A comfort index for public transportation riders

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This is to certify that the thesis prepared

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ABSTRACT

A comfort index for public transportation riders

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Some municipalities cannot succeed at making its citizens use public transportation. The use of private cars is usually preferred and this leads to more congestion, longer commuting time, more fuel consumption and gasses' emissions. Travel preferences of commuters are commonly estimated with discrete choice methods that consider their socioeconomic characteristics, along with some form of travel cost, failing to incorporate any measure of comfort. This research develops a standardized indicator of comfort for mass transportation systems. The functional form for a proposed index is developed over three key indicators: vehicle vibrations, air quality and noise levels, and the index is illustrated on a case study of the city of Montreal with comparisons to London and Santo Domingo (Dominican Republic). The index was developed in a way that allows an objective calculation, avoiding qualitative judgment from commuters, thus eliminating individuals' subjectivity, and enabling comparisons among cities and modes. It was found that the automobile is the most comfortable mode, explaining its popularity. The data showed that, the number of stops is the most important factor affecting total vibration levels, and hence the comfort of buses and trains. Noise was found to be linked to vehicle's vibrations. Newer metro cars in London and Dominican Republic showed better comfort levels, suburban trains in Montreal performed better and close to their counterparts in the United Kingdom. Express bus line was more comfortable than the local bus, performing better in the level of vibrations and noise, but not in terms of air quality.

DEDICATION

*T**o***

To everyone who served me coffee and help me keep awake through the whole thing and to (*insert your name if you believe I should dedicate this to you and "I'll mean It"*) for all the support.

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LIST OF ABBREVIATIONS

AASHTO American Association of State Highway and Transportation Officials

ABS American Boat Society

ASHRAE American Society of Heating, Refrigerating, and Air-Conditioning Engineers

dB, decibel

dBA A-weighted decibels

DIN *Deutsches Institut für Normung* , German Institute for Standardization

DNV *Det Norske Veritas*

DOT or USDOT Department of Transportation of the United States of America

GPS Global Positioning System

ISO International Organization for Standardization

IRI International Roughness Index

RI Ride Index

RINA *Registro Italiano Naval,* Italian Naval Registry

RMS Root Mean Square

SAE Society of Automotive Engineers

VER Vehicle Evaluation Rating

CHAPTER 1

INTRODUCTION

1.1 Problem background

Some municipalities cannot succeed at making its citizens use public transportation. The use of private cars is usually preferred and this leads to more congestion, longer commuting time, more fuel consumption and more carbon emissions.

Often, Urban Planners and Transportation Engineers employ discrete choice methods to model user decision making processes; however such traditional Modal Choice Estimation is based on statistical regressions that attempt to capture the relation between the individual socioeconomic characteristics and their preferred choice ignoring the level of comfort provided by each alternative mode as experienced by the users. Furthermore, the data in which these regression analyses are based depend on the observed preferences of those users of a mode of transportation but doesn't take into account the user's awareness of other alternate modes. There is an Imperfect Access to Information. The determination of these values can prove important to change the passengers' habits.

It can be argued that there is a need to develop a theory of preferences for choices based on the characteristics of each mode, specifically on the need to estimate the level of comfort.

We already have the technology to measure and register most of the information we need to estimate the quality of the ride and overall comfort.

1.2 Problem Statement

There is a need to develop a standardized indicator of comfort applicable to mass transportation riders. Even with the congestion and high cost associated to private cars, some passengers will still prefer them. For large cities this is a problem that affects both the dense downtown areas and long distance commuters.

1.3 Research Objective

1.3.1 General Objective

The main purpose of this work is to develop a standardized indicator of comfort for mass transportation riders. Such an indicator is expected to facilitate the analysis and comparison of different modes of transportation and will serve in the future to forecast traveller's behavior choices along with travel time and cost.

1.3.2 Specific Objectives

- To identify comfort factors that could be objectively measured with the help of smart phones
- To develop of a Comfort Index for public transportation
- To test the proposed index on a case study

1.4 Scope and limitations

This research focuses on the measurable variables that affect passengers comfort. The ergonomic variables won't be measured, only described.

The instruments used for measuring the accelerations and noise are about 90% accurate (Aksoy, 2013). We can use them to compare results (assuming the same margin of error) but further studies might need better instrumentation.

The number of measurements used in this research is enough for an accurate estimation of acceleration value. The measurements change from driver to driver and from one street to another. In the case of passenger automobiles, the vertical acceleration values are determined by the pavement IRI and the vehicle damping system. To determine the incidence of each factor, we would need an extensive study comparing different cars and roads. (Haas, 2001).

The measurements should also be based on routes with the same origin and destination and compare several modes.

1.5 Research Significance

This thesis contributes in the following ways:

- It uses cheap already available technology to measure some contributing factors to passenger comfort.
- It compares comfort of different modes of transportation.
- It will serve to expand discrete choice methods by adding a new dimension (comfort) in addition to travel time and travel cost.

1.6 Organization of the Thesis

This document comprises five chapters: Chapter 1 provides a general description of the problem, the objectives and the structure of the thesis; Chapter 2 revises of the concepts on which the thesis is formulated, such as vibrations, vehicles and their behavior, noise and its effects on humans; Chapter 3 describes the methodology employed for the data collection; Chapter 4 is a comparison between various modes of transportation and presents the proposed index; Chapter 5 summarizes the conclusions of the research, provides recommendations and suggest future research that escaped the scope of this document.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter explains the base concepts of comfort that apply to the index calculation and the comparisons performed in this research. The first part deals with the general definition of comfort. Some of the concepts have been accepted for three or four decades while others have been introduced as early as 1997.

Comfort is very subjective and varies across individuals. The factors that determine it could involve, among others, the waiting time, waiting zone conditions, the degree of crowding inside the vehicle, temperature, humidity, lighting, atmospheric pressure, air quality. For Dukkipati, the factors that affect discomfort are (Dukkipati *et al*, 2008):

1) Vibration magnitude: very small and very large are imperceptible
2) Frequency: as with the above factor, there is an optimal range.
3) Direction
4) Duration
5) Occupants posture position
6) Body size
7) Age
8) Gender
9) Noise
10) Others to eventually add any possible factors.

Also that "ride comfort is subjective and. It depends greatly on the appreciation of the user and this can in turn be affected by his expectations" (Dukkipati *et al*, 2008). Other factors include the seats, suspension, ergonomic factors, decoration, expectations and ambient music.

Next the nature of the vibrations for each mode of transportation is explained. Movement along all axes are identified and described. The cause of vibrations on cars, rail vehicles, boats and planes are shown.

2.2 Comfort principles

Helander and Zhang (2012), define comfort as: "a pleasant state or relaxed feeling of a human being in reaction to its environment and discomfort is seen as an unpleasant state of the human body in reaction to its physical environment" (Vink, P., and S. Hallbeck, 2012)

According to them, there is a distinction between comfort and discomfort. The main principle is that, when all the causes of discomfort are removed, there is no sensation left and one should add something positive to gain comfort Helander and Zhang (1997). Some factors related to comfort and discomfort are shown on table 2.1

Table 2.1-Factors influencing comfort and discomfort during sitting according to Zhang et al. (1996)

Discomfort related factors:	**Comfort related factors:**
Fatigue	Luxury
Pain	Safe
Posture	Refreshing
Stiffness	Well-being
Heavy Legs	Relaxation

A widely accepted model of comfort and discomfort was proposed by De Looze and it classifies the sensation range into two different zones: one for comfort and one for discomfort (Kee and Lee, 2011).

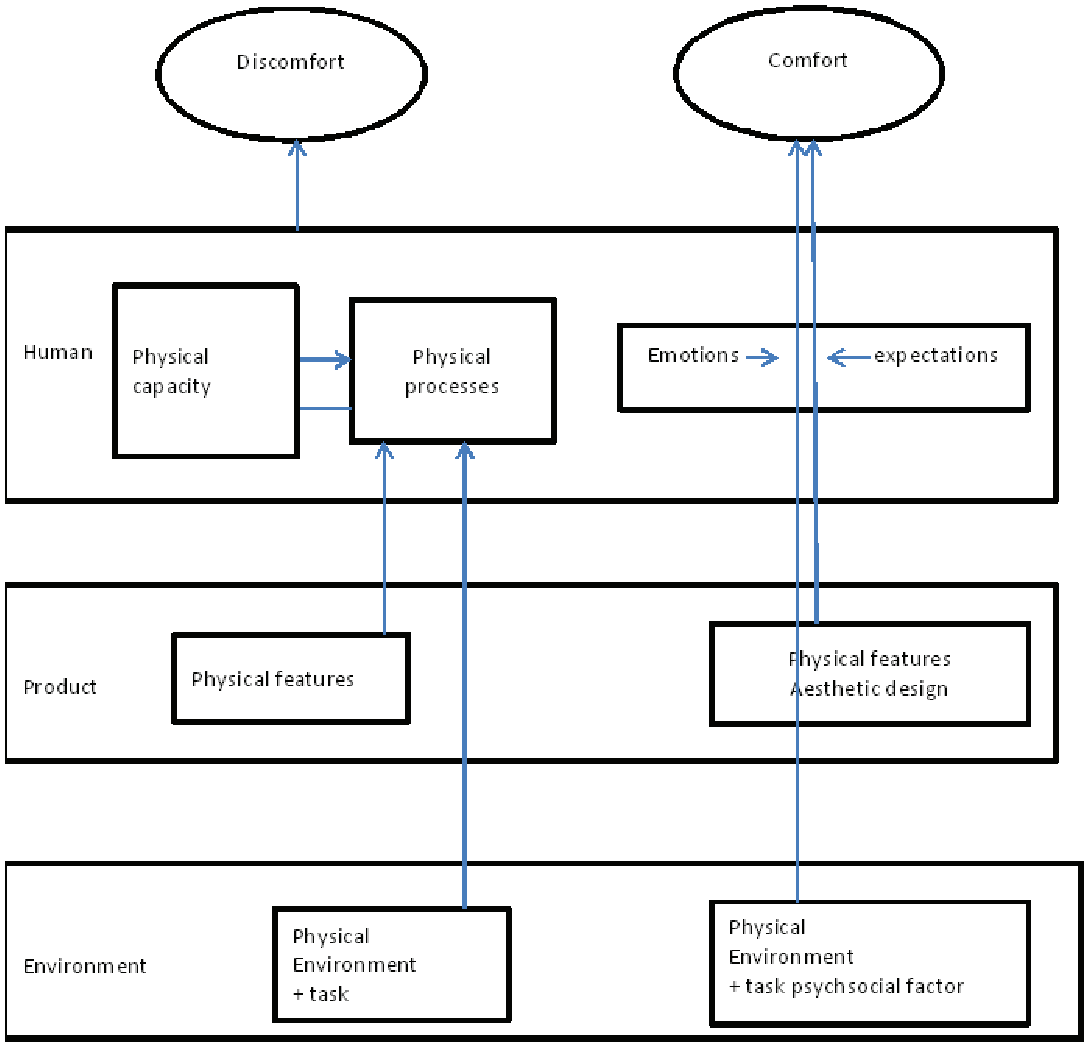


Figure 2.1 De Looze sitting comfort model. (Kee and Lee, 2011)

Most models trying to explain comfort focus on the right side of Figure 2.1. By making airplane passengers perform some tasks on a screen, Vink *et al.* (2012) determined that, when there is more than one sense involved, the feeling of comfort can be enhanced but not every stimulus is helpful (Kee and Lee, 2011). Also, the expectations of the passengers affect their level of comfort; this is why coach and business class passengers rated different seats as equally comfortable. This could happen if a passenger receives or perceives higher comfort levels beyond his expectations.

These models are complicated because they deal with a lot of psychological and physical variables. Although this is very useful to determine the overall causes of comfort or discomfort, they can be too complicated to apply to many simple questions, like correlating the level of vibration or noise level of a ride to the feeling of the passengers.

Dohyung Kee and Inseok Lee (2011) took a different approach. They tried to create a scale, not unlike the Borg CR10 pain scale. Posture holding times were studied and quantified and then compared with verbal adjectives. The stresses to the different joints were evaluated and the time to hold a posture was determined. Figure 2.2 shows the level of discomfort as a function of the posture holding time.

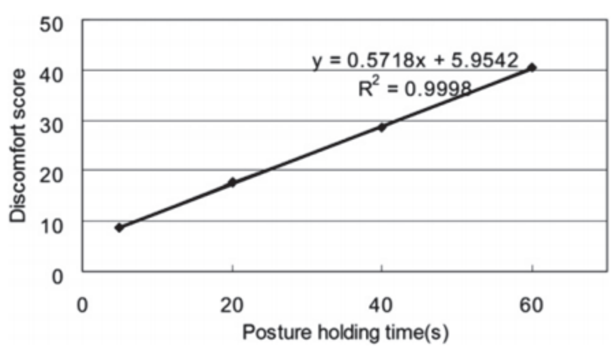


Figure 2.2 Discomfort scores for posture holding time (Kee, 2004)

For Ortúzar and Willumsen (2010), the characteristics of the transport facility can be divided into two different groups (p.208):

- Quantitative:
    - Travel time, waiting and walking,
    - Monetary Cost (fares, tolls, fuel and others)
    - Availability and cost of parking
    - Reliability of travel time and regularity of service.

- Qualitative
    - Comfort and convenience,
    - Safety, protection and security,
    - The demands of the driving task,
    - Opportunities to undertake other tasks.

The qualitative factors affecting the choice of transportation are a little harder to measure and, quite often, very subjective. Usually the transportation engineers conduct surveys to try to determine the preferences of the passengers. This raises numerous questions about the way personal conditions affect these polls. Also, the lack of knowledge of different alternatives may cause the users to ignore improvements.(Ortúzar and Willumsen, 2010)

Manheim (1979) states that “the prediction of future impacts of changes in transportation system is a different task” and that current information can be very useful to take near future decisions about small changes. For bigger solutions and more permanent measures, there is more uncertainty.

The level of service can be expressed in a many different ways. Ultimately, many models reduce it to cost or price. The problem with this approach is that many seemingly equal options might be very different indeed. If we consider a hypothetic case in which a passenger has two different transportation options, at the same price, same comfort and same travel time but he’s awarded a certain reward of something he likes or needs for one option or a reward of the same cost of something he doesn’t need or like on the other, he would obviously chose the first one.

2.3 Vehicle’s Vibrations

The use of cars has risen steadily since its invention. It may be one of the most practical forms of transportation if not the best. Not only it was convenient as cities grew and spread into suburbs but also, the manufacturers have improved the quality of the ride. It has been more advantageous for car manufacturers to improve the overall quality of their vehicles. The automobile industry keeps including new features all the time to their products that improve safety and comfort.

Dukkipati *et al.*, (2008) in Road Vehicle Dynamics, studied the factors that cause discomfort. For his studies, he classified the vibrations in two types: Periodic and Nonperiodic. Those are also sub classified into Sinusoidal and Complex Periodic and Almost periodic and Transient Nonperiodics. Regarding comfort, he reasons that ride quality depends on the vibrations as perceived by the whole body and not just part of it even though vibrations only need one point of contact with the body. The ride quality is, thus, defined by the degree of comfort or discomfort (Dukkipati *et al.,* 2008).

They consider the factors that influence comfort are:

11) Vibration magnitude: very small and very large are imperceptible.
12) Frequency: as with the above factor, there is an optimal range. The range that affects human bodies the most. Both ISO and BS consider this to be between 0.5 Hz and 80 Hz.
13) Direction. The axis along which the vehicle shakes is very important to the feeling of the passenger. The body is more sensitive to vertical vibrations. Both ISO and BS account for this fact. Motion along the other axes is deemed less important to the overall sensation. Sudden moves like those provoked by braking and accelerating can be more disturbing than lateral movement due to cornering but this is not taken into account.
14) Duration. Longer periods of vibration are more disturbing than brief ones.
15) Occupants posture position. The position relative to the motion changes the capacity of reacting to it as the center of gravity of the passenger may result in additional moment that would need to be compensated by the body.

Dukkipati (2008) considers some factors that will be ignored in this research as the objective is to characterize comfort for the average individual capable of being representative of the entire population.

16) Body size
17) Age
18) Gender
19) Noise
20) Others

Both Strandemar (2005) and Dukkipati (2008) use SAE's Vehicle Evaluation Rating (VER) as shown in the table 2.2 and is used to correlate a subjective evaluation of a ride or vehicle with a number. Dukkipati (2008) also make use of ISO's 2631 and 2631-1 shown on figure 2.2.

Table 2.2 Vehicle Evaluation Rating

Unacceptable				Borderline	Acceptable				
1	2	3	4	5	6	7	8	9	10
Not acceptable		Objectionable		Requires Improvement	Medium	Light	Very Light	Trace	Not Noticeable

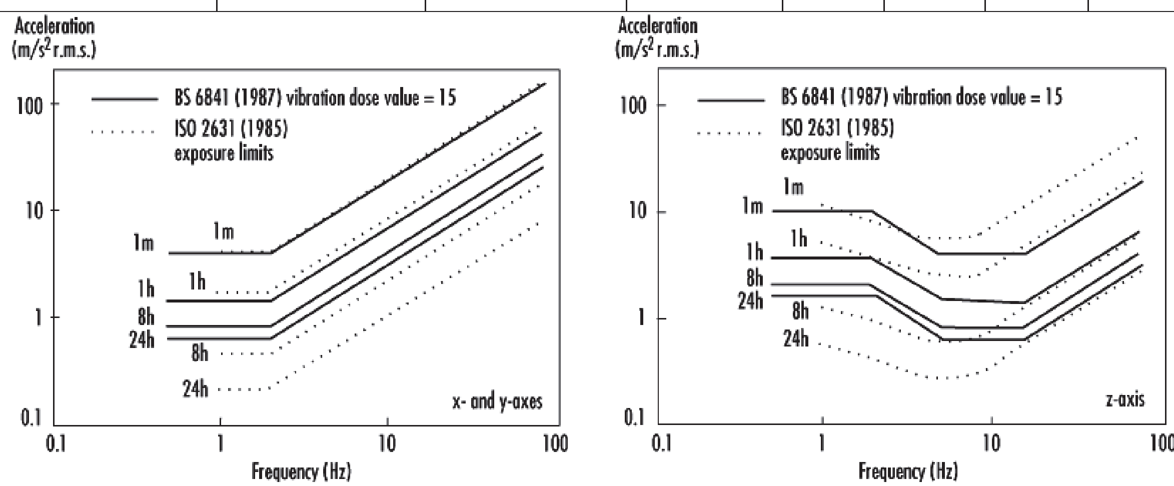


Figure 2.3 ISO acceleration and frequency exposure limits (International labor office 2012)

Based on these studies, ISO recommends keeping accelerations to values under 0.5 m/s^s.

2.3.1 Vibrations on automobiles

When riding a vehicle, it transfers energy to its passengers in the form of accelerations. These can be periodic or non-periodic. Sometimes, the driver has control on the level of accelerations he can induce on the passengers.

The accelerations along the X axis are the results of the sideways movement. Turning at a given radius produces a centrifugal force directly proportional to the square of the speed and inversely proportional to the radius. The driver's influence along this axis is the result of over or under steering, the corrections needed to remedy them and unnecessary zigzagging. (Dukkipati, 2008)

Along the third axis, the Y axis, the driver has a lot more power to affect the accelerations. He can greatly change the braking and acceleration speeds, making the ride more or less gentle. The movement that is parallel to the longitudinal axis of the road is also affected by the vehicles damping system, the braking system and the drivetrain.

On a road vehicle the accelerations along the Z axis are mainly influenced by pavement roughness. The vehicle will move up and down following the road imperfections. The amount of transferred energy will be partially dissipated by the damping system. Different road vehicles are equipped with various systems that will suit their design and the driver can only affect the movement along this axis by steering the vehicle over bad pavement spots. (Amador-Jimenez, and Al-Dabbagh, 2015)

Usually, luxury cars have a damping system that dissipates some of the energy. They allow for the most comfortable rides. Sport cars are equipped with shocks that let the drivers feel more and interact with the pavement by noticing imperfections, skids and bumps. Off-road vehicles need stiff shocks that are also longer to allow for more bouncing and still stop the vehicle and help keep it controlled. The long shocks usually cause more movement along the Y axis. (Zhang and Sizhong, 2014)

Movement around the Y axis (roll) is the product of lateral tilting. Higher vehicles have a higher center of gravity and this distance from the pavement causes the cabin to move left and right.

Around the X axis (pitch) the Z axis (yaw), the vehicle is subject to the vertical and horizontal alignments respectively.

According to Park (2013), human exposure to vibration can be classified in two types: localized and whole-body and, as they imply, localized affects a specific part of the body while whole-body affect the entire person. (Park, 2013) "Whole body vibration is transmitted through the seat surfaces, backrest and through the floor"(Park, 2013). Vibration on humans can be measured and assessed using one of two main standards (ISO 2631 and BS 6841). For the purpose of studying the effect on a seated human vibration is measured along 8 different axes: three translational axes placed at the feet, three other and the hips and two at the back. (Park, 2013)

Although the study of vibration is very important to the comfort and general well-being of the passengers, and that there is a great number of studies, there is not an accepted standard for car sales specifications. When an individual buys a car, or a city orders a number of buses or train wagons, there is not an absolute way to request a desired level of comfort. Most often, design parameters are a trade secret. Airline jets are designed based on previous models, always trying to make improvements. The suspension system of passenger cars takes into consideration the use of the car. Sport cars, sport utility vehicles and luxury cars differ in the way the handle and dissipate the energy as needed for different uses. The railway industry has standards developed to protect cargo. Only the luxury boat industry has tried to set a standard for boat design and construction.

Griffin states that “vibration transmission has a large influence on comfort, performance and health” (Griffin, 1990). What this means, in reality, is that vibration affects how well a person may perform any task. Under high levels of vibration, a driver might not be able to even control his automobile. When it comes to public transportation, the passengers usually read, write or talk while traveling. A high level of vibration will affect these tasks. Furthermore, many passengers could be affected by motion sickness or even suffer from chronic health effects (Hostens, 2004).

Park goes on affirming that the effects of whole-body vibration have to evaluated the measurement of the accelerations that affect the individuals.(Park, 2013) In his experiments, and many others he quotes, the effect of vibration is measured using as many as twelve sensors, most often B&K accelerometers. In most studies, the level of comfort is obtained by asking the participants of the experiment. These responses are, then, correlated to the vibrations measured. It has been found that human body is more affected by vibrations in the 4 to 8 Hz range (Geluk, 2005).

The tires are probably the most important part of the motor vehicle. They are responsible for the traction, the skid resistance and the suspension thus, being ultimately responsible for loss of control in adverse conditions, fuel efficiency and damage to other parts of the suspension system. An over inflated tire makes the ride more uncomfortable and an underinflated wears faster and diminishes fuel efficiency.

A.J. Healey, from the University of Texas at Austin, summarized previous studies by saying that we needed to measure and analyze movement in all six degrees of freedom and vibration in the range of 0.1 to 40 HZ and with amplitude of 0.01 to 0.2 g. (Healey, 1977).

Most studies before Healey, measured a wider range of frequencies and amplitude but he recommends the use of filters to eliminate unneeded data. He worked with analog and hybrid equipment and was very concern about the amount of data to collect. A lot of data was very hard to handle back then. He was concerned about random vibrations more than with predictable vibration. He needed a record period long enough to allow him to predict the vehicle behavior but not so long that the amount of data resulted too large.

The information obtained must be correlated to the passenger ratings and this is not as simple as it sounds. A model used in one city may prove completely inadequate in another. Different societies are accustomed to different level of sensory perceptions. Furthermore, this changes within many smaller groups within a larger one. The perception is affected by previous knowledge and by expectations. A user who has never ridden in different trains is unable to compare the ride quality of the one he uses every day. He is only capable of comparing the different modes of transportation he can access.

The ISO 2631 standard method demands the inclusion of the Weighted Root Mean Square acceleration (R.M.S acceleration). The advantage of using this method is that both positive and negative accelerations are taken into account.

$$a_w = \left(\frac{1}{T} \int_o^T a_w^2(t)\, dt \right)^{\frac{1}{2}}$$

Where $a_w(t)$ is the weighted acceleration in either rotation or translation as a function of time in either (m/s^2 or rad/^{2}) and T is the duration of the measurement in seconds.

The running R.M.S. method includes an integration time constant to take the occurrence of occasional shocks into account.

$$a_w(t_0) = \left[\frac{1}{\tau}\int_{t_0-\tau}^{t_0}\left[a_w(t)^2\right]dt\right]^{\frac{1}{2}}$$

$$MTVV = \max\left[a_w(t_0)\right]$$

Which adds some new variables, namely τ as the integration time for running averages and t_0 is the time of observation.

MTVV is the maximum transient vibration value (the maximum in time of a_w.

Another important variable to take into account is the Vibration Dose Value (VDV). This value is considered more suitable to assess vibration by the BS6841 (Griffin 1998) as it measures the total exposure to vibration, considering frequency, magnitude and exposure duration. It is calculated with the following formula:

$$VDV(m/s^{1.75}) = \left(\int_0^T [a^4(t)]dt\right)^{\frac{1}{4}}$$

This method is more sensitive to peaks in the acceleration.

Park arrives again at the same issue; the quality of the ride is subjective. Each individual has a different level of comfort and the knowledge of different methods affects the feeling of the passengers.

The tires perform four basic functions:

1. Support the weight of the vehicle
2. Cushion the vehicle over surface irregularities
3. Provide sufficient traction for driving and braking
4. Provide adequate steering control and directional stability

A lot of research has been done with persons and mannequins strapped to seats. This is how both ISO and BS require the measurement of vibration. These parameters apply to the design of moving vehicles and fixed machinery. It certainly is useful to analyze the motion and forces that affect passengers in cars or planes; however, they might not be so useful when measuring passengers standing up in trains or flight attendants. They will also change if the passenger sits in a different fashion.

Geluk (2005) performed an experiment in which he tried to measure the smoothness of a ride. He measured the vibration on three different axes and focusing on the 4-8 Hz range. The smoothness was a subjective value obtained by asking the participants in the experiment to evaluate the ride using words from a list that included fairly comfortable, uncomfortable, very uncomfortable, etc. He compared different roads. The same trajectory and speed was chosen for each participant. The vibrations were measured at the steering wheel and the driver\s seat. He compared different cars as well.

Geluk (2005) concluded that the ISO method is not the best one to assert the smoothness of a ride because the participants' opinion had a better correlation on a range that fell out of ISO's established one. Basically, the vibrations outside this range were still perceived by the test subjects.

2.3.2 Vibrations on Railways

Along railways, the conductors have even less power to influence the ride. Usually, the only way they can affect it is by accelerating and braking. Steering is not possible, since they ride on tracks. The vibrations and accelerations of railways have been widely studied and controlled because they could lead to loss of cargo which is more objectively quantifiable than comfort.

Freight trains had to improve the quality of the ride, if we measure the vibrations produced, to avoid losing cargo and to prevent excessive wear to the rails. Engineers had to determine the causes of collapse cars, derailments and wear and then find a way to improve the performance of the trains while maintaining, and even increasing, speed and performance of the overall railroad system. Quite often, passenger trains use the same tracks destined to freight trains, thus benefiting from the quiet ride.

Trains can be equipped with a double suspension that would absorb more vibration but this would make the trains taller. For underground trains, this can be an important issue because the tunnels would need to be larger.

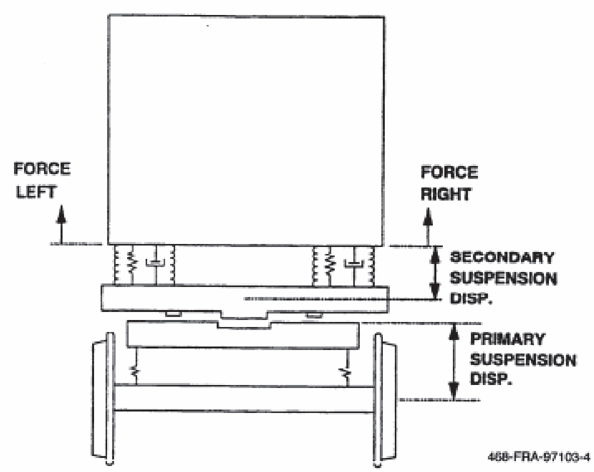


Figure 4. Vertical suspension characterization test

Figure 2.4 DOT Railway car suspension schematics (US DoT 2002)

Following Manheim's precept (Manheim, 1979), improvements to railways and trains are slow. A railway network, a passenger train or a city metro system have a life spam of decades. The changes arrive in leaps and at a great cost. The multimillion projects usually need government size budgets and the bureaucracy associated with it.

When designing a mass transportation system, a small improvement in the ride's quality might amount to a very large sum. The decision makers are always faced with the mutually exclusive options of giving more quality at a higher cost or less quality for a lesser sum. The problem is that the nature of these decisions is more permanent than the choice of an individual to purchase a personal vehicle.(Manheim, 1979)

Improvements to smaller vehicles (automobiles and buses) come at smaller intervals. A driver might not think twice about buying an automobile but will certainly complain if taxed with the same amount for public transportation. A manufacturer needs to compete for market share for the preference of the users, hence the need for the improvement of personal vehicles.

The choice of the mode of transportation and the living location sometimes go hand by hand. It's what Ortúzar and Willumsen (2011) calls "decisions made elsewhere". When choosing where to move, an individual may consider the different choices of transportation available to him. He will very likely consider the costs of all the options and he will decide if the quality of the ride is acceptable.

A passenger faced with different options will have to consider the quality of the ride. However, the task of defining it can be a little complicated. "Ride quality can be described by the degree of discomfort or comfort." (Dukkipati *et al.*, 2008). Some authors will add the length of the ride and consider a shorter bumpy ride preferable to a very long one, as comfortable as it might be.

Ride comfort is subjective. It depends greatly on the appreciation of the user and this can in turn be affected by his expectations.(Dukkipati *et al.*, 2008)

More factors can be added to the list. Some like temperature, amount of passenger per square meter and quality of air will be briefly explained.

There are also some objective methods to try to quantify the level of comfort or the Ride Quality Index. The United States of America Department of Transportation has developed a Ride Index and guidelines to design and build train cars. All new rolling stock needs to be tested and comply with the requirement.

Most of the research concerning light vehicle comfort focuses on vibration. Usually they try to correlate some objectively measurable data (vibration most often) with the subjective evaluation of the comfort level by a number of passengers. These studies have found or established relations between the comfort ratings and the vibrations. The passengers are in direct contact with the seats and, therefore making them the final element of the vehicle to register vibration and making them the best place to measure the effects of vehicle and road interaction with the human passengers. It's important to note that no standard exist as to how many persons should be used for one of these studies.

When comparing different modes of tranportation, not necessarily used by all passengers, the subjective factor becomes even more important. It may be complicated to see side by side, the poll results of two different countries populations or of one group that hasn't seen any different vehicle to use as comparison. The lack of these benchmark makes it impossible to effectively compare the comfort. Even airplane and car manufacturers tend to use their own criteria. Only the boat industry has tried to set an universal standard.

2.3.3 Vibration on Airplanes

Airplane manufacturing is based on previous models. They try to achieve a more comfortable ride each time they develop a new model. They measure vibrations and accelerations and have created what may be the most comfortable transport: the high altitude jet airliner. They have restricted the allowed vibrations and acceleration levels. An airliner should't exceed these parameters unless absolutely necessary. They extensively use simulators to train pilots. For a fighter plane, these parameters are, of course different. (Brumaghm and McKenzie 1977)

Definition of the Passenger Transfer Function in Aircraft

The aircraft manufacturing industry bases its designs on one of two common approaches:

1- The ride quality of a plane should be equal or better than that of pre-existing plane of good acceptance (AGA-As Good As).
2- Not to exceed certain levels of vibration and accelerations.

They both arrived to the same point. For the first method, the airline executives collect data from the passengers and their experience serves as model for future modifications. These subjective criteria must be translated into vibrations and accelerations. The weakness of the AGA approach lies in the fact that, an aircraft too different than an existing one, may be difficult to design based on subjective data and that the resulting airplane may not be more comfortable.

The study of acceleration and vibrations allows designers to conceptualize a plane to fit a number of measurable parameters regardless of the opinion of the passengers. The task is to decide which parameters values should be used. From fighter aircraft to giant passenger planes, the values of acceptable G forces, vibration, air quality and seat comfort will differ greatly. (Brumaghm and McKenzie 1977)

The industry focuses on “not-to-exceed” limits for the vibrations and accelerations as well as for the position of the aircraft. These limits have been set using flight simulators with few subjects of study. “The commercial jet passenger ride serves as standard of ride comfort” due to the cabin insulation from outside noise, the controlled environment and the smooth air found at high altitudes. Usually, vibration is considered as the factor that affects comfort the most. (Brumaghm and McKenzie 1977).

The automobile industry has moved in the same direction. The suspension on an all-terrain vehicle is more rigid than that of a luxury sedan. It’s designed for a different use. The ride comfort expected from an all-terrain is less than that of the sedan. On the other hand, the soft suspension of the sedan will result inadequate to control the vehicle in off-road conditions.

2.3.4 Vibration on boats

The boat industry is the only one that has tried to set a standard to quantify the comfort level. The certificate issued by an accredited institution stating that a ship has certain level of comfort would allow its owner to collect more income than the owner of a less comfortable boat. Compliance with the class specifications would entitle the boat to said certification. When building a large cruiser, the builders seek such certification. Even though they are more focused on shipping boats, their accreditation is valuable.

It's interesting that, the level of comfort is not based, for these cases, on the quality of the interior trim or the materials used but on a combination of movement and noise. *Lloyds*, *Det Norske Veritas* (DNV) now *Det Norske Veritas – Germanischer Lloyd* (DNV GL), *Registro Italiano Navale* (RINA) and the American Bureau of Shipping (ABS) have all taken the same approach.

One main difference between this industry approach and other modes of transportation resided in the fact that they only consider movement along one axis: the Z axis. This might be due to the fact that most movement can be translated, in the case of boats, to the up and down movement experienced by the ship when cruising. The following table shows Lloyds requirements.

Table 2.6 Lloyds Luxury Requirements

Vibration Limitation Goal	**Underway** **Flat seas (Moving)**	**Harbor (Docked)**
Avoiding motion sickness, and extreme discomfort	7 mm/sec	N/A
Avoidance of vibration induced fatigue (24 hr)	5 mm/sec	N/A
Ability to sleep comfortably	3 mm/sec	1 mm/sec
Luxury smooth (not aware of vibration)	1 mm/sec	0.25 mm/sec

A boat's translation movement, like in most other forms of transportation, occurs along the Y axis. However, the waves create an up and down movement. The hull's characteristics and the ship's displacement together with the speed convert this forward motion and beating of the waves to a vertical movement that adds to the natural waves. A cruising ship is not subject to the same movement as a docked one.

The lateral stability of a ship depends on the moment formed my it's buoyancy center and it's gravity center. The forces acting on those points are the weight of the water displaced and the ship's weight respectively. Obviously, this coupled moment changes with the boat's inclination.

This is why, inclination experiments are performed on models before building a new ship. This will allow the designers to place counterweights or ballast if needed. For a given ship's weight, a wider hull would provide a shorter distance between the buoyancy and gravity center, thus providing more stability to the ship. A keel might be added to lower the center of gravity and add lateral resistance to capsizing (roll). The keel also provides additional area to help the rudder in turning the boat if the lateral plane (projection of the ship over the floating surface) is not adequate.

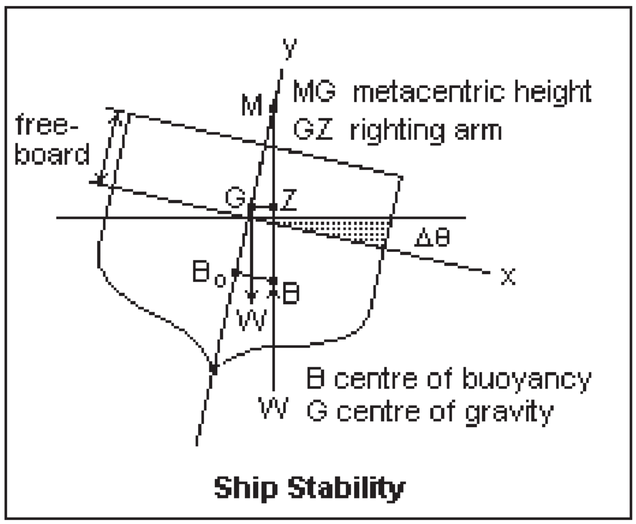


Figure 2.5 Boat's buoyancy schematics
Calvert, JB "Hydostatics" Online source. January 2007

Anderson (Anderson, Bryon D. "The Physics of Sailing Explained" Sheridan House 2003) explains that the hull of the ship, being the part of the boat in contact with the water, determines the behavior of the ship. Boats move in one of two possible ways:

1- They move over the water like speedboats and hovercraft. Figure 2.7
2- They move through the water like most boats. Figure 2.6

Figure 2.6 Speedboat

Elements of Yacht Design. P.142

Figure 2.7 Hovercraft on land **Figure 2.8 Hovercraft on water**

Griffon Hoverwork Ltd.

A boat moving through water generates waves and their size depends on the boat's speed, among other factors. When the boat is moving slowly, the waves are rather small and move alongside the boat. As the boat increases speed, the waves become longer until there is one single wave along the hull. This wave has two crests: one at the bow and one at the stern. If the boat goes any faster, the length of the wave will increase and the boat will start hitting the water (the wave's crest) and then fall ahead of it. This movement will require more power to overcome and will render the ride more agitated. Hull speed is that case when the wavelength is that of the boat. For displacement boats, hull length is the determining factor of the boat's maximum speed.

The hull speed formula is

$$v = 1.53\sqrt{(\tau)}$$

Where τ is the wave/hull's length

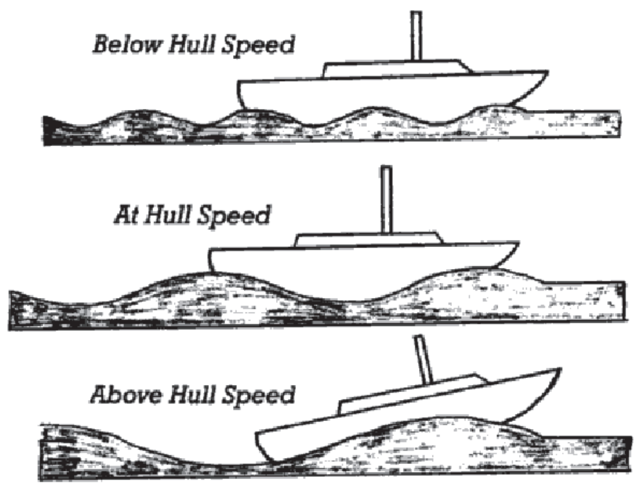


Figure 1.1 Bow Wave and Boat Speed. "Hull Speed" occurs when there is just one wave along the side of the boat, with a crest at the bow and the next crest at the stern of the boat.

Figure 2.9 Bow wave and boat speed
Anderson, Bryon D "The Physics of Sailing Explained" NY: Sheridan House Inc.2004

Table 2.7 Bow wave and boat speed

Hull/Wavelength(ft)	Speed				
	ft/s	Mph	Knots	m/s	Kph
1	2.3	1.6	1.4	0.3	1.0
5	5.0	3.4	3.0	0.6	2.1
10	7.1	4.8	4.2	0.8	3.0
20	10.1	6.9	6.0	1.2	4.3
30	12.4	8.5	7.4	1.5	5.3
50	16.0	10.0	9.5	1.7	6.2
75	19.5	13.3	11.6	2.3	8.3
100	22.6	15.4	13.4	2.7	9.6
200	31.9	21.8	18.9	3.8	13.5
300	39.1	26.7	23.2	4.6	16.6

Powerboats and speedboats plane from one crest to the next. Their hulls are not in touch with water at all times. The ideal speed boat hardly ever touches the water surface. Only the propeller is submerged to supply the power needed to advance the ship. Hovercraft, like helicopters, float above the water thanks to the powerful fans facing down and the curtain surrounding them and concentrating the air on a smaller surface. These two types of boats movements are closer to flying than to sailing. (Skeene, 2001)

Boats are designed taken into account their displacement when partially submerged and their stability (statical stability) or rotation along the longitudinal axis or roll. The stability depends on the moment generated by the buoyancy and the weight. Another variable to take into account is the) motion comfort ratio. This ratio is based on the motion generated by a sailing ship on choppy water.

$$Displacement/(65\ x\ (0.7\ LWL + 0.3\ LOA) x\ B\text{^}1.333$$

where LWL and LOA are the boats overall length and at water level respectively and B the width.

The hull's shape will affect the way it passes through water. If the hull is narrow and shallow, it will require less energy to move. A wide and deep hull requires more energy but may provide a quieter ride.

When specifying the level of comfort on a boat, designers need to point out three different factors:

1- Noise levels required when the ship is cruising and at the docks.
2- Vibration levels when the vessel is cruising and docked.
3- The acoustic privacy between the different rooms or compartments.

Some marine institutions have begun publishing Comfort Class Rules to guide naval architects and engineers. The first one was DNV in 1995.

For example, in the case of large yachts the rules that apply are:

DNV — Rules for Ships, Part 5 Chapter 12 — Comfort Class (July 1995)

RINA — Rules for the Evaluation of Noise and vibration Comfort on Board Pleasure Vessels

Lloyd's - Provisional Rules, Passenger and Crew Comfort, Feb. 1999

ABS — Guide for Passenger Comfort on Ships, December 2001.

The rules take into account the fact that faster boats and slow boats behave differently. They acknowledge that the human tolerance threshold is different. At night, when sleeping, a passenger might need a quieter environment. Since faster yachts need a lighter structure and higher power, they will be noisier, however, it's expected that they won't be at sea for a long periods of time since they cannot make long trips. The rules for a given class are different depending on the type of boat (Smullin, 2008).

Figures 2.10 and 2.11 show the noise and displacement limits for a luxury performance class boats.

Table I.

Upper and Lower Acceptance Bounds for Noise, dB(A), for Yachts in Harbor Conditions
Various Classification Societies
Lower Bound is Highest Quality - Upper Bound is Acceptable

		Harbor Conditions						
		Salon		Cabins		Open Decks		
Displacement	DNV	40	55	35	45	50	60	
	RINA	40	50	40	50	40	50	
	Lloyds	50	55	45	50	55	60	
	ABS -passenger vessels	45		45		65		taken from underway limits
		Harbor Conditions						
		Salon		Cabins		Open Decks		
Semi Displacement - Planning	DNV < 50 m DNV > 50 m	**40**	**55**	**35**	**45**	**50**	**60**	DNV taken from yacht
	RINA	45	55	45	55	55	65	
	Lloyds	55	65					taken from underway
	ABS -passenger vessels	45		45		65		

Figure 2.9 Upper and Lower acceptance noise levels for Yachts in Harbor Conditions

Smullin, 2008

Table II.

Upper and Lower Acceptance Bounds for Noise, dB(A), for Yachts Underway
Various Classification Societies
Lower Bound is Highest Quality - Upper Bound is Acceptable

			Underway							
			Salon		Cabins		Open Decks		Wheel House	
Displacement	*contract normal speed or at least	DNV	53	62	44	55	75	85	60	65
		RINA underay at "normal cruising speed"	55	65	50	60	65	75	60	65
		Lloyds underway at 85% power unless prior agreed lower poer normal operation	55	60	50	55	60	65	60	65
		ABS -passenger vessels	55		45		65		55	
			Underway							
			Salon		Cabins		Open Decks		Wheel House	
Semi Displacement - Planning	DNV "Fast Craft" limit *contract normal speed or at least 85% MCR	DNV < 50 m	65	75					60	65
		DNV > 50 m	60	68					60	65
		RINA underay at "normal cruising speed"	60	70	-	-	-	-	65	70
	Lloyd's "Fast Craft" limit	Lloyds underway at 85% power unless prior agreed lower poer normal operation	60	70						
		ABS -passenger vessels	55		45		65		55	

Figure 2.9 Upper and Lower acceptance noise levels for Yachts underway Smullin, 2008

2.3.6 Vibrations on Trains

For trains, the movements along the three axes and around them are the same but the DOT defines two different Roll attitude vibrations: Upper center and lower center roll.

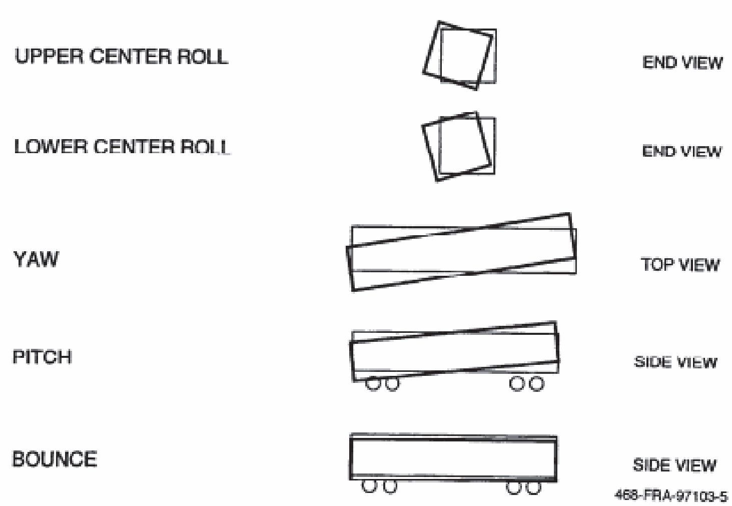


Figure 5. Rigid body modes

Figure 2.12 Movements of a railcar. (Samavedam, US DoT 2002)

The Department of Tranportation requires that the performance of the rolling stock be measured using vertical and lateral accelerometers positioned on the body and close to the center of the bogie and all measurements should be done at 10 Hz.

The average acceleration shall be the mean peak one.

Lateral hunting is not allowed for longer than 10 seconds. Furthermore the lateral accelerations due to hunting should not exceed 3.5g at 0.5 Hz.

Table 2.8 Allowed lateral hunting (Samavedam, US DoT 2002)

Parameter	**Limit**	**Test Speed**
Maximum lateral acceleration	+/- 0.5g	110% design
Average lateral acceleration	+/- 0.35g	110% design
Maximum vertical acceleration	+/- 0.8g	110% design
Average vertical acceleration	+/- 0.5g	110% design

One of the typical movements found in trains is the bogie hunting. This consists in the lateral sinusoidal motion product of the alignment of the rail joints. When the joints are not placed next to each on other, the train will move left to right. It's recommended to keep the joints always at the same station. Department of Transportation requirements specify that sustained bogie hunting should not be allowed. They define sustained bogie hunting as the "sinusoidal lateral oscillations of the wheelset resulting in greater than 0.5 Hz lateral body accelerations measured ath the bogie center of greater than 0.15 g sustained for 10 seconds or longer".(Samavedam-DOT, 2002). If the suspension springs cannot guarantee the vibrations to stay below this value, the speed should be decreased.

Table 2.9 Allowed Ride Index (Samavedam, US DoT 2002)

Vehicle Type	**Speed (Km/h)**	**Vertical Ride Index**	**Lateral Ride Index**
Locomotives	Maximum design speed	3.2	3.0
Track Maintenance Vehicle	Maximum design speed	3.2	3.0
Passenger vehicles	Maximum design speed	2.5	2.5

The DOT has developed its own ride index. The methodology to calculate it is shown in table 2.10:

The accelerations should be weighted with the function

$$\boldsymbol{R_i = 7.07\,(V_i)^{0.1}}$$

Table 2.10 DOT Ride Index

Frequency Range (Hz)	**V_i (Vertical)**	**V_i (Lateral)**
0 – 6	0.32 fa^3	4.32 fa^3
6- 20	400 a^3/f^3	650 a^3/f^3
20+	a^3/f	a^3/f

i is derived from a Fast Fourier Transform
f is the frequency
a is the amplitude
g is 9.81 m/s^2

$$\boldsymbol{RI_{total} = \left[\sum_{i=1}^{n} (RI_i)^{10}\right]^{0.1}}$$

The Fast Fourier Transform is used to obtain a discrete value from a signal. This is not the case for digital data. Digital data is the same as the transformed signal. (Samavedam-DOT, 2002)

Two other vibrating movements unique to railways are pitch and bounce. They occur at certain speeds. Irregularities on the tracks at a given repeating pattern met by a train traveling at certain speed may be in resonance resulting in an amplification of those vibrations. Ultimately, these high vertical amplitudes may cause the train to derail.

Table 2.11 Pitch and bounce limits

Parameter	**Limit**	**Test speed**
Maximum vertical acceleration	+/- 0.8g	Up to 110% of design
Average vertical acceleration	+/- 0.5g	Up to 110% of design
Minimum vertical wheel load	10% of static	Up to 110% of design

2.3.5 Measurements of vibrations

The most relevant parameters to evaluate time signals according to Michael Bellman are (Bellman,2002):

Table 2.12 Measurement of timed signals

Parameter	**Definition**
Mean	$x = \frac{1}{N}\sum x_i$
Standard deviation	$\tau = \left[\frac{1}{N}\sum (x(i) - \hat{x})^2\right]^{1/2}$
Root-mean-square	$\mathrm{R.M.S} = \left[\frac{1}{N}\sum x^2(i)\right]^{1/2}$
Crest factor	$\frac{peak\ value}{R.M.S}$
Root-mean-quad-value	$r.m.q. = \left[\frac{1}{N}\sum x^4(i)\right]^{1/4}$
Vibration Dose Value	$VDV = \left[\frac{T_s}{N}\sum x^4(i)\right]^{1/4}$
Estimated Vibration Dose Value	$eVDV = [(1.4(r.m.s))^4 T_s]^{1/4}$

Vibrations are measured with accelerometers. They have been used for decades to evaluate machine vibrations and for navigational systems. Usually they are firmly attached to the vehicle or surface tested. For railway car evaluation, the DOT requires an accelerometer to be attached to the car's base. The price of accelerometers has dropped over the years and so has its size. The automobile industry now uses it extensively and there are new applications every day. Cars use them to deploy airbags in case of collision, to evaluate road conditions and engage driving aids like Antilock Braking Systems (ABS) and traction control systems.

Tablets and phones simplify the task of measuring accelerations. Nowadays, they come equipped with accelerometers and can be ready to use as soon as you start the application chosen for the study. Their low price makes them affordable to small municipalities. In addition, they can be used individually or with other devices to share data in a cooperative environment. Castellanos and Fruett used them in a study to determine the comfort level of a train. All the data was collected without regard to the passengers' position and then the total accelerations were determined for each phone and the data correlated to the comfort level experienced by each user. (Castellanos and Fruett 2014)

The use of tablets and smartphones has made data collection somehow easier but it raises the question of whether they are suitable or not for scientific purposes. Many researchers are using data collected by such devices and the public in general to use it on several fields. This form of data collection is called crowdsourcing (Kardous and Shaw, 2014). All such studies using smartphones and tablets extensively must employ rigorous collection protocols as the result's validity is very dependent on the quality of the data obtained.

Regarding sound levels, Chucri A. Kardous and Peter B. Shaw (2014) determined that the mean deviation of the measurements taken with smartphones and those from reference values is not greater than 2dB and consider them suitable for occupational noise measurements. They cite four commissioned studies using these devices. They analyzed normal noise level (dB) and weighted noise levels (dBA). The low frequencies (under 100 Hz) are not heard by humans hence, many studies focus on this value instead of decibels.

In the "Future Network & Mobile Summit" 2010 Conference, Sian Lun and Klaus showed how accurate a smartphone can be to capture movement. For the phones studied, and a 20Hz sampling rate, they determined that the accuracy ranged between 92.54% and 99.27%. The results change between phones but the accuracy is mostly the same along all three axes. For a 10Hz sampling rate, the accuracy dropped to 88.50% at the worst. This study aimed at recognizing what kind of movement the phone user was making. It was able to recognize sitting, walking, standing or walking up and down stairs. It's interesting that, the best accuracy was obtained when comparing phones accelerometers at 1, 2 or even 4 seconds.

Hemminki, Nurmi and Tarkoma (2013)used smartphones' accelerators to determine the mode of transportation used. They determined the signature of many different modes of transportation with an accuracy of 0.2 m/s^2 and were able to match those to the type of vehicle used. Figure 2.10 shows unfiltered horizontal acceleration measured with three different phones on three different locations on a tram ride (Hemminki,2013).

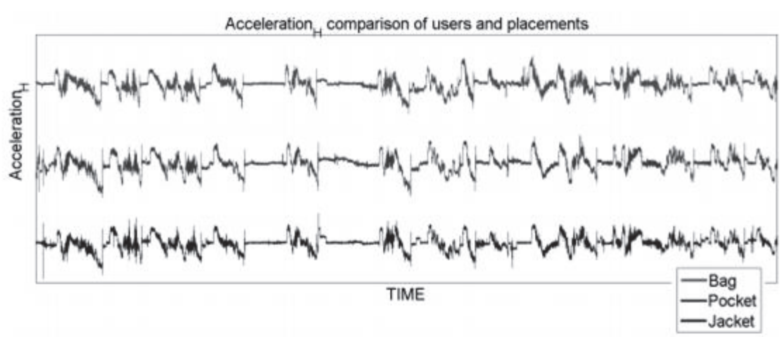


Figure 2.10 Vibrations from three different phones on the same vehicle (Hemminki, Nurmi and Tarkoma 2013)

When analyzing data from smartphones, it should be noted that phones name the axes differently than the usual convention. In many papers, the X and Y axes (the horizontal plane) are defined as X the one in the forward-backward direction and Y is the lateral axis. On smartphones and tablets, the convention is different. The forward axis is the Y axis and the lateral is the X axis.

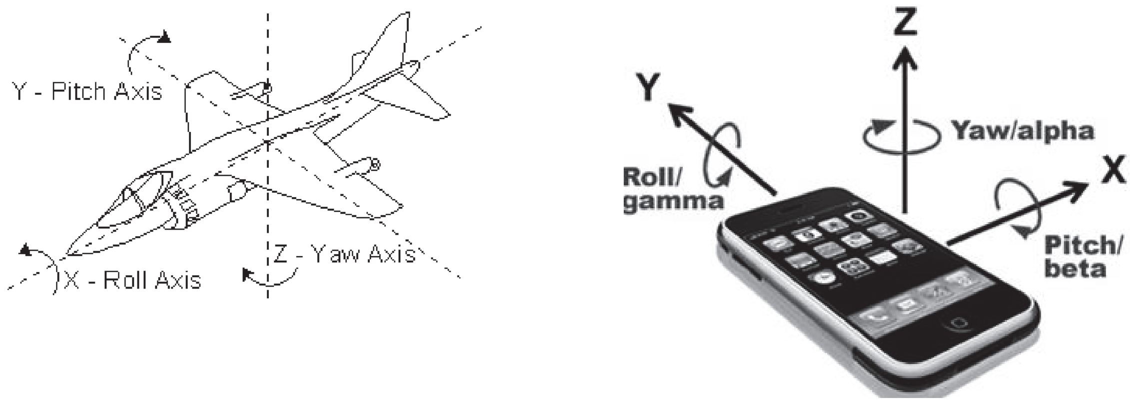


Figure 2.11 Coordinates used regularly and on phone applications (Newbius, 2016)

For an objective evaluation, one can use the RMS to evaluate ride comfort. The advantage of this method is that takes into account the vibration magnitudes and their duration. The acceleration used in the formula is the result weighted average of the frequencies studied (W (f)) obtained by using a Normalizing Factor for each frequency (f). This is the recommendation of both ISO and British Standards. However, this method has been used since the measurements of motion were taken with analog technology. At the time, with large equipment, it was possible to register vibration at many frequencies simultaneously. After collecting this data, the magnitude values for different frequencies were then sorted. (Smith et al. 1976)

Once these values were properly tabulated, the RMS was calculated following guidelines that were developed to account for human sensitivity for different frequencies.

Vertical	
$0 < f <$ or = 1Hz	W(f)=(0.1738)/NF
$1 < f <$ or = 4 Hz	W(f)=(0.1738)/NF
Normalizing factor (NF)=9.386	

Table 2.3Frequency Weighting of Accelerations

Transverse (Lateral)	
0 < f < or = 2Hz	W(f)=(4.0)/NF
2 < f < or = 100 Hz	W(f)=(16/f^2)/NF
Normalizing factor (NF)= 16.12	

Table 2.4 Frequency Weighting of Accelerations (Smith et al. 1976)

The root mean square value is then calculated as

$$\bar{a}_w = \left[\frac{1}{T}\int_0^T a_w{}^2\,(t)dt\right]^{1/2}$$

Nowadays, with the use of digital sampling, most devices produce output in only one frequency. This simplifies the calculations but doesn't allow studying many frequencies. One could only study frequencies that were multiples of the sampled data. Furthermore, many small ranges are not sampled.

In 1986, Kozawa *et al.* developed a Vibration Number (VN) and created a portable device that provided a measurement for the comfort of the passengers. The apparatus was created and calibrated on a two axis table. The scale was graduated between 0 and 100. The lower value was assigned to the threshold of human sensitivity and the 100 was assigned to the healthy limit.

Later Leatherwood (1979), working from NASA, developed another index and its corresponding apparatus to measure it. He also worked with the combined exposure to vibrations and noise. His goal was to find a single number to rate the combine annoyance effect product of the exposure to both (Leatherwood 1990). However, his experiment was to measure their effect, not on passengers but on people living close to railways. He placed subjects in a small room, on the same kind of seat and exposed them to six different noise levels and compensated the lack of frequencies by using the same one for a different time interval.

Table 2.5 Relation between Ride Discomfort and Vibration Acceleration (Strandemar, 2005)

Vibration (m/s^2)	**Reaction**
<0.315	Not uncomfortable
0.315-0.63	A little uncomfortable
0.5-1	Fairly uncomfortable
0.8-1.6	Uncomfortable
1.25-2.5	Very uncomfortable
>2	Extremely uncomfortable

2.3.6 Statistical Error of measurement devices

One of the main differences between analog and digital tools resides in the continuity of the data obtained. Both ISO and USDOT base their comfort and vibration analysis on an arrangement of frequencies. This type of data can be collected by using an analog sensor that measures all movement or by using collectors that will sample the required frequencies.

The digital sensors on a tablet, on the other hand, will collect data with a fixed sample rate. If this rate is high enough, you could filter the data to obtain the values on the required frequencies however, if the sample rate is not high enough, you can only use this rate as your frequency. This raises the question of whether the data is representative of the movement or not.

A simple analysis can help to estimate the relevance of the data. If a sensor could sample 1, 2, 4, 8, 20 and 40Hz during one hour it would produce 270,000 measurements. During the same time, a tablet with a sampling rate of 2Hz would collect 7,200 measurements. This sample provides a 99% confidence level with a 1.5 confidence interval.

2.4 Noise and its effect on humans.

Noise and sound level in general is measured in Bels, a unit developed to express the energy required to increase the sound levels but, since the increments of this unit are too large, it's more practical to use a subdivision the decibel (dB). Decibels use a logarithm scale. This means that a 10dB increment amounts to 10 times the energy delivered but it's only about twice the loudness of the sound level. Zero is set at the human threshold of hearing. The tenfold change in energy delivered is an objective measurement and the twofold increment in perception is an average developed by Robinson and Dadson (1956) and subjective but it's widely accepted and it's the basis for ISO 2003. While there is not theoretical limit to the scale, at 140 dB the human ear suffers extreme pain. 140 dB is the same as 1 followed by 14 zeroes (1014) but human perception would be 214=16384.

Another characteristic of sound is that, the vibrations that produce it must travel through a media and they do it at different frequencies. These frequencies depend on the nature of the vibration source. They are affected by the amount of energy produced by the vibration. Not all sounds are audible to humans. The human ear only perceives sounds in the range of 20Hz to 20,000 Hz (or 500 to 10,000 for some authors). Many prefer the weighted decibel (dBA) to measure noise levels. This method leaves out most of the lower frequencies. (St. Pierre, McGuire 2004).

Table Change in Sound Levels vs Change in Perceived Loudness St. Pierre, McGuire 2004

Change in Sound Level	Change in Perceived Loudness
3	Just perceptible
5	Noticeable difference
10	Twice (or (1/2) as loud
15	Large change
20	Four times (or ¼) as loud

.

Although some studies show that humans can perceive a 1dB change in sound and remember a 2 dB from one day to another (Lloyd's), the reality is that only 3-5 dB increments are noticeable only everyday conditions (Cheng) as shown on table 2.14

The dBA scale was developed around 60dB so it's not accurate a different ranges of sound intensity. Also, this form of measurement was developed under controlled conditions and using single tone signals. In reality, noise comprises many different frequencies. (St. Pierre, McGuire 2004).

On the other hand, the dBA scale seems to predict more accurate any hearing damage. Since it leaves out part of the low frequency sounds, any measurable inaudible sound is bound to cause some damage. (St. Pierre, McGuire 2004).

In addition to the dB scales, there are many other units used to evaluate sound levels: the Phon scale, SONE, Sound Pressure Level (SPL) and the Articulation Index. The Phon scale was developed using single tones. It's defined as the SPL at a given frequency. The Sone was proposed in 1936 as a measurement of loudness. It's a linear scale. The Articulation Index evaluates the difficulty of maintaining conversation (Da Silva2001).

Lloyd's marine design regulations explain that a one decibel increment is noticeable but it's not recognizable from one day to another while a 3 dB change is.

The hierarchy of allowed noise levels is shown on table 2.14

Table 2.14 Lloyds Noise Requirements

Goal	**Limit**	**Comment**
Avoidance of hearing damage	Spaces louder than 85dB and upper limits of 110dB	Ear protection required
Ability to orally communicate at less than 0.5 meter distance	80 dB upperlimit	Water noise at the deck. Loud voice.
Avoidance of noise induced fatigue	60 to 65dB	65 for lounging areas and 60 dB for crew spaces
Ability to sleep	60 dB upper limit	

Luxury to comfort quiet	38 to 48 dB	
Super quiet	18 to 23 dB	Recital Halls

The sound in vehicles can be airborne or structural transmitted.(Da Silva) Many sources of noise can cause both types (engine, for example). Others are caused by the car moving and passing through the layers of air. Suspension, brakes and other mechanical parts are a source of noise. The vehicle construction affects both the production and the transmission of noise. The interaction of the tires and the pavement can be another source of noise.Airborne sound transmission is affected by atmospheric pressure and temperature.

2.5 CO_2 effects on humans.

Carbon dioxide is one of the products of combustion. Combustion is the chemical combination of carbon and oxygen. It is a component of air as the product of animal and plant breathing and metabolic activity, and of volcanic eruptions and other natural processes. In vehicles, it is a product of engine combustion and human breathing.(Da Silva, 2001)

The concentration of carbon dioxide is usually measured in particles per million (PPM). The American Association of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) considers CO_s concentrations of 5,000 PPM as the safe limit for occupational exposure (standard 62). This level doesn't pose health threats (Prill, 2000). Outdoor concentrations are usually around 380 PPM. Adults exhale CO_2 concentrations ranging 35,000 to 50,000 PPM. ASHRAE recommends indoors concentrations of 1,000 ppm in schools and 800 ppm in offices and, based on those figures determines the ventilation requirements for an enclosed environment. (Energy Institute, 2015)

ASHRAE also considers carbon dioxide as a surrogate for odors. By regulating the air recirculation values to maintain 1,000 ppm concentrations, the air is supposed to remain free from odors. Carbon dioxide is colorless and odorless (1) but it serves to measure other products of human activity that may cause odors. Measuring this simple value can substitute the need to monitor many other gases. At around 1,000 to 1,500 ppm, building occupants may complain about the air’s quality. Most people will notice concentrations 600 ppm above outdoors levels. Concentrations above 2,500 ppm can cause drowsiness. (Energy Institute, 2014)

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter explains the methodology used in the study contained on chapter 4: first, the data collection steps, then data processing, indices preparation and comfort index creation (Fig. 3.1). Several protocols for data collection were developed and qualitative notes taken and recorded during the trips (notes log). The data was processed to remove unexplained peaks and sorted before the preparation of individual indices per component (accelerations, noise and air quality). The final goal was to characterize comfort in order to explicitly include it in a decision making system. Data from various modes of transportation was used in this study, and, in some cases, the analysis extended to the same mode in different countries.

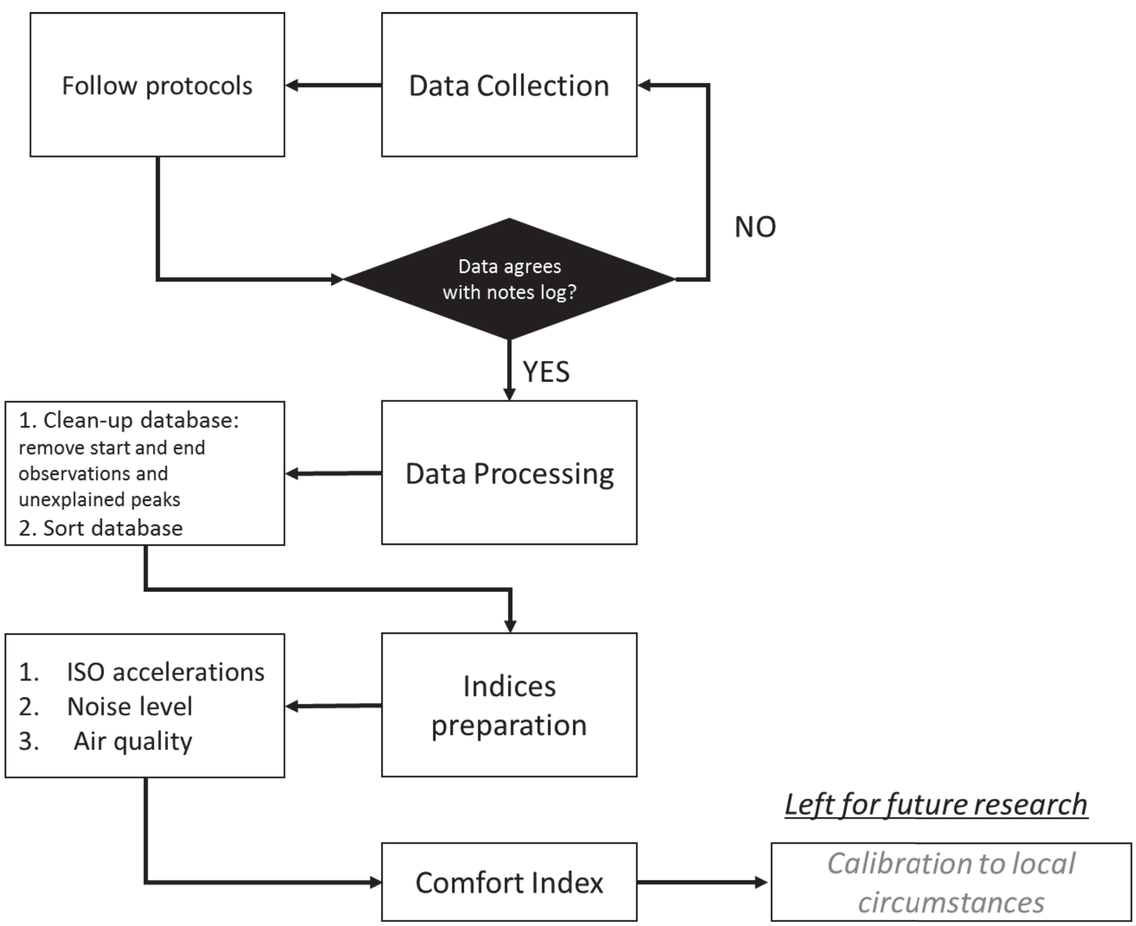


Fig. 3.1 Methodology

In this research, a case study for Montreal considered three different variables: 1) vehicle vibration and accelerations, 2) noise level and 3) CO_2 concentrations (Figure 3.1). Other practical applications could include temperature, lighting, humidity, and etcetera. For the remaining cases, the CO_2 levels were not quantified.

The proposed rider's comfort index is based on these elements in a way that is applicable to different modes of transportation and it can enable their comparison from comfort perspectives. This index could be calibrated for an specific urban area.

Details of the equipment and methods used for data collection, data processing and index preparation are explained in the following sections.

3.2 Data collection

A portable accelerometer was used to measure the vehicle's accelerations on all three axes (x,y,z). Nowadays, accelerometers are standard in most phones and tablets. This makes the data collection easier than in the past, when one needed very specialized equipment. The device can be used to obtain the accelerations and geographical position of the device relative to three axes. The vibrations were monitored along X, Y and Z axes and rotations around both horizontal axes. Although the rotation around the vertical angle can be collected it is not useful for the estimation of the comfort levels.

When a vehicle moves, its relative position to the horizontal plane changes experiencing certain accelerations and, if a tablet device is attached to the vehicle, it will register the same vibrations. The forward movement from an initial resting position or when breaking, it is submitted to accelerations on the longitudinal axis(y). The magnitude of these vibrations can be affected by the breaking and accelerating rates. A driver has the ability to influence these parameters. The seats are the last vibration damper on the whole chain of their transmission. If there were space constraints the tablet was be placed on the seats however, it is preferable to place it on the floor to avoid additional movement.

Bouncing induces accelerations along the vertical or normal axis (z). In the case of a car, the pavement condition and the suspension/damping system can affect the value of these measurements. A driver has somewhat less power to affect these values. He might choose a bad lane or decide to ride directly into potholes. A train conductor has even less power to affect these values. The vehicle runs on rails. The condition and initial placement of these, together with the suspension and damping system are the only factors involved.

When it turns, the vehicle is submitted to radial forces that translate into lateral acceleration (x). This variable is affected by the driver when he chooses the traveling speed and when he negotiates the curves. A sharp turn will increase the acceleration normal to the car axis and produce radial acceleration. This is also true for rail-guided vehicles. The road and railway alignment also influence the lateral forces affecting the vehicle. The design for these alignments is regulated to limit the maximum forces affecting the vehicles.

Carbon dioxide levels can be measured using a portable device such as the Node Clima 2.0 sensor. This device registers readings at rates as little as one second. This data collection rate shows a lot of values; however it is possible that no significant changes are detected, especially if the ventilation system keeps a stable air quality. The readings are affected by the location of the device inside the vehicle and proximity to a source of fresh air hence it is a durable to identify the locations of the farthest and closest points and take readings at an intermediate location.

A mobile phone or tablet loaded with an application for mobile phones such as the Decibel application by Pico Brothers can be used to register noise levels. This application can measure the sound levels and keep a record of the highest peak value. The level of noise was measured in decibels. The location or time of occurrence of these peaks could be measured and recorded by some device. The device has a sample rate of 5 measurements per second. The overall accuracy of smartphones in the range of 70 to 95 db is around 3% depending on the device. (Chucri A. Kardous and Peter B. Shaw, 2014). The smartphone should be taken out of its case to measure the sound levels to avoid its muffling effect.

3.4.1 Protocol for vibrations and noise

The following steps illustrate the protocol follow to collect the data for vibrations and noise

1- Turn on the device and start the applications. At this point, the device is reading but not recording data.

2- Board the bus at the chosen location.
3- Set the tablet device firmly on the floor and secure it in place with duct tape to prevent additional vibrations. The device's longitudinal axis was aligned as good as possible with the bus's longitudinal axis.
4- Press the 'Record' button to start recording data.
5- In addition read the noise levels
6- Make sure the device doesn't turn off automatically.
7- Pause the recording after the bus stops at the destination.
8- Stop the applications and the device. The data is saved automatically.

3.4.2 Protocol for Carbon Dioxide

The following steps illustrate the protocol follow to collect the data for CO2 gases

1- Board the vehicle.
2- Turn on the device and start the application.
3- There is no need to attach device to the vehicle.
4- Press the start button on the device.
5- Record data at 1 second intervals.

3.5 Data Processing

The obtain data is studied looking for errors. The most common errors may be due to different sampling rates on the device. The data at the beginning and the end of the recording is removed and only values contained within a starting and finishing complete stop are used.

The peaks on the graphics are compared to the notes taken along the road (notes log). Brakes, accelerations and sharp turns produce accelerations on all three axes which are identifiable rather easily. Long rough patches of pavement correspond to increased z-axis accelerations. Passenger stops show as zero or near zero values of the accelerations along the three axes. Punctual bumps on the road are harder to identify. If recorded values of accelerations do not match the notes' log, then it is preferable to repeat the data collection, otherwise, if there is good agreement between accelerations and the notes' log then the data can be used on the next step. Data processing followed these steps:

1. Data was sorted (accelerations along each axis, rotation along each axis, and GPS coordinates) and unnecessary information removed. The values of accelerations used were those that did not contain the gravity constant (g).
2. The graphics for the acceleration along each axis are generated. The vertical scale for each graphic may be different depending on the maximum accelerations to display. When comparing two examples of the same mode of transportation, the scales used are the same to facilitate said comparison.
3. The graphic's horizontal axis's scale was fixed to display the accelerations in a way that may show the accelerations compressed enough to understand the way the vehicles behave, but not in a way that makes it difficult read. The horizontal compression allowed the identification of patterns. A four second moving average line helps to soften the peaks.
4. The data contained on each column is used to calculate the acceleration along each axis. The values used are: simple average, standard deviation and root mean square, although, ultimately most of the calculations are based on the root mean square (R.M.S.).
5. Once the R.M.S. is calculated for every acceleration, the pertinent ride index is calculated: DOT Ride index and ISO ride index, following recommended weights to combine accelerations.
6. An un-weighted acceleration vector is calculated as a benchmark.
7. A graph showing the ride index on the horizontal axis and, the noise level on the vertical axis, serves as an indicator of comfort across vehicles and modes.

3.6 Comfort index development

There is a lack of a comfort index that considers several elements of different nature important to riders. Some organizations have set up some standards; however, they are not mandatory. For the boats industry, compliance with them is a requirement for a certification. On other modes of transportation, comfort is not considered as a safety issue and sometimes left outside the vehicle's performance parameters and specifications. The high number of variables involved in determining comfort forces researchers to focus on a few elements at a time of the same nature. The aim of this research is to characterize comfort from a multidimensional perspective, in the future a comfort index can be used to forecast passenger's trip behavior in addition to the common factors of cost and travel time.

In this study, we have used some parameters that are usually considered separately and tried to combine them to create a value that would express the comfort level and allow us to compare different forms of transportation. Such parameters have been considered independent although, in reality, some degree of correlation exists between noise and vibrations. This correlation will be considered negligible for the purpose of this research.

The proposed index will be an indicator of comfort or, more appropriately, discomfort. It should behave as a percentage. Its values would change within an open range; zero means total lack of discomfort or absolute comfort, 1 means total discomfort according to the accepted parameters and values above 1 are to be interpreted as very uncomfortable.

It is important to mention that the main purpose of this research is to serve as a proof of concept of the feasibility of how to develop a comfort indicator for riders ignoring proper experimental design to estimate sample since an applicable statistical test to validate the data.

The index formulation could take additive or multiplicative shape. The multiplicative model could take two different shapes too. The generic expression for the additive model would be

$$Index = \sum_{i=1}^{n} \alpha_i \frac{|(x_i - xmin_i)|}{(xmax_i - xmin_i)}$$

Where

x_i is the measured variable
$xmax_i$ is the maximum or recommended value for that variable and
$xmin_i$ is the minimum
α_i is the weight factor and

$$\sum_{i=1}^{n} \alpha_i = 1$$

There can be a xi variable for every factor measured and added to the index. The measurable variables could be:

- Vibration
- Sound level
- Carbon dioxide
- Illumination
- Room Temperature
- Humidity
- Atmospheric pressure

The value for *xmax* should be the maximum allowed or the recommended for the parameter studied.

- When the variable could take values on a scale that starts at zero (like sound levels or vibrations), the quotient would be equal to the measured value divided by the maximum recommended value.
- When the variable's measured values should be kept within a given range (like room temperature), the comfort percentage will be calculated for the values within that range.
- When the scale has a practical minimum value (like carbon dioxide which is around 380 PPM for outdoor rural environments), the minimum should be zero to allow for improvement.

When a variable reaches the value of 1, it means that the maximum level for the corresponding factor has been reached and the comfort percentage is, thus, uncomfortable. The theoretical *zero* value corresponds to the most comfortable state this factor can reach. Values above 1 mean that the comfort level has been exceeded.

A lower comfort index value means a more comfortable ride. The maximum values for the parameters in this research are shown on table 3.1

Table 3.2 Maximum limits of chosen parameters

Factor	Maximum value
Accelerations, vibrations	2.5 m/s^2
Noise, sound levels	80 dB
Air quality (CO_2)	1,000 PPM

Multiplicative models could be simple product or geometric average.

The simple product is the multiplication of the partial comfort percentages (for each variable) and a scaling factor. It's simple and convenient for few variables. The index would be directly proportional to the variables included. The inclusion of any additional variables would increase the value of the index. The range would be from zero on one end and open on the other.

The simple product formula is

$$Index = K\prod_{i=1}^{n} x_i$$

The weighted geometric average model can be calculated with the formula

$$Index = \bar{x} = \left[\prod_{i=1}^{n}\left(\frac{|(x_i - xmin_i)|}{(xmax_i - xmin_i)}\right)^{\alpha_i}\right]^{1/\sum_{i=1}^{n}\alpha_i}$$

which, when all weights (α) are the same, can be simplified as:

$$Index = \bar{x} = \sqrt[n]{\prod_{i=1}^{n}\left(\frac{|(x_i - xmin_i)|}{(xmax_i - xmin_i)}\right)}$$

CHAPTER 4

RESULTS

4.1 Introduction

A case study for the city of Montreal was developed to test the proposed method. Data was collected and compared for several modes of transportation as shown in Table 1. At the beginning the purpose was to identify the most significant elements related to ride comfort, then moving into the creation of an indicator of comfort. Vehicle's acceleration and movement were collected for buses, trains, metro cars and automobile on several countries (Table 4.1). These indicators helped to characterize the ride quality of a given mode of transportation. Even though the data collection was rudimentary, it is expected that in the future a cooperative application installed on smart phones and other portable devices, could serve to automatically obtain data from passengers, and hence automatized the monitoring of ride quality as a continuous task.

Table 4.1Case Study

Location	Modes/vehicles	Measured Elements
Montreal, Canada	• Slow bus • Express/Coach bus • Suburban/intercity train • Metro	• Vibrations/accelerations • Noise levels (noise) • Air quality (CO_2)
	• Boat	• Vibrations/accelerations • Noise levels (noise)
Manchester-London, United Kingdom	• Suburban/Intercity train • Metro	• Vibrations/accelerations • Noise levels (noise)
Santo Domingo, Dominican Republic	• Metro • Automobile	• Vibrations/accelerations • Noise levels (noise)
Miami, USA	• Airplane	• Vibrations/accelerations • Noise levels (noise)

4.2 Data Collection

In order to collect the data for this experiment, three different devices were used: ASUS ZenPad 210 Z300C-A1-BK 10.1" 16 GB Tablet to measure the vibrations, the Nokia C6-01 for noise levels and the Node+ Clima 2.0 for CO2 levels. Available commercial applications were used to collect each of the abovementioned indicators.

4.3 Data Processing

The goal of the data processing is to enable a comparison between two different modes of transportation for the same origin-destination (St-Jean-sur-Richelieu to Montreal), from the comfort point of view, vehicle movement data along all three axis was plotted versus time. Then, each value was matched to the corresponding observed movement taken during the trip, this allowed the measurement of the magnitude of movement relative to each variation type (i.e., vehicle start and stop, turning movements, etc).

The average and standard deviation of the data can provide a good idea of the quality of the ride. In addition, the number of turns, steep hills, and other movement related locations (bridge crossing) were manually logged. The particular values of these less comfortable spots were calculated separately and tabulated.

4.4 Quality of the Ride

The comfort of the ride was considered as a function of:

1- The accelerations on each axis.
2- The variation on pitch and roll.
3- The noise level.
4- The carbon dioxide levels.

Although it’s easy to compare these variables individually, it is more difficult to provide a composite value of comfort based on them. The first portion of the analysis of results is devoted to run individual comparisons; a later section exposes the method used to combine individual indicators into an overall comfort index.

4.5 Results

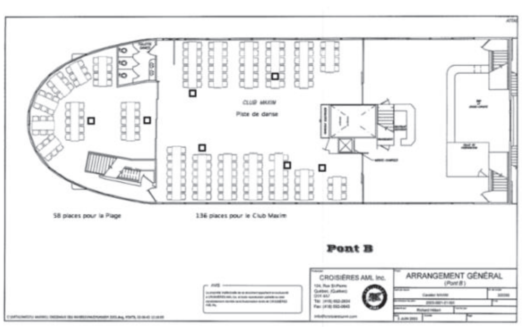
4.5.1 Boat

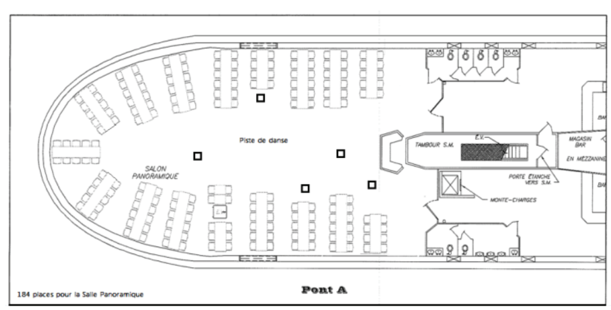
Boat’s measurements were taken on the Cavalier Maxim, a boat that makes a tour along the St-Laurent River in Montreal during the summer. The boat is 60 meters long and 12 meter wide. It has three decks and accelerations were measured on the middle deck. The two lower levels are closed and more isolated from outside noise and wind than the top deck. Noise levels were measured on the top and middle decks. The lower level was not accessible.

The boat can accommodate up to 750 passengers. The seats are arranged around a number of dining tables. Throughout the trip, passengers are able to eat and drink without disruption due to movement, accelerations or sudden jolts, hence this boat was used as a benchmark for comfort when looking at comfort across modes of transportation.

The traveling speed was around 12 knots (22 Km/h), the duration of the trip was 90 minutes with a total travel distance close to 30 km. The tablet was placed on a table in the middle deck, its longitudinal axis aligned with the ship axles.

The noise levels were registered in both decks. Outside noise levels were measured at 75 dB with occasional peaks of 90 dB. On the top deck, the wind was around 24 Km/h according to the local forecast. On the middle deck, noise levels were lower: 46-55 dB with 65 dB peaks. The ship’s horn reached 95 dB.





Second level (Inside) Third level (Deck)

Fig 4.1 Cavalier Maxim Boat Schematics (Croissières AML, Retrieved 2015)

Figures 4.2, 4.3 and 4.4 show accelerations along all three axes (x,y,z) as seen accelerations in x and y are almost imperceptible, only those at the z-axis seem to matter. Figures 4.4d and 4.4e show the variations in pitch and roll. It's clear that after the 350th second, there's some change. In this case, the boat accelerated. Throughout the manoeuvre, the acceleration increased and also both pitch and roll increased. Contrary to the expectations, the z accelerations remained fairly unchanged.

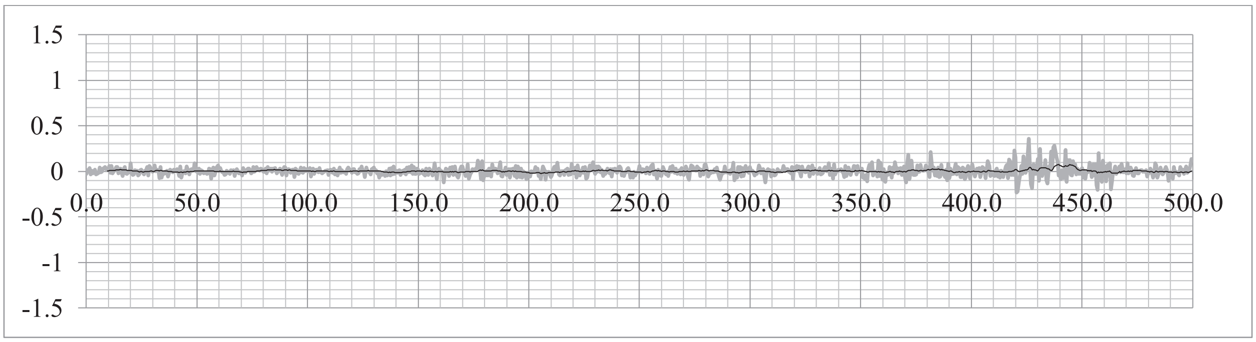


Figure 4.2 Accelerations in X axis

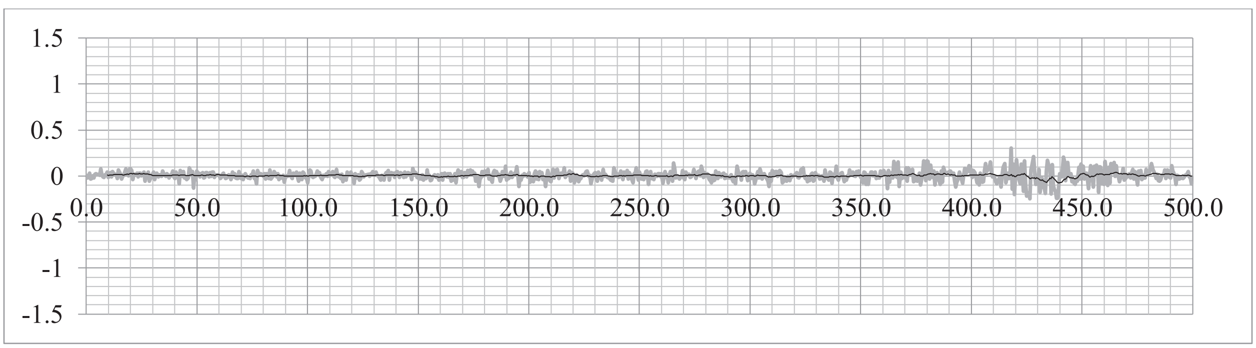


Figure 4.3 Accelerations in Y axis

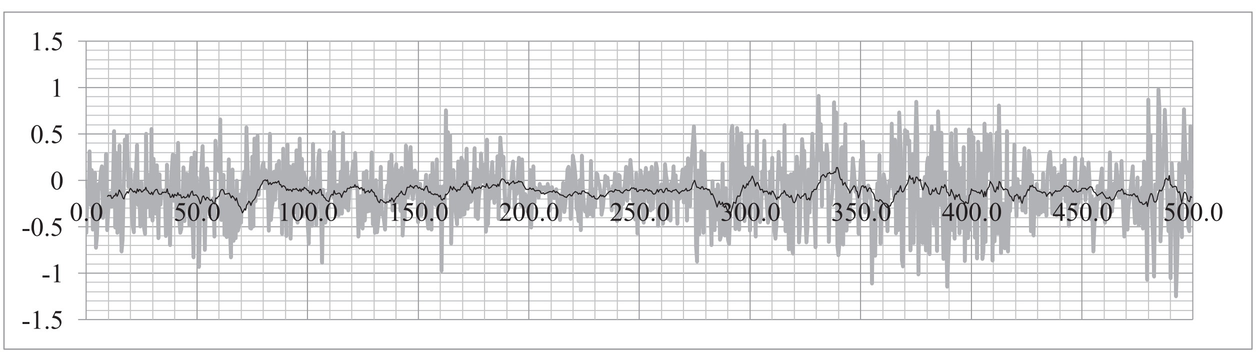


Figure 4.4 Accelerations in Z axis

Scale
X-axis: time in seconds.
Y-axis: acceleration in m/s².

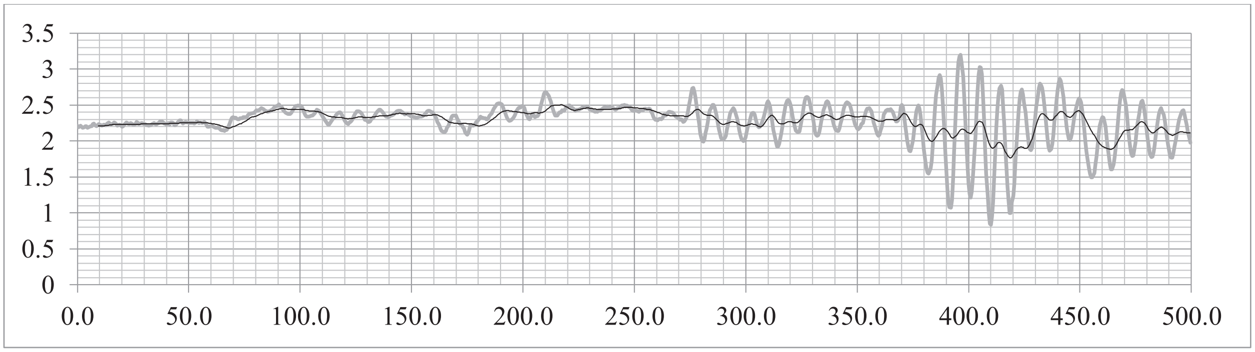


Figure 4.5 Orientation along X axis (Pitch)
Scale
X-axis: time in seconds.
Y-axis: rotation in rad.

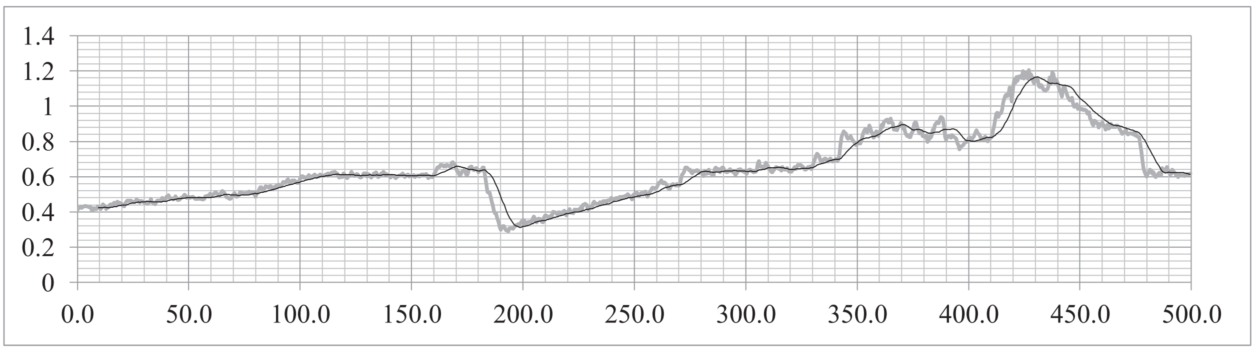


Figure 4.6 Orientation along Y axis (Roll)
Scale
X-axis: time in seconds.
Y-axis: rotation in rad.

When analyzing cars and trains, the pitch graphic shows less change (Fig 4.5 and 4.6). The variations are minimal and due to braking and accelerating when arriving or leaving a station. Pitch on the boat shows a slow, more ample oscillation due to bopping motion. Pitch variation is the only parameter used by Lloyds (1999), DNV GL and other naval organizations to measure a ships motion's comfort; however, they measure it in mm/s. The accelerometer measures only radians. Without an in-depth analysis of the movement, this data is not enough to calculate the overall movement.

4.5.2 Buses

The route between the south shore locality of *St-Jean-sur-Richelieu* and Montreal was used to compare the several indicators between the express and local buses. This trip is operated under the bus line 96. These buses travel during the day-time along two different routes (Figure 4.11 and 4.12). The Express and Super Express buses use a luxury coach vehicle while the local bus uses an urban bus. Other important differences are that the local bus makes more stops and takes a longer road, but its users have control over the windows in order to obtain fresh air from outside.

On both cases, the tablet was placed on a seat, its longitudinal axis roughly aligned with that of the bus. The incidences of the ride were recorded simultaneously with the register of the tablet.

Comparison of St-Jean-sur-Richelieu to Montreal Buses
Accelerations along X axis

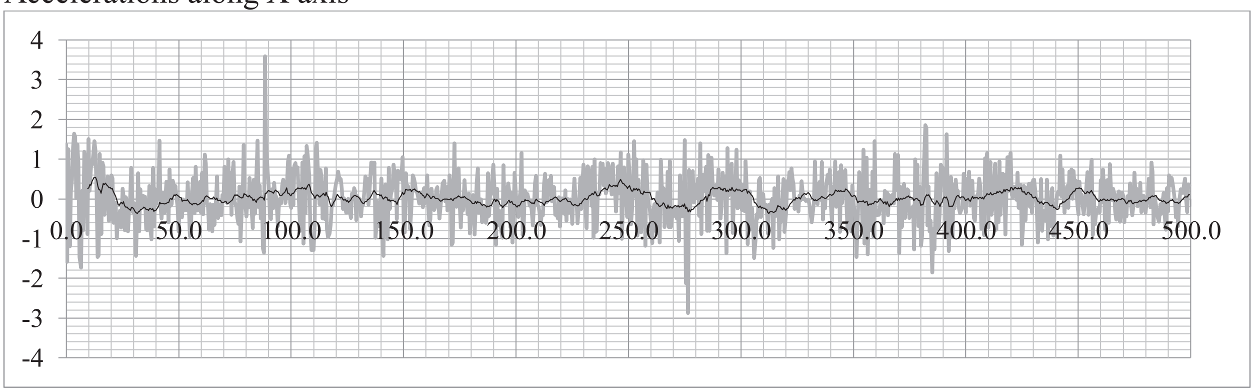


Figure 4.7 Express Bus

Scale
X-axis: time in seconds.
Y-axis: acceleration in m/s².

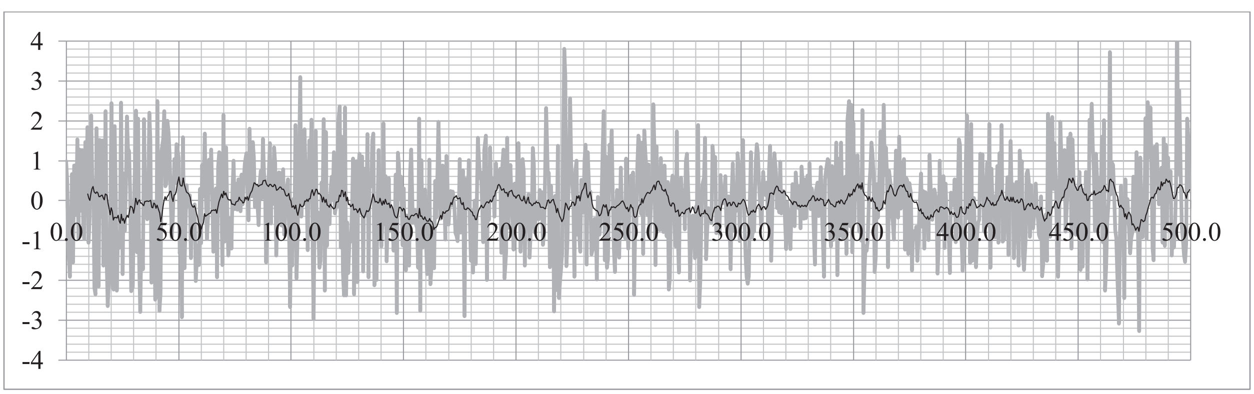


Figure 4.8 Local Bus
Scale
X-axis: time in seconds.
Y-axis: acceleration in m/s².

The accelerations along the X axis are the product of side motion when changing lanes, turning and of the rolling motion of the bus. The commuter bus showed a far smoother ride than the local bus (Figures 4.7 and 4.8). It makes fewer stops to pick up or leave passengers. The local bus is lower and should be more stable; however the suspension is stiffer than its counterpart on the luxury bus.

The same is true for Y axis accelerations: the coach bus makes fewer stops and keeps a steady speed for larger portion of the drive. There are fewer peaks therefore, fewer jolts (Figure 4.9 and 4.10i)

Comparison of St-Jean-sur-Richelieu to Montreal Buses
Accelerations along Y axis

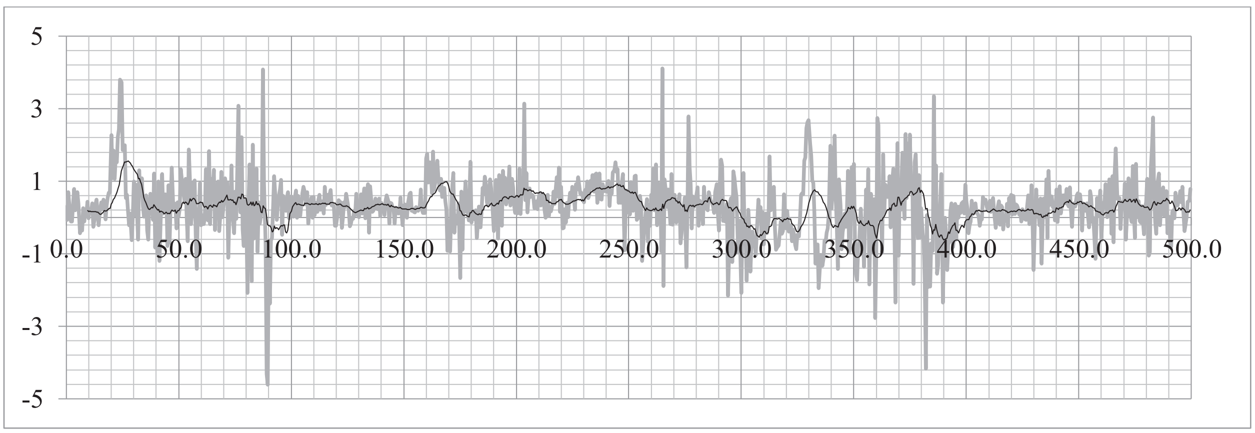


Figure 4.9 Express Bus

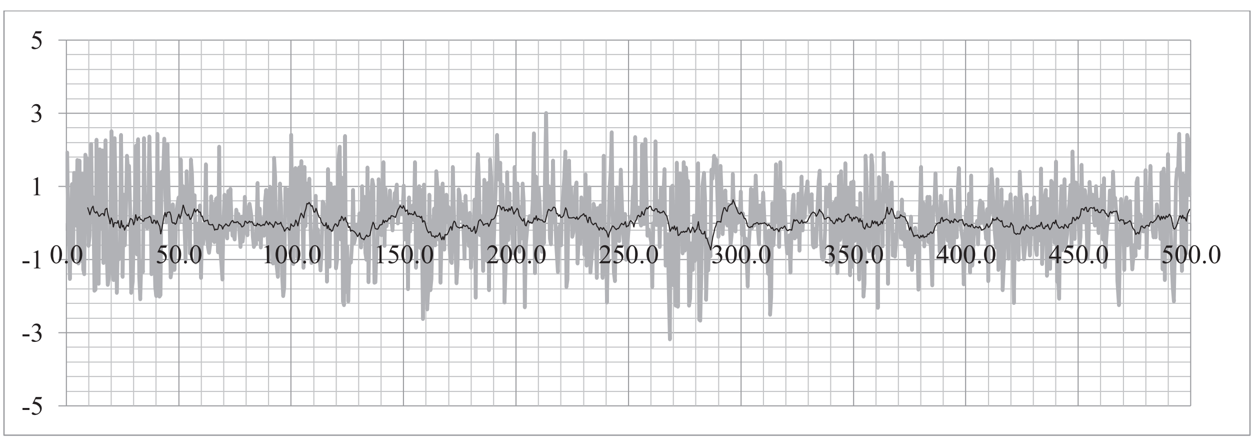


Figure 4.10 Local Bus
Scale
X-axis: time in seconds.
Y-axis: acceleration in m/s².

Figure 4.11– Bus from St-Jean-sur-Richelieu to Montreal. Express bus route.

Figure 4.12– Bus from St-Jean-sur-Richelieu to Montreal. Local bus route.

The accelerations along Z axis are shown on Figures 4.13 and 4.14. These graphics show vertical (up and down) motion, which is an indicator of suspension and pavement interaction. Both vehicles got exposed to the same mechanical excitation: Pavement Roughness, however, each suspension dampens the vertical accelerations in a different matter. Figures 4.11 and 4.12 illustrate a common link for both vehicles, even though the exact location of the wheel path may not match, the overall experience is a good proxy of vibrations experienced by the user.

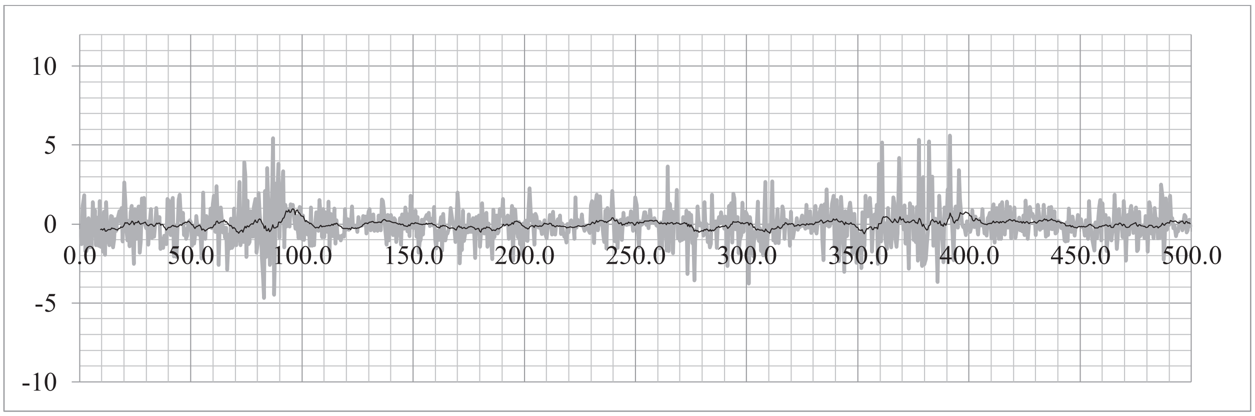


Figure 4.13 Express Bus
Scale
X-axis: time in seconds.
Y-axis: acceleration in m/s².

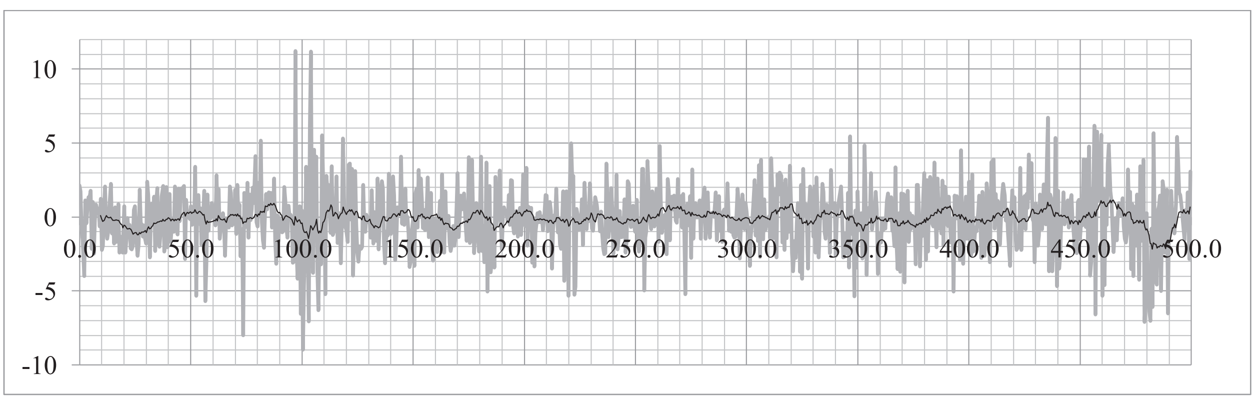


Figure 4.14 Local Bus
Scale
X-axis: time in seconds.
Y-axis: acceleration in m/s².

4.5.3 Metro

Three different metro train systems were compared in this research: 1) Montreal metro, 2) London Underground and 3) Santo Domingo metro. Montreal metro uses the oldest cars and rails of the three (1966), London Northern Line cars date from 1995 and Santo Domingo Metro presents the newest (2013). Montreal runs on Canadian Vickers or Bombardier stock. Santo Domingo uses Alstom Metropolis 9000-Barcelona and London's Northern Line also uses Alstom cars but from 1995.

Accelerations along X-axis

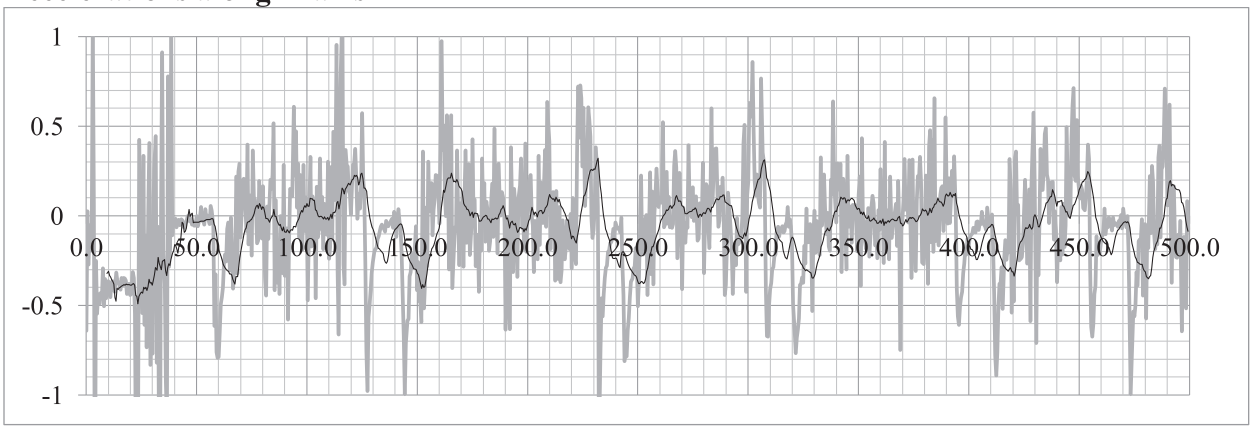


Figure 4.15 Metro Montreal Angrignon-Honoré Beaugrand

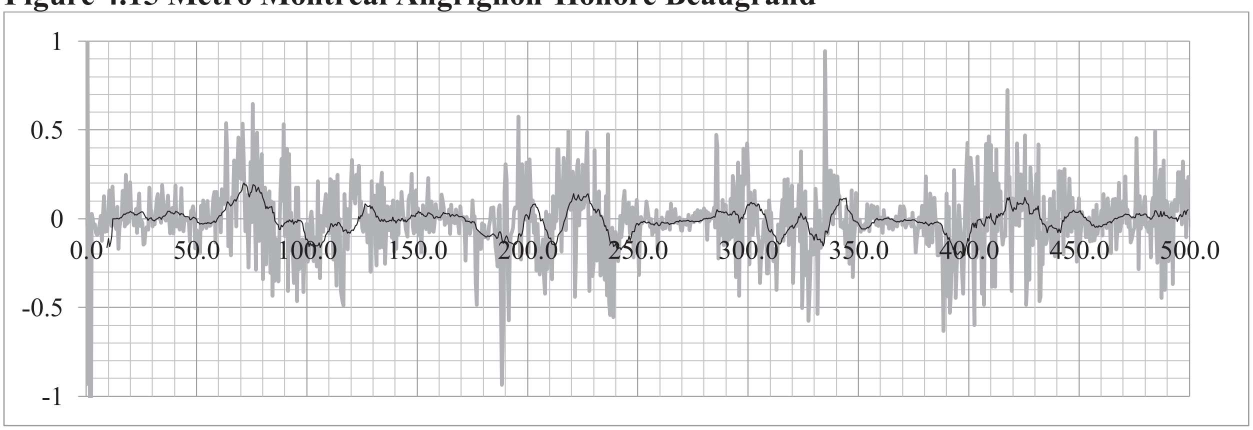


Figure 4.16 Metro Santo Domingo Line 2

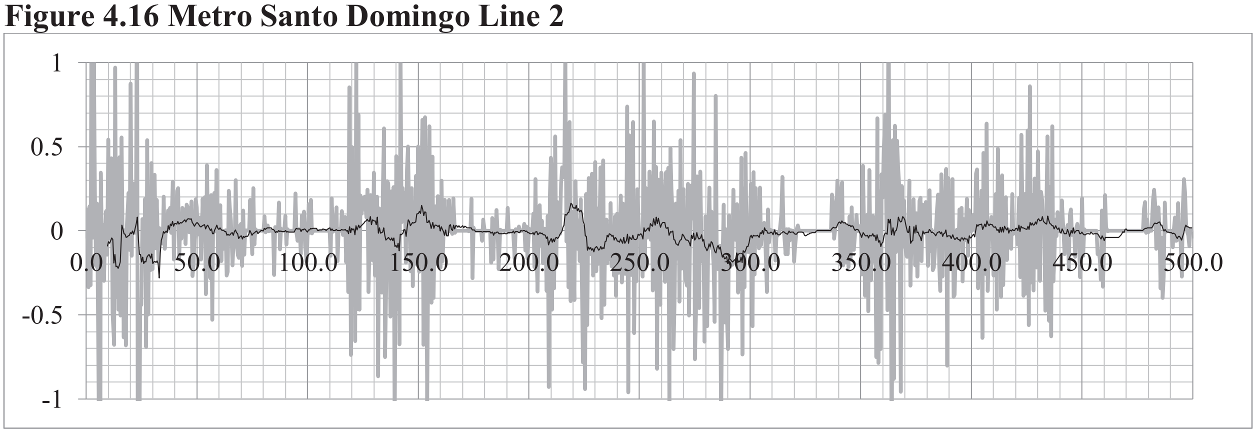


Figure 4.17 London Underground Northern Line Bank to Euston

Scale

X-axis: time in seconds.

Y-axis: acceleration in m/s².

The accelerations along the Y-axis are shown on figures 4.15, 4.16, 4.17., the graphics of acceleration in the direction of the train's movement showed a clear braking and accelerating signature for London's Underground and Santo Domingo Metro (Figure 4.19 and 4.20). Braking, by definition, is the decrease of the speed but the graphic shows that this deceleration is also performed gradually. Montreal Metro cars are considerably older and the braking is done manually on some of the oldest cars with some exceptions on computer controlled braking through the newer models, this could explain the irregular patterns observed in Figure 4.7a.

The braking and accelerating rates on London Underground and Santo Domingo Metro are shown on Table 4.2, while those of the Santo Domingo (Alstom Metropolis 9000 cars -Barcelona model) are shown on Table 4.2 . Most of the operations are computer controlled and build in 2008.

Table 4.2 Train acceleration and braking rates

Metro	Acceleration Rate	Braking Rate
London Underground Northern Bank-Euston	0.04 m/s^3	0.04 m/s^3
Santo Domingo Metro Line 2	0.05 m/s^3	0.10 m/s^3

Table 4.2 Metro-train car dimensions (*Badia, Xavier 2009)*

Train Length	86.094 m (282.46 ft)
Width	2,710 mm (107 in)
Height	3,859 mm (151.9 in)

Table 4.2 London Northern Line dimensions of Alstom 1995 stock cars.
"Rolling Stock Data Sheet 2nd Edition" (PDF). Transport for London. March 2007.

Train Length	17.77 m (58 ft 3.6 in)
Width	2.63 m (8 ft 7.54 in)
Height	2.875 m (9 ft 5.19 in)

Montreal Metro uses 1967-76 Canada Vickers cars refurbished in 1993 by Alstom. These cars are driverless too but, apparently, the braking and accelerating uses a different system, their dimensions are shown in Table 4.2.

Table 4.2 Montreal metro dimensions

Train Length	152,4 (three wagons)
Width	2.5 m (8 ft 2.4 in)
Height	-

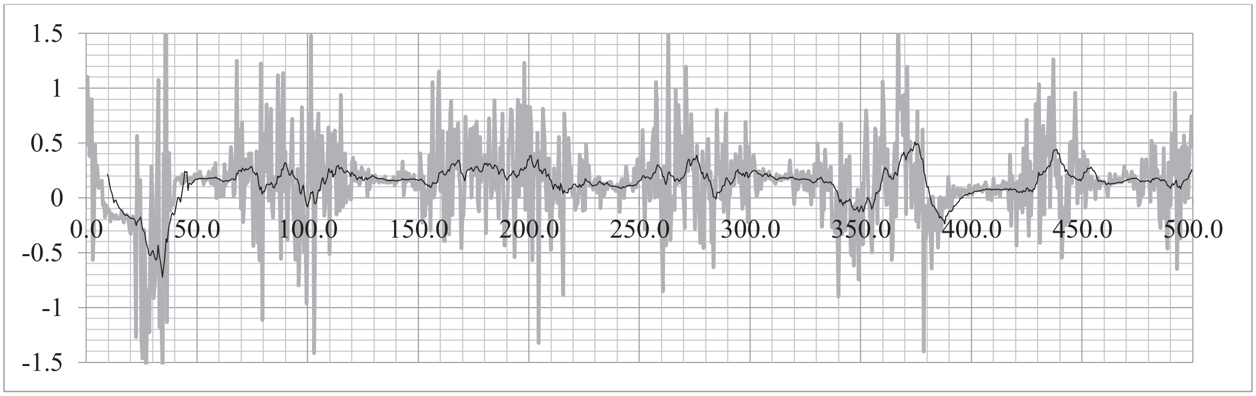


Figure 4.18 Metro Montreal Angrignon-Honoré Beaugrand

Scale
X-axis: time in seconds.
Y-axis: acceleration in m/s².

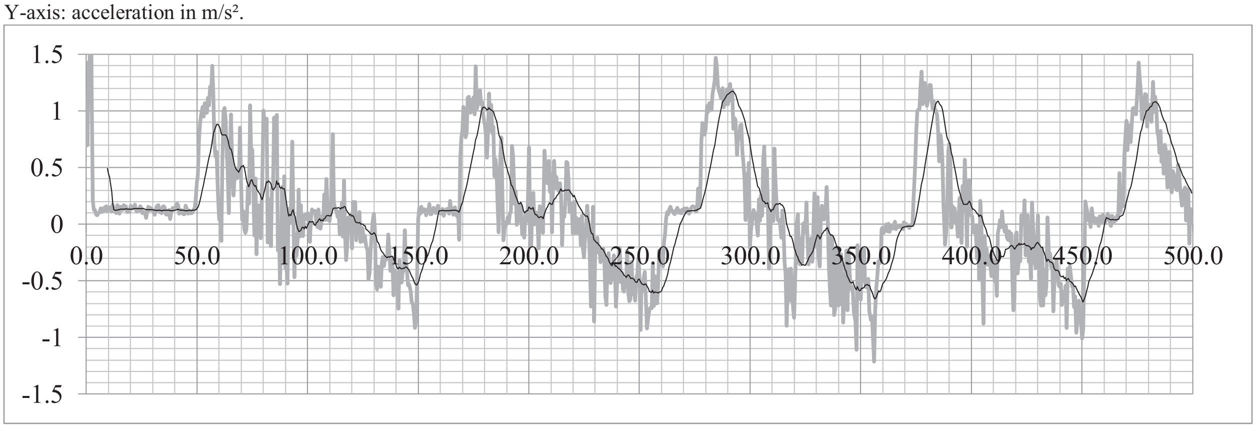


Figure 4.19 Metro Santo Domingo Line 2

Scale
X-axis: time in seconds.
Y-axis: acceleration in m/s².

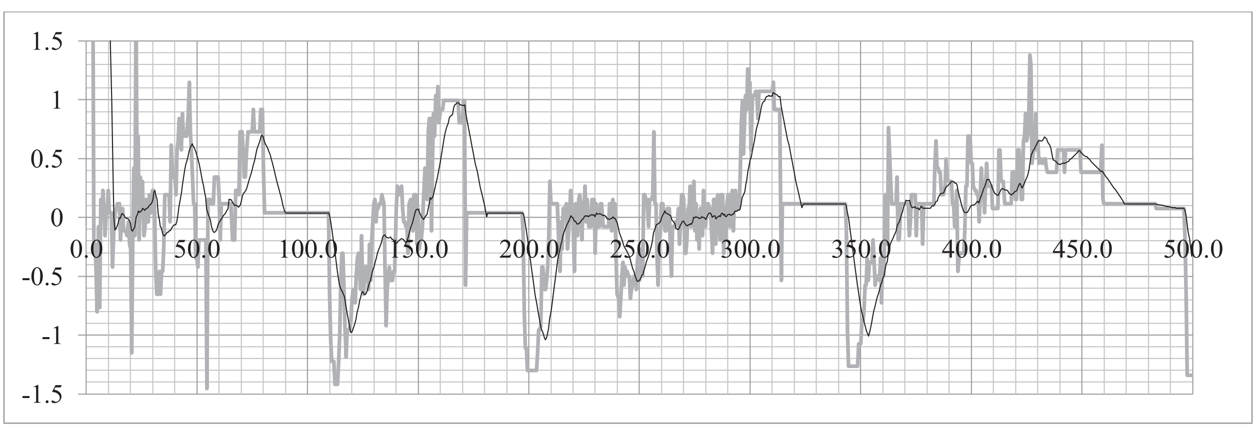


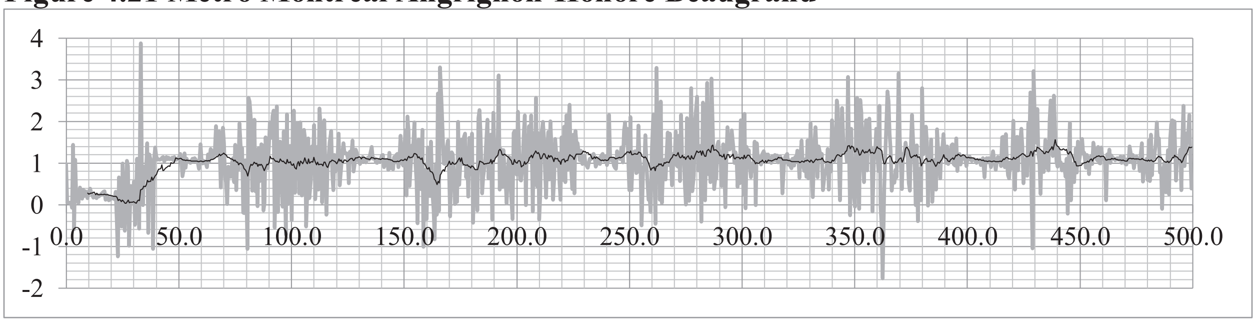
Figure 4.20 London Underground Northern Line Bank to Euston

Scale
X-axis: time in seconds.
Y-axis: acceleration in m/s².

Figures 4.21, 4.22 and 4.23 show the bouncing of the metro cars. This movement is due to the interaction of the rails and the cars. The quiet ride of the London Underground can be explained by two possibilities: a better damping system or better rails. The quality of the tracks and their placement can reduce or augment the amplitude of the movement.

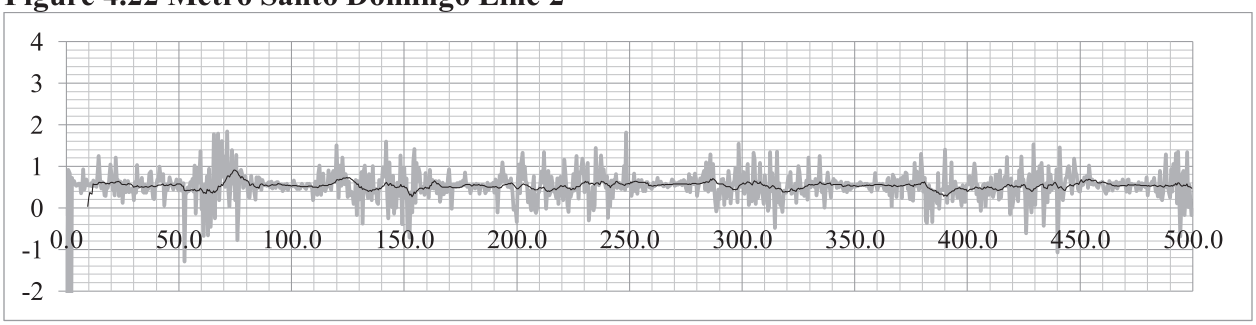
Accelerations along Z-axis

Figure 4.21 Metro Montreal Angrignon-Honoré Beaugrand



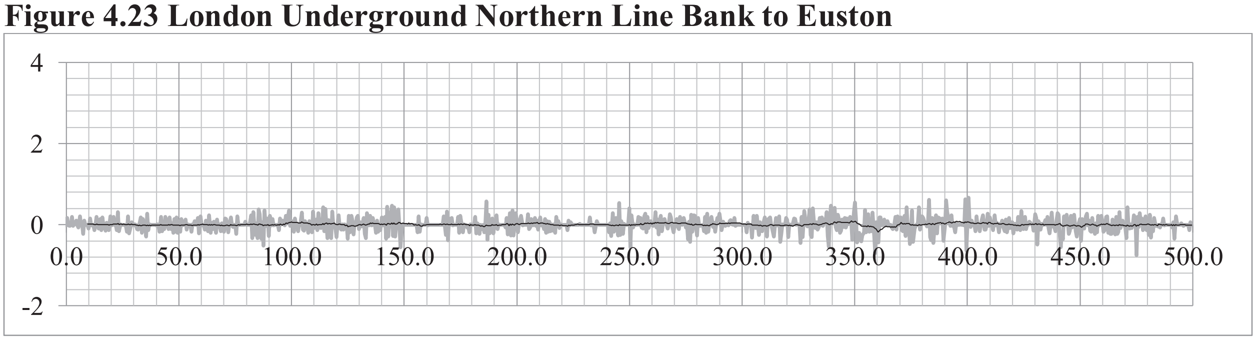
Scale
X-axis: time in seconds.
z-axis: acceleration in m/s².

Figure 4.22 Metro Santo Domingo Line 2



Scale
X-axis: time in seconds.
z-axis: acceleration in m/s².

Figure 4.23 London Underground Northern Line Bank to Euston



Scale
X-axis: time in seconds.
z-axis: acceleration in m/s².

Figures 4.24, 4.25k and 4.26 compare the pitch among metro-cars, the Montreal line performs better than the other lines possibly given the more straight nature of the line, with no so many horizontal curves in the portions shown.

Accelerations along Pitch

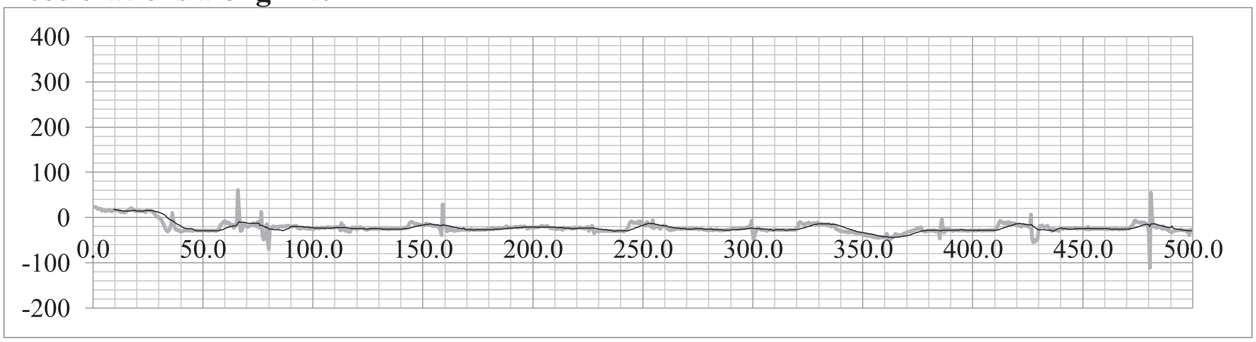


Figure 4.24 Metro Montreal Angrignon-Honoré Beaugrand

Scale
X-axis: time in seconds.
Y-axis: pitch

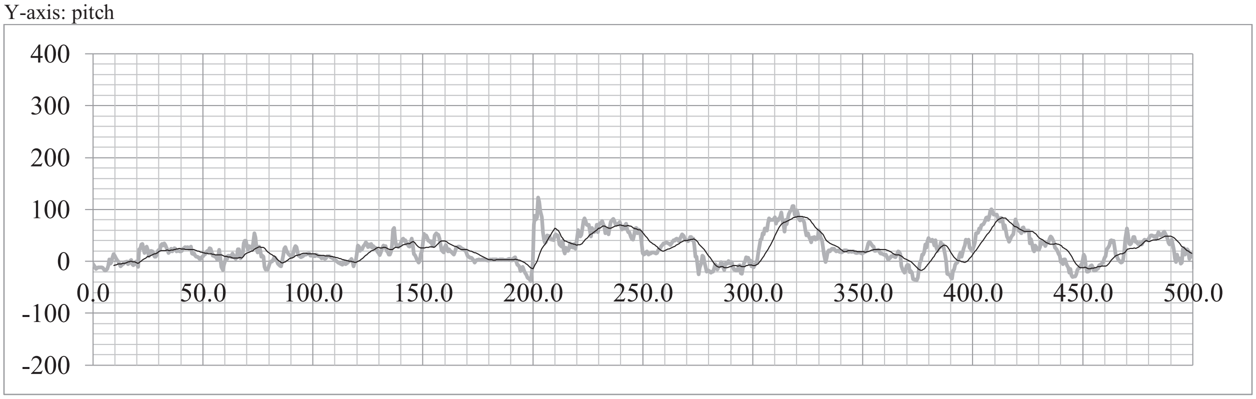


Figure 4.25 Metro Santo Domingo Line 2

Scale
X-axis: time in seconds.
Y-axis: pitch

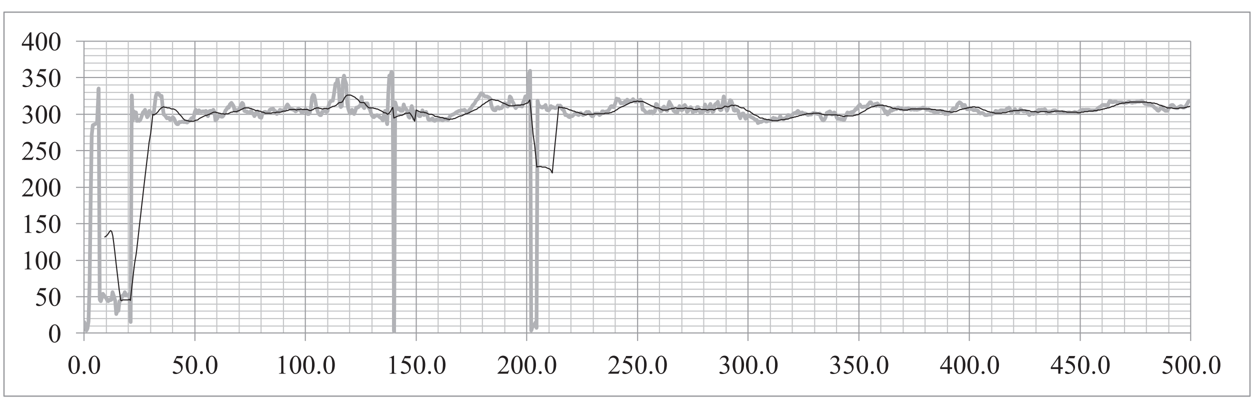


Figure 4.26. London Underground Northern Line Bank to Euston

Scale
X-axis: time in seconds.
Y-axis: pitch.

Figures 4.27, 4.28 m and 4.29 show the roll movement among the metro cars. As seen the roll in Santo Domingo follows a specific pattern that seems to be controlled but that is much larger than its counterparts for Montreal or the much smoother ride of London train.

Accelerations along Roll

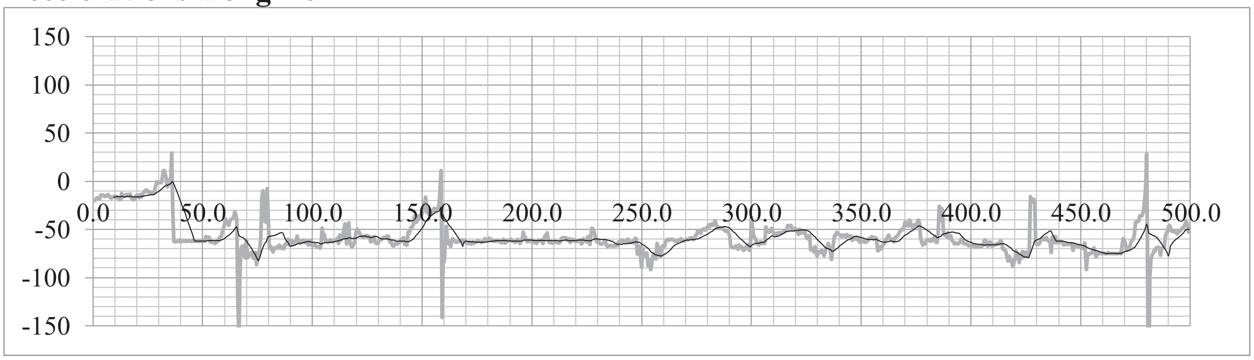


Figure 4.27 Metro Montreal Angrignon-Honoré Beaugrand

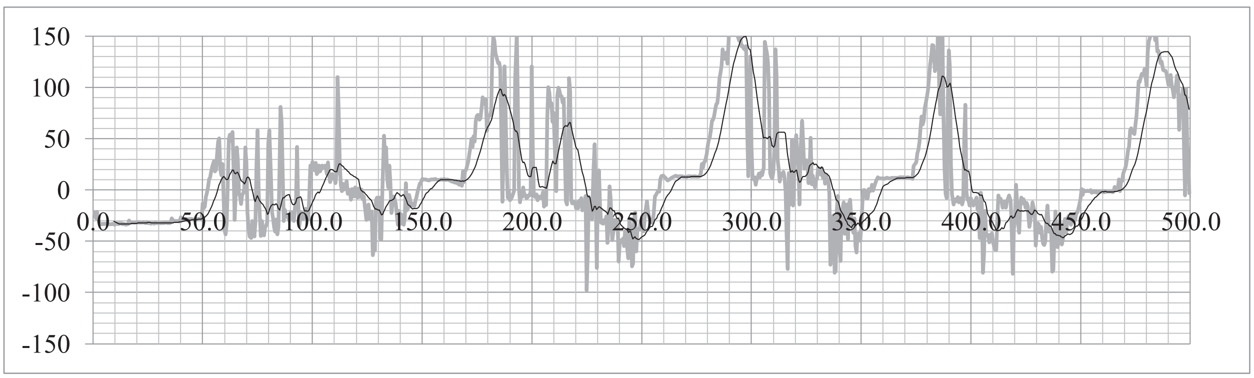


Figure 4.28 Metro Santo Domingo Line 2

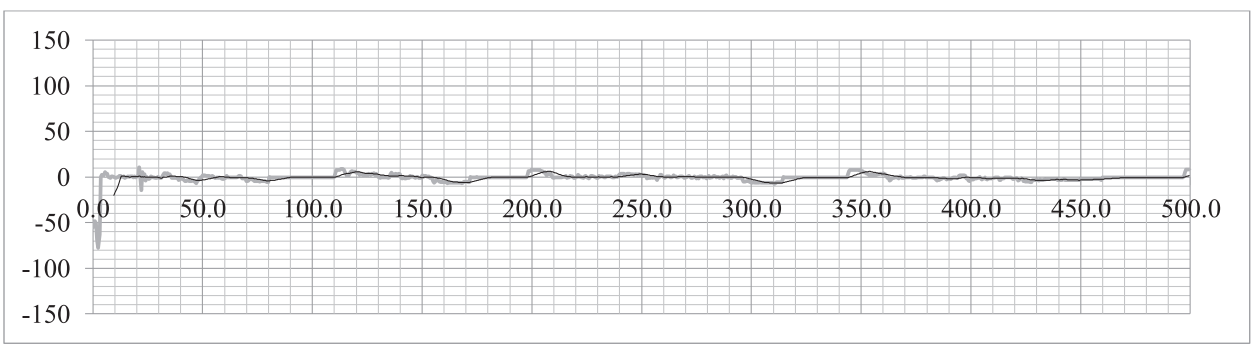


Figure 4.29 London Underground Northern Line Bank to Euston

Scale
X-axis: time in seconds.
Y-axis: acceleration in radians.

4.5.4 Commuter Trains

Similar to metro-cars, comparison across trains are only at an overall qualitative basis since the trajectories correspond to trains in three different geographical locations. Comparison of Commuter Trains show similar smooth patterns in the x-axis given the industry practices of controlling such movement Figure 4.30 and 4.31), braking and acceleration seems smoother in Montreal train than in London (Figure 4.32 and 4.33), accelerations in z seem very similar and as previously stated they are mainly influenced by the rails condition and damping system (Figure 4.34 and 4.35.

Accelerations along X-axis

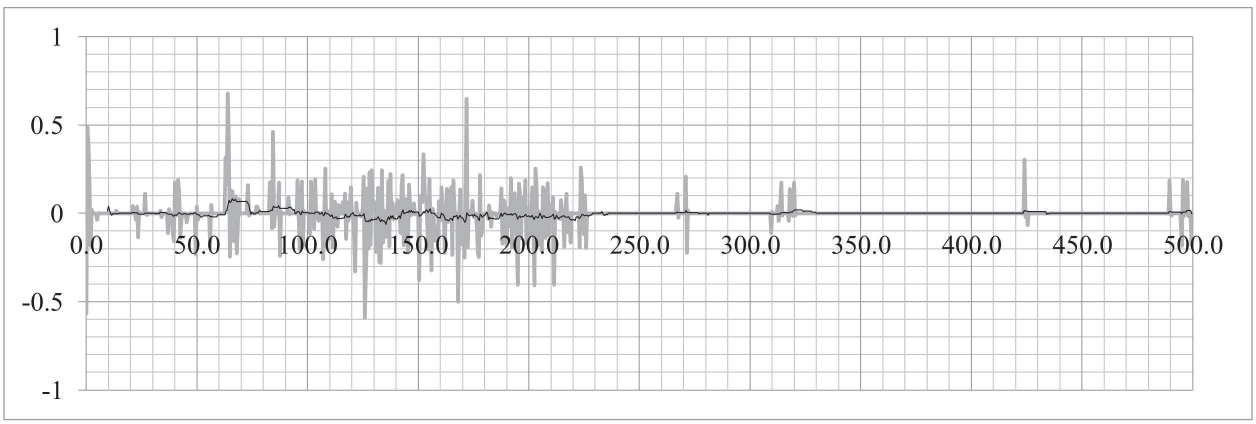


Figure 4.30 UK Stafford Line

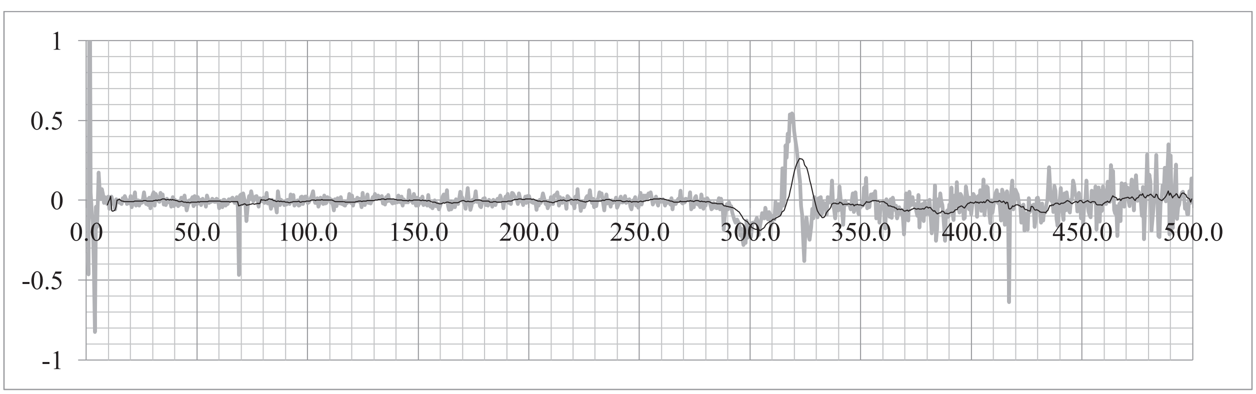


Figure 4.31 Montreal-St.Jerome Line

Scale
X-axis: time in seconds.
Y-axis: acceleration in m/s².

Comparison of Commuter Trains

Accelerations along Y-axis

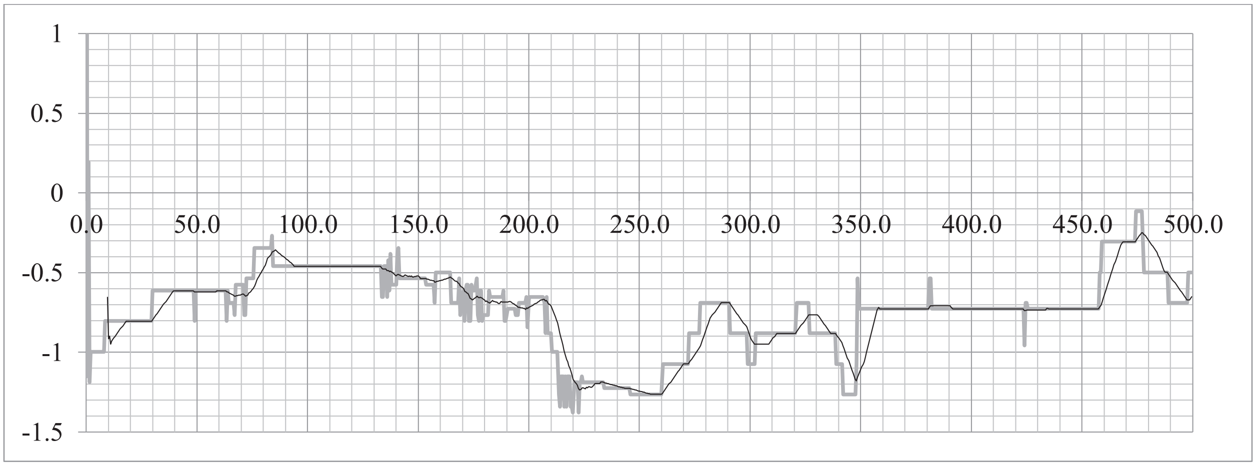


Figure 4.32 UK Stafford Line

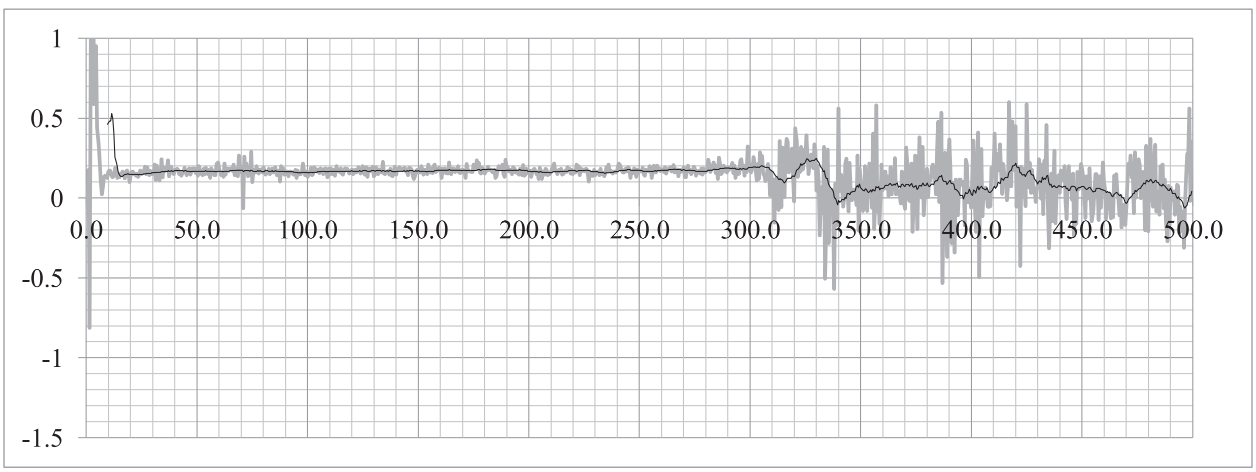


Figure 4.33 Montreal-St.Jerome Line

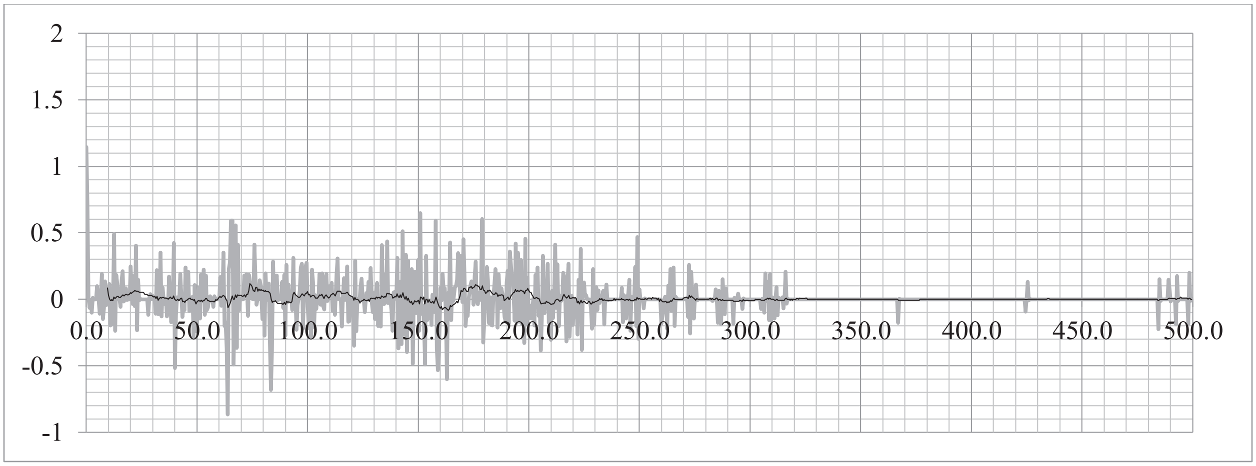


Figure 4.34 UK Stafford Line

Scale
X-axis: time in seconds.
Y-axis: acceleration in m/s².

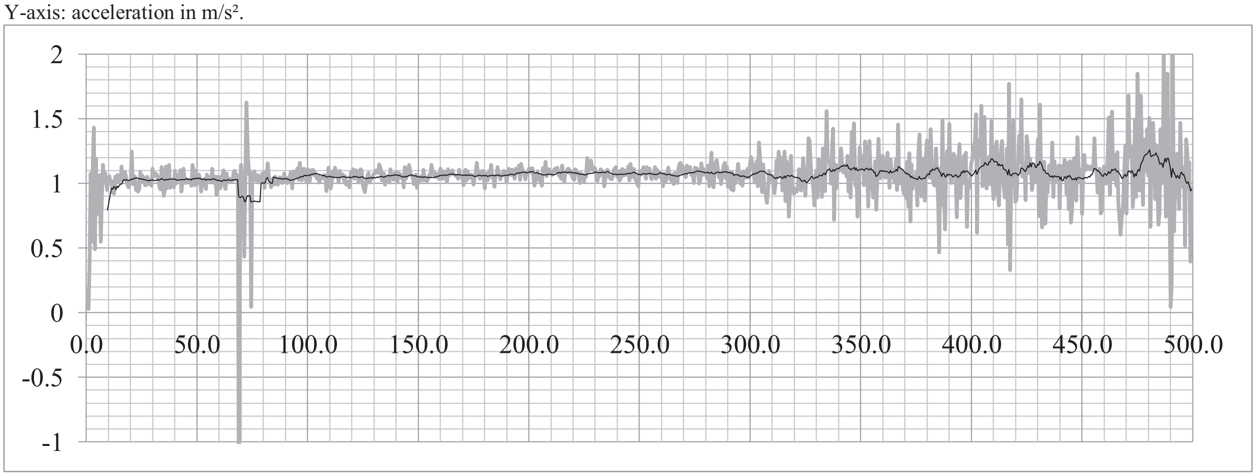


Figure 4.35 Montreal-St. Jerome Line

Scale
X-axis: time in seconds.
Y-axis: acceleration in m/s².

Trains also showed smooth patterns in terms of pitch and roll movements as seen on Figures 4.36 to 4.39 with slightly higher roll on the Montreal commuter train.

Pitch

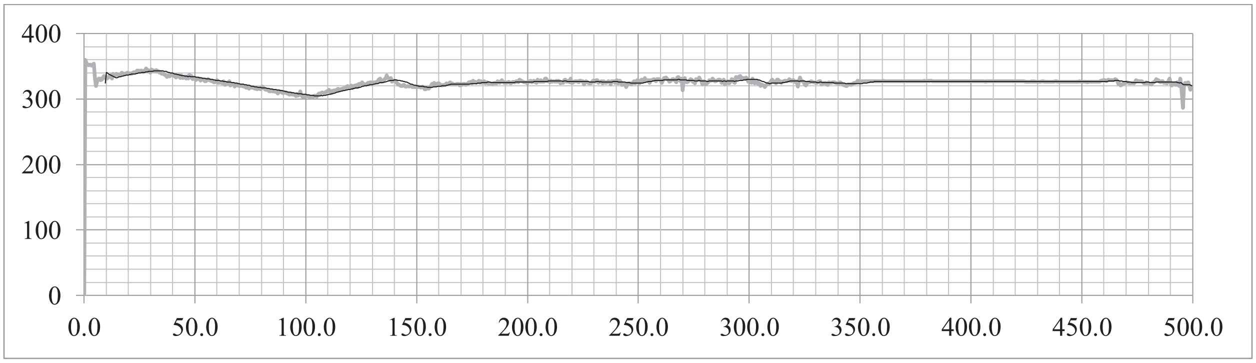


Figure 4.36 UK Stafford Line

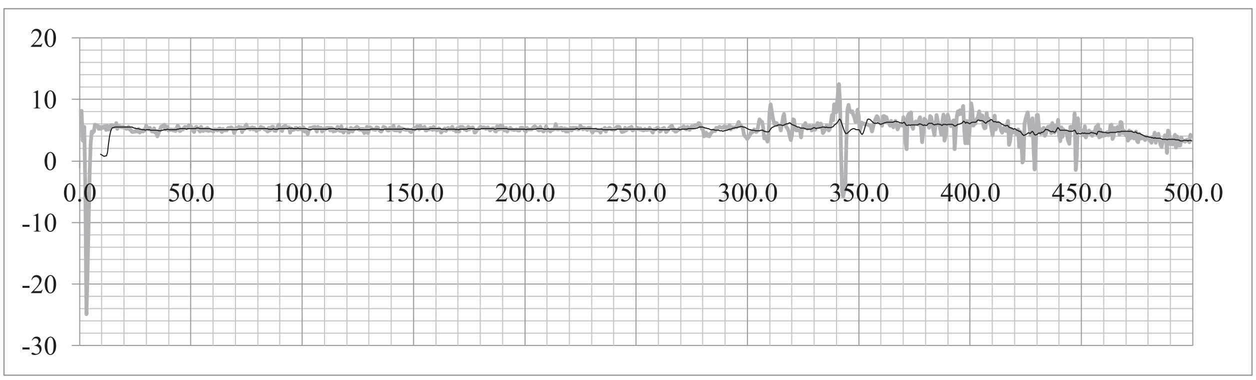


Figure 4.37 Montreal-St.Jerome Line

Roll

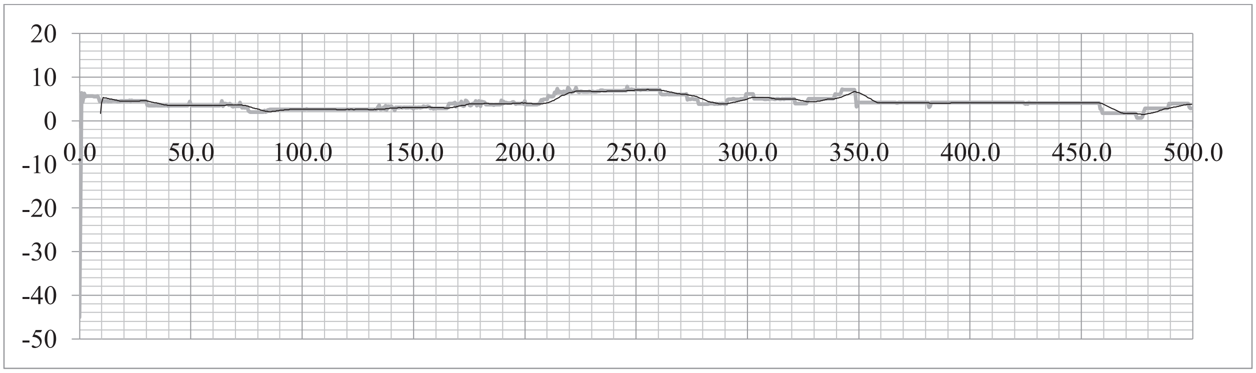


Figure 4.38 UK Stafford Line

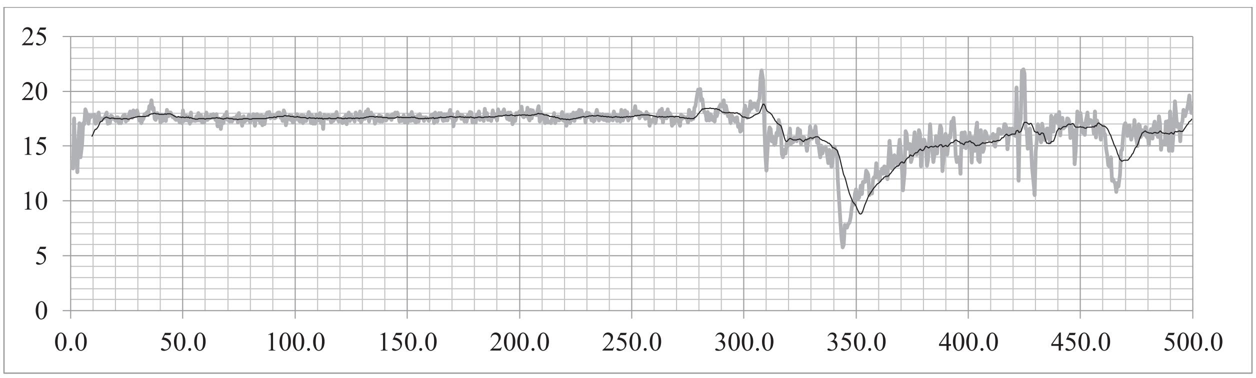


Figure 4.39 Montreal-St.Jerome Line

4.5.5 Plane

Plane vibrations along axis x, y and z are shown on Figures 4.40, 4.41, 4.42c. These vibrations were registered midflight.

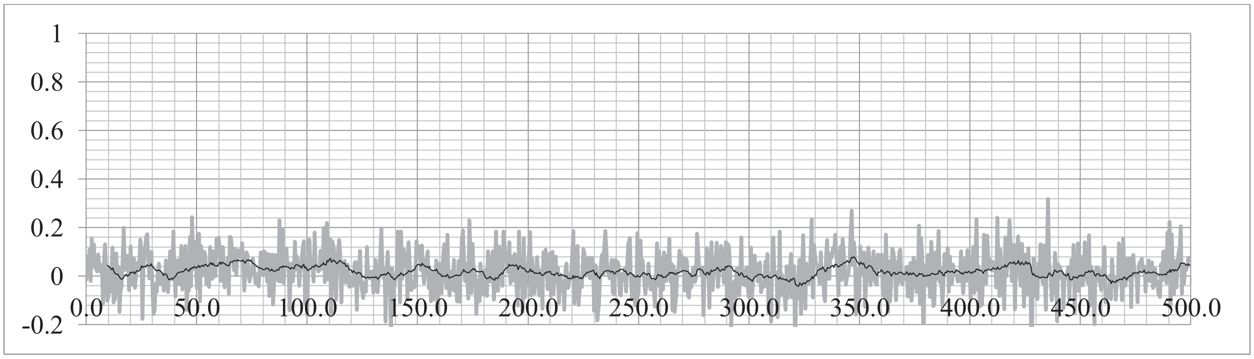


Figure 4.40 Accelerations along X-axis

Scale
X-axis: time in seconds.
Y-axis: acceleration in m/s².

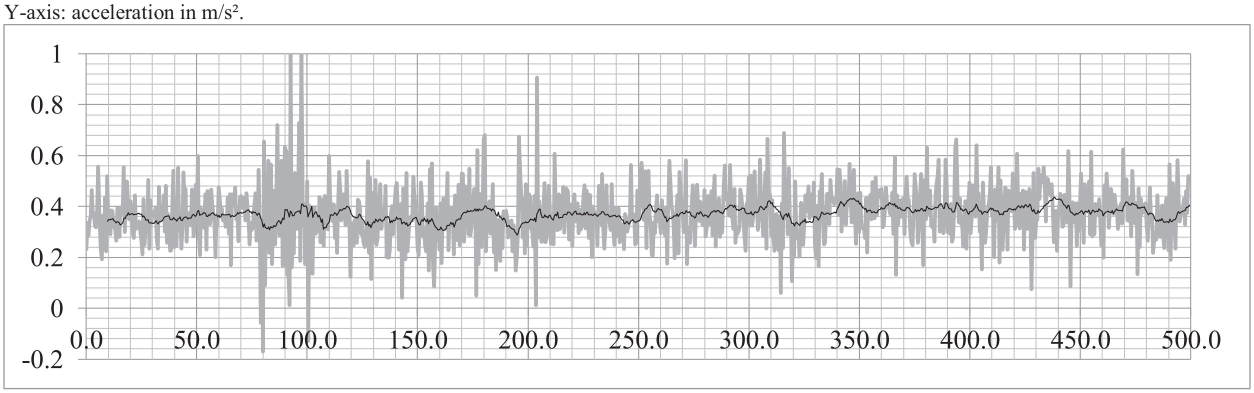


Figure 4.41 Accelerations along Y-axis

Scale
X-axis: time in seconds.
Y-axis: acceleration in m/s².

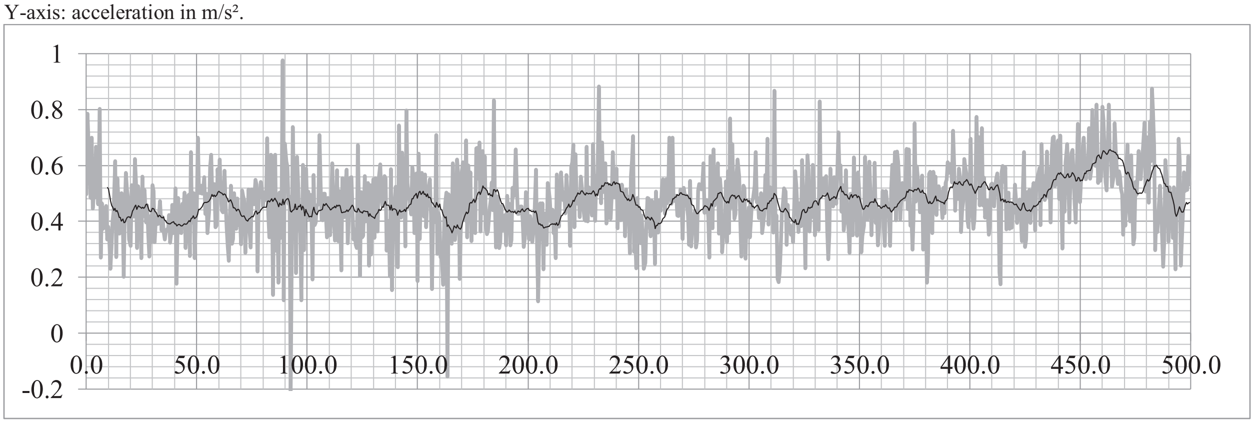


Figure 4.42 Accelerations along Z-axis

Scale
X-axis: time in seconds.
Y-axis: acceleration in m/s².

While these show the acceleration when the plane lands.

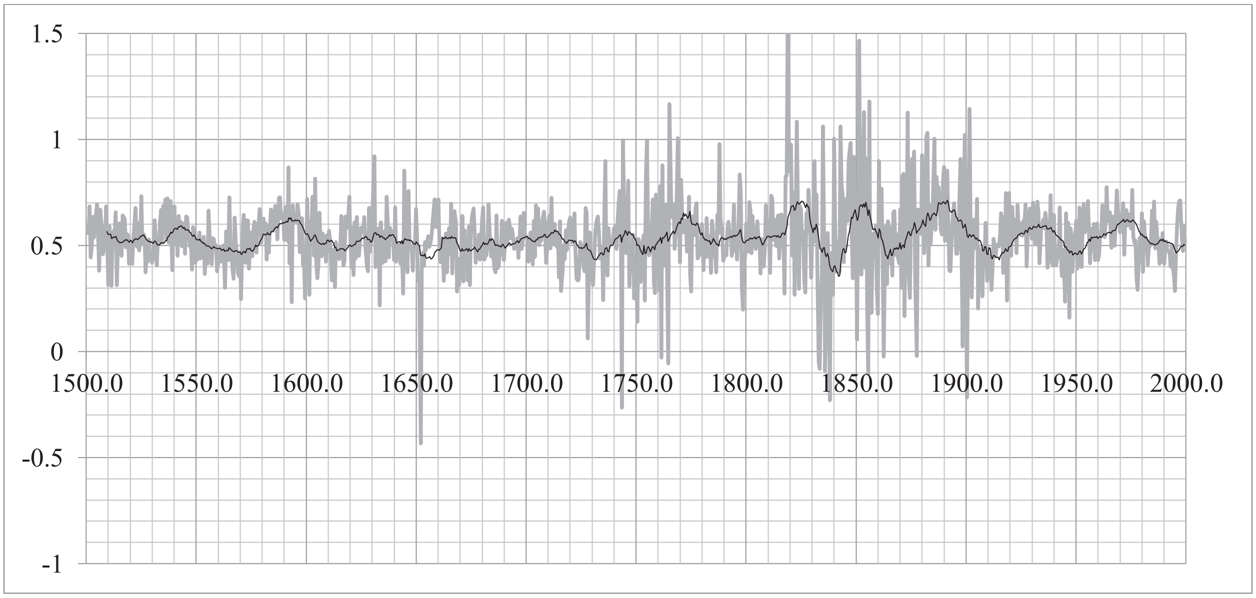


Figure 4.43 Accelerations along Y-axis

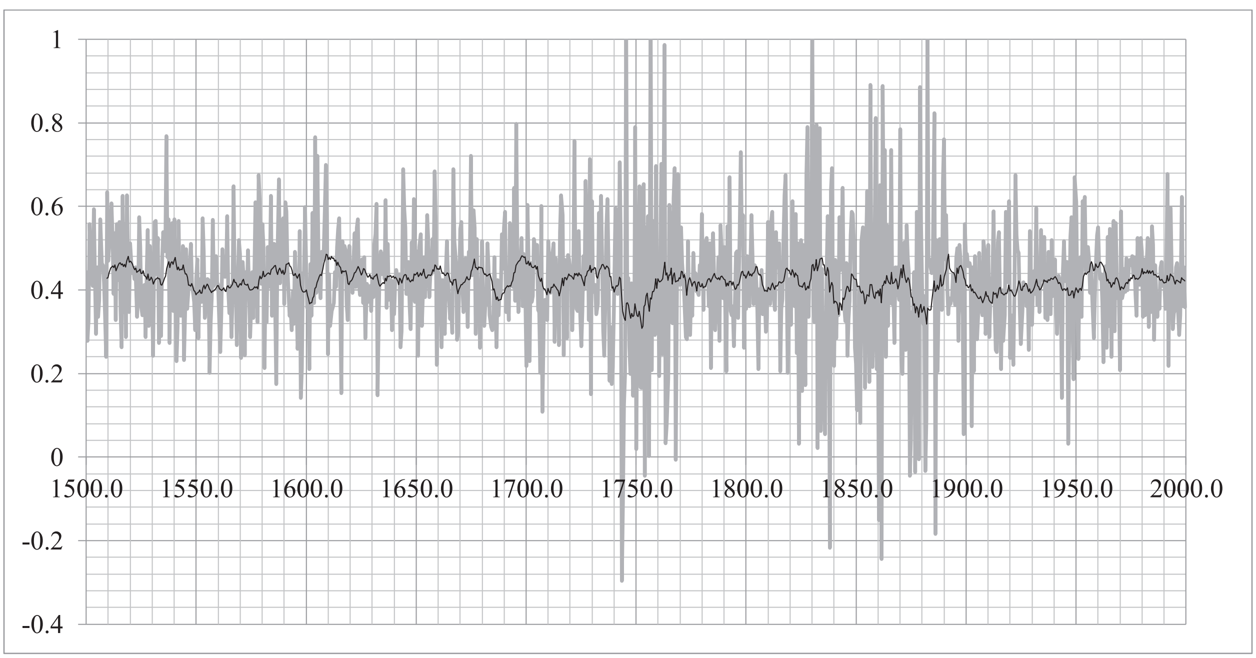


Figure 4.44 Accelerations along Z-axis

Figure 4.45 and 4.46 show that the nose of the plane oscillates up and down but maintains a mostly upward angle. Besides the oscillations, the roll only changes (and abruptly) when the plane changes bearings. Unlike cars, planes need to roll to take sideways turns. When approaching the landing strip, planes need to perform a series of manouvers.

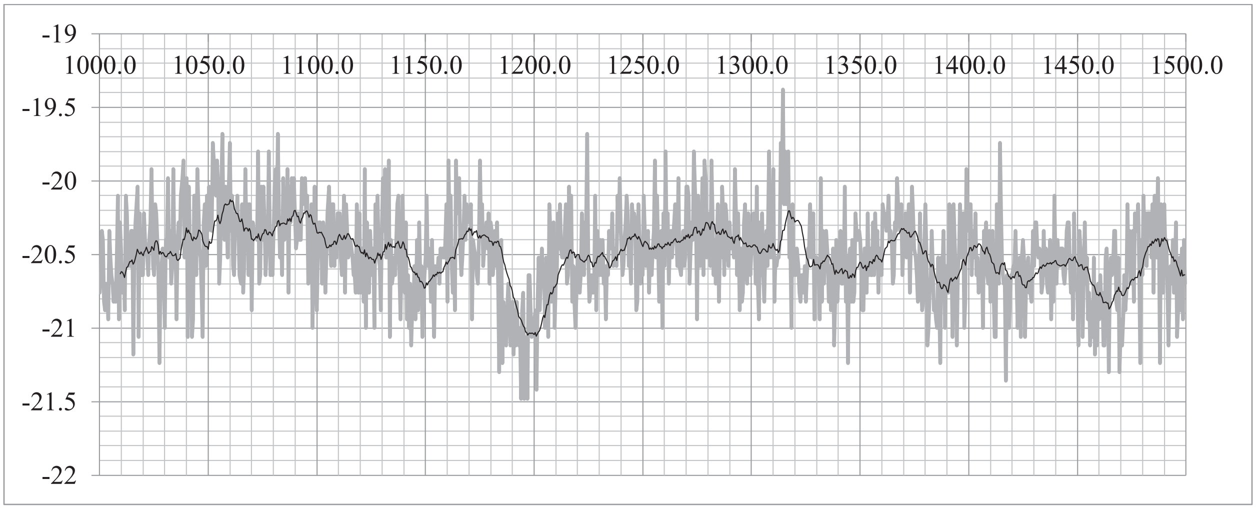


Figure 4.45 Pitch

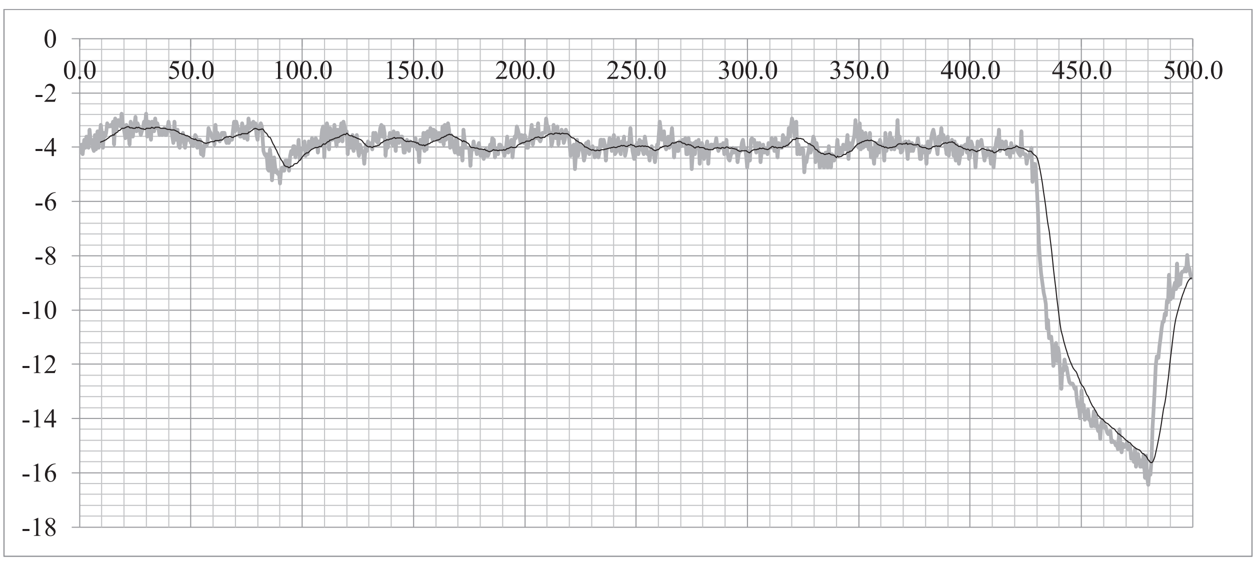


Figure 4.46 Roll

4.5.6 CO2 results

Carbon dioxide concentrations from the Montreal vehicles were below the recommended values given by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). According to the guidelines, these values may indicate the absence of unwanted odors, but not necessarily as the contrary may be also true: values over 1,000 PPM may not mean that there were foul odors. The average values for each vehicle are shown on table 4.4

Table 4.4 Average Values of CO2 values for various modes of transportation

	Average Value (PPM)
Slow Bus	*783*
Coach Bus	*895*
Montreal Metro	*762*
Montreal Suburban Train	*562*

These values are well below the safe values. On the local bus and the Montreal metro there were sporadic odors, most likely attributed to sources outside of the vehicle. It couldn't be determined how long it took for the values to change or if they changed at all.

There was not enough data to determine the reasons why the CO2 concentrations behave in this way. The local bus appears to have better ventilation as it rides along a semi-rural road while the coach bus has air conditioning unit that may not refresh the air considering outside concentrations.

Table 4.5 Accelerations and noise levels

		Slow Bus	Coach Bus	Automobile
Average Acceleration (m/s²)	**X**	*-0.0673*	*0.0224*	*-0.0107*
	Y	*0.0142*	*0.0904*	*-0.0007*
	Z	*0.0093*	*0.1551*	*0.5388*
RMS of Acceleration (m/s²)	**X**	*0.9588*	*0.4593*	*0.2392*
	Y	*0.8213*	*0.5802*	*0.1099*
	Z	*1.6938*	*0.7897*	*0.5548*
Standard Deviation of Acceleration	**X**	*1.2562*	*0.6817*	*0.3623*
	Y	*0.9808*	*1.1057*	*0.1827*
	Z	*2.2856*	*1.6652*	*0.2640*
Noise Level (dB)	**Peak**	*94*	*87*	*75*
	Avg	*83*	*62*	*45*

Table 4.6 Accelerations and noise levels

		Montreal Metro Train	Santo Domingo Metro Train	London Underground
Average Acceleration (m/s²)	**X**	*-0.0194*	*-0.0084*	*0.0042*
	Y	*0.0169*	*-0.0078*	*-0.0092*
	Z	*1.1897*	*0.5198*	*0.3566*
RMS of Acceleration (m/s²)	**X**	*0.1943*	*0.0547*	*0.1512*
	Y	*0.1918*	*0.2162*	*0.1794*
	Z	*1.2134*	*0.5534*	*0.4609*
Standard Deviation of Acceleration	**X**	*0.2942*	*0.0825*	*0.4853*
	Y	*0.3028*	*0.2955*	*0.4208*
	Z	*0.6408*	*0.3502*	*0.5265*
Noise Level (dB)	**Peak**	*96*	*70*	*75*
	Avg	*80*	*65*	*65*

Table 4.7 Accelerations and noise levels

		Montreal Suburban Train	UK Train
Average Acceleration (m/s²)	**X**	*-0.0090*	*0.0016*
	Y	*0.0126*	*0.0015*
	Z	*1.1073*	*-0.0013*
RMS of Acceleration (m/s²)	**X**	*0.1386*	*0.0434*
	Y	*0.1155*	*0.0236*
	Z	*0.1865*	*0.0923*
Standard Deviation of Acceleration	**X**	*0.1386*	*0.1170*
	Y	*0.1155*	*0.1524*
	Z	*0.1865*	*0.1988*
Noise Level (dB)	**Peak**	*75*	*81*
	Avg	*55*	*56*

Table 4.8 Accelerations and noise levels

		Airplane	Boat
Average Acceleration (m/s²)	**X**	*0.0164*	*0.0008*
	Y	*0.0173*	*0.0053*
	Z	*0.5058*	*-0.1022*
RMS of Acceleration (m/s²)	**X**	*0.0782*	*0.0367*
	Y	*0.1012*	*0.0381*
	Z	*0.5057*	*0.3180*
Standard Deviation of Acceleration	**X**	*0.0977*	*0.0638*
	Y	*0.1326*	*0.0684*
	Z	*0.1456*	*0.3819*
Noise Level (dB)	**Peak**	*98*	*66*
	Avg	*70*	*55*

4.6 Comparison with the DOT Ride Index

The DOT ride index, like the ISO guidelines, uses a range of frequencies to compute the weighted accelerations. Since the digital data obtained comes only in the sampled frequency, these methods might not be suitable for comparison. ISO and DOT formulas calculate lateral accelerations for the index with different formulas than the ones used for the vertical ones.

The assumption that one could judge the quality of the ride by measuring only one frequency would mean that the method of comparison might need to change. Also, the accelerations and braking may be different than the vibrations. In long rides, the braking and accelerating is less important than in short rides. When comparing a metro that stops every three minutes with a bus on a highway that slows down every ten minutes, the stops are more important and affect de standard deviation.

The ISO method uses the RMS to compute the acceleration data while DOT uses the Fast Fourier Transform-FFT (no specific algorithm). These methods won't apply when the data comes from a single frequency. It's impossible to weight different frequencies.

DOT and ISO rely on periodic vibrations. Their methods use the wave's amplitude as the main magnitude of the vibration. For non-periodic accelerations, the amplitude is not the best way to measure the magnitude of the vibrations. The absolute value of the accelerations will be used for these calculations as it is equivalent to the amplitude of each peak.

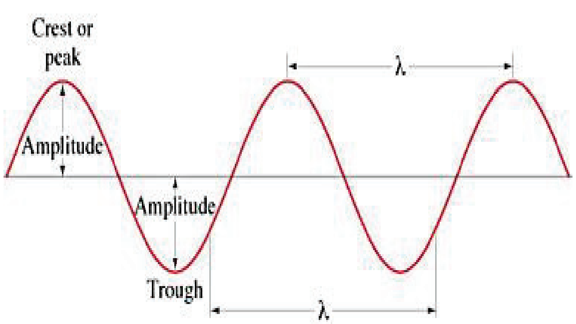
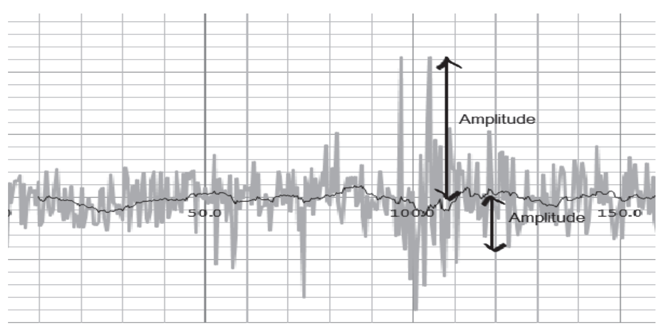


Figure 4.47 Vibration amplitude



Amplitude of the accelerations measured digitally.

Following the DOT method we obtain the following results:

Table 4.9 DOT results

	Vehicle	Vibrations	Noise
1	*UK Train*	0.000354	*56*
2	*Slow Bus*	3.811834	*83*
3	*Boat*	0.005145	*55*
4	*Coach Bus*	0.843745	*62*
5	*London Underground*	0.024974	*65*
6	*Airplane*	0.020690	*70*
7	*Santo Domingo Metro Train*	0.043667	*65*
8	*Automobile*	0.059112	*45*
9	*Montreal Suburban Train*	0.011505	*55*
10	*Montreal Metro Train*	0.285849	*80*

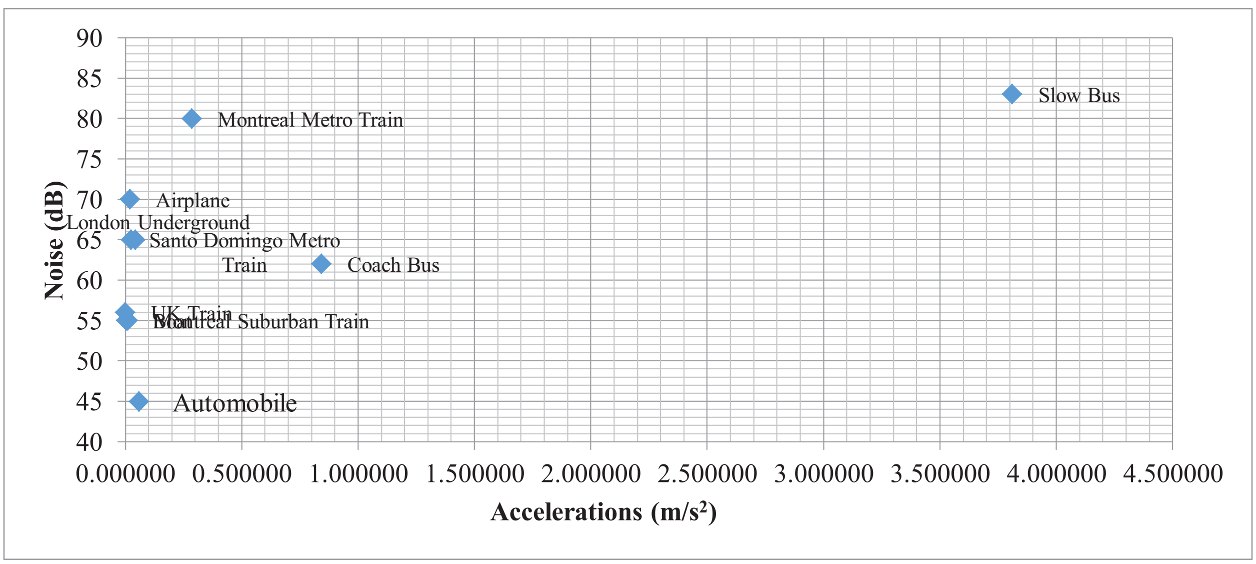
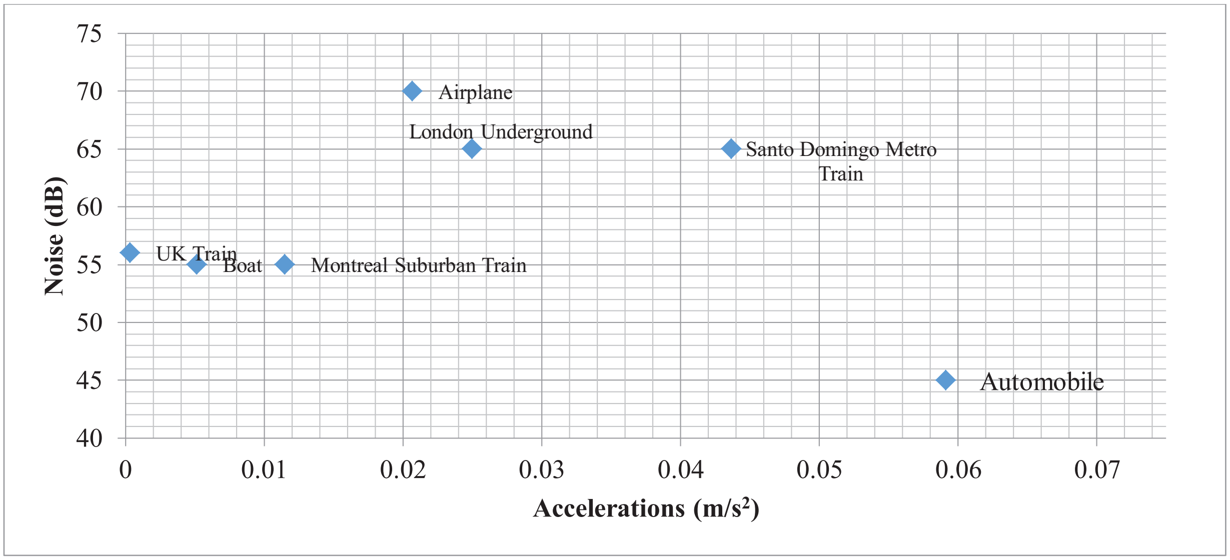


Figure 4.48 DOT Ride Index and Noise

The slow bus ride is the most uncomfortable if we use the DOT algorithm. It is at least 3 times less quiet than the next one and quite noisier. In comparison, all other rides are more comfortable.

If we leave out the largest values (slow bus, Montreal metro and interurban coach, it looks more like this:



4.49 DOT Ride Index and Noise (selected data)

If we add the accelerations as a vector and plot the resultant acceleration, we obtain the following result:

Table 4.10 Acceleration vector

	Vehicle	Vibrations	Noise
1	*UK Train*	0.1047	*56*
2	*Slow Bus*	2.1126	*83*
3	*Boat*	0.3224	*55*
4	*Coach Bus*	1.0822	*62*
5	*London Underground*	0.5172	*65*
6	*Airplane*	0.5216	*70*
7	*Santo Domingo Metro Train*	0.5966	*65*
8	*Automobile*	0.6140	*45*
9	*Montreal Suburban Train*	0.2595	*55*
10	*Montreal Metro Train*	1.2437	*80*

The vector addition is equivalent to the actual accelerations. This acceleration is the resultant of the combination of the three accelerations. It's the real vector. It differs with the ISO method in the fact that it is not distorted to reflect human sensibility to lateral accelerations.

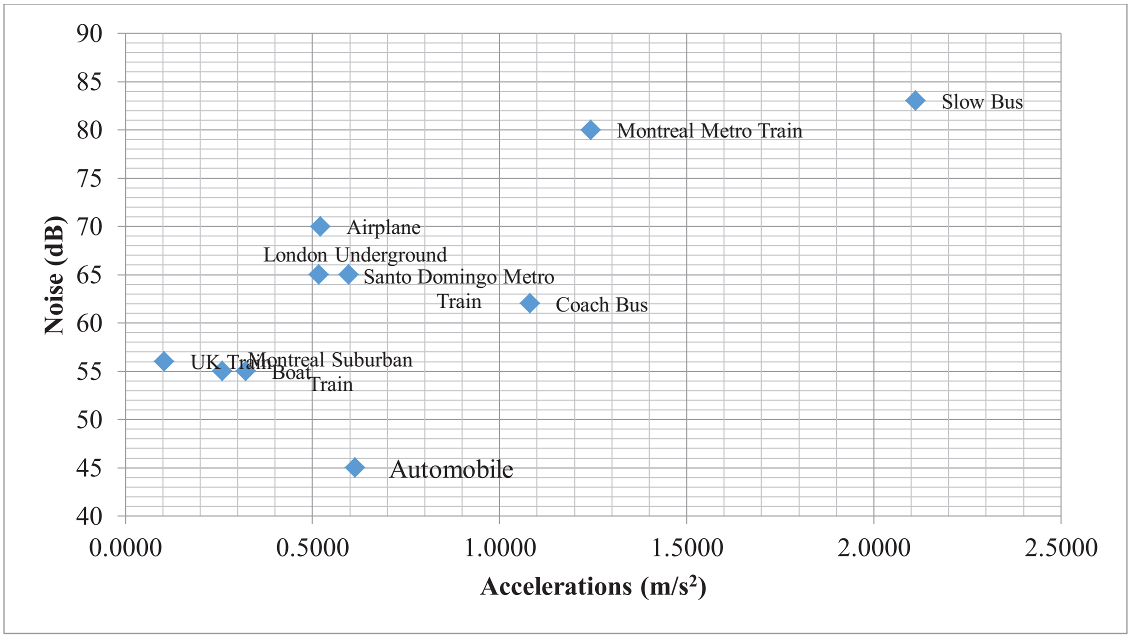


Figure 4.50 Vector Addition without ISO correction and Noise

It's important to notice that the accelerations are not weighted to ISO's standard of human sensitivity. The following figure presents the results of vibrations using the ISO method and noise in decibels.

Table 4.11 ISO method acceleration

	Vehicle	*VIB (m/s2)*	*Noise (dB)*
1	UK Train	0.30	56
2	Boat	0.41	55
3	Airplane	0.52	70
4	Santo Domingo Metro Train	0.73	65
5	Automobile	0.77	45
6	Montreal Suburban Train	1.11	55
7	London Underground	1.33	65
8	Montreal Metro Train	1.44	80
9	Coach Bus	1.60	62
10	Slow Bus	2.89	83

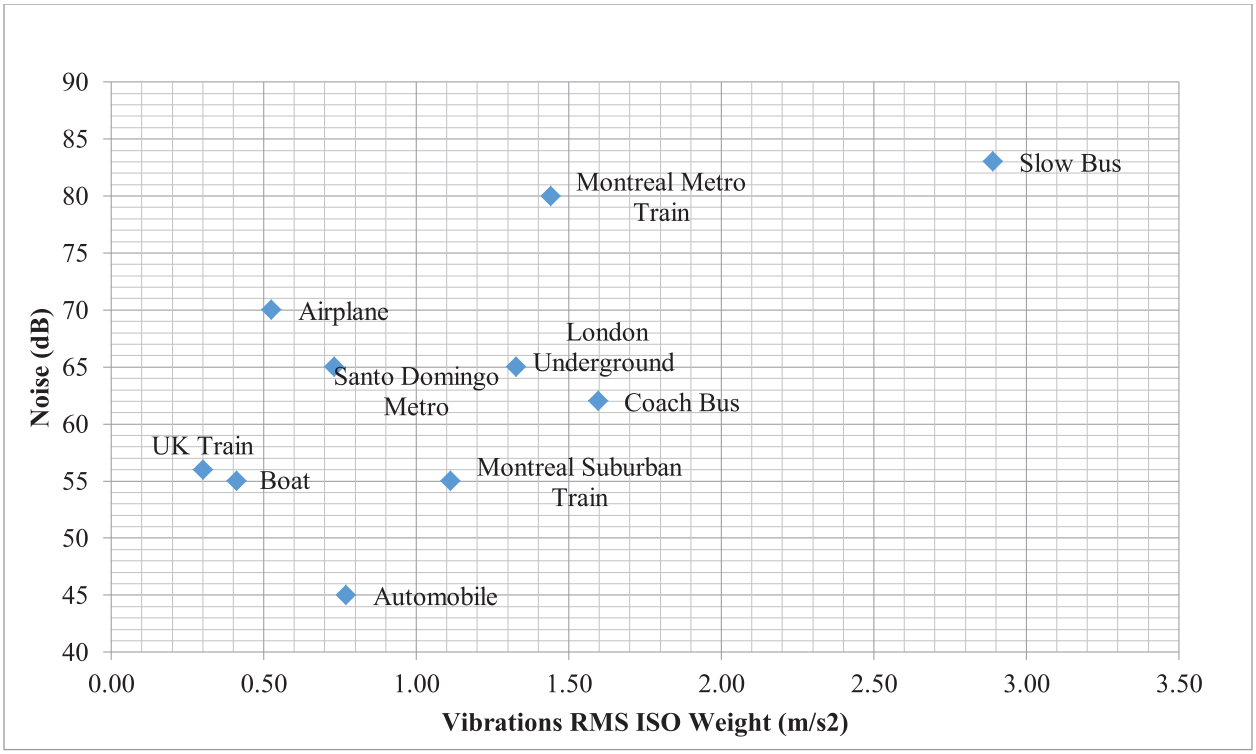


Figure 4.51 ISO accelerations and Noise

The values for the different vehicles are spread out. We can infer that the DOT railway formulas focuses on the largest values and exponentially augments them (it uses a cubic exponent) while ISO's doesn't amplify these differences. The amplification of these values should lead to the design of quieter railway cars.

4.7 Index Preparation

The comfort index was developed based on Lloyd's Boat Luxury Standards and DNV (*Det Norske Veritas*) now DNV GL (*Det Norske Veritas – Germanischer Lloyds*) principles. The boat industry requires both the noise levels and movement to be under certain values to certify the luxury class yachts.

Only the boat and sailing organizations have attempted to set a standard. Aviation, automobile and railroad manufacturers have their own standards. The index establishes a linear relationship between its values, thus enabling somebody with a choice of two different vehicles to determine how many times more comfortable is one compared to another.

Although there is literature regarding comfort indexes, there is no an accepted one. Furthermore, most researchers attempt to determine the comfort level of only one vehicle and compare it with the opinion survey at the end of the ride. These results, even if they are correct for the ride under observation, cannot be used to predict passengers' level of comfort using other vehicles. The results are not very accurate to compare different populations and the expectations affect the overall rating of the rides.

This index takes the vibration levels of multiple modes of transportation and compares them to each other. The rides can then be sorted in order of comfort regardless of the user's ratings. The model has to be calibrated later on to determine the weight of each variable.

Lloyd's *luxury smooth* oscillations limits are set in mm/s, a measure of their amplitude. The degree of comfort is measured and evaluated, thus, as the maximum amount of millimeters the ship moves up and down per second. Our experiment was performed measuring the accelerations per unit of time. The data coming from our devices has to be transformed into the same used by Lloyd's or vice versa. Since the accelerations are measured at each tenth of a second, the amplitude (as mm/s) will be equivalent to the change rate (acceleration) per second, in other words, the product of the acceleration by the time.

$$v = 1000(a)(t)$$

v = speed in mm/s
a = acceleration in m/s^2
t = time in seconds

The modes that provided the lower values for accelerations were considered the most comfortable. However, none of them was considered as zero to provide for future improvement in ride quality and zero accelerations (full stop) was set as the threshold for human sensing.

The Lloyd standard considers the most luxurious boat, the one with the lowest noise levels and the lowest amplitude of oscillations. As those values increase, the ride becomes less comfortable. Although it specifies a limit, it leaves room for faster boats to be a little noisier and to bob a little higher. Furthermore, different locations within the boat are held to different noise levels. However, since it was developed for boats, the specifications only consider movement along the z axis and it doesn't take into account lateral movement (x-axis) and only indirectly the one along y-axis.

The vibrations along the three axis were weighted considering the ranges between those that experienced less vibrations and those that showed more; the least and most comfortable respectively. Only the accelerations without their gravity component will be used for the development of the index. This will be done due to two main reasons:

1- The gravity component affects mainly the z axis. While the acceleration along the other axes reaches values of 0.5 at the most, the z values reach g plus the acceleration oscillations. Acceleration along the x and y axes are about 10% those of the z-axis accelerations.
2- Gravity is always present and, since the human body is subjected to at all times, only the values net of gravity are variations.

ISO's weight function for vibrations gives different weight to vertical vibrations (z axis) and to lateral ones (x and y axes). According to the Department of Transportation of the United States of America (DOT), the human sensation of comfort is correlated to this weighted value.

Index = f(a_x,a_y,a_z,η)

Where

x = accelerations along x axis in m/s²
y = accelerations along x axis in m/s²
z = accelerations along x axis in m/s²
η= noise level in dB

The accelerations along the different axes are added, not as a regular vector but, taking into account the different sensitivity of the human body to them. (Da Silva, 2001)

$$\sum = \sqrt{(1.4a_x)^2 + (1.4a_y)^2 + (a_z)^2}$$

Where all units are given in m/s^2.

The noise level tolerance and effects on the human body has been studied extensively. The proposed index takes the values from Environmental Protection Agency standards and considers 40 decibels as a quiet office, bedroom or living room and for the level of discomfort; the accepted value was 90 dB as "very annoying – hearing damage after 8 hrs." A sound level generated by ten times less energy would be perceived as half intense (80 dB). It would be perceived as a sound level hindering conversation. One of the advantages of the decibel scale is that, 0 is the threshold of human hearing. This means that we can take this scale as our base without any changes. It works like an absolute scale. The main disadvantage is that it is a logarithmic scale which makes the interpretation of the data more complicated and not linear. Furthermore, the decibels are based on the air pressure measured when the sound is produced. It's designed to cover a wide range of sound levels: from a mosquito three meters away to a jet taking off. Every ten decibels, the sound pressure is 10 times higher but the perception is different. Every 10 dB, the sound is perceived as twice (or half) as intense.

The evaluation of sound level poses an additional problem. Sound levels increased in an exponential fashion and are measured using a base 10 logarithm scale while loudness is perceived in a base 2 exponential manner. Furthermore the perception scale varies from person to person and doesn't correspond to the dB scale at lower levels. For values less than 30 dB, sound perception scale might result in negative values. For the purpose of this index, the Bel values (dB/10) will be used as the power of 2.

The percentage of comfort associated with sound levels will be estimated as:

$$Comfort\ Percentage = \frac{2^{dB/_{10}}}{256}$$

Where dB is the measured sound level in decibels and which is derived from the formula accepted by *Deutsches Institut für Normung* (DIN) standards.

$$Loudness = log^{-1}\left[\left(\frac{SPL - 40}{10}\right)\log 2\right]$$

The accelerations, on the other hand, are measured using a linear scale. When combining these two measurements there are many possibilities to display the results.

Table 4.12 Results Summary

	ISO	DOT	Vector Addition	Noise
Slow Bus	2.89	3.81	2.11	83
Coach Bus	1.30	0.84	1.08	62
Automobile	0.77	0.06	0.61	45
Montreal Metro Train	1.44	0.29	1.24	80
Santo Domingo Metro Train	0.73	0.04	0.60	65
Montreal Suburban Train	1.11	0.01	0.26	55
Airplane	0.52	0.02	0.52	70
UK Train	0.30	0.00	0.11	56
London Underground	1.33	0.03	0.52	65
Boat	0.41	0.01	0.32	55

The basic assumption for combining these two variables (vibrations and noise) is that comfort is directly proportional to both of them. We can assume this because the decibel scale already considers human sensitivity to noise (hence the creation of a logarithm scale) and it progresses in an exponential manner. The DOT ride index, although not about comfort, also uses an exponential formula.

Since the ISO ride index is widely accepted to rate vibration in vehicles, this value will be used to develop the index. The assumption that the index is proportional to both variables dictates that its value will go up as the variable's value goes up. Also, since ISO already provides values considered uncomfortable for vibrations and sound level, the overall comfort (or discomfort) can be expressed as a proportion of those values.

$$Index = a\left(\frac{Vib}{2.5m/s^2}\right) + b\left(\frac{2^{dB/10}}{256}\right)$$

Where

Vib is the mean acceleration calculated according to the ISO standard.
dB is the level of noise measured.
a and b are the weighting coefficients.

Or that the index, being proportional to both variables

$$Index = K(Vib)(dB)$$

Where K is a scaling factor = *1/(256x2.5)*

The third possible way is the geometric average which is good to create an index from unrelated variables, however it doesn't allow for customization of the weight for each one. For two variables it takes the shape of:

$$Index = \sqrt{\left(\frac{Vib}{2.5}\right)\left(\frac{2^{(dB/10)}}{256}\right)}$$

Table 4.13Indices Summary

	$Index = \frac{(Vib)\left(2^{dB/10}\right)}{(256)(2.5)}$	$Index = a\left(\frac{Vib}{2.5m/s^2}\right) + b\left(\frac{2^{dB/10}}{256}\right)$	$Index = \sqrt{\left(\frac{Vib}{2.5}\right)\left(\frac{2^{(dB/10)}}{256}\right)}$
	Product	**Additive Model**	**Geometric Average**
		a=b=0.50	
UK Train	0.02	0.16	0.15
Montreal Suburban Train	0.08	0.31	0.28
Automobile	0.03	0.20	0.16
Boat	0.03	0.17	0.17
London Underground	0.19	0.44	0.43
Santo Domingo Metro Train	0.10	0.32	0.32
Airplane	0.10	0.35	0.32
Coach Bus	0.18	0.46	0.43
Montreal Metro Train	0.58	0.79	0.76
Slow Bus	1.42	1.19	1.19

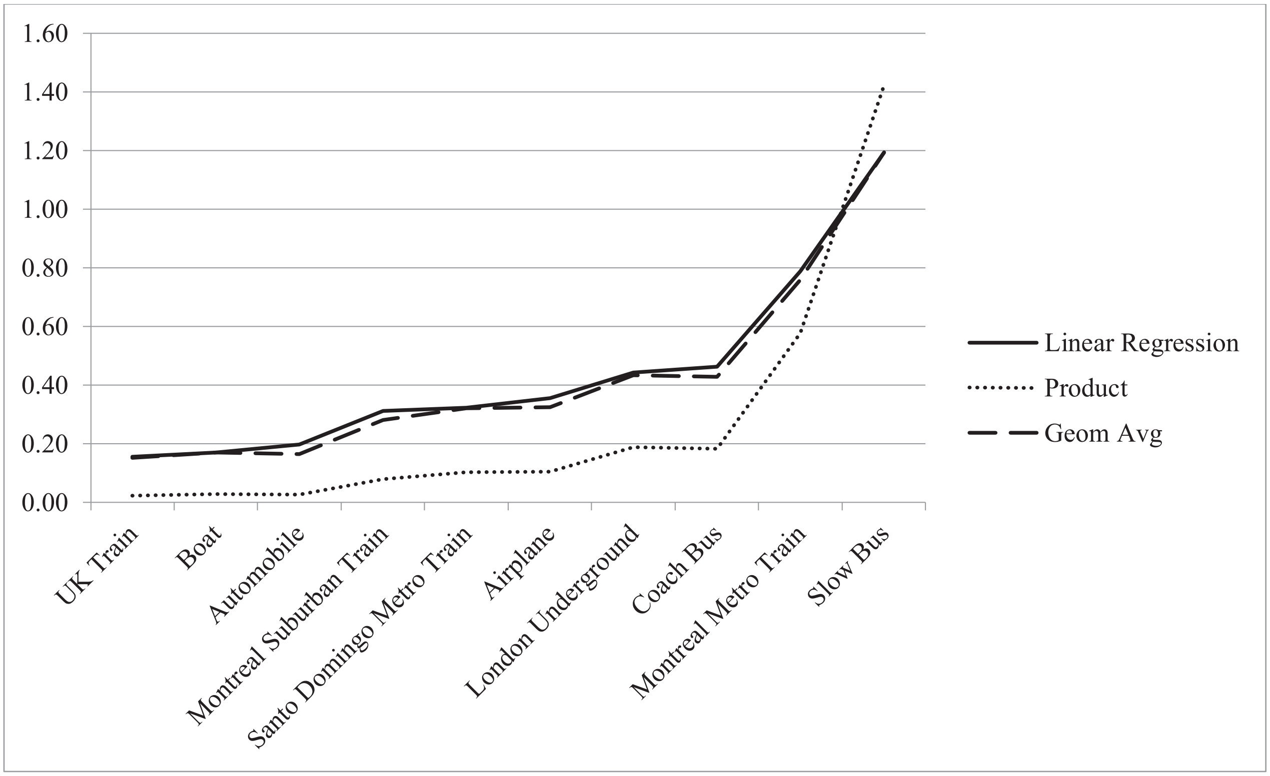


Figure 4.52 Comfort Indexes Models

Both models seem to behave similarly at low levels but as the sound levels get higher, the index generated by using the sound level as a factor multiplying the accelerations rise quickly in value due to the logarithmic nature of the variable while there's a range where they cluster together. The additive model, on the other hand, spreads the values in the lower range more evenly so it may be more adequate to show small changes in the studied range.

Graphics 4.15 a through c show how the index values group behave using each possible model.

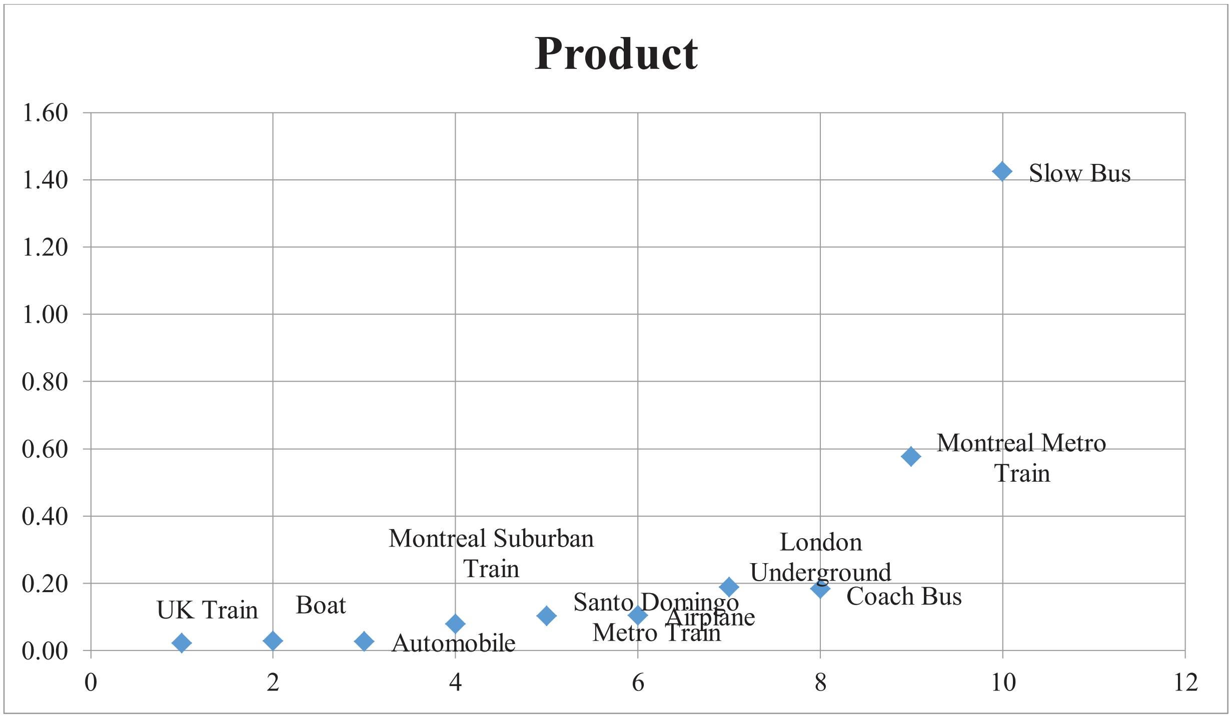
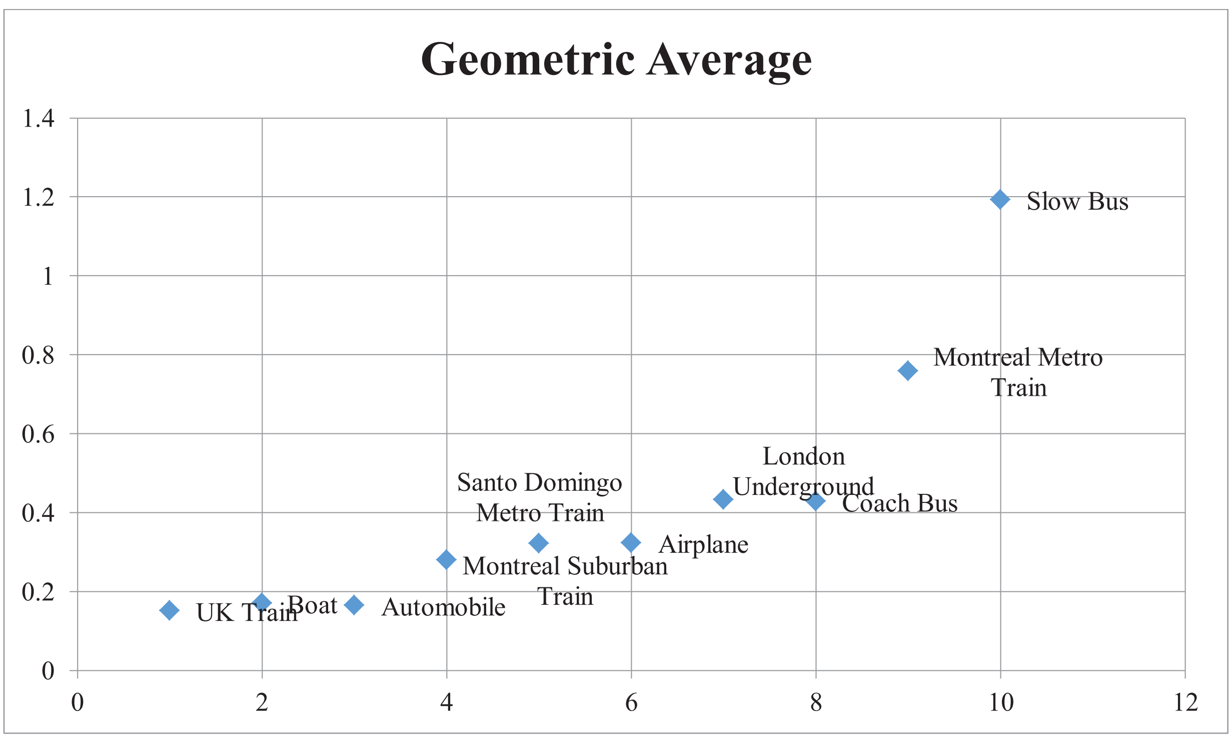


Figure 4.53



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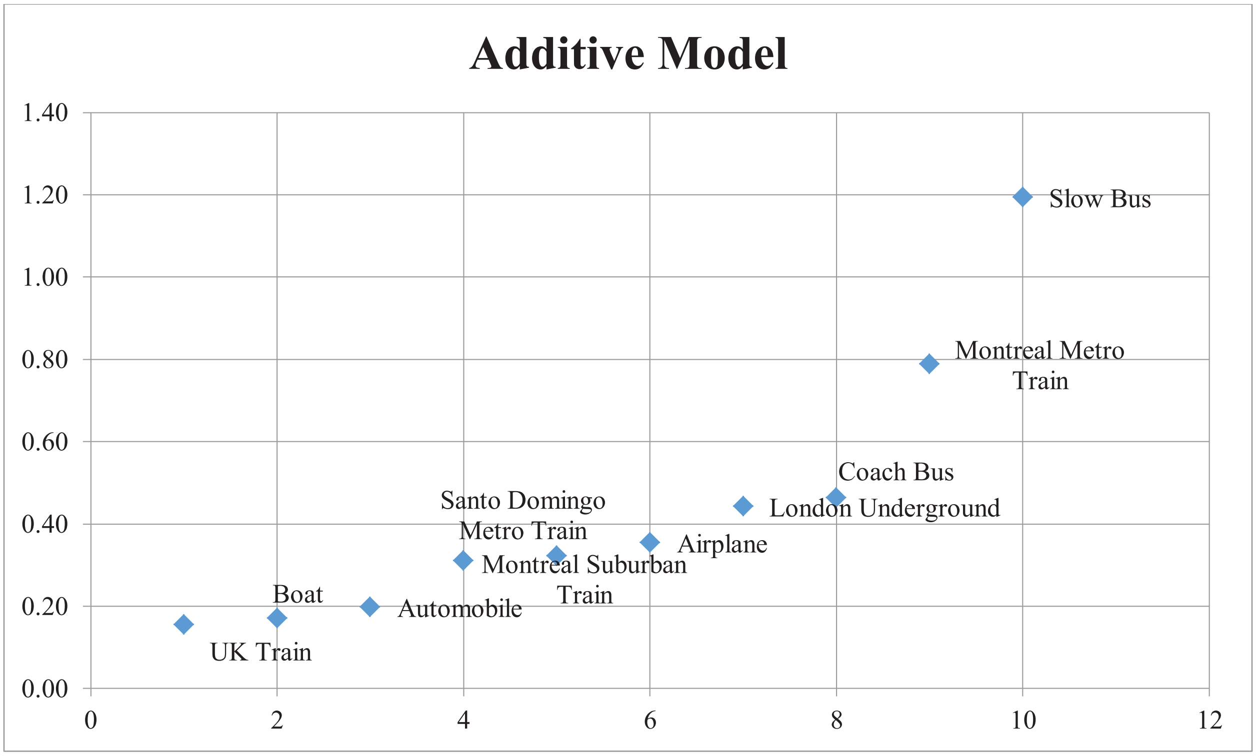

Figure 4.55

4.8 Sensitivity of the Proposed Index

The discomfort index is supposed to serve as indicator of the unpleasantness experienced by the passengers. The index has been developed based on two main assumptions: 1) that more vibrations cause more discomfort and 2) higher noise levels cause more discomfort too. When combining the two variables, the weight given to each variable causes the index to change greatly. It is impossible to know from the obtained data, which combination causes more discomfort. At this point, the need of surveys becomes unavoidable.

The spread of the index product of the different combinations of the accelerations and the noise levels is shown in Figure 4.15. The value of the index tends to increase when the weight of the sound levels are higher compared to the weight of the vibrations. For the most uncomfortable vehicle (the slow bus), the index values range from 1.17 to 1.22 while, for the most comfortable (the automobile) the range is 0.13 when the sound level is weighted at 80% and 0.15 when weighted at 20%.

The combination of the factors results in a series of numbers that, in some cases, unexpected. Some of the vehicles that subject passengers to less acceleration have a higher index rating because of their higher noise levels. The lines showing the different combinations cross when we assign different weights to the *a* (accelerations) and *b* (sound level) weight coefficients.

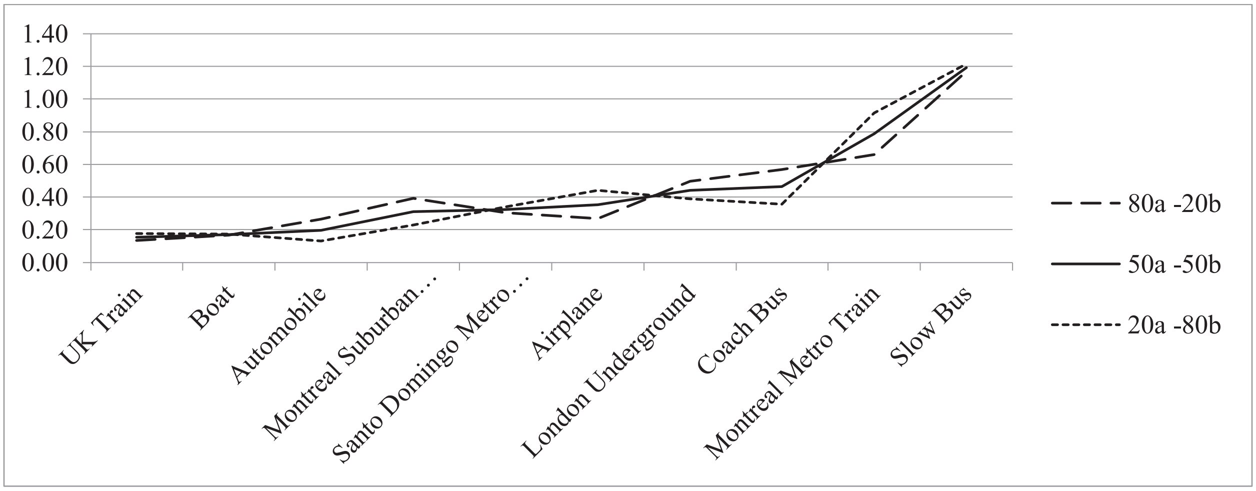

Figure 4.56 Selected Comfort Index Sensitivity

80a-20b line refers to 80% accelerations and 20% sound level weights
20a-80b line refers to 20% accelerations and 80% sound level weights

A sensitivity study should provide the appropriate values for the weighting coefficients.

4.9 Expanded Index

The Index can be further developed to include the concentration of carbon dioxide. If the same format is kept, the concentration of CO_2 could take the form of a percentage of the recommended ASHRAE value.

The value of the index for the slow bus is a little lower than the maximum of 1.00 because the air quality was slightly higher. In the case that the concentration of carbon dioxide exceeded 1,000 PPM, the third term of the equation would be higher than 1 and would increase the total value of the index.

Table 4.14 Expanded Index

				$Index = a(Vib/2.5) + b(2^{dB/10})/256 + c\,(CO_2/1000)$		
				a	b	c
	ISO	Noise	CO_2	0.45	0.45	0.1
Montreal Suburban Train	0.28	55	562	0.34		
Montreal Coach Bus	1.18	62	895	0.51		
Montreal Metro Train	1.26	80	762	0.79		
Montreal Slow Bus	2.26	83	783	1.15		

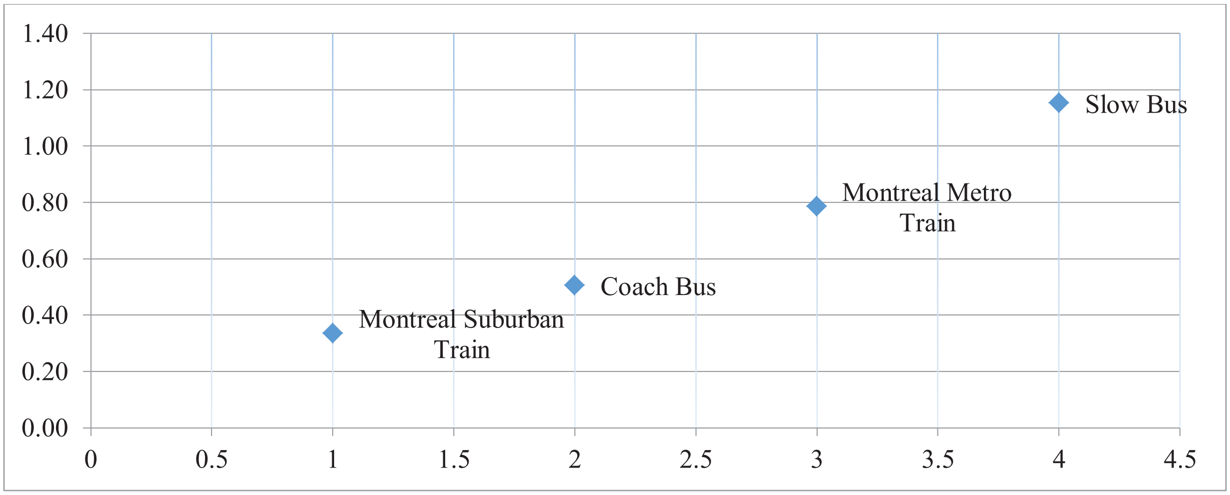

Figure 4.57 Expanded Index

CHAPTER 5

CONCLUSIONS

5.1 Conclusions

This research presents a method to collect data and compare the comfort levels of different vehicles. By eliminating the human surveys from this part of the analysis, a comfort index was developed in a way that allows other researchers to calculate an absolute value relative to the ride quality and then compare the result to any population, thus eliminating part of the need of sampling different populations and the error associated with this method.

This index could help municipalities compare different choices of mass transportation. Some insurance companies and cities are already collecting acceleration data to measure the quality of their mass transport systems. The sensor can help evaluate:

- driver's dexterity
- suspension and damping system quality
- quality of the road
- quality of braking
- alignment of the road

Of the data collected, the vibrations are the noise levels were the only ones considered in the development of the index. Although rotation was measured, it was impossible to incorporate it to the calculation for this research.

The data shows that for buses and trains, the number of stops is the most important factor affecting the total vibration levels. Modern trains have changed the braking system to allow for smoother decelerations. The pattern seems to be exactly the same every time the trains stop. When the train's brakes are manually activated, there is not recognizable pattern.

When the stations are placed further apart, the increase of accelerations and decelerations gets to dilute amongst longer periods of lower vibrations, logically, the overall average and the standard deviation are lower (comparing average with or without peaks).

The acceleration/deceleration rate over time seems to affect comfort along Y axis. In other words, the quicker the stop (speed and accelerations) are performed the most noticeable the jolt and, hence the less the comfort. Just like accelerations are the rate of change of the speed, the rate of change of the accelerations (derivative over time) seems to be related to the overall comfort. This is a noticeable change in modern trains.

When comparing road modes of transportation, our method shows that the automobile is the most comfortable. That could explain why is preferred by so many passengers. The accelerations along the Y and Z axis were lower than those of the bus but, the accelerations along X were larger, due to more lane changes and smaller turning radii. The boat was the overall most comfortable. We used the measured vibrations to compare the other vehicles. We can now compare them to the Lloyd's comfort specifications.

When a vehicle is stuck in traffic, its index value will be lower. When the vehicle is fully stopped and not running, the vibration level should be zero. However, if there's noise, the index's value would be zero even though the vehicle might uncomfortable. This would mean that the index might not be adequate at lower values of the scale.

Many other aspects seem to affect comfort more than vibrations themselves (convenience, seats). A sensitivity analysis to other factors should reveal more about the passenger's preferences.

The boat and England's slow train move less and make less noise. On the other side of the chart, the slow bus shows more accelerations and it's the noisiest. Either most of the noise is the product of mechanical vibration or sound insulation diminishes vibrations.

The only environmental condition monitored was the concentration of Carbon dioxide. The different levels were not perceptible. According to ASHRAE, the concentration of carbon dioxide is imperceptible until it reaches 1,500. At this point, long exposure causes drowsiness but it doesn't mention discomfort. Higher carbon dioxide concentrations may correspond to presence of odors but not necessarily. However, the environment conditions should be studied further since at many times, especially when raining, the air felt heavy. Other factors important are: humidity, other gases and temperature. Certain environment conditions, such as odor and visual stimuli, are harder to assess.

5.2 Limitations of this study

The optimal levels of the index should be further studied. The possibility of a combination of either low noise with high vibration or loud noise with low vibration may produce the same value for the index while the sensation of comfort may be very different.

The lower values of both noise and vibrations were not considered to be uncomfortable although some people experience sickness or dizziness in very quiet rooms.

The sensibility of the noise sensors doesn't take into account noise not heard by humans but low frequency noise may be perceived as whole body vibration.

Future research should measure noise level in empty vehicles and use it as a baseline or minimum value.

Further analysis of vibrations and harmonics might be needed to substitute the DOT and ISO methods with a tablet or telephone. The tablet's sample rate leaves out the DOT and ISO's recommended frequencies. The measurements from a tablet should be compared with a professional accelerometer's.

5.3 Recommendations and future studies

Future research should utilize the comfort index herein presented in a discrete choice exercise in order to gain deeper understanding of how the comfort will play a role in addition to the cost of travel (time) and how the addition of comfort shifts the modal split in number of trips among alternative modes of transportation.

Further research is needed to determine the values that would allow a group of passengers to experience a given level of comfort. This value can, then, be correlated to the index. A sensitivity analysis would show the comfort sensation variation corresponding to index variation.

Some modes of transportation are not mutually exclusive (substitutes) but their comfort can be assessed, nevertheless. Even if there is no ferry linking a given origin-destination trip, a boat can indirectly be used as reference to analyze a train ride.

Apparently, since more speed causes more vibrations, a vehicle moving at higher speeds might be less comfortable but this would need to be studied.

This index can be pegged to the sensibility of a given population (ie: Moscow passenger tolerance is higher/lower to the index).

References

Amador-Jimenez, Luis, and Mohammed Al-Dabbagh. 2015. A low-cost method to develop an initial pavement management system in one year. Paper presented at Transportation Research Board 94th Annual Meeting,

Anderson, Bryon D. The physics of sailing explained. Sheridan House, Inc., 2003.

Badia, Xavier (2009), "Trens S-9000 - Railgrup Octubre 09" (PDF), Barcelona Metròpolis L-9 (Alstom Transport), retrieved 6 April 2015

Bellman, Michael A. "Perception of Wholebody Vibrations: From basic experiments to effects on seats and steering-wheel vibrations on the passengers comfort inside vehicles" Oldenburg University. 1972

Berman Alex, Hannibal Alan J. "Digital Processing of Measured Vibration Data for Automobile Ride Evaluation"- The Design Engineering Technical Conference Chicago, Illinois September, 1977

Brumaghm, S. H., and J. R. McKenzie. "RIDE TECHNOLOGY APPLICATIONS TO LARGE PASSENGER AIRCRAFT." In ASME AMD V24, 1977: Passenger Vib in Transp Veh, presented at DesEng Tech Conf, Chicago, Illinois, 26-28 September 1977. 1977.

Carayon, Pascale, and Wiley Online Library. 2012. Handbook of human factors and ergonomics in health care and patient safety. Human factors and ergonomics. 2nd ed. Boca Raton, FL: CRC Press.

Calvert, JB "Hydrostatics" Available at http://mysite.du.edu/~jcalvert/tech/fluids/hydstat.htm Accesed on January 2016

Crocker, Malcolm J. 2007. Handbook of noise and vibration control. Hoboken, N.J.: John Wiley & Sons.

Croissières AML Available at http://www.croisieresaml.com/documents/images /L'experience%20AML/Bateaux/maxim-pont-b.png Accessed on September 15,2015

da Silva, MC Gameiro. "Measurements of comfort in vehicles."Measurement Science and Technology 13, no. 6 (2002): R41.

Dukkipati, Rao; Pang, Jian; Qatu, Mohamad; Sheng, Gang; Shuguang, Zuo "Road Vehicle Dynamics" SAE International. Warrendale, PA USA 2008

DUMITRIU, Madalina. 2014. Considerations on the geometric filtering effect of the bounce and pitch movements in railway vehicles. Annals of the Faculty of Engineering Hunedoara - International Journal of Engineering 12 (3) (08): 155-64.

Eger, Tammy R., Aaron M. Kociolek, and James P. Dickey. 2013. Comparing health risks to load-haul-dump vehicle operators exposed to whole-body vibration using EU directive 2002/44EC, ISO 2631-1 and ISO 2631-5. Minerals (2075-163X) 3 (1) (03): 16-35.

General Properties and Uses of Carbon Dioxide, Good Plant Design and Operation for Onshore Carbon Capture Installations and Onshore Pipelines". Energy Institute. Retrieved 2015-10-15.

C.T.T. Geluk 2005 Vehicle vibration comfort: the influence of dry friction in the suspension Master's thesis Technische Universiteit Eindhoven Department Mechanical Engineering Eindhoven, September, 2005

Griffin, M. J. 1990. Handbook of human vibration. London; Toronto: Academic Press.

Griffon Hoverwork Available at http://www.griffonhoverwork.com/products-services/links.aspx accessed on October 15, 2015

Haas, Ralph. "Reinventing the (pavement management) wheel." In 5th Annual Conference on Managing Pavements. 2001.

Healey, A. J. "Digital processing of measured vibration data for automobile ride evaluation." ASME AMD V24 1977: Passenger Vibration in Transportation Vehicles, presented at Design Eng Conf, Chicago, Illinois, September 26-28, 1977. 1977.

Helander, Martin, and Martin Helander. 2006. A guide to human factors and ergonomics. 2nd ed. Boca Raton, FL: CRC Taylor & Francis.

Hemminki, Samuli, Petteri Nurmi, and Sasu Tarkoma. "Accelerometer-based transportation mode detection on smartphones." In Proceedings of the 11th ACM Conference on Embedded Networked Sensor Systems, p. 13. ACM, 2013.

Hostens, Ivo. "Analysis of seating during low frequency vibration exposure." PhD diss., Katholieke Universiteit Leuven, 2004.

Encyclopaedia of Occupational Health and Safety 4th Edition ILOCIS Geneva 2012

"General Properties and Uses of Carbon Dioxide, Good Plant Design and Operation for Onshore Carbon Capture Installations and Onshore Pipelines". Energy Institute. Retrieved 2012-03-14.

Kai-Liang Lu, Wei-Guo Zhang, Yuan Liu, Guo-Wei Li, and Zhi-Yong Hao. 2014. 1404. container vehicle-truss bridge coupled vibration analysis and structural safety assessment under stochastic excitation. Journal of Vibroengineering 16 (6) (09): 3122-36.

Kardous, Chucri A., and Peter B. Shaw. "Evaluation of smartphone sound measurement applicationsa)." The Journal of the Acoustical Society of America 135, no. 4 (2014): EL186-EL192.

Kee, Dohyung, and Inseok Lee. 2012. Relationships between subjective and objective measures in assessing postural stresses. Applied Ergonomics 43 (2) (3): 277-82.

Lau, Sian Lun, and Klaus David. "Movement recognition using the accelerometer in smartphones." In Future Network and Mobile Summit, 2010, pp. 1-9. IEEE, 2010.

Leatherwood, Jack D., Sherman A. Clevenson, and David G. Stephens. "The development of interior noise and vibration criteria." (1990).

Leatherwood, Jack D., Thomas K. Dempsey, and Sherman A. Clevenson. "A design tool for estimating passenger ride discomfort within complex ride environments." Human Factors: The Journal of the Human Factors and Ergonomics Society 22, no. 3 (1980): 291-312.

Manheim, Marvin L. 1979. Fundamentals of transportation systems analysis. MIT press series in transportation studies. Vol. 4-. Cambridge, Mass.: MIT Press.

Ming, Foong Soong, Rahizar Ramli, and Wan Mahadi Wan Nor Liza. 2014. 1145. vehicle suspensions with parallel inerter: Effectiveness in improving vibration isolation. Journal of Vibroengineering 16 (1) (02): 256-65.

Moyar, Gerald J., Pilkey, Walter D., Pilkey, Barbara F., ed “Track/Train Dynamics and Design” Advanced technques. New York: Pergamon Press. 1977

Múcka, Peter. 2013. Correlation among road unevenness indicators and vehicle vibration response. Journal of Transportation Engineering 139 (8) (07): 771-86.

Nopiah, Zulkifli Mohd, Ahmad Kadri Junoh, and Ahmad Kamal Ariffin. 2015. Vehicle interior noise and vibration level assessment through the data clustering and hybrid classification model. Applied Acoustics 87 (01): 9-22.

Northwestern University Available at http://faculty.wcas.northwestern.edu/~infocom/

Ideas/waves.html Accessed on September 15, 2015

Newbius Available at https://rpappalax.wordpress.com/category/mobile-device/ Accessed on January 15, 2016

Ortúzar S., Juan de Dios, and Luis G. Willumsen. 2011. Modelling transport. Fourth ed. Chichester, West Sussex, United Kingdom: John Wiley & Sons.

Paddan, G. S., and M. J. Griffin. "Evaluation of whole-body vibration in vehicles." Journal of sound and vibration 253, no. 1 (2002): 195-213.

Pierre Jr, Richard L. St, R. S. P. Acoustics, Daniel J. Maguire, and Cooper Standard Automotive. "The impact of A-weighting sound pressure level measurements during the evaluation of noise exposure." Noise-Con 2004(2004): 12-14.

Prill, Rich. "Why measure carbon dioxide inside buildings." Published by Washington State University Extension Energy Program WSUEEP07 3 (2000).

Park, Se Jin and Murali, Subramaniyam "Evaluating Methods of Vibration Exposure and Ride Comfort in Car" Journal of the Ergonomics Society of Korea Vol. 32, No. 4 pp.381-387, August 2013

Samavedam, G., and John Gomes. Safety of Railroad Passenger Vehicle Dynamics: OMNISIM Simulation and Test Correlations for Passenger Rail Cars. No. DOT/FRA/ORD-01/07,. 2002.

Skene, Norman L. Elements of yacht design. Sheridan House, Inc., 2001.

Smith, Craig C., McGehee, David Y., Healey, Anthony J. "The Prediction of Passenger Riding Comfort From Acceleration Data" (Smith et al. 1976) Department of Transportation. Research Report 16. Washington DC: 1976

Smullin, Joe "Noise and Vibration Engineering Specifications for Large Yatch" Massachussets: J&A Enterprises Inc. 2008

Stevens, Brian L., Lewis, Frank L., "Aircraft control and simulation" USA: John Wiley and Sons Inc. 1992

Stevens, Brian L., Lewis, Frank L., "Aircraft control and simulation" USA: John Wiley and Sons Inc. 2003

Strandemar, Katrin. "On objective measures for ride comfort evaluation." (2005).

"Rolling Stock Data Sheet 2nd Edition" (PDF). Transport for London. March 2007. Archived from the original (PDF) on 20 December 2013. Retrieved 10 May 2013.

Sun, Wenjing, Jinsong Zhou, David Thompson, and Dao Gong. 2014. Vertical random vibration analysis of vehicle–track coupled system using green's function method. Vehicle System Dynamics 52 (3) (03): 362-89.

U.S. Department of Transportation. Federal Railroad Administration "Safety of Railroad Passenger Vehicle Dynamics" 2002

Vasconcellos, J. M., and R. G. Latorre. 2001. Recreational boat noise level evaluation. Ocean Engineering 28 (9) (9): 1309-24.

Vink, P., C. Bazley, I. Kamp, and M. Blok. 2012. Possibilities to improve the aircraft interior comfort experience. Applied Ergonomics 43 (2) (3): 354-9.

Vink, P., and S. Hallbeck. 2012. Editorial: Comfort and discomfort studies demonstrate the need for a new model. Applied Ergonomics 43 (2) (3): 271-6.

Zhang, Junwei, and Sizhong Chen. 2014. Modelling and study of active vibration control for off-road vehicle. Vehicle System Dynamics 52 (5) (05): 581-607.