PREDICTION OF HUMAN DISCOMFORT PERCEPTION FROM COMBINATION OF NOISE AND TRANSLATIONAL VIBRATION EXPOSURE IN A VIBRO-ACOUSTIC ENVIRONMENT

By

MOHD FARID BIN ALADDIN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

July 2020

FK 2020 101

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the Degree of Doctor of Philosophy

PREDICTION OF HUMAN DISCOMFORT PERCEPTION FROM COMBINATION OF NOISE AND TRANSLATIONAL VIBRATION EXPOSURE IN A VIBRO-ACOUSTIC ENVIRONMENT

By

MOHD FARID BIN ALADDIN

July 2020

Chairman : Nawal Aswan Abdul Jalil, PhD
Faculty : Engineering

This thesis study the human discomfort feeling from the noise and Whole-Body vibration (WBV) exposure. The first part of the study involved the measurement of noise and vibration signals from five (5) vehicles operating on highway road. The whole-body vibration exposure on the seat-pan were averagely identified in the range of 0.1 to 0.8 m/s^2 with operating speed from 40 to 110 km/h. The interior noise exposure was identified in the range of 65 to 75 dBA. In laboratory work, three (3) experiments were conducted to study human responses to noise and vibration. The first experiment involved thirty-six (36) combinations of the noise and random vertical vibration which imposed on twelve (12) subjects to study the subjective equivalence of noise and vibration. The subjective equivalence correlation was identified as $L_{AE} = 35.04\ \log_{10} a_{vdv} + 79.122$ where L_{AE} is the A-weighted sound exposure level and a_{vdv} is the vibration dose value. The second experiment studied the discomfort feeling from the vibration on the seat pan in vibro-acoustic environment. Forty-two (42) combinations of noise and vibration were exerted to twelve (12) subjects which asked to be seated in a relaxed position on the vibration expander with a static feet support. Through the experiment, the discomfort model from vertical vibration expose on seat pan were identified as $\psi_v = 170.6082 a_{vdv}^{0.6662}$ where ψ_v is the discomfort feeling from vertical WBV. The findings and data become the basis for analysis in the experiment three. The experiment was repeated in the third experiment with different condition where the static footrest was replaced with the vibrating footrest. Finally, a new model of discomfort from vibration and the noise in a vehicle cabin was proposed as $\psi_{overall} = 170.6082 a_{vdv}^{0.6662}(1 + \epsilon_n + \epsilon_{f-n})$ where the ϵ_n is the perturbation caused by noise exposure and the ϵ_{f-n} is the perturbation effect cause by vibration on feet with existence on noise exposure

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

RAMALAN PERSEPSI KETIDAKSELESAAN MANUSIA TERHADAP PENDEDAHAN KEPADA GABUNGAN KEBISINGAN DAN GETARAN DALAM PERSEKITARAN VIBRO-AKUSTIK

Oleh

MOHD FARID BIN ALADDIN

Julai 2020

Pengerusi : Nawal Aswan Abdul Jalil, PhD
Fakulti : Kejuruteraan

Tesis ini mengkaji tahap ketidakselesaan manusia terhadap kebisingan dan getaran seluruh badan (WBV). Bahagian pertama kajian melibatkan pengukuran tahap kebisingan dan getaran dalam kenderaan yang beroperasi di atas jalan raya. Pendedahan terhadap WBV pada permukaan tempat duduk dalam kenderaan dikenalpasti pada julat 0.1 hingga 0.8 m/s^2 pada kelajuan daripada 40 sehingga 110 km/h. Tahap kebisingan dalam kenderaan dikenalpasti dalam julat 54 ke 75 dBA. Dalam kerja makmal, tiga (3) eksperimen telah dijalankan untuk mengkaji tindak balas manusia terhadap kebisingan dan getaran. Eksperimen pertama melibatkan tiga puluh enam (36) kombinasi rangsangan kebisingan dan getaran menegak rawak dikenakan terhadap dua belas (12) orang subjek untuk mengkaji persamaan subjektif antara kebisingan dan getaran. Perhubungan persamaan subjektif telah dikenalpasti sebagai $L_{AE} = 35.04 \log_{10} a_{vdv} + 79.122$ dimana L_{AE} adalah tahap pendedahan terhadap bunyi dengan pemberat A (A-weighting) dan a_{vdv} adalah dose pendedahan terhadap getaran (VDV). Eksperimen kedua pula mengkaji ketidakselesaan terhadap getaran seluruh badan yang dikenakan pada permukaaan tempat duduk dalam persekitaran "vibro-acoustic". Sebanyak empat puluh dua (42) kombinasi tahap kebisingan dan getaran telah dikenakan terhadap dua belas (12) subjek yang duduk dalam posisi badan selesa di atas permukaan mesin penala getaran dengan kaki diletak diatas permukaan yang statik. Memalui eksperimen ini, model ketidakselesaan terhadap pendedahan kepada getaran menegak pada permukaan kerusi dikenalpasti sebagai $\psi_v = 170.6082 a_{vdv}^{0.6662}$ dimana ψ_v adalah tahap ketidakselesaan terhadap WBV. Dapatan kajian dan data-data daripada eksperimen ini menjadi asas kepada analisa dalam eksperimen ketiga. Eksperimen ini di ulang dalam eksperimen ketiga tetapi dengan keadaan berbeza dimana keadaan kaki subjek diletak kan pada permukaan yang menghasilkan getaran. Sebagai dapatan kajian yang akhir, model ketidakselesaan terhadap kebisingan dan getaran dalam kenderaan telah dicadangkan sebagai $\psi_{overall} = 170.6082 a_{vdv}^{0.6662}(1 + \epsilon_n + \epsilon_{f-n})$ dimana ϵ_n

adalah kesan gangguan daripada perdedahan terhadap kebisingan dan ϵ_{f-n} adalah kesan gangguan daripada getaran pada kaki bersama pendedahan kepada kebisingan.

ACKNOWLEDGEMENTS

I would like to express my gratitude to Allah The Almighty for giving me the strength to finish this wonderful journey of knowledge. I like to thank my supervisor, Assoc. Prof. Ir. Dr. Nawal Aswan Abdul jalil for his patience in guiding me throughout the study period. I also like to thank Dr Ng Yee Guan and Dr Khairil Anas for their precious knowledge and support. A special thanks to all the members in the Sound and Vibration Research Group (SVRG) UPM for their support and great teamwork spirit. Last but not least, to my parents, my lovely wife, my two energetic sons and our newborn baby girl, thank you for the love, the support and the inspiration.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Nawal Aswan Abdul Jalil, PhD
Associate Professor, Ir
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Khairil Anas Md Rezali, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Ng Yee Guan, PhD
Associate Professor
Faculty of Medicine and Health Sciences
Universiti Putra Malaysia
(Member)

____
ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 12 November 2020

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: ________________________ Date: __________________

Name and Matric No.: _______________________________________

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: ______________________________
Name of Chairman of Supervisory Committee: ______________________________

Signature: ______________________________
Name of Member of Supervisory Committee: ______________________________

Signature: ______________________________
Name of Member of Supervisory Committee: ______________________________

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

WBV	Whole Body Vibration
r.m.s	Root mean square
r.m.q	Root mean quad
VDV	Vibration dose value
HAV	Hand-arm vibration
KM/H	Kilometre per hour
NVH	Noise, vibration and harshness
VAE	Vibro-acoustic environment
HAVS	Hand-arm vibration syndrome
ISO	International Standards Organization
RME	Relative magnitude estimation
AME	Absolute magnitude estimation
LRT	Light Rapid Transit
VACI	Vehicle Acoustic Comfort Index
CMM	Constant measurement method
SSM	Subjective scaling method
STRIDE	Science and Technology Research Institute of Defence
HVAC	Heating, ventilation and air-conditioner
ADP	Averaged discomfort projection
F-S ratio	Foot-to-seat pan vibration ratio
HAT	Head and Torso
RDMV	Relative Discomfort Monitoring Value
IQR	Inter-quartile range

CHAPTER 1

INTRODUCTION

1.1 Research Background

Determining human comfort in a vehicle cabin has been a great challenge for automotive manufacturers. It is the heart of the quality improvement works in a vehicle development since it plays a significant role in meeting customers expectation. In research, the interpretation of comfort is associated with discomfort where comfort is defined as the absence of discomfort (M. . Griffin, 1996). Human comfort level in a vehicle cabin is caused by environmental factors such as temperature, noise, vibration and vision, and intrinsic factors which originate from human expectation, sensitivity of senses and behavior. Human exposure to noise and vibration in a vehicle cabin is one of the key factors in understanding an overall comfort level in a vehicle. In a vibro-acoustic system such as in a vehicle cabin, exposure to noise and vibration has a direct impact on a vehicle passenger. In the scope of a commercial and passenger vehicle, a seated person will be exposed to the vibration on the seat pan, back rest, feet and an additional of hand arm exposure for a driver. The exposure to noise and vibration are longer viewed as the only source of annoyance which need to be reduced. In fact, the appropriate noise and vibration exposure have been viewed as a source of pleasant driving experience and an attractiveness of a vehicle which are affecting the perception of the quality impression of a product (Genuit, 2008). The understanding on the comfort level perceived from the noise and vibration by a human requires a multidisciplinary knowledge of noise and vibration from engineering, a theory of noise and vibration from physics, human physiology and senses, as well as human responses from psycho-physics which is a sub-field of an experimental psychology.

Human discomfort in a vehicle cabin is a very complex issue since it involves multiple internal and external factors that could affect the sensation based on the scope of the research. To simplify the condition, a passenger can be regarded as a part of a vibro-acoustic system coupled via the contact points of a steering wheel, seat, floor panels and pedal as a coupled person-machine system in vehicle cabin environment (Genuit, 2009). The exposure to the vibration can be categorized into two parts which are the whole-body-vibration (WBV) and the local vibration. The Whole-body vibration is about how the vibration transmitted to a human body affects the overall sensation or prevalence which can potentially affect health. The vibration is exerted at certain parts of the limbs but it affects the whole human body as if the whole body is undergoing vibration. It occurs when a human body part is supported by a vibrating surface and the vibration affects the other parts which is remote from the vibrating area (Mansfield, 2005). The effect of the WBV on human is associated with the feelings of discomfort, health issues (lower back pain), motion sickness, interference in activity and perception threshold. Previous studies indicated a strong evidence of correlation between the lower back pain with an exposure to the whole body vibration

(Bovenzi, Schust, & Mauro, 2017; Burström *et al.,* 2017; Burström, Nilsson, & Wahlström, 2015; Health and Safety Executive, 2005; Ismail *et al.,* 2015b; Robb & Mansfield, 2007; Rozali *et al.*, 2009; Sani *et al.*, 2015; Seidel, 2006; Troxel *et al.,* 2016). The local vibration is the vibration effect on human where the effect only involves the body part which is in contact with the vibrating object or surface such as the hand-arm vibration (HAV) and the vibration on feet. The significant impact of an exposure to HAV has been associated with the white finger syndrome (Anselm *et al.*, 2013; Bahri *et al.*, 2016; Burgess & Foster, 2012; Fe, 2001; Futatsuka *et al*., 2005; Sharma & Singh, 2016; Shivakumara & Sridhar, 2010; Su *et al.*, 2013; Welsh, 2012; Yamada & Sakakibara, 1994). In terms of human physiology, the construction of the hand arm and the foot knee system are similar which lead to a theory indicating that the vibration transmission on feet most likely to have the same effect as hand-arm vibration (HAV).

The exposure to noise in a vehicle cabin originates from various parts in a motor vehicle such as the engine, transmission, exhaust, tire rolling noise, wind noise and powertrain parts which are transferred directly to human hearing in a vehicle through the structure borne or the airborne noise. The dominant pathway for low frequency noise between 400 Hz to 500 Hz is through the structure borne, whereby the mid to high frequency is through the airborne (Crocker, 2007). The objective evaluation of noise involves the measurement of the sound pressure level (SPL) or the psychoacoustics parameters such as loudness, sharpness, roughness and fluctuation strength. Various methods have been explored to precisely quantify the vehicle interior noise and subsequently determine the sound quality level of the vehicle (Al-Dhahebi *et al*., 2017; Duan, Wang, & Xing, 2015; Eisele *et al.*, 2010; Krylov, 2002; Musser, Manning, & Peng, 2012; Putra, Wong, & Jalil, 2014; Skrúcaný *et al.*, 2015). The sensation towards noise is studied in psycho-physics where the responses from the noise stimuli can be correlated with the objective noise parameter by applying the Steven's Power law. The growth function and constant were quantified to predict the human responses from noise. This concept has been used to quantify the discomfort level perceived by a human (or so-called annoyance) when exerted with the noise stimulus.

Human exposure to noise and the whole-body vibration level in a vehicle cabin have been studied extensively which involved the work of measurement, evaluation and an assessment of noise and vibration level separately according to recognized standards. The measurement process involves the usage of a transducer which converts physical signal into electrical signal. The signal will then be amplified through the signal conditioning process before it undergoes through the signal processing stage where the signal will be filtered accordingly. The accelerometer is the transducer used for the vibration whereby the measurement microphone for quantifying the noise through the recording of a sound pressure fluctuation. The accuracy of the measurement will depend on the good selection of the sensitivity and the dynamic range of the transducer.

Besides the measurement, the evaluation of noise and the vibration step are also important in order to consider "human factor" to the quantity measured. The evaluation of process is done by referring the values to the related theory of human sensitivity to noise and vibration so that the value is quantified accordingly. The measured value will need to be evaluated with different weightings for different frequencies and directions. In the case of the whole-body vibration, the weighting of "W_k","W_d" and "W_f" were suggested in International Standard ISO 2631 part 1 (International Standard Organization, 1997) to quantify the vibration exposure on the seat pan, back rest, on the feet and in a recumbent position with respect to its translational axes of X-axis, Y-axis or Z-axis. It also depends on the mode of a human responses which can be in term of the comfort level, vibration perception, health related factor or motion sickness. In the quantification of the noise, the weightings used to address the human hearing sensitivity towards the frequency of sound are the A-weighting, B-weighting or C-weighting. Previous studies suggested some range of values of noise and vibration exposures on human in a vehicle but for different environment, condition and measurement setting (Galvagno, Vigliani, & Nesci, 2018; Nahvi *et al.*, 2006; Nahvi, Fouladi, & Nor, 2009; Nassiri *et al.*, 2014). Thus, these previous findings can be as references or benchmark, but not to be generalized to suit certain conditions in a study.

In an automotive noise and vibration harshness (NVH) practice, the noise and vibration in a vehicle are evaluated and assessed separately. The bench-marking process will be identified as the target objective evaluation. The noise and vibration level will be measured, and the quality refinement will be conducted to meet the benchmark values of the noise and vibration. The recent advancement in the study of human response to the noise and vibration suggested that the noise and vibration caused different effect on human when it is exposed separately and as a combined modality. The interaction between the effect of noise towards discomfort from the vibration and the effect of vibration towards discomfort from the noise could lead to a different interpretation of the real comfort felt by a human in a vehicle cabin. In addition, the effect of "masking" between noise to noise, vibration to vibration, noise to vibration and vibration to noise will alter the comfort and subsequently cause a misleading evaluation on the comfort level when evaluating the noise and vibration separately in a vehicle cabin.

The integration of knowledge in a human response to noise and vibration into the knowledge of automotive NVH is an important step towards improving the vehicle quality refinement process. It involves the application of psycho-physics investigation towards stimuli (noise and vibration) which convert into a meaningful model to predict the comfort or discomfort level from the noise and vibration in a vehicle. Thus, this study investigates the human discomfort level when exposed to the combined noise and the whole-body vibration in the vibro-acoustic environment such as in a vehicle cabin. It explores the application of knowledge in human response to noise and vibration into an automotive refinement process for noise, vibration and harshness (NVH). The concept of subjective equivalence of noise and vibration are further explored with applicable interpretation. The perturbation effect caused by different stimulus to the discomfort from the whole-body vibration in a vehicle is also investigated. The vehicle quality assessment from the noise and vibration in a vehicle cabin is proposed for an enhanced comprehensive approach in the vehicle development stage.

1.2 Research Objectives

The aim of this research is to enhance the understanding of how a human respond to the effect of noise and vibration as combined modalities, and subsequently predict the discomfort from the whole-body vibration in vibro-acoustic environment. The predictive model explores the improved method on quantifying the discomfort level in a vehicle cabin from the combination of noise and vibration. The main objective of the research is to predict the human feelings of discomfort from the combination of noise and the translational whole-body vibration in a vibro-acoustic environment. To address the research gap from the literatures, some important research questions need to be answered.

1. What is the range of the noise and vibration level exposed to a human when a vehicle operates at different speeds on a typical highway road?
2. How is the subjective equivalence curve of the noise and the vibration being formulated? The curve quantifies the subjective feeling of human from exposure to the combination of noise and vibration. The investigation of subjective equivalence of the noise and the vibration will improve the understanding of how the noise can be subjectively felt as the same sensation towards the vibration which leads to the knowledge of relative discomfort feeling between the noise and the vibration.
3. How do the interior noise exposure and the vibration on the foot rest affect the feelings of discomfort from the whole-body vibration? The application of the perturbation theory is introduced to address the perturbation effect caused by an additional stimulus in discomfort.
4. How can a comprehensive model of discomfort from the noise and vibration in a vehicle cabin be developed?

Specifically, four research objectives have been identified to address these concerns. These objectives are:

1. to identify the range of noise and vibration exposure of a passenger vehicle operating on highway with different operating conditions;
2. to investigate the subjective equivalence of the noise and vibration in a vehicle by formulating the subjective equivalence curve of discomfort from the combination of the noise and vibration.
3. to investigate the perturbation effect caused by noise and the foot-transmitted vibration towards discomfort from the vertical whole-body vibration; and
4. to formulate a novel model for predicting the discomfort from the noise and vibration in a vehicle cabin.

It is hypothesized that the range of noise and vibration exposure for a passenger vehicle operating with different speeds on the highway road is consistent with the previous findings from the literatures with the same condition of measurement and evaluation. The usage of different backgrounds such as different vehicle types, different operating speeds and a potentially different road surfaces roughness on the highways are expected to produce different values of noise and vibration. However, the range is expected to be consistent. The other research concern is that the subjective equivalent curve which is expected to be different based on the range of noises and vibrations, as well as the frequency content used in the study. However, the similar trend is expected to be derived accordingly. The quantification of masking or synergistic effect caused by the noise and the foot-transmitted vibration on discomfort from the whole-body vibration and the application of perturbation theory are expected to produce more realistic approximation to predict the discomfort level in a vehicle cabin.

1.3 Research Scope and Limitation

The research scope and limitation were determined earlier while planning the research work. The work was narrowed down to smaller scope to prevent more complexity and uncertainties. The scope and limitation of the research can be discussed in term of field work and laboratory experiment.

1.3.1 Scope and limitation in field work

This research focuses on investigating the noise and the vibration in vehicle cabin of five used vehicles with updated record of periodic maintenance and no major problem while in operation. The vibration measurement work in the vehicles focused only on the seat pan, back rest and foot rest as to reflect the vibration occur to vehicle passenger in relaxed upright seating posture with the head not touching the head rest. Therefore, the vibration on the steering wheel and head rest was excluded in the research. The measurement of the vibration is limited to the translational vibration of x- y- and z-axis from the vehicle seat-pan, back rest and foot rest. The vibration on the vehicle floor is only measured in a vertical direction. The vibration measurement only considers the vibration from 1 to 100 Hz. This is aligned with ISO 2631-1 which indicated that the vibration measurement frequency range to study comfort must consider 0.5 Hz to 80 Hz and the frequency below 1 Hz only suitable to study motion sickness. In addition, the frequency band limitation for the frequency weighting band-limiting filters is indicated to be at 100 Hz for the low pass (International Standard Organization, 1997). For noise, the range was selected to be 20 Hz to 20000 Hz which according to the range of human hearing and quantified using A-weighting. The condition for all the vehicles were ensured to follow the same setting as below:

1) All vehicles were driven on the same road lane during measurement.
2) The measurement only involve vehicle at speed of 40,60,90 and 110 km/h.
3) All vehicle window will remain closed during the measurement period.
4) The age of all the vehicles used was between 4 to 17 years with valid periodic maintenance record and did not produce any abnormal noise and vibration during operation on highway road. Therefore, no significance difference due to vehicle condition and age.

5) The extreme condition which can cause extreme signal of noise of noise and vibration was avoided. As the control measure, the measurement was conducted without pass-by noise from heavy vehicles, motorcycle and very minimal pass-by noise from another vehicle. The road also considered smooth highway road without pot hole, rumble strip, bumps or other type of irregularities.

In term of the safety of the measurement process, the vehicle driver must possess a valid driving license and was asked to focus on the driving all the time during the session. The driver is required to just listen to the instruction of the vehicle speed that need to be driven. All the road safety regulations were followed strictly. The random vibration measured on the seat pan, back rest of the seat and the feet in vehicle originated from the vehicle powertrain, road excitation and engine which transferred through vehicle structure, to the vehicle seat then reach human who seated on the vehicle seat. For noise, the recorded noise in vehicle cabin on highway road would capture the vehicle interior noise as well as exterior noise. However, the pass-by noise from other vehicle during driving had been minimized during measurement period. The measurement was conducted without any heavy vehicle or motorcycle pass-by nearby the vehicle during the session.

1.3.2 Scope and limitation for laboratory experiment

For the lab experiment, the vibration stimulus only involves the random vertical vibration with frequency range of 1 to 20 Hz which generated by electrodynamic shaker. The noise stimulus for the lab experiment was only limited to the study of noise exposure level for 61, 71, 77, 84, 87 and 89 dBA which reproduced from noise sample from a sedan vehicle at the operating speed of 60 km/h. The human subjects were instructed to pay attention and only evaluate the noise stimulus from the head phone and the vibration stimulus from the vibration shaker. The safety measures taken for the laboratory experiments are as below:

1) The subject must wear the 2-point safety belt which provided during the experiment.
2) The subject must fill up the consent form before participate in the experiment.
3) The emergency button is available on the vibration machine. In the case of emergency, the subject is required to say ‘stop”. Then the emergency button will be pushed immediately.

Besides, only healthy subjects were selected for the experiment. All the subjects were interviewed and declared to have no hearing issues and no disease related to back pain or musculoskeletal disorder. The vibration limited on the seat pan and foot. No backrest is considered as it will add the complexity to the model and can change human responses due to the vibration exerted on backrest.

1.4 Novelty and Contribution

The research involves an in-depth investigation on the human discomfort feelings from the combination of the noise and the vibration exposure in a vehicle cabin. The novelty parts of the research are

1) The formulation of the new predictive model of a human discomfort from the combined noise and the vibration by quantifying the perturbation effect from noise and vertical vibration on footrest. The significant contribution of the research work is a new method to quantify human discomfort from the combination of noise and vibration.
2) The investigation of the antagonistic and the synergistic effects from the interaction of the noise exposure and the vibration of feet to the discomfort from the whole-body vibration. The concept of the "perturbation effect" is introduced as part of an overall discomfort model using the perturbation theory.
3) The new subjective equivalence curve was formulated to improve the understanding of the relative discomfort from the noise and the vibration. The work of measurement and the evaluation of noise and vibration signal in vehicles contribute to strengthen the existing literatures for the similar work conducted in Malaysia environment. It would be beneficial for any future work related to the vehicle interior noise and vibration.

The new predictive model of discomfort from noise and vibration will contribute to the potential application in automotive industry. Vehicle manufacturer can apply the model to evaluate the relative discomfort level from noise and vibration in vehicle cabin during vehicle refinement process. In term of contribution to any standards, the new model is believed to be more accurate compared to evaluation using relative value of the stimulus (either noise or vibration). The synergistic effect or antagonistic effect will tend to make the evaluation to be underestimate or overestimate from the real feeling of discomfort. As the vibro-acoustic environment exert both noise and vibration stimuli concurrently, the complexity to describe discomfort level can be approach using this new model. The effect of synergistic and antagonistic of noise and vibration can be reviewed by the National Standards Center such as SiRIM to improve the existing standardized methodology on measuring and evaluating noise and vibration in a vibro-acoustic environment.

1.5 Research planning and thesis arrangement

1.5.1 The research milestone

To achieve the research objectives, the sequence of research works has been designed according to the needs of information and the necessary understanding before commencing to the formulation of the predictive model. The first stage of literature reviews accumulated the required basic knowledge related to human response from the combination of noise and vibration as well as the progress on the development of human response model which spans from the basic idea on quantifying noise and vibration separately into the idea to model the responses to noise and vibration as a combined stimuli. The recent progress of the knowledge on interaction of noise and vibration stimulus on human sensation has open up an idea of new predictive model of discomfort from noise and vibration based on the concept adapted from perturbation theory. The model is expected to be applicable in automotive noise, vibration and harshness (NVH) refinement process.

The second stage involves the measurement and evaluation of noise and vibration signal in vehicle. The field study verified that the range of noise and vibration stimuli used in the laboratory experiments so that the result from the experiment can be applied to the case of noise and vibration exposure in vehicle cabin. Besides, the literatures related to noise and vibration exposure for operating vehicle in Malaysia was found to be scarce. The work of measurement and evaluation of noise and vibration signal in this research is expected to contribute to the existing literatures in terms of verifying or providing new perspective of noise and vibration exposure in vehicle cabin. It is vital to highlight that the objective of the measurement was not to study the comparison of vehicle brands. The key information behind this measurement work was to obtain the range of noise and vibration exposure in operating vehicles and study the consistency of the findings with existing literatures of noise and vibration exposure in operating vehicle. The idea was that the field study in the literatures were conducted in different environment setting. Highway road on different geographical surface, different vehicle used and different soundscape might cause different vibration excitation. The significant impacts of the field measurement work are to:

1) Contribute in verifying or compare the existing literature of the range of noise and vibration exposure in vehicle with various operating speed on highway road.
2) Verify that the noise and vibration exposure used for this research include the range on exposure in vehicle so that the resulting model can be applied to predict discomfort state in vehicle cabin.

The third stage involves a psychophysics experiment to study the subjective equivalence from noise and vibration. As human perceives noise and vibration differently, the relative sensation from noise and vibration will improve the understanding on how human perceive discomfort from the two different stimuli. This will contribute to the framework of modelling the sensation to the noise and the vibration as a combined modality. The output of this experiment was the subjective equivalence curve of noise and vibration. The fourth stage was the extension of the third experiment where the experiment was conducted with different setting to study how human responses when exerted with different combination of noise and vibration level. The feeling of discomfort was evaluated by human subjects and translated into mathematical expression through statistical approach. The experiment produced an equation of human discomfort from whole-body vibration. The effect for perturbation noise also can be quantified when the data of this experiment combined with the final experiment. The summary of overall flow as in Figure 1.1.

The last experiment was designed to study the perturbation effect of noise and vibration on feet on the discomfort from whole-body vibration of human in vibro-acoustic environment. The study involved the development of vibrating footrest which will vibrate relative to the vibration of the shaker expander. Human subject would feel the vibration generated on the seat as well as at the feet at different vibration magnitude ratio. The analysis of the result produced the perturbation effect caused by the existence of vibration on the feet. The ultimate outcome of the research is a predictive model of discomfort from noise and vibration which can be applied to analyze noise and vibration exposure in vehicle through relative comparison value. The formulation also introduced a chart of perturbation effect of noise to the discomfort from whole-body vibration, as well as the perturbation. The application of the overall discomfort equation was discussed in the scope of automotive noise, vibration and harshness refinement work. The equation could be applied to identify the "relative" discomfort feeling of passenger from noise and vibration in vehicle cabin. The relative value can be quantified by setting the benchmark level that need or desired to be achieved.

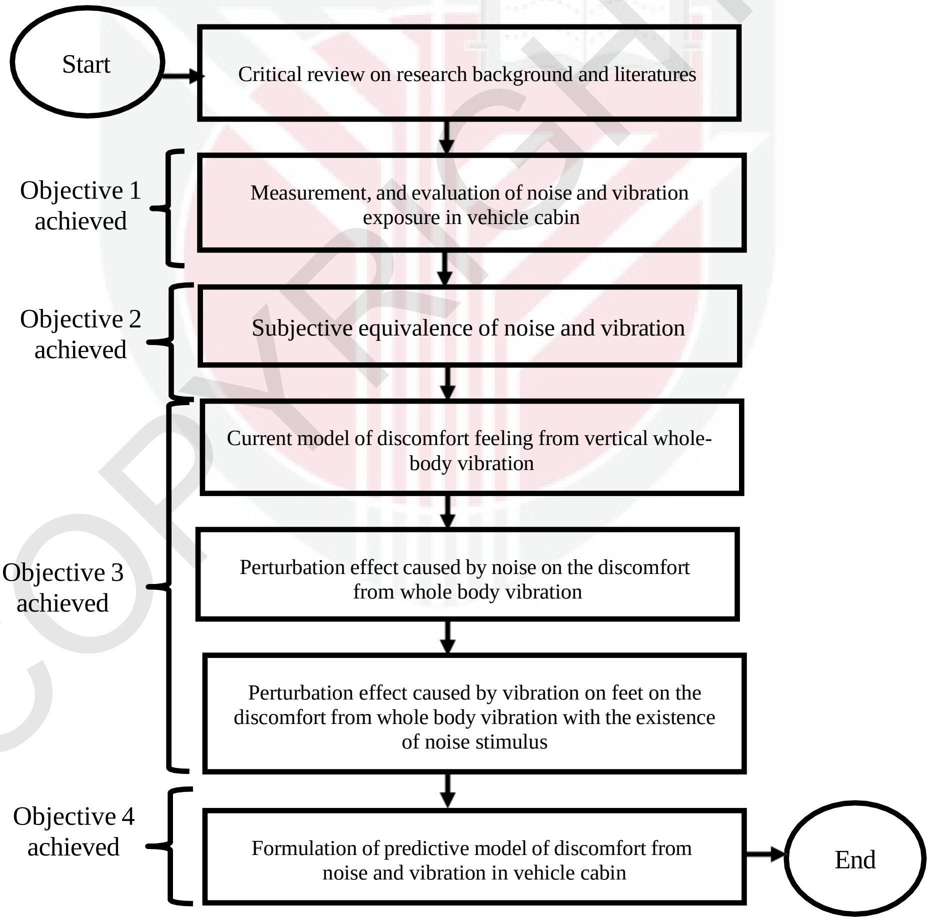

Figure 1.1: The simplified flow chart of the research project

The findings from this research are expected to open up a different perspective on noise and vibration assessment in vibro-acoustic environment. The quantification of interaction between two stimuli of noise and vibration to human paved the way to more accurate prediction of how noise and vibration affects human discomfort level. The current practice of noise and vibration assessment as a separate entity has been successfully applied by neglecting the significance of the antagonistic or synergistic effect of noise and vibration. This can lead to a misleading indication of the real feeling or effect to the human.

1.5.2 Thesis arrangement

The thesis is divided into five chapters including the introduction, literature reviews, the research methodology, result and discussion as well as conclusion. Chapter 1 discusses the research background of a human response to noise and vibration. The research questions are generated based on the current issues and previous research findings which lead to the current research needs. The research objectives are identified as a guide to develop the research methodology and the case study.

Chapter 2 highlights the literature review which consists of fundamental principles of a human response to the noise annoyance and the discomfort from the whole-body vibration. The related previous research literatures are reviewed in detail. The concept of noise and vibration as a combined stimulus are elaborated extensively to highlight the importance of this study.

Chapter 3 elaborates on the methodology used in the research which involves laboratory experiments as well as the field measurement of the noise and the vibration in vehicles on highway roads. In overall, three psycho-physics laboratory experiments had been carried out for this research. The setting of all the three experiments were elaborated in term of the facility, machines and apparatus, the experiment instruction, safety measures, human subjects, human subject consent as well as the noise and the vibration source for the experiment. The reproduction of the vibration stimulus in the laboratory involves the usage of the electrodynamic shaker which set to produce different levels of random vertical vibration magnitude. The noise reproduction generated from the recorded sound in a vehicle operated on the road.

Chapter 4 focused on the result and discussion of the research findings in the field study and the three laboratory experiments. The work of measurement and evaluation of noise and the vibration exposure to a human in a vehicle cabin were elaborated extensively. The vibration exposure on seat pan, backrest and foot rest in vehicle were discussed in details. The noise exposure in vehicle cabin operating speed of 40,60,90 and 110 km/h were tabulated analyzed. Finally, the range of noise and vibration exposure in vehicle within 40 to 110 km/h were discussed and compared with previous literatures. The findings from the three laboratory experiments also discussed thoroughly. The first experiment highlighted the new subjective equivalence curve was derived from the experiment and the equation was applied to verify discomfort model from this research. The second experiment highlighted the new model o discomfort from noise and vibration. The last experiment produced the perturbation effect charts from noise and vibration on feet and subsequently led to the formulation of a new model of overall discomfort from noise and vibration.

Chapter 5 summarized the thesis by elaborating the conclusion and recommendation. The conclusion recap on how the objectives of the research were achieved and the potential application of the new model which developed from this research work. The recommendation outlined the future research gap as well as further extensive work that can be considered to improve the model.

REFERENCES

Abdul Jalil, N. A., & Griffin, M. J. (2007). Fore-and-aft transmissibility of backrests: Variation with height above the seat surface and non-linearity. *Journal of Sound and Vibration*, *299*(1–2), 109–122.

Al-Dhahebi, A. M., Junoh, A. K., Mohamed, Z., & Muhamad, W. Z. A. W. (2017). A computational approach for optimizing vehicles' interior noise and vibration. *International Journal of Automotive and Mechanical Engineering*, *14*(4), 4690–4703.

Anselm, T. S., Fukumoto, J., Darus, A., Hoe, V. C., Miyai, N., Isahak, M., … Miyashita, K. (2013). A comparison of hand-arm vibration syndrome between Malaysian and Japanese workers. *Journal of Occupational Health*, *55*(6), 468–478.

Aziz, S. A. A., Gani, A., Suhaimi, A. F., Kalil, S., Md Yusuf, A. Y., & Nuawi, M. Z. (2017). Noise exposure inside a passenger car cabin in tropical environmental condition. *Defence S and T Technical Bulletin*, *10*(3), 290–296.

Azizan, A., Zali, Z., & Padil, H. (2017). Evaluation of reaction time performance and subjective drowsiness during whole-body vibration exposure. *IOP Conference Series: Materials Science and Engineering PAPER*, 1–7.

Bahri, S., Tamrin, M., Maizurayusoff, N., Rahman, A. A., Mansour, A., Sciences, H., … Arabia, S. (2016). Original Article the Prevalence of Hand Arm Automobile Assembly Workers Vibration Syndrome. *Malaysian Journal of Public Health Medicine*, *16*, 128–136.

Basner, M., Babisch, W., Davis, A., Brink, M., Clark, C., Janssen, S., & Stansfeld, S. (2014). Auditory and non-auditory effects of noise on health. *The Lancet*, *383*(9925), 1325–1332.

Basri, B., & Griffin, M. (2013). Predicting discomfort from whole-body vertical vibration when sitting with an inclined backrest. *Applied Ergonomics*, *44*(0), 423–434.

Bauer, B. (2009). Does stevens's Power Law For Brightness extend to Perceptual Brightness averaging? *The Psychological Record*, *59*, 171–186.

Bernard, P. (2014). Leq & SEL What? Why? When? In *Brüel & Kjær; application notes*.

Beutel, M. E., Jünger, C., Klein, E. M., Wild, P., Lackner, K., Blettner, M., … Münzel, T. (2016). Noise annoyance is associated with depression and anxiety in the general population- the contribution of aircraft noise. *PLoS ONE*, *11*(5), 1–10.

Borg, G. (1990). Psychophysical scaling with applications in physical work and the perception of exertion. *Scand J Work Environ Health*, *16*(1), 55–58.

Bovenzi, M., Schust, M., & Mauro, M. (2017). An overview of low back pain and occupational exposures to whole-body vibration and mechanical shocks. *Medicina Del Lavoro*, *108*(6), 419–433.

British Standards Institution. (1987). *BS 6841: British Standard guide to* *measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock.*

Brysbaert, M. (2019). How Many Participants Do We Have to Include in Properly Powered Experiments ? A Tutorial of Power Analysis with Reference Tables. *Journal of Cognition*, *2*(1), 1–38.

Burdzik, R., & Dolecek, R. (2012). *Research of Vibration Distribution in Vehicle Constructive*. *VII*(4), 16–25.

Bureau of Indian Standards. (2010). *IS12832:2010*. New Delhi.

Burgess, M., & Foster, G. (2012). *Overview of the occupational exposure limits for hand-arm and whole-body vibration*. Proceeding of Acoustics,Fremantle,Australia.

Burström, L., Aminoff, A., Björ, B., Mänttäri, S., Nilsson, T., Pettersson, H., … Wahlström, J. (2017). Musculoskeletal symptoms and exposure to whole-body vibration among open-pit mine workers in the Arctic. *International Journal of Occupational Medicine and Environmental Health*, *30*(4), 553–564.

Burström, L., Nilsson, T., & Wahlström, J. (2015). Whole-body vibration and the risk of low back pain and sciatica: a systematic review and meta-analysis. *International Archives of Occupational and Environmental Health*, *88*(4), 403–418.

Choi, J., & Loftness, V. (2012). *Investigation of human body skin temperatures as a bio-signal to indicate overall thermal sensations*. *58*, 258–269.

Crocker, M. J. (2007). Introduction to Interior Transportation Noise and Vibration Sources. In *Handbook of Noise and Vibration Control* (pp. 1147–1158).

Da Silva, L., Bortolotti, S. L. V., Campos, I. C. M., & Merino, E. A. D. (2012). Comfort model for automobile seat. *Work*, *41*(SUPPL.1), 295–302.

Da Silveira Brizon, C. J., & Medeiros, E. B. (2010). Improving the acoustic evaluation of motor cars. *20th International Congress on Acoustics 2010, ICA 2010 - Incorporating Proceedings of the 2010 Annual Conference of the Australian Acoustical Society*, *3*(August), 2108–2111. Sydney, Australia.

Damijan, Z. (2010). Investigation of the vibroacoustic climate inside the buses Solaris MAN SG242 used in public transport systems. *Acta Physica Polonica A*, *118*(1), 27–30.

Daruis, D. D. I., Nor, M. J. M., Fouladi, M. H., & Deros, B. M. (2009). Driver's perception on the influence of interior sound to vertical whole-body vibration. *16th International Congress on Sound and Vibration 2009, ICSV 2009*, *1*(July), 5–9.

Dempsey, T. K., & Clevenson, S. A. (1976). *Noise and Vibration Ride Comfort Criteria*. Virginia.

Drewes, C. (2004). Proceeding of the Association for Biology Laboratory Education (ABLE),2004. *Touch and Temperature Senses*, 1–15. Ohio, United States of America.

Duan, Z., Wang, Y., & Xing, Y. (2015). Sound Quality Prediction of Vehicle

Interior Noise under multiple working condition using Back propagation Neural Network Model. *Journal of Transportation Technologies*, *5*(April), 134–139.

Ebe, K., & Griffin, M. (2000). Quantitative prediction of overall seat discomfort. *Ergonomics*, *43*(6), 791–806.

Eisele, G., Wolff, K., Alt, N., & Hüser, M. (2010). Application of Vehicle Interior Noise Simulation (VINS) for NVH Analysis of a Passenger Car. *SAE Technical Paper Series*, *1*.

El-naggar, B. (2012). Forced vibrations of cantilever beams. *Canadian Journal of Pure and Applied Science*, *6*(3), 2187–2190.

Fleming, D., & Griffin, M. (1975). A study of the subjective equivalence of noise and whole-body vibration. *Journal of Sound and Vibration*, *42*(4), 453–461.

Fletcher, H., & Munson, W. A. (1933). Loudness, its Definition, Measurement and Calculation. *Journal of Acoustical Society of America*, *5*(82), 82–108.

Funakoshi, M., Taoda, K., Tsujimura, H., & Nishiyama, K. (2004). Measurement of Whole-Body Vibration in Taxi Drivers. *Journal of Occupational Health*, *46*(2), 119–124.

Futatsuka, M., Shono, M., Sakakibara, H., & Quan, P. Q. (2005). Hand arm vibration syndrome among quarry workers in Vietnam. *Journal of Occupational Health*, *47*(2), 165–170.

Galvagno, E. (2018). *Acoustic and Vibrational comfort in passenger vehicles*. Politecnico Di Torino.

Genuit, K. (2005). The sound quality of vehicle interior noise: a challenge for the NVH-engineers. *International Journal of Vehicle Noise and Vibration*, *1*(1/2), 158.

Genuit, K. (2008). NOISE-CON 2008 Vehicle Interior Noise – A Combination of Sound , Vibration and Interactivity. *NOISE-CON 2008*, (March). Dearborn,Michigan.

Genuit, K. (2009, December). Vehicle Interior Noise – Combination of Sound , Vibration and Interactivity. *Sound and Vibration*, (December), 8.

Giacomin, J., & Fustes, F. (2005). Subjective Equivalence of Steering Wheel Vibration and Sound. *International Journal of Industrial Ergonomics*, *35*, 517–526.

Goggins, K. A., Tarabini, M., Lievers, W. B., & Eger, T. R. (2019). Biomechanical response of the human foot when standing in a natural position while exposed to vertical vibration from 10–200 Hz. *Ergonomics*, *62*(5), 644–656.

Griffin, M. (2007). Discomfort from feeling vehicle vibration. *Vehicle system dynamics:International Journal of vehicle mechanics and mobility*, *45*(7–8), 679–698.

Griffin, M. J. (1990). *Handbook of Human Vibration.* California,USA: Academic Press.

Gyi, D. E. (2013). Driving posture and healthy design. In *Automotive Ergonomics: Driver-Vehicle Interaction* (pp. 123–130). Boca raton: CRC Press.

Hammersen, F., Niemann, H., & Hoebel, J. (2016). Environmental noise annoyance and mental health in adults: Findings from the cross-sectional German health update (GEDA) study 2012. *International Journal of Environmental Research and Public Health*, *13*(10), 1–12.

Harrison, M. (2004). *Vehicle Refinement Controlling Noise and Vibration in Road Vehicles*. Burlington,USA: SAE International.

Health and Safety Executive. (2005). *Whole-body vibration in ports HSE information sheet*.

Helander, M. G. (2003). Forget about ergonomics in chair design? Focus on aesthetics and comfort! *Ergonomics*, *46*(13–14), 1306–1319.

Helander, M. G., & Zhang, L. (1997). Field studies of comfort and discomfort in sitting. *Ergonomics*, *40*(9), 895–915.

Hempstock, T. I., & Saunders, D. J. (1976). Cross-modality determination of the subjective growth function for whole-body vertical, sinusoidal, vibration. *Journal of Sound and Vibration*, *46*(2), 279–284.

Howard, D., & Angus, J. (2009). Acoustics and Psychoacoustics. In *Focal Press* (fourth). Elsevier

Howart, H., & Griffin, M. (1990). Subjective response to combined noise and vibration: summation and interaction effects. *Journal of Sound and Vibration*, *143*(3), 443–454.

Howarth and Griffin, M. J. (1991). The annoyance caused by simultaneous noise and vibration from railway. *J.Acoust.Soc.Am*, *89*(5), 2317–2323.

Howarth, H., & Griffin, M. J. (1990). The relative importance of noise and vibration from railways. *Applied Ergonomics*, *21*(2), 129–134.

Howarth, Henrietta, & Griffin, M. (1988). The frequency dependence of subjective reaction to vertical and horizontal whole-body vibration at low magnitudes. *Journal of the Acoustical Society of America*, *83*, 1406–1413.

Howarth, Henrietta, & Griffin, M. (1990). Subjective response to combined noise and vibration: summation and interaction effects. *Journal of Sound and Vibration*, *143*, 443–454.

Huang, Y., & Li, D. (2019). Subjective discomfort model of the micro commercial vehicle vibration over different road condition. *Applied Acoustics*, *145*, 385–392.

Huang, Yu. (2012). *Human response to combined noise and vibration*, Phd Thesis,University of Southampton. UK

Huang, Yu. (2015). The Negative Masking of Mechanical Noise in the judgement of subjective intensity of Whole-Body Vibration. *50th UK Conference on Human Response to Vibration*, (September), 1–8. Southampton.UK

Huang, Yu, & Griffin, M. (2014a). The relative discomfort of noise and vibration: effects of stimulus duration. *Ergonomics*, *57*(8), 1244–1255.

Huang, Yu, & Griffin, M. J. (2010). The relative importance of noise and vibration to the sensation of comfort in vehicles. *45th UK Conference on Human Response to Vibration*, *10*(September), 6–8.

Huang, Yu, & Griffin, M. J. (2012). The effects of sound level and vibration magnitude on the relative discomfort of noise and vibration. *The Journal of the Acoustical Society of America*, *131*(6), 4558–4569.

Huang, Yu, & Griffin, M. J. (2014b). Comparison of absolute magnitude estimation and relative magnitude estimation for judging the subjective intensity of noise and vibration. *Applied Acoustics*, *77*, 82–88.

Huang, Yu, & Griffin, M. J. (2014c). The discomfort produced by noise and whole-body vertical vibration presented separately and in combination. *Ergonomics*, *57*(11), 1724–1738.

Huang, Yu, & Li, D. (2020). An empirical category-ratio scale for evaluating the subjective intensity of noise based on the comparison of estimated magnitudes and categories. *Applied Acoustics*, *158*(October), 107048.

Hussain, B., Ali, M., Qasim, M., Masoud, M. S., & Khan, L. (2017). Hearing impairments, presbycusis and the possible therapeutic interventions. *Biomedical Research and Therapy*, *4*(4), 1228.

International Standard Organization. (1997). *ISO 2631-1 Mechanical vibration and shock- Evaluation of human exposure to whole-body vibration Part 1: General requirement*. Geneva,Switzerland.

International Standard Organization. (2003). *ISO 1996-1: Description, measurement and assessment of enviromental noise*. Geneva: International Standards Organization.

International Standards Organization. (2003). *ISO/TS 15666:2003 - Acoustics — Assessment of noise annoyance by means of social and socio-acoustic surveys*.

International Standards Organization. (2016). ISO 10326-1:2016 - Mechanical vibration — Laboratory method for evaluating vehicle seat vibration — Part 1: Basic requirements. In *International Standard Organization*.

Ismail.A.R., Nuawi, M. Z., Kamaruddin, N. F., & Bakar, R. A. (2010). Comparative Assessment of the whole-body vibration exposure under different car speed based on Malaysian road profile. *Journal of Applied Sciences*, *10*(14), 1428–1434.

Ismail, A. R., Abdullah, S. N. A., Abdullah, A. A., & Deros, B. M. (2015a). Whole-body vibration exposure of Malaysian taxi drivers. *International Journal of Automotive and Mechanical Engineering*, *11*(1), 2786–2792.

Ismail, A. R., Abdullah, S. N. A., Abdullah, A. A., & Deros, B. M. (2015b). Whole-Body vibration exposure of Malaysian taxi driver. *International Joural of Automotive and Mechanical Engineering (IJAME)*, *11*(June), 2786–2792.

Jang, H., & Griffin, M. J. (1999). The effect of phase of differential vertical vibration at the seat and feet on discomfort. *Journal of Sound and Vibration*, *223*(5), 785–794.

Janssen, J. H. (1969). *A Proposal for standardize measurements and annoyance rating of simultaneous nise and vibrations in ships*. Delft, Netherland.

Kaneko, C., Hagiwara, T., & Maeda, S. (2005). Evaluation of Whole-Body

Vibration by the Category Judgment Method. *Industrial Health*, *43*, 221–232.

Kjellberg, A. (1990). Psychological aspects of occupational vibration. *Scandinavian Journal of Work, Environment and Health*, *16*(SUPPL. 1), 39–43.

Kjellberg, A., WikstrÖm, B., & Dimberg, U. (1985). Whole-body vibration: exposure time and acute effects — experimental assessment of discomfort. *Ergonomics*, *28*(3), 545–554.

Kolich, M. (2003). Automobile seat comfort: Occupant preferences vs. anthropometric accommodation. *Applied Ergonomics*, *34*(2), 177–184.

Krueger, L. E. (1989). Reconciling Fechner and Stevens: Toward a unified psychophysical law. *Behavioral and Brain Sciences*, *12*(2), 251–320.

Krylov, V. V. (2002). Simplified analytical models for prediction of vehicle interior noise. *Proceedings of the 20th International Conference on Noise and Vibration Engineering (ISMA 2002)*, 1973–1980.

Kumaresh, S. A., & Aladdin, M. F. (2019). A study of vibration transmission on seated person in passenger vehicle. *AIP Conference Proceedings*, *2137*(August).

Kwon, G., Jo, H., & Kang, Y. J. (2018). Model of psychoacoustic sportiness for vehicle interior sound: Excluding loudness. *Applied Acoustics*, *136*, 16–25.

Laming, D. (1997). *The Measurement of Sensation* (Oxford Psy; L. Mackintosh, N.J., Shallice, T., Treisman, A., McGaugh, J.L., Schacter, D., and Weiskrantz, Ed.). New York: Oxford University Press.

Landström, U., & Lundström, R. (1985). Changes in wakefulness during exposure to whole body vibration. *Electroencephalography and Clinical Neurophysiology*, *61*(5), 411–415.

Lauwers, K., Acke, S., Verbrugghe, M., Dumoulin, G., Schmickler, M.-N., & Braeckman, L. (2018, April). *424 Whole body vibration among professional bus drivers – evaluation of an intervention study to reduce low back pain*. A524.2-A524.

Leatherwood, J. D. (1979). *NASA Technical Paper 1374: Human Discomfort Response to Noise Combined With Vertical Vibration*. Virginia.

Leatherwood, J., & Dempsey, T. (1976). *Psychophysical relationships Characterizing Human Response to Whole-Body Sinusoidal Vertical Vibration*. Washington D.C.

Lee, P. J., & Griffin, M. J. (2013). Combined effect of noise and vibration produced by high-speed trains on annoyance in buildings. *The Journal of the Acoustical Society of America*, *133*(4), 2126–2135.

Lepore, S. J., & Evans, G. W. (1996). Coping with Multiple Stressor in the environment. In N. Zeidner, M.,Endler (Ed.), *Handbook of coping : theory, research, applications* (pp. 350–377).

Lewis, C. H., & Griffin, M. J. (1998). A comparison of evaluations and assessments obtained using alternative standards for predicting the hazards of whole-body vibration and repeated shocks. *Journal of Sound* *and Vibration*, *215*(4), 915–926.

Li, D., & Huang, Y. (2018). The discomfort model of the micro commercial vehicles interior noise based on the sound quality analyses. *Applied Acoustics*, *132*(December 2017), 223–231.

Li, Q., Qiao, F., & Yu, L. (2017). Risk Assessment of In-Vehicle Noise Pollution From Highways. *Environment Pollution and Climate Change*, *01*(01).

Liu, Q., Kang, Z., Song, R., Zhang, L., & Wu, Q. (2017). Study on perception threshold for whole-body vibration. *Vibroengineering Procedia*, *14*, 244–249.

Maeda, S. (2005). Necessary Research for Standardization of Subjective Scaling of Whole-Body Vibration. *Industrial Health*, *43*, 390–401.

Maigrot, P., Marquis-Favre, C., & Parizet, E. (2017a). Annoyance due to railway noise and vibrations: A comparison of two methods of collecting annoyance scores. *The Journal of the Acoustical Society of America*, *141*(5), 3693–3694.

Maigrot, P., Marquis-Favre, C., & Parizet, É. (2017b). Two laboratory methods of assessing annoyance due to railway noise and vibration. *The Journal of the Acoustical Society of America*, *142*(5), 3284–3287.

Mansfield, N.J. (2013). Human response to vehicle vibration. In N. Gkikas (Ed.), *Automotive ergonomics : driver-vehicle interaction* (pp. 77–94). Boca raton: CRC Press.

Mansfield, N. J. (2005). *Human Response to vibration*. New York: CRC Press LLC.

Mansfield, N. J., Ashley, J., & Rimell, A. N. (2007). Changes in subjective ratings of impulsive steering wheel vibration due to changes in noise level: a cross-modal interaction. *International Journal of Vehicle Noise and Vibration*, *3*(2), 185–196.

Mansfield, N. J., Mackrill, J., Rimell, A. N., & MacMull, S. J. (2014). Combined Effects of Long-Term Sitting and Whole-Body Vibration on Discomfort Onset for Vehicle Occupants. *ISRN Automotive Engineering*, *2014*, 1–8.

Mansfield, Neil, Naddeo, A., Frohriep, S., & Vink, P. (2019). Integrating and applying models of comfort. *Applied Ergonomics*, *82*(2020).

Marjanen, Y., & Mansfield, N. J. (2010). Relative Contribution of Translational and Rotational Vibration to Discomfort. *Industrial Health*, *48*(5), 519–529. .

Maugeri, S. (2018). *Modelling The Response of the Human Feet to Vertical Whole-Body Vibration*. Masters Thesis, Politico Di Milano.

McMinn, T. (2013). “A-weighting”: Is it the metric you think it is? *Annual Conference of the Australian Acoustical Society 2013, Acoustics 2013: Science, Technology and Amenity*, (November), 165–168. Victor Harbour, Australia.

Meram, A., & Shahriari, M. (2019). Evaluation of whole-body vibration in automobile on routine travel: A case study, *Occupational and Environmental Safety and Health*. Springer.

Merchel, S., Altinsoy, M. E., & Schwendicke, A. (2015). Tactile Intensity

Perception Compared to Auditory Loudness Perception. *IEEE World Haptics Conference (WHC)*, 356–361.

Miśkiewicz, A., & Letowski, T. (1999). Psychoacoustics in the Automotive Industry. *Acustica*, *85*(5), 646–649.

Miwa, T., & Yonekawa, Y. (1973). Measurement and evaluation of environmental vibrations. *Industrial Health*, *11*(4), 177–184.

Mohd Noor, A., Yahya, M., Ghazali, M. I., & Selvan, H. K. T. (2015). The Study on Whole Body Vibration Exposure Induces Low Back Pain among UTHM Bus Drivers. *Applied Mechanics and Materials*, *773–774*, 75–79.

Morioka, M., & Griffin, M. (2005). Perception thresholds for vertical vibration at the hand , seat and foot Results 3 . 1 Effect of frequency. *ForumAcusticum*, 1577–1582. Budapest.

Musser, C. T., Manning, J. E., & Peng, G. C. (2012). Predicting vehicle interior sound with statistical energy analysis. *Sound and Vibration*, *46*(12), 8–14.

Naddeo, A., Cappetti, N., Vallone, M., & Califano, R. (2014). New trend line of research about comfort evaluation : proposal of a framework for weighing and evaluating contributes coming from cognitive , postural and physiologic comfort perceptions. *Proceedings of the 5th International Conference on Applied Human Factors and Ergonomics AHFE 2014*, (July). Krakow, Poland.

Nahvi, H., Nor, M. J. M., Fouladi, M. H., & Abdullah, S. (2006). Evaluating Automobile Road Vibrations Using BS 6841 and ISO 2631 Comfort Criteria. *1st Regional Conference on Vehicle Engineering & Technology*, 1–8.

Nahvi, Hassan, Fouladi, M. H., & Mohd Nor, M. J. (2009). Evaluation of whole-body vibration and ride comfort in a passenger car. *International Journal of Acoustics and Vibrations*, *14*(3), 143–149.

Nakashima, A. M., Borland, M. J., & Abel, S. M. (2005). Characterization of vibration and noise exposure in Canadian Forces armored vehicles. In *DRDC Toronto TR 2005-241* (Vol. 118). Toronto.

Nassiri, P., Ebrahimi, H., Monazzam, M. R., Rahimi, A., & Shalkouhi, P. J. (2014). Passenger Noise and Whole-Body Vibration Exposure—A Comparative Field Study of Commercial Buses. *Journal of Low Frequency Noise, Vibration and Active Control*, *33*(2), 207–220.

Nor, M. J. M., Fouladi, M. H., Nahvi, H., & Ariffin, A. K. (2008). Index for vehicle acoustical comfort inside a passenger car. *Applied Acoustics*, *69*(4), 343–353.

Ordonez, R., De Toro, M. A. A., & Hammershoi, D. (2010). Time and frequency weightings and the assessment of sound exposure. *Inter.Noise 2010*. Lisbon, Portugal.

Paddan, G., & Griffin, M. (2002). Evaluation of Whole-body Vibration in vehicles. *Journal of Sound and Vibration*, *253*(1), 195–213.

Parizet, E., Brocard, J., & Piquet, B. (2004). Influence of Noise and Vibration to Comfort in Diesel Engine Cars Running at Idle. *Acta Acustica United with Acustica*, *90*(5), 987–993.

Parizet, Etienne, Amari, M., & Roussarie, V. (2010). Contribution of noise and vertical vibration to comfort in a driving car. *EuroRegio 2010*, Ljubijana,Slovenia

Park, S. J., & Subramaniyam, M. (2013). Evaluating Methods of Vibration Exposure and Ride Comfort in Car. *Journal of the Ergonomics Society of Korea*, *32*(4), 381–387.

Parsons, K. C., & Griffin, M. J. (1988). Whole-body vibration perception thresholds. *Journal of Sound and Vibration*, *121*(2), 237–258.

Paulraj, M. P., Yaacob, S., & Andrew, A. M. (2010). Vehicle noise comfort level indication: A psychoacoustic approach. *Proceedings - CSPA 2010: 2010 6th International Colloquium on Signal Processing and Its Applications*, (June 2010).

Paulsen, R., & Kastka, J. (1995). Effects of combined noise and vibration on annoyance. *Journal of Sound and Vibration*, *181*(2), 295–314.

Picu, A. (2009). a Study on Stevens ' Power Law Applied on the Human Perception of a Running Vehicle Transmitted Vibrations. *Power. The annals of Dunarea De Jos,University of Galati*.

Plewa, K. M., Eger, T. R., Oliver, M. L., & Dickey, J. P. (2012). Comparison between ISO 2631–1 Comfort Prediction Equations and Self-Reported Comfort Values during Occupational Exposure to Whole-Body Vehicular Vibration. *Journal of Low Frequency Noise, Vibration and Active Control*, *31*(1), 43–53.

Pope, M. H., Wilder, D. G., & Magnussen, M. L. (1999). A review of studies on seated whole body vibration and low back pain. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, *213*(6), 435–446.

Profant, O., Tintěra, J., Balogová, Z., Ibrahim, I., Jilek, M., & Syka, J. (2015). Functional Changes in the Human Auditory Cortex in Ageing. *Plus One*, *10*(3), e0116692.

Putra, A., Wong, H. K., & Jalil, N. A. A. (2014). *Measurement of Structure-Borne Noise From Road Input*.Asean Engineering Journal Part A, *4*(2), 29–41.

Quehl, J. (2001). *Comfort Studies on Aircraft Interior Sound and Vibration*.PhD Dissertation, Universitat Oldenburg

Radhakrishna, D. V., Kallurkar, S. P., & Mattani, A. G. (2012). Noise & vibrations mechanics: Review and diagnostics. *International Journal of Applied Engineering Research*, *7*(1), 71–78.

Rao, S. S. (2018). *Mechanical Vibrations* (6th editio). United Kingdom: Pearson.

Robb, M. J. M., & Mansfield, N. J. (2007). Self-reported musculoskeletal problems amongst professional truck drivers. *Ergonomics*, *50*(6), 814–827.

Robinson, D. W., & Dadson, R. S. (1956). A re-determination of the equal-loudness relations for pure tones. *British Journal of Applied Physics*, *7*(5), 166–181.

Romaszko, B., Sapinski, B., & Sioma, A. (2015). Forced Vibration Analysis of a Cantilever Beam. *Journal of Theoretical and Applied Mechanics*, *53*(1), 243–254.

Rossi, F., & Nicolini, A. (2010). Psychoacoustic analysis of squeaking and rattling noises inside vehicle cabins. *Noise Control Engineering Journal*, *58*(4), 441–454.

Rozali, A., Rampal, K. G., Shamsul Bahri, M. T., Sherina, M. S., Shamsul Azhar, S., Khairuddin, H., & Sulaiman, A. (2009). Low back pain and association with whole body vibration among military armoured vehicle drivers in Malaysia. *Medical Journal of Malaysia*, *64*(3), 197–204.

Sani, J. S., Zaid, M. F., Yahya, M. N., Ismail, S. M. S., Tajedi, N. A., Aziz, R., & Zein, R. (2015). Evaluation of Whole Body Vibration and Back Pain Problem among Light Rapid Transit (LRT) Drivers. *Applied Mechanics and Materials*, *773–774*, 845–849.

Satou, Y., Ando, H., Nakiri, M., Nagatomi, K., Yamaguchi, Y., Hoshino, M., … Ishitake, T. (2007). Effects of short-term exposure to whole-body vibration on wakefulness level. *Industrial Health*, *45*(2), 217–223.

Seidel, H. (2006). On the Relationship between Whole-body Vibration Exposure and Spinal Health Risk. *Industrial Health*, *43*(3), 361–377.

Sharma, P., & Singh, M. P. (2016). Effect of Hand Arm Vibration Exposure in Manufacturing Industry. *International Journal of Mechanical Engineering and Technology (IJMET)*, *7*(3), 112–128.

Shen, W., & Parsons, K. C. (1997). Validity and reliability of rating scales for seated pressure discomfort. *International Journal of Industrial Ergonomics*, *20*, 441–461.

Shibata, N., Ishimatsu, K., & Maeda, S. (2012). Gender Difference of Subjective Responses to Whole-Body Vibration Under Standing Posture. *International Archives of Occupational and Environmental Health*, *85*, 171–179.

Shivakumara, B. S., & Sridhar, V. (2010). Study of vibration and its effect on health of the motorcycle rider. *Online Journal of Health and Allied Sciences*, *9*(2), 2–5.

Shoenberger, R. W. (1972). Human Response to Whole-Body Vibration. *Perceptual and Motor Skills*, *34*(1), 127–160.

Singh, P., Eger, T., Dickey, J., House, R., & Oliver, M. (2011). Evaluation of gender difference in foot-ytansmitted vibration. *Canadian Acoustics*, *39*(2), 62–63.

Skrúcaný, T., Kendra, M., Issues, T., & Kendra, M. (2015). Noise Measurement in the Interior of Passenger. *Technical Issues*, *2*, 40–46.

Stevens, S. S. (1955). The measurement of loudness. *The Journal of the Acoustical Society of America*, *27*(5), 815–829.

Stevens, S. S. (1960). The psychophysics of sensory function. *American Scientist*, *48*(2), 226–253.

Su, A. T., Maeda, S., Fukumoto, J., Miyai, N., Isahak, M., Yoshioka, A., … Miyashita, K. (2013). A cross sectional study on hand arm vibration syndrome among a group of tree fellers in a tropical environment. *Journal of the University of Malaya Medical Centre*, *16*(Special), 31–32.

Sun, W., Liu, Y., Li, H., & Pan, D. (2013). Determination of the response distributions of cantilever beam under sinusoidal base excitation Determination of the response distributions of cantilever beam under sinusoidal base excitation. *Journal of Physics:Conference Series*.

Thite, A. N. (2017). Predictive vehicle ride discomfort model based on *in-situ* Stevens power law parameters. *International Journal of Vehicle Noise and Vibration*, *13*(3/4), 326.

Troxel, W. M., Helmus, T. C., Tsang, F., & Price, C. C. (2016). Evaluating the Impact of Whole-Body Vibration (WBV) on Fatigue and the Implications for Driver Safety. *Rand Health Quarterly*, *5*(4), 6.

US Department of Transportation. (2017). Highway Traffic Noise Analysis and Abatement Policy and Guidance Noise Fundamentals.

Welsh, C. L. (2012). Hand–arm vibration syndrome. *Medicolegal Reporting in Orthopaedic Trauma*, *2080*(2080), 509–514.

Yamada, S., & Sakakibara, H. (1994). Research into hand-arm vibration syndrome and its prevention in Japan. *Nagoya Journal of Medical Science*, *57 Suppl*, 3–17.

Zhang, L., Helander, M. G., & Drury, C. G. (1996). Identifying factors of comfort and discomfort in sitting. *Human Factors*, *38*(3), 377–389.

Zhang, N., Fard, M., Bhuiyan, M. H. U., Verhagen, D., Azari, M. F., & Robinson, S. R. (2018). The effects of physical vibration on heart rate variability as a measure of drowsiness. *Ergonomics*, *61*(9), 1259–1272.