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Ride comfort in road vehicles: a literature review

Diana Dacova
Technical University of Sofia, Bulgaria
ddacova@tu-sofia.bg

Abstract: *Passengers and the driver in vehicles are subjected to vibrations, noise, acceleration, etc., which affect the comfort, activity and health of people. The effect of vibrations on the human body depends on their frequency, amplitude, duration and direction of impact. Prolonged exposure to vibration causes fatigue in the driver and passengers, which reduces their performance and worsens their functional condition. This can affect traffic safety, so one of the main requirements for modern vehicles is to increase ride comfort. The ride comfort is a set of conditions, impacts and sensations of the driver and passengers when traveling in vehicles. Over the years, there have been many studies and scientific developments aimed at measuring, evaluating and analysing the various factors that affect ride comfort. This paper presents a review on the research studies that have been done on dynamic factors that affect the ride comfort in road vehicles and methods used for measurement and its evaluation were discussed. Finally, some existing suggestions for improving the ride comfort in road vehicle are presented.*

Keywords*: RIDE COMFORT, ROAD VEHICLES, MOTION SICKNESS, VEHICLE VIBRATION, ACCELERATION*

1. Introduction

Nowadays, people spend most of their time traveling by private or public transport. Passengers and the driver in vehicles are exposed to vibrations, noise, acceleration, etc., which affect the comfort, activity and health of people. The effect of vibrations on the human body depends on their frequency, amplitude, duration and direction of impact. Prolonged exposure to vibration causes fatigue in the driver and passengers, which reduces performance and worsens their functional condition. This can affect traffic safety, so one of the main requirements for modern vehicles is to increase the ride comfort. Over the years, there have been numerous studies and scientific developments aimed at measuring, evaluating and analysing the various factors that affect ride comfort.

The comfort is subjective state of well-being or absence of mechanical disturbance in relation to the induced environment (concerning mechanical vibration or repetitive shock) [1]. The car passenger comfort is determined by the complex impact of many factors, which can be separated in the following areas [2, 3]:

- **dynamic factors** influencing the ride comfort (mechanical comfort - vibrations with low and very low frequency, shocks and accelerations) and the levels of vibrations with high frequency and noise (vibroacoustic comfort);
- **the microclimate** in the passenger compartment (cabin) of the vehicle (thermal comfort, air quality, atmospheric pressure, etc.);
- and factors depending on the **ergonomic position** of the passengers.

The driver and passengers assess the ride comfort subjectively based on their own feelings.

This paper reviews research on the dynamic factors that influence the vehicles ride comfort, methods for its evaluation and suggestions for its improvement.

2. Impact of Vibrations in Vehicles on Passengers

The ride comfort depends on the characteristics of the forces that cause oscillations and vibrations, on the design of the car, the parameters of the suspension, the driving conditions etc. The forces that cause low-frequency vibration (oscillations) and high-frequency vibrations of the car arise because of internal (unbalanced rotating masses of the engine and transmission, uneven engine operation) and external causes (uneven roads).

The unpleasant and harmful effects of vibrations on human being depend primarily on the way they are transmitted to the human body and on the transmission of vibrations in the body, on the physical nature of vibrations, on the time a person is exposed to vibrations and from the individual characteristics, etc.

The vibrations of the car in real road conditions are varied, and the sprung mass can receive low-frequency 1–3 Hz, high-frequency 7–15 Hz, vibration 15–30 Hz and complex shocks. The human driver or passenger is also a system with a fundamental frequency of free vibrations, which is in the range of 3.5-5 Hz. The human being is adapted to exposure with a frequency of about 1 to 2 Hz corresponding to the frequency of the everyday walking [2, 4].

In [5] is noted that when humans exposed to interference with certain frequencies, resonant phenomena occur, which must be considered in the vibrations of the driver, operator and passengers. The resonant frequencies of the human body are eyes 12–27 Hz; throat 6–27 Hz; chest 2–12 Hz; legs, arms 2–8 Hz; head 8–27 Hz; face-jaw 4–27 Hz; lumbar part of the back 4–14 Hz; stomach 4–12 Hz. At significant vibration values in the frequency range 4–10 Hz, the person may feel painful sensation and discomfort due to resonant oscillations of the “breast-stomach” system. According to the authors of [4, 5] vibrations with a frequency of 3–5 Hz cause reactions of the vestibular apparatus and can cause motion sickness.

It is important to study the effects of vibrations on the human body and their consequences is to study the mode of head vibrations. Regardless of the direction of disturbance (vertically or horizontally), the head always makes movements in space with an elliptical trajectory. In [6] the author notes that nodding head movements have a resonant frequency of 2 Hz and vertical ones 8–27 Hz. According to the author, the human vestibular apparatus also responds to low-frequency vibrations and the symptoms of motion sickness appear at a frequency of 0.5–1.3 Hz.

There are many international standards for assessing the vibrations to which a person may be exposed. The international standard ISO 5349-1:2001 “Mechanical vibration – Measurement and evaluation of human exposure to hand-transmitted vibration – Part 1: General requirements” refers to the measurement and assessment of the impact of vibrations transmitted to the human hand [7]. The second part of this standard is a practical guide for measuring human hand vibration in the workplace: ISO 5349-2: 2001/Amd 1:2015 “Mechanical vibration – Measurement and evaluation of human exposure to hand-transmitted vibration – Part 2: Practical guidance for measurement at the workplace – Amendment 1” [8]. Another international standard for the assessment of mechanical vibration is ISO 10326-1:2016 “Mechanical vibration – Laboratory method for evaluating vehicle seat vibration – Part 1: Basic requirements”. ISO 10326-1:2016 applies to specific laboratory tests on seats that assess the transmission of vibration to passengers in any type of seat used in vehicles and mobile off-road vehicles. It shall specify the test method, the instrumentation requirements, the measurement evaluation method and the method of reporting the test result [9]. The second part of the international standard ISO 10326 is ISO 10326-2:2001 “Mechanical vibration – Laboratory method for evaluating vehicle seat vibration – Part 2: Application to railway vehicles”. It concerns tri-axial rectilinear vibration within the frequency range 0.5 Hz to 50 Hz [10]. Another standard for comfort assessment is the standard BS EN 12299:2009 “Railway applications. Ride comfort for passengers. Measurement and evaluation”. This standard specifies methods for quantifying the effects of vehicle body motions on ride comfort for passengers and vehicle assessment with respect to ride comfort [11].

The main document for vibration assessment is the international standard ISO 2631:1997 “Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration”. It consists of five parts: Part 1: General requirements [ISO 2631-1:1997/Amd 1:2010]; Part 2: Vibration in buildings (1 Hz to 80 Hz) [ISO 2631-2:2003]; Part 3: Evaluation of exposure to whole-body z-axis vertical vibration in the frequency range 0.1 to 0.63 Hz [canceled and replaced with International Standard ISO 2631-1:2010]; Part 4: Guidelines for the evaluation of the effects of vibration and rotational motion on passenger and crew comfort in fixed-guideway transport systems [ISO 2631-4:2001/Amd 1:2010]; Part 5: Method for evaluation of vibration containing multiple shocks [ISO 2631-5: 2018]. The international standard ISO 2631-1 repeals and replaces the first edition ISO 2631-1:1985, as well as ISO 2631-3: 1985. The revised edition of this part of ISO 2631 combines the new experience and research results published in the literature. In this revised edition, the frequency range is extended below 1 Hz. The main objective of ISO 2631-1 Part 1: General requirements is to define methods for the quantification of whole-body vibrations in relation to human health and comfort; the probability of perception of vibrations; manifestation of motion sickness (travel disorders). ISO 2631-1 defines methods for measuring periodic, random and transient vibrations of the whole body. This section identifies the main factors that are combined to determine the extent to which the impact of vibration is acceptable. The frequency ranges considered are from 0.5 Hz to 80 Hz for health, comfort and perception and from 0.1 Hz to 0.5 Hz for motion sickness [12]. Low frequency acceleration can cause discomfort, instability and motion sickness, leading to impaired travel comfort.

3. Motion Sickness

The term "motion sickness" was first introduced by Irwin in the publication [13]. He suggests that the term motion sickness is more correct than sea-sickness because "not only does it occur on lakes and even on rivers, but as is well known, a sickness identical in kind may be induced by various other motions than that of turbulent water,…". Motion sickness is a response to real or apparent movement to which human being is not adapted. According to [14] motion sickness is a misnomer for this response, the symptoms can be caused both by the absence of expected movement and by the presence of unexpected movement (examples of this are sickness associated with wide-screen movies and simulators).

Motion sickness occurs when there is a contradiction between the perceptions of movement coming from the eyes and the vestibular apparatus, i.e., a person sees that he is moving but does not feel it, or vice versa – he feels that he is moving but does not see it. The vestibular apparatus consists of two main parts – an organ responsible for the perception and reflection of angular accelerations and an organ responsible for the perception and reflection of rectilinear accelerations and gravity. The assessment of the change in the position of the human body in space also depends on the change in the position of the eyeball, the musculoskeletal system, the skin tissue, the constituent ligaments, etc. (Fig. 1). An example of a contradiction between the perceptions of movement coming from the eyes and the vestibular apparatus is when reading in a car when it is dark outside; the vestibular system then gives signals for movement, but the visual system does not confirm this movement and these contradictory factors can cause motion sickness [15]. Another example of a conflict between the perceptions of movement and the vestibular apparatus is with a person parking a car in a parking lot and the one next to him left. Another such situation can occur when a driver/passenger in a car is waiting at a traffic light and the stopped bus in the next lane set off.

Motion sickness occurs when traveling by car, bus, train, plane (mismatch between visual and vestibular irritation), sailing (unusual complexes of linear and angular acceleration with a slow frequency – less than 1 Hz), use of a simulator, when flying in weightlessness, as well as when using virtual reality, computer games, etc. [16–18]. According to [17] motion sickness is a general term for many symptoms and signs, generally unfavourable due to exposure to abrupt, periodic, or unnatural accelerations.

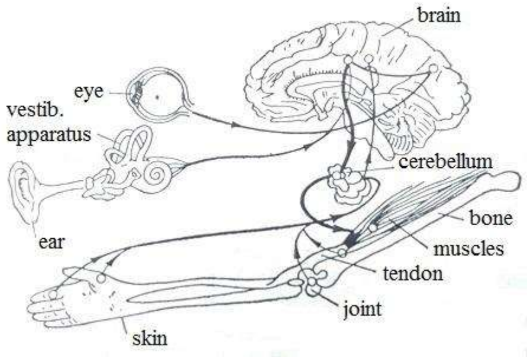

Fig. 1 *Scheme of the relation between the vestibular apparatus and other organs of external influences. Adapted from [4].*

Factors that contribute to the onset of motion sickness symptoms can vary such as air quality, odour, temperature, taste, vibration, visual contribution, oxygen ions, stress, sound, head position, and body posture [19]. The symptoms of motion sickness increase with increased exposure to lateral acceleration at low frequencies (<0.5 Hz) and mainly on predominantly curvy cross-country routes [15]. In [20] the authors conducted a road experiment on a fixed suburban route. During the journey, the spectra of fore-and-aft and lateral acceleration are similar in the frequency range 0.1–0.5 Hz and consequently the motion sickness dose values are similar along these axes. At frequencies less than 0.1 Hz, the fore-and-aft acceleration is slightly greater than the lateral acceleration. According to the authors, the low-frequency fore-and-aft and lateral acceleration in cars are more dependent on the driver's behaviours. After a road experiment, the authors conclude that the dose of the sickness for fore-and-aft and lateral acceleration is significantly higher than motion sickness dose values for vertical acceleration.

The main factors that cause motion sickness are shown in Fig. 2. According to some studies [16, 17, 21] women are more sensitive than men, the most vulnerable to the symptoms of motion sickness are children. However, the age group 4 to 12 years is not included in the standardized dynamic vehicle tests in either regulatory or consumer assessment programs [22].

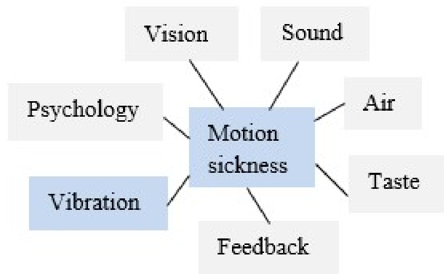

Fig. 2 *The main factors that cause motion sickness. Adapted from [19].*

The vestibular system is what helps us keep our balance. It registers changes in position caused by motion and controls the position of the head through regulation of muscle tension which helps us keep our posture. The vestibular system is affected by vertical and horizontal vibrations and forces of acceleration [19] that results in motion sickness and ride discomfort (Fig. 3).

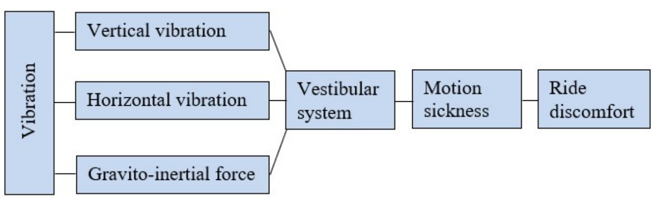

Fig. 3 *Vibrations and forces of acceleration that affect the vestibular system that results in motion sickness and ride discomfort. Adapted from [19].*

Drivers follow the road all the time, do not keep their eyes on stationary objects for a long time and they do not exhibit symptoms of motion sickness. One reason for this may be that the driver can predict the direction of the vehicle and therefore aligns his/her head with the GIF (Gravito Inertial-Force) [19]. The known fact that drivers rarely become motion sick may be due to the driver's prediction of low-frequency horizontal accelerations as they depend on the driver's behaviour [23]. Thus, the conflict between the visual perceptions and the sensations of the vestibular apparatus in the driver is less pronounced than in the passengers. With the advent of autonomous cars, the driver changes his/her role and becomes a passenger. As a passenger, he/she may also at some point show symptoms of motion sickness due to lack of vehicle control in addition to sensory conflicts [24]. In a conflict situation, he/she probably will not be able to take control of the car. In recent years, the possibility of autonomous cars entering has increased, and in this connection, consideration should be given to reducing the mechanical effects that cause the symptoms of motion sickness.

4. Methods for Measurement the Ride Comfort

There are various methods for assessing the ride comfort. In most cases, the acceleration, the frequency of oscillations, the vibrations, the noise to which the passengers in the land vehicles are exposed are measured with the help of equipment. The obtained results are compared with the existing international standards. Various factors can affect a person's response to vibrations such as gender, height, health, driver or passenger etc. Some researchers use methods such as conducting interviews with a lot of participants of different age groups, gender, nationality, etc. The comfort that people feel can be classified as a subjective assessment, as it is possible to detect significant variations in the responses of different people to the same situation [25]. Mathematical models and computer simulations are used to obtain results, which can subsequently be compared with results obtained in road experiments [26–29]. Various vibration measuring test bench are also used in the laboratory [30] and simulators of driving conditions [31]. The main value for the magnitude of the vibration is the acceleration. Accelerometers are used to measure the accelerations to which passengers are exposed when traveling in road vehicles, which record the accelerations on all three axes of movement (Fig. 4). In some cases, the accelerations are measured only in single axis, for example if the researchers work on improving the design of the suspension they are mostly interested in vertical accelerations; if they are working on active transverse stabilizers or tilting systems, they are mostly interested in a change in the lateral accelerations [32]. In [33] the authors explore the possibility of using smartphones to measure comfort when traveling on trains. They conclude that the accelerometers found in modern smartphones are of sufficient quality to be used in assessing ride comfort.

Fig. 4 *Accelerometer and DAQ devise used for data acquisition [32].*

To predict the onset of motion sickness symptoms, the authors of [31], studied the effect of lateral oscillations at frequencies between 0.0315 and 0.2 Hz. The experiment was performed using a simulator capable of a horizontal displacement of 12 m and simulating six motion conditions. After conducting an experiment with 120 people, the authors summarize that there is a very significant effect of the frequency of lateral vibrations on the appearance of mild nausea.

In [34] is studied the effect of vehicle vibration on humans. The calculations are made using a simulation program using a full vehicle model with a driver and the results are evaluated using the international standard ISO 2631. Road irregularities are chosen as the impact. The physical model of the studied system is formed by a full vehicle model and a driver. The conclusions made by the authors after the study: if the driver travels at a speed of 72 km/h from 5 to 6 hours on a smooth road, at frequency ranges from 8 to 10 Hz he/she feels uncomfortable and should not be exposed to vibration more than 5 hours under these conditions.

In the publication of M. Brogioli at all [35] a mechanical model of a seated passenger is presented and through its validation an analysis of the key parameters that affect ride comfort is performed. According to the authors, the size and weight (percentile) of the human object are crucial for assessing ride comfort. Another important component is the seat and its parameters – stiffness, damping and geometric parameters.

In [30] the influence of vibration frequency and pitch motion and roll motion on motion sickness are studied using a vibrating test bench. The conclusions of the experiment are that vertical vibrations and pitch motion at 0.5 Hz or lower affect the frequency of the sickness when the vehicle is moving. The authors present a formula that can be used to assess the level of motion sickness, using differences in vibration levels and coefficients of influence of the direction and frequency of vibrations on motion sickness. Road tests have been carried out with many vehicles to confirm that the level of motion sickness assessed using the developed formula is in good agreement with the result of the subjective assessment. The methods proposed by the authors are applied to verify the effectiveness of an improved suspension system, which is installed in vehicles and suppresses low-frequency vibrations.

5. Suggestions for Improving the Ride Comfort

Most research and development to improve ride comfort relates to ride comfort at frequencies greater than 1 Hz, where movement depends on the dynamic response of the car's suspension and seat.

At these frequencies, in addition to the suspension and the seat that serve as isolation from the road, the characteristics of the tires also influence, as at frequencies up to 30 Hz the comfort depends on the pressure in them and over 30 Hz on the tire design [36, 37]. Other sources of high frequency vibrations are the engine and transmission. Elastic engine mounts and drive shaft bushes are used to dampen their vibrations [38]. Dynamic vibration absorbers and crankshaft dampers is widely used in most vehicle engines [39]. Modern engines with a small number of cylinders and high power often use a dual flywheel [40].

Vehicle movements at frequencies less than about 1 Hz result from the road surface profile (for vertical vibrations), cornering (for lateral acceleration) and acceleration and braking (for fore-and-aft movements). All three are affected by the speed of the vehicle and differently by the behavior of the driver. In newer suspension designs, mainly for high class vehicles, active or semi-active suspensions are used which can reduce roll and pitch angle in this case.

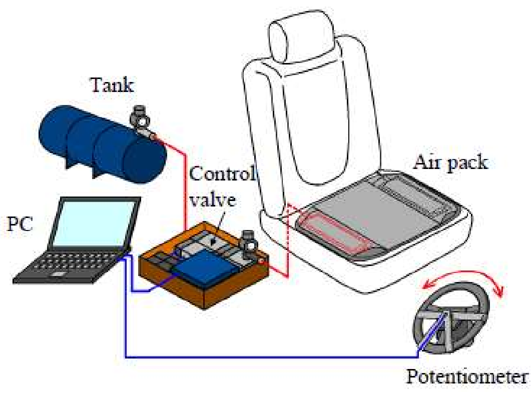

Fig. 5 *Posture Control Device [28].*

Some studies have shown that by tilting the head to the center of the corner, following the example of the driver, the symptoms of motion sickness in car passengers can be significantly reduced, leading to improved ride comfort [28, 41–43]. In [28] is present posture control device when traveling by car (Fig. 5). The proposed device has the effect of increasing the stability of the posture and increasing the comfort of passengers when driving in a corner.

In [44] experimental results performed with a tilting vehicle that was developed by modifying a small electric vehicle are presented. The driver's seat is fixed to the cab, which is attached to the chassis of the vehicle and their relative movement is about the axis of rotation. An electric motor is attached to one end of the axis of rotation to simulate a spring and a shock absorber. The tilting movement of the cab is mainly based on the lateral acceleration of the chassis. The tilt angle is limited to approximately 20º (0.35 rad) with a mechanical stopper. The results show that the tilting function significantly reduces the severity of motion sickness and increases ride comfort.

Tilting the chassis, following the example of railway transport, can compensate lateral accelerations of 1–2 m/s^2. The tilting angle should be approximately 6–12°. This overall tilting angle can be represented by the road bank angle, the vehicle configuration roll angle and the seat angle. To achieve compensation in the specified range, this would only be possible by applying (separately or additionally) tilting the seat [45]. To reduce the vibrations in lateral and vertical direction a seat system is necessary that allows an independent movement in both considered directions. In [46] the design of an active seat suspension is described. As it is difficult to redesign an existing car seat structure, it is possible to make a tilting car child seat [32].

6. Conclusion

This paper introduced a review of scientific papers and standards related to the ride comfort in road vehicles. The methods and the technical equipment for measuring and assessing comfort are considered. Special attention is paid to low-frequency oscillations below 1 Hz and their influence on the occurrence of motion sickness. Some suggestions are given for reducing the lateral inclination or for tilting towards the centre of the corner of the passenger's head, of his body by means of a pad in the seat or of the whole seat, and of the whole body of the car (chassis).

Despite existing research, lateral tilting systems have not been used in road transport, unlike rail transport. The reasons for this are the increase in the cost of construction, reduction of stability in case the whole chassis is tilted, lack of space for tilting the seats, etc. Therefore, the author of the present publication suggests a tilting child seat construction, thus will avoid many of the listed disadvantages and improving the ride comfort of the most vulnerable age group.

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