transmissibility resonances and antiresonances frequency values of all subjects' results.

By analysing AP comfort and standard seat results, it was detailed that transmissibility peak values decreased for higher foam thicknesses. The EFDD method permitted evidence of the similar structural behaviour of both AP seats and identified the movement's generation. Five modes were identified. Mode 1 is related to the vertical foam local movements. Mode 2 depicts a rigid body motion of the seat structure associated with a slight foam movement in the vertical and longitudinal directions. These movements are induced by a global movement of the vehicle's carbody. The flexibility of the connection elements between the seat and carbody promoted a seat frame rigid body movement around 3 Hz frequency, representing Mode 3. A seat movement transition is demonstrated by Mode 4, as the seat frame presents an entirely well-defined bending movement coupled with a torsion movement. The bending movement is associated with the externally induced vibration and the passenger mass. Furthermore, in this mode, the foam strictly follows the seat frame movement. Concerning Mode 5, it is linked to the association between both, carbody and seat frame movements. The former induces a rigid body movement, whereas the latter demonstrates a bending movement. Standard and comfort seats' main difference is linked with the foam capacity to absorb vibration, as that range is higher regarding the latter foam.

Regarding IC seats, comfort and standard seats have different seat frame structures, being expected to have varying dynamic behaviour. The comfort seat is similar to the one used by multiple authors in laboratory experiments. As expected, its dynamic behaviour is similar to those approximations, reinforcing the influence of the cover restrictions. IC seat experimental setup conclude about the presence

of seatback movements. The match between those prominent seatback resonance frequencies with the fore-and-aft movements identified on the EFDD method, validated the applied methodology and experimental setup. It should be highlighted that the work reported in Chapter V is the first-ever conducted regarding this topic and analysis. Moreover, it is also sustained by being performed under a rail environment instead of laboratory approaches.

Once the dynamic analysis of the seats was completed, a static analysis of different foams and covers was performed. This included an analysis of the influence of foam mechanical properties and its induced interface pressure in sitting impressions, and an infrared thermographic assessment of the temperatures resulting from the passenger-cover interaction. Sitting impressions were ranked based on both, objective and subjective evaluations.

The influence of user's characteristics on interface pressure was first ascertained. Contradicting previous studies, results showed higher mean and peak pressures and larger contact areas for the heavier subject. Additionally, matching both pressure profiles and discomfort ratings, it was noticed that the ischial tuberosities zone significantly influences sitting impressions and, therefore, is directly related to discomfort levels.

To investigate the better foam and cover for railway seating applications, foams with different densities (40 and 80 kg/m³) and different covers (leather and fabric) were tested. The combination of mechanical properties (high SAG factor and low 25% ILD hardness) and pressure profiles (lower average and maximum pressures and more uniform pressure distribution) identified the higher-density foams as the most suitable. Furthermore, analysing the transmissibility and interface pressure results, applying foams with higher thicknesses is recommended to obtain higher comfort levels. That parameter does not influence interface pressure, but thicker foams presented a larger vibration absorption range. Concerning the selection of the cover, the fabric induced lower maximum, minimum and average temperatures than the leather cover. Based on the assumption that lower interface temperatures promote higher comfort levels, the fabric cover can be identified as the most suitable for railway applications.

In summary, the present study employed both, objective and subjective evaluations to assess the influence of static and dynamic comfort in railway seating applications. The evidence reported here may be helpful for designing more comfortable seats and predicting both, rail vehicles and track infrastructure maintenance requirements.

7.2 Scientific impact

Due to the nature of the present work, which is expected to prove the candidate's scientific capability to be considered for a Doctor of Philosophy (PhD) degree, it is fundamental that the contents produced during this research are accepted and disseminated among the scientific community. Table 7.1 presents a compilation of the published articles and those under review or being prepared for submission in scientific journals. The findings disseminated at scientific conferences are also identified.

Table 7.1. Compilation of scientific production.

Article	Type	Status
Indirect Assessment of Railway Infrastructure Anomalies Based on Passenger Comfort Criteria (2023)	Journal paper	Published in <i>Applied Sciences</i> , 2023, 13, 6150
Railways Passengers Comfort Evaluation through Motion Parameters: A Systematic Review (2023)	Journal paper	Published in <i>Machines</i> , 2023, 11, 465
Modal Identification of Train Passenger Seats Based on Dynamic Tests and Output-Only Techniques (2023)	Journal paper	Published in <i>Applied Sciences</i> , 2023, 13, 2277
Seat vibration transmissibility of the Portuguese Alfa Pendular tilting train (2022)	Oral presentation	DSM2022 2 ^a Conferência Nacional de Dinâmica de Sistemas Multicorpo
Comfort analysis comparison between Alfapendular and Intercity Portuguese trains at the North Rail (2022)	Oral presentation Conference paper	III International Scientific-Practical Conference MIMCS22: Modern Information, Measurement and Control Systems: Problems, Applications and Perspectives 2022
ISO 2631 as a complementary maintenance method for trains and rails (2022)	Poster	TMOB-HUB Transport and Mobility Research
Ride comfort evaluation on Alfa Pendular trains during the Porto – Lisbon connection (2022)	Oral presentation	RAILWAYS 2022 The Fifth International Conference on Railway Technology: Research, Development and Maintenance
ISO 2631 vibration analysis in Portuguese Alfa Pendular trains (2022)	Oral presentation	ICIE'2022

	Conference paper	International Innovation in Engineering	Conference
Design, Development, and Validation of a Whole-Body Vibration Measurement Device (2022)	Journal paper	Published in <i>ASME Journal of Engineering, 2022,1</i>	
Passengers Comfort Perception and Demands on Railway Vehicles: A Review (2019)	Oral presentation Conference paper	ICEUBI2019 International Engineering – Evolution	Congress on Engineering for
Railway's passenger comfort/discomfort: objective evaluation (2023)	Book chapter	Accepted – Book <i>New Research on Railway Engineering and Transport</i>	
Influence of static factors in sitting comfort: foam properties, interface pressure and temperature	Journal paper	In progress	

7.3 Future works

Following different approaches, the present work answered the proposed research questions. Nevertheless, it is pertinent to recognise the study limitations and identify possible future works. More experiments should be conducted to quantify the Portuguese railway passengers' comfort levels, covering a more comprehensive range of trains. Those experiments can also be used to assess maintenance requirements outside of the current tested line.

Regarding the methodology developed to investigate rail track maintenance requirements, more work must be performed to achieve a model capable of detecting the abnormality type. That may be achieved by employing machine learning procedures that define comfort levels as the learning parameter according to the dynamic behaviour of each abnormality type.

Modal identification should be performed in railway vehicles with seats with different carbody-seat connections than those already experimented. For example, the seats of Porto urban trains (3400 train series) are connected with the carbody by a lateral 1-point support beam.

The main limitation of the experiments conducted in Chapter VI is the reduced number of volunteers; the study should continue and being applied to a broader range of subjects to solidify its conclusions. Technical limitations prevent the realisation of mechanical experiments on seat covers. This factor should be considered in the future.

Finally, once children are also railway passengers, experiments must be conducted to assess their comfort levels as well while travelling.

Appendix I

University of Minho Ethics Committee approval



Universidade do Minho
Conselho de Ética

Comissão de Ética para a Investigação em Ciências Sociais e Humanas

Identificação do documento: CEICSH 062/2022

Relator: Cristina Maria Moreira Flores

Título do projeto: *Study, analysis and improvement of the Comfort index levels on railways*

Equipa de Investigação: Patrícia Filipa Pinheiro da Silva (IR), Programa Doutoral em Engenharia Mecânica, Escola de Engenharia, Universidade do Minho; Diogo Rodrigo Ribeiro, Instituto Superior de Engenharia do Porto; Eurico Augusto Rodrigues Seabra, Departamento de Engenharia Mecânica, Escola de Engenharia, Universidade do Minho; Joaquim Gabriel Magalhães Mendes, Departamento de Engenharia Mecânica, Faculdade de Engenharia do Universidade do Porto

PARECER

A Comissão de Ética para a Investigação em Ciências Sociais e Humanas (CEICSH) analisou o processo relativo ao projeto de investigação acima identificado, intitulado *Study, analysis and improvement of the Comfort index levels on railways*.

Os documentos apresentados revelam que o projeto obedece aos requisitos exigidos para as boas práticas na investigação com humanos, em conformidade com as normas nacionais e internacionais que regulam a investigação em Ciências Sociais e Humanas.

Face ao exposto, a Comissão de Ética para a Investigação em Ciências Sociais e Humanas (CEICSH) nada tem a opor à realização do projeto nos termos apresentados no Formulário de Identificação e Caracterização do Projeto, que se anexa, emitindo o seu parecer favorável, que foi aprovado por unanimidade pelos seus membros.

Braga, 26 de julho de 2022.

O Presidente da CEICSH

(Acílio Estanqueiro Rocha)

Anexo: Formulário de identificação e caracterização do projeto

Comissão de Ética para a Investigação em Ciências Sociais e Humanas (CEICSH)



Formulário de identificação e caracterização do projeto

Universidade do Minho

Identificação do projeto

Título do projeto	Study, analysis and improvement of the comfort index levels on railways		
Data prevista de início	Maio 2022	Data prevista fim	Agosto 2022

Nota: As datas ficam dependentes daquilo que é o condicionamento pandémico, apesar de serem prazos que pretendemos cumprir.

Investigador principal e filiação	Patrícia Filipa Pinheiro da Silva (Programa Doutoral em Engenharia Mecânica, Universidade do Minho) Diogo Rodrigo Ribeiro (Professor Adjunto, Instituto Superior de Engenharia do Porto)
Orientador(es) e filiação	Eurico Augusto Rodrigues Seabra (Departamento de Engenharia Mecânica, Universidade do Minho) Joaquim Gabriel Magalhães Mendes (Departamento de Engenharia Mecânica, Faculdade de Engenharia da Universidade do Porto)

Instituição proponente	Universidade do Minho
Instituição onde se realiza a investigação	UMAV – Unidade de Manutenção de Alta Velocidade

Entidades financiadoras	Este projeto não detém qualquer recurso e/ou financiamento. A investigadora Patrícia Silva detém bolsa FCT SFRH/BD/143161/2019.
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Questões relativas ao envolvimento de investigadores exteriores		
Estão envolvidos no projeto, colegas de outra (s) Escola(s)/Instituição(ões)?	S ☒	N
Se sim, este pedido de parecer cobre o seu envolvimento?	S ☒	N

Qualificação dos investigadores
A investigadora Patrícia Silva leva a cabo este projeto para obtenção do grau de doutor no âmbito da tese do Programa Doutoral em Engenharia Mecânica. O investigador Diogo Ribeiro é Doutor em Engenharia Civil pela Universidade do Porto.

Caracterização do projeto e questões de carácter ético relativas à sua execução

Introdução

O comboio é, atualmente, um dos meios de transporte mais utilizados do mundo. Devido aos elevados níveis de poluição, os meios de transporte e o modo como as pessoas comutam representam uma forte preocupação para governos e são um dos maiores desafios das atuais gerações. O comboio surge como um meio de transporte alternativo que apresenta uma baixa taxa de emissão de CO₂ e é capaz de transportar um elevado número de passageiros. Assim, este posiciona-se como uma das soluções mais atrativas para os transportes públicos.

Contudo, apesar de na última década o número de passageiros estar continuamente a aumentar, existe ainda espaço para melhorias. Estas revelam-se de extrema importância, não só para manter os números de passageiros, como ainda para atrair novos utilizadores, melhorando o conforto, uma das maiores preocupações dos passageiros.

Os níveis de conforto/desconforto em viagens de comboio estão associados a diversos fatores, sendo que se destacam a comodidade do banco e a vibração. O conforto pode ser avaliado de dois modos diferentes, estático e dinâmico. Enquanto o primeiro pode ser caracterizado pela pressão na interface entre o utilizador e o banco, o segundo pode ser avaliado considerando os níveis de vibração da viagem e a transmissibilidade do banco. Assim, aceder e estudar estes fatores torna-se crucial para caracterizar o conforto nas viagens de comboio.

Em Portugal, apenas foram realizados estudos de transmissibilidade nos comboios Alfa Pendular antes da sua renovação de meia vida (R1). Assim, existe uma necessidade de realizar estudos de conforto nos comboios portugueses. Este projeto surge com o objetivo de caracterizar os atuais níveis de conforto e identificar possíveis melhorias. Para tal, propõe a realização de testes de transmissibilidade e de pressão de interface. Estes testes irão ainda permitir concluir acerca da influência de diferentes variáveis antropométricas nestes fatores e comparar a transmissibilidade dos bancos pré e pós renovação. De forma cumprir este objetivo, pretende-se realizar uma seleção de voluntários saudáveis, de ambos os géneros, de diferentes idades, pesos e alturas. Será utilizada uma população heterógena, constituída maioritariamente por funcionários da UMAV, sendo que as crianças recrutadas para o estudo serão familiares dos mesmos e dos investigadores do projeto.

Após a identificação e seleção da amostra, será pedido aos participantes que preencham um questionário onde serão recolhidas informações sobre os mesmos como o género, idade, altura e peso. Os voluntários deverão sentar-se num banco do comboio Alfa Pendular e, consoante indicação dos investigadores, adquirir diferentes posturas. Devido aos equipamentos utilizados, os voluntários poderão observar em tempo real os resultados obtidos. Este estudo não acarreta riscos para os mesmos. Adicionalmente serão efetuadas análises estatísticas de modo a cumprir os objetivos do projeto.

Por fim, a partir dos resultados obtidos, pretende-se, avaliar o desempenho relativo ao conforto dos bancos atuais dos comboios Alfa Pendular, identificar parâmetros técnicos a melhorar/otimizar e estudar a influência de diferentes características antropométricas nos níveis de conforto.

Hipóteses de investigação e principais resultados esperados

A partir da análise dos resultados obtidos, poder-se-á completar a caracterização dos níveis de conforto dos comboios Alfa Pendular. A análise da transmissibilidade nos bancos fornecerá dados importantes relativamente ao comportamento vibracional dos bancos e, consequentemente, ao seu conforto dinâmico. Em oposição, a análise da pressão na interface utilizador – banco fornecerá dados

relativos ao conforto estático do banco. Além disso, será ainda estudada a influência de fatores como género, idade, altura, peso e reclinção do banco nestes dois parâmetros.

Objetivos do estudo

- Recolha de informação sobre os indivíduos em estudo, como género, idade, altura e peso;
- Realização de testes de caracterização dos níveis de conforto nos bancos do comboio Alfa Pendular;
- Realização de testes para avaliação da influência de múltiplos parâmetros nos níveis de conforto;
- Análise e discussão dos resultados obtidos;
- Tendo em consideração os resultados obtidos, compreender quais os fatores que mais influenciam os níveis de conforto, nomeadamente a idade, peso, altura ou género do utilizador, ou a reclinção do banco;
- Aferir aspetos técnicos que podem/devem ser melhorados/otimizados de modo a proporcionar uma melhor experiência ao utilizador.

Participantes

Nos testes realizados na UMAV, o estudo será realizado com participantes maioritariamente adultos e um número reduzido de crianças, sendo todos voluntários saudáveis, de diferentes géneros e apresentarem diferentes características antropométricas.

Recrutamento e triagem

Os sujeitos voluntários serão crianças e adultos, sem diferenciação no género.

O recrutamento será feito com envolvimento direto dos investigadores responsáveis. Este recrutamento será sempre realizado de modo a respeitar a livre, voluntária e informada participação dos envolvidos ou, no caso das crianças dos seus pais. Adicionalmente, este recrutamento poderá ser feito através de apelo à participação neste estudo, via correio eletrónico, para a rede de e-mails interna da Universidade do Minho, de estudantes, investigadores e professores, entre outros.

Compensação e custos

O participantes neste estudo serão voluntários, não estando previsto qualquer pagamento a título de deslocções ou contrapartidas dado que, este projeto não detém qualquer recurso e/ou financiamento.

Procedimento

Inicialmente será efetuado um teste piloto para o estudo da transmissibilidade do banco, sem utilização de pessoas, de modo a validar o sistema de medição. Este consistirá na colocação de 2 acelerómetros no habitáculo do comboio, sendo um acelerómetro PCB colocado na interface de conexão entre o banco e chão do comboio e, o segundo acelerómetro PAD PCB acoplado ao banco (2 localizações, assento e encosto). De seguida, um dos investigadores principais aplicará uma reduzida excitação no chão do comboio através de movimentos como caminhar, correr e/ou saltar.

Os dados serão recolhidos durante a realização do teste através da conexão dos equipamentos a um computador. Este teste terá a duração máxima de 5 minutos e será repetido 5 vezes.

Após a verificação do equipamento, será efetuada a seleção dos candidatos para a realização dos testes sistemáticos. Esta deverá ocorrer de acordo com os objetivos do presente estudo. Assim, os voluntários, saudáveis, devem ser de ambos os géneros e apresentar diferentes características antropométricas. Num momento inicial será dada prioridade a funcionários da UMAV.

Uma vez que o parqueamento dos comboios Alfa Pendular acontece na UMAV os testes serão localizados neste local. No primeiro teste o utilizador deverá sentar-se no banco, mantendo contacto total com o assento e o encosto, sendo realizadas medições nos 2 locais. No teste seguinte o voluntário deve permanecer apenas em contacto com o assento. Por último, o banco será reclinado na máxima amplitude permitida pelo mesmo e, nesta posição, serão efetuados 2 ensaios, medindo a vibração no encosto e no assento. Cada ensaio terá a duração máxima de 5 minutos, e um intervalo da mesma duração.

Finalizados os testes de transmissibilidade serão conduzidos os testes de pressão na interface utilizador – banco. Estes testes consistem em colocar um sensor de pressão matricial flexível no assento do banco, sentando-se o voluntário durante 5 minutos. Estes testes serão realizados nas mesmas posições, previamente descritas para os testes de transmissibilidade.

Os resultados obtidos e dados recolhidos serão sujeitos à análise estatística utilizando o Microsoft Excel 365 ou o SPSS 24. A análise estatística será conduzida de forma a avaliar a reprodutibilidade dos ensaios e a variabilidade promovida pelas diferenças antropométricas (género, altura, peso e idade). A partir dos resultados obtidos pretende-se concluir sobre a transmissibilidade e a pressão induzidas sobre o banco, o seu comportamento relativamente à heterogeneidade da população e consequentes variações antropométricas, e ainda identificar características técnicas do banco a melhorar.

As tecnologias de medição utilizadas permitem uma análise em tempo real dos dados, pelo que os voluntários poderão no fim dos ensaios ver, e solicitar uma cópia dos seus resultados. Todos os dados serão recolhidos de forma anonimizada.

Benefícios, Riscos e Desconforto

Este estudo não é invasivo, nem está associado a situações de risco ou desconforto, físicas, psicológicos, económicos ou sociais.

Também não se esperam potenciais benefícios para os participantes, uma vez que os testes a realizar servirão apenas para averiguação técnica dos bancos do comboio, comparação com resultados previamente obtidos em comboios portugueses, estudo da influência de variáveis antropométricas na transmissibilidade do banco e avaliação da pressão na interface utilizador - banco.

Confidencialidade

Todos os indivíduos, ou os seus pais/tutores (no caso de crianças) que participarem neste estudo preencherão um consentimento informado, livre e esclarecido para participação na investigação de acordo com a Declaração de Helsínquia e a Convenção de Oviedo. Este estudo não será invasivo nem colocará em causa a integridade física do indivíduo. O participante poderá abandonar o estudo a qualquer altura com garantia de que não existirão quaisquer prejuízos, assistenciais ou outros, caso recuse a participação. Os dados adquiridos serão mantidos em confidencialidade e anonimato durante a realização do estudo.

Conflito de interesses

Não existe qualquer situação de conflito de interesses uma vez que este projeto será levado a cabo somente pelos investigadores principais auxiliados pelos orientadores.

Consentimento Informado

A investigação envolve apenas voluntários saudáveis?	☒ S	☐ N
A investigação envolve grupos vulneráveis: crianças, menores, idosos ou outras pessoas com incapacidade temporária ou permanente?	☒ S	☐ N
O pedido de parecer inclui a declaração de consentimento informado, livre e esclarecido?	☒ S	☐ N

Aqui tem de escolher o formato de consentimento informado

- ☒ Consentimento informado, livre e esclarecido para participação em investigação - de acordo com a Declaração de Helsínquia e a Convenção de Oviedo
- ☐ Consentimento informado não assinado - E.g. formulário para questionários preenchidos online. Deverá adicionar a informação incluída e o modo de os participantes concordarem em participar
- ☐ Consentimento informado alterado - Um formulário de consentimento informado que omite informação requerida. E.g., se não indica o objetivo do estudo para evitar o viés na resposta dos participantes. Deve explicar o racional no procedimento e os processos de *debriefing*
- ☐ Isenção de consentimento - quando não é obtido consentimento informado - esta opção pode ser apropriada para utilização de dados já disponíveis. Justifique

Anexe o formulário de consentimento informado e outro material informativo relevante quando adequado, ou justifique a isenção de consentimento

Assinatura do Investigador Responsável

.....
Patricia Filipa Pinheiro da Silva.....

.....

Assinado por : **DIOGO RODRIGO FERREIRA RIBEIRO**
 Num. de Identificação: B1115296239
 Data: 2022.04.28 22:04:49+01'00'



Appendix II

Informed consent and subjective rankings

Anexos

i) Questionário a realizar aos voluntários

INQUÉRITO

Tema: Study, analysis and improvement of the comfort index levels on railways. (Estudo, análise e melhoria dos níveis de conforto em ferrovias)

Investigadores responsáveis: Patrícia Silva, Diogo Ribeiro

Orientadores: Eurico Seabra, Joaquim Mendes

Objetivos Gerais do Inquérito/Estudo:

- Adquirir informações acerca da transmissibilidade e níveis de conforto do banco;
- Conhecer os principais aspetos que influenciam a transmissibilidade;
- Adquirir informações acerca dos níveis de pressão na interface utilizador – banco.

1. Género

Feminino ☒ Masculino ☐

2. Idade

25 anos

3. Altura

170 cm

4. Peso

58 kg

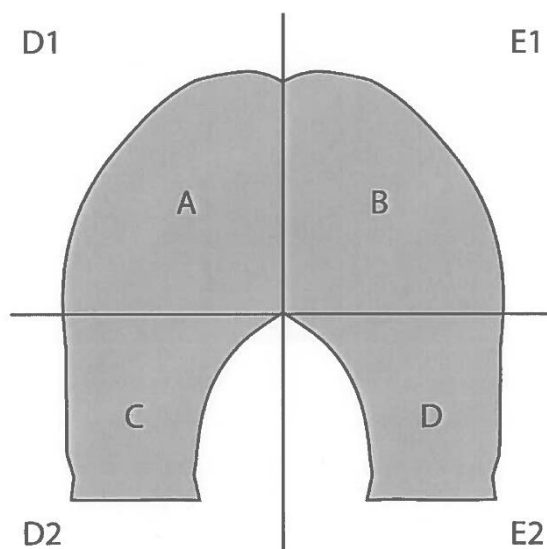
AP

Teste de pressão de interface (H2) → S1

Classifique, utilizando a seguinte escala numérica, o nível de conforto/desconforto geral que sentiu Neutro (banco RS / classe C).

Classificação	Nível
-3	Muito desconfortável
-2	Desconfortável
-1	Ligeiramente desconfortável
0	Neutro
1	Ligeiramente confortável
2	Confortável
3	Muito confortável

Classifique cada uma das zonas com o nível de conforto/desconforto



A -1
 B 0
 C -1
 D 0

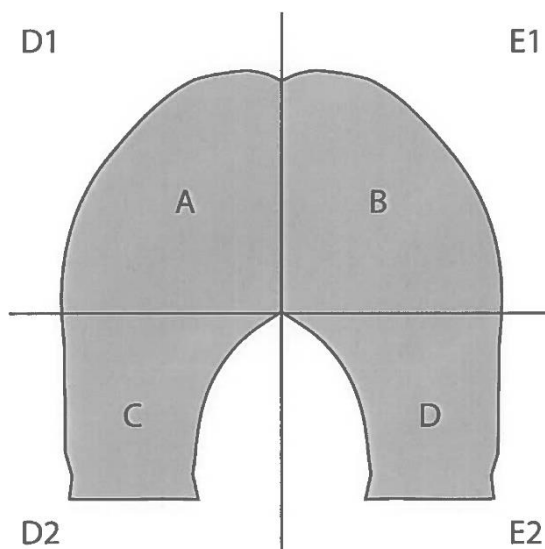
AP

Teste de pressão de interface (172) → S1

Classifique, utilizando a seguinte escala numérica, o nível de conforto/desconforto geral que sentiu Neutro (banco 16 / classe I).

Classificação	Nível
-3	Muito desconfortável
-2	Desconfortável
-1	Ligeiramente desconfortável
0	Neutro
1	Ligeiramente confortável
2	Confortável
3	Muito confortável

Classifique cada uma das zonas com o nível de conforto/desconforto



A -1
 B 0
 C 0
 D 0

Anexos

i) Questionário a realizar aos voluntários

INQUÉRITO

Tema: Study, analysis and improvement of the comfort index levels on railways. (Estudo, análise e melhoria dos níveis de conforto em ferrovias)

Investigadores responsáveis: Patrícia Silva, Diogo Ribeiro

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Objetivos Gerais do Inquérito/Estudo:

- Adquirir informações acerca da transmissibilidade e níveis de conforto do banco;
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1. Género

Feminino ☐ Masculino ☒

2. Idade

26 anos

3. Altura

1,87 cm

4. Peso

80 kg

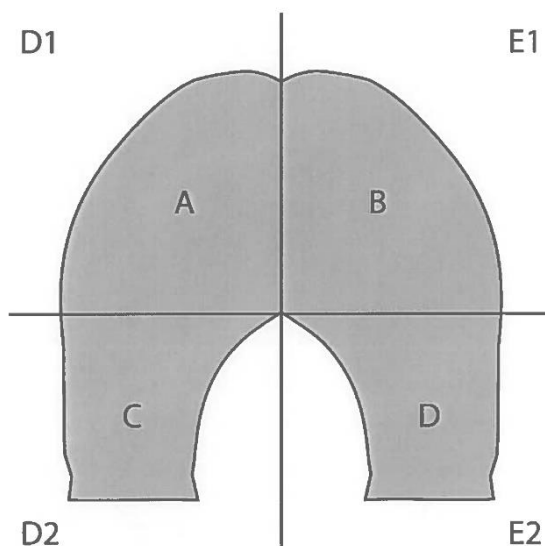
AP

Teste de pressão de interface (113) → SZ

Classifique, utilizando a seguinte escala numérica, o nível de conforto/desconforto geral que sentiu -1 (banco 85 / classe C).

Classificação	Nível
-3	Muito desconfortável
-2	Desconfortável
-1	Ligeiramente desconfortável
0	Neutro
1	Ligeiramente confortável
2	Confortável
3	Muito confortável

Classifique cada uma das zonas com o nível de conforto/desconforto



A -1
 B -1
 C 0
 D 0

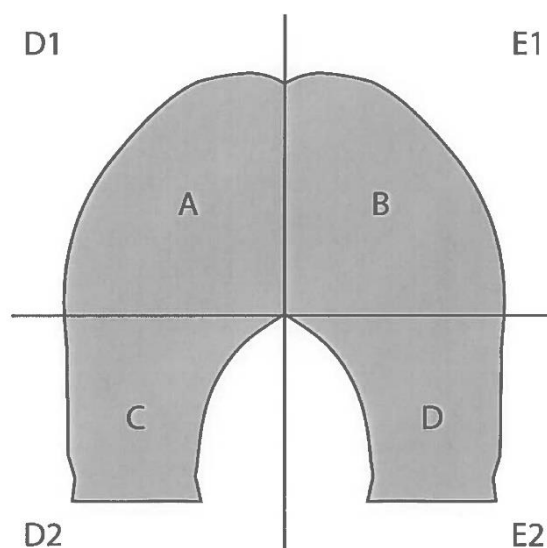
AP

Teste de pressão de interface (13) → S2

Classifique, utilizando a seguinte escala numérica, o nível de conforto/desconforto geral que sentiu -1 (banco 16 / classe T).

Classificação	Nível
-3	Muito desconfortável
-2	Desconfortável
-1	Ligeiramente desconfortável
0	Neutro
1	Ligeiramente confortável
2	Confortável
3	Muito confortável

Classifique cada uma das zonas com o nível de conforto/desconforto



A -2

B -2

C 0

D 0

Anexos

i) Questionário a realizar aos voluntários

INQUÉRITO

Tema: Study, analysis and improvement of the comfort index levels on railways (Estudo, análise e melhoria dos níveis de conforto em ferrovias)

Investigadores responsáveis: Patricia Silva, Diogo Ribeiro

Orientadores: Eurico Seabra, Joaquim Mendes

Objetivos Gerais do Inquérito/Estudo:

- Adquirir informações acerca da transmissibilidade e níveis de conforto do banco;
- Conhecer os principais aspetos que influenciam a transmissibilidade;
- Adquirir informações acerca dos níveis de pressão na interface utilizador – banco.

1. Género

Feminino ☐ Masculino ☒

2. Idade

39 anos

3. Altura

1.85 cm

4. Peso

115 kg

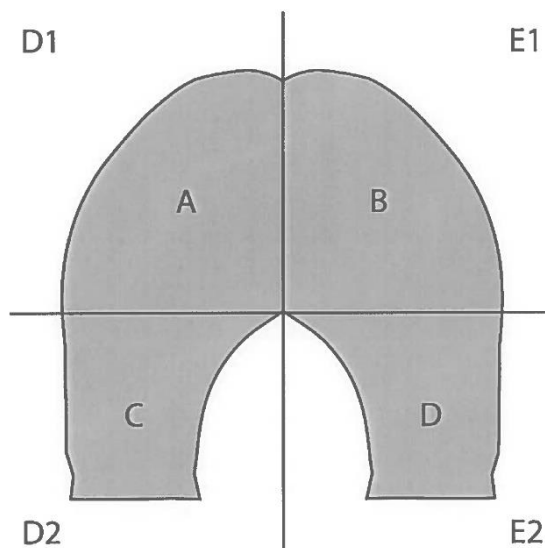
AP

Teste de pressão de interface (14) → S3

Classifique, utilizando a seguinte escala numérica, o nível de conforto/desconforto geral que sentiu 1 (banco 85 / classe C).

Classificação	Nível
-3	Muito desconfortável
-2	Desconfortável
-1	Ligeiramente desconfortável
0	Neutro
1	Ligeiramente confortável
2	Confortável
3	Muito confortável

Classifique cada uma das zonas com o nível de conforto/desconforto



A 1
 B 1
 C 1
 D 1

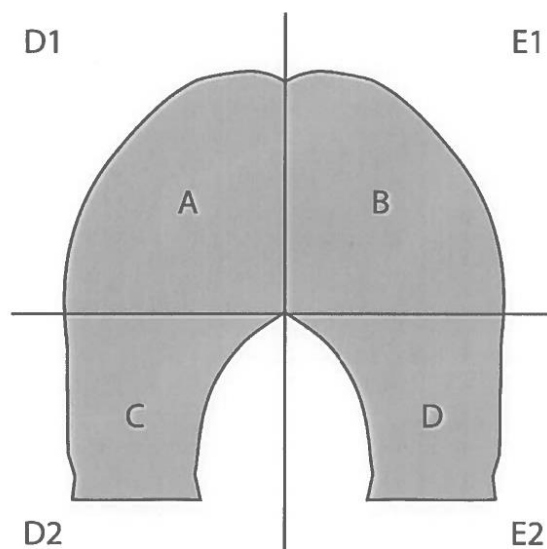
AP

Teste de pressão de interface (H4) → S3

Classifique, utilizando a seguinte escala numérica, o nível de conforto/desconforto geral que sentiu Neutro (banco 16 / classe T).

Classificação	Nível
-3	Muito desconfortável
-2	Desconfortável
-1	Ligeiramente desconfortável
0	Neutro
1	Ligeiramente confortável
2	Confortável
3	Muito confortável

Classifique cada uma das zonas com o nível de conforto/desconforto



A -1

B -1

C -2

D -2