Evaluation of Sound Attenuation Abilities of Various Asphalt Pavements

by

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ABSTRACT

Road traffic noise is becoming a major public concern. Many transportation agencies are looking for practical and economical means to reduce traffic noise generation and propagation. In 2003, the University of Waterloo's Centre for Pavement and Transportation Technologies (CPATT) and the Regional Municipality of Waterloo embarked on a partnership to design quiet pavement test sections and to conduct controlled sound level measurement on four different types of asphalt surface courses.

Four different surface courses, two Rubberized Open Graded Friction Course Asphalt Pavements (rOFC and rOGC), Stone Mastic Asphalt Pavement (SMA), and a control mix Hot-Laid 3 (HL-3), were placed in lengths of 600 m. The overall 2.4 km test area was closed to traffic and test vehicles were driven through the test area at the prescribed control speeds with sound level meters recording sound levels both at the tire/pavement interface as well as at the monitoring stations off the roadway. Impedance Tube Method and Reverberation Time Method were performed to determine the sound absorption coefficients of the pavement mixes.

In order to evaluate the sound attenuation ability of the mixes, the results from rOFC, rOGC, and SMA were used to compare with the result from the control mix HL-3. Statistical analysis of measurement results was performed to see whether the differences between mixes are significant at a 95% confidence interval. Life cycle cost analysis was also performed in order to determine the cost effectiveness of each asphalt mix.

Results indicate that traffic sound level increases as vehicle speed and size increase regardless of asphalt types. rOFC and rOGC perform significantly better than HL-3, but the performance slightly deteriorate after one year because of the clogging problem. SMA does not attenuate sound as effectively when compare to HL-3 at the early age. However, sound attenuation ability improves after one year of service. Overall result indicates that rOGC performs the best among all mixes in terms of the sound attenuation ability. Life cycle cost analysis shows that HL-3 is the most economical mix but it is the worst mix in terms of sound attenuation ability.

It is recommended to conduct additional sound level and skid resistance measurements in the future to monitor the long-term pavement performance. Also investigation of the relationship between the sound level and sound absorption coefficient measurements is beneficial for the future acoustical evaluation for the asphalt mix.

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CHAPTER 1: INTRODUCTION

This Chapter includes a brief background on the rationale and provides the scope and objectives of the research. A research methodology and organization of the thesis are also provided.

1.1 Background

Noise is defined as a sound that is loud, unpleasant, or disturbing [Pearsall 02]. Whether at home, at work, or at play, people will be affected when exposed to excessive noise. Over-exposure to excessive noise will result in negative impacts to the community. This can range from physical discomfort (e.g. disturbs sleep or rest) to substantial impacts to health (e.g. loss of hearing).

Within the transportation field, noise can emanate from a variety of sources. This may include construction work, air traffic, road traffic, rail traffic, and industry. A Health*Insider* survey was carried out by PWC Consulting National Survey Center in Canada in 2002 with the following results [Leung 07, PWC 02]:

- Half of Canadian participants indicated that they were bothered, disturbed or annoyed by noise outside their home.
- Road traffic noise is ranked as the most annoying type of noise, as it affects communities or residents who live within close proximity to highways and heavy trafficked areas.

1.2 Current Ontario Traffic Noise Abatement Policy

The Ontario Ministry of the Environment (MOE) has implemented a guideline to control excessive road traffic sound levels, as shown in Table 1.1 [MOE 97].

Table 1.1 – Road Traffic Noise Criteria for Noise Sensitive land Uses [MOE 97]

Receiver Category	Time Period	Road Traffic
Outdoor Living Area (OLA)	0700-2300	L_{eq} = 55 dBA
Indoor Living Area (ILA)	0700-2300	L_{eq} = 55 dBA
Indoor Living Area (ILA - Sleeping Quarters)	2300-0700	L_{eq} = 50 dBA

According to the MOE guideline, if the sound level in the OLA is greater than 55 dBA and less than or equal to 60 dBA, physical noise mitigation methods may be applied to reduce the sound level to 55 dBA. If no physical noise mitigation methods are provided, prospective purchasers or tenants shall be informed of potential noise problems by a warning clause [MOE 97]. If the sound level in the OLA is greater than 60 dBA, physical noise mitigation methods are required to reduce the level to 55 dBA. The criteria of physical noise mitigation methods at the ILA are similar as OLA's, but the MOE guideline allows 10 dBA tolerances for the ILA rather than 5 dBA in OLA [MOE 97].

This guideline provides a challenge to engineers as a balance must be met between constructability and the in-service sound level. There are several noise mitigation methods available to engineers with respect to controlling sound. This may include the following:

Outdoor Living Area

- Construct noise barriers or earthberms adjacent to the roadway. The goal is to protect the outdoor living area from unwanted sound. Noise is absorbed, reflected, and/or deflected from a specific area by the noise barriers or earthberms.

Indoor Living Area

- Upgrade building façade components including windows, walls and doors where applicable. Increasing the insulating properties of building materials will isolate the occupancy area from the exterior noise.
- Install central air conditioning units. The goal is to also isolate noise from the living areas through closing exterior openings such as windows or doors.

Unfortunately, these noise mitigation methods are neither economical nor practical. It is because the focus of the above mitigation methods is to control the noise propagation to the receiver, but not actually reduce noise from the original source.

1.3 Traffic Noise Sources

An alternative to controlling noise to the receiver is to focus on the noise source. In order to have a better understanding on how to mitigate road traffic noise, it is important to understand the primary causes of road traffic noise. Road traffic noise is caused by a combination of vehicle aerodynamics, vehicle powertrain, and tire-pavement interaction [Bernhard 05a]. Vehicle aerodynamic noise is a result of air turbulence created by a moving vehicle and the level is determined by the vehicle shape and speed. Powertrain noise includes sound generated from the vehicle engine, exhaust system, transmission, and cooling system. It is usually generated at a greater height above the road surface than the tire-pavement noise. Also, powertrain noise can only be controlled by vehicle manufacturers and proper maintenance. The tire-pavement interaction generates sound as a function of the tread pattern, pavement surface texture, and various environmental factors. In fact, for a properly maintained vehicle, tire-pavement noise dominates over aerodynamics and powertrain noise when the vehicle is exceeding 50 km/h, which is illustrated in Figure 1.1 [Bernhard 05b].

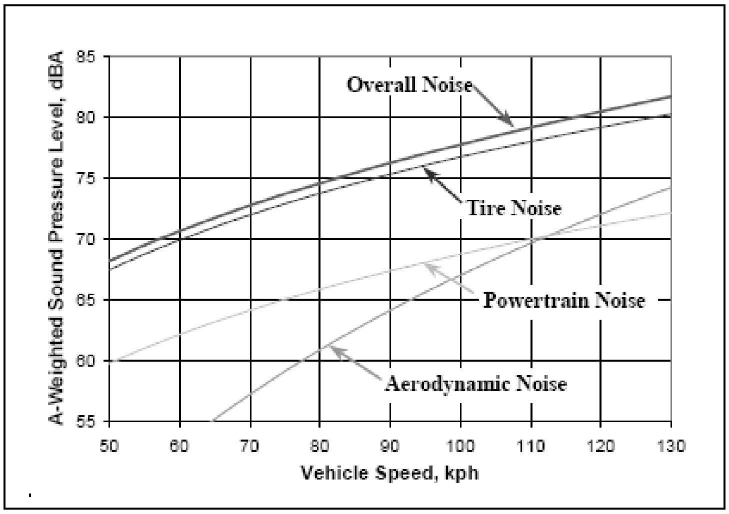

Figure 1.1 – Traffic Noise Sources [Bernhard 05b]

To be more specific, tire-pavement noise predominates over aerodynamics noise and powertrain noise when a vehicle accelerates a speed greater than 30 to 45 km/h for passenger cars and 45 to 50 km/h for trucks. When the vehicle is under cruise control, tire-pavement noise becomes dominant at a speed of 15 km/h to 25 km/h for passenger cars and 30 km/h to 35 km/h for trucks [Sandberg 02]. It has also been proven that tire-pavement noise increases as vehicle speed increases. Figure 1.1 also illustrates the relative magnitude of the noise sources. In fact, the total overall noise sound level is similar to the sound level generated from the tire-pavement.

Therefore, many provincial and state transportation agencies are using or investigating quiet pavement to reduce traffic noise.

1.4 Type of Pavements

In Canada, the total length of roads and streets is about 840,000 km. Approximately 64% of the Canadian road network is unpaved or gravel type roads with the remainder paved or surface treated [Haas 97]. Paved roads refer to a road topped with asphalt (flexible) or Portland cement concrete (PCC) (rigid) pavement. PCC pavement consists of four sub-types: jointed unreinforced, jointed reinforced, continuously reinforced, and prestressed. The first two types of PCC pavement are commonly used in Canada. The latter two have been used on an experimental or research basis only [Haas 97].

Asphalt pavement is primarily used in Canada, which constitutes more than 90% of the paved road network. In the province of Ontario, 89% of the road network consists of asphalt concrete roads [Haas 97]. The most common type of asphalt pavement is Hot Mix Asphalt (HMA). Within HMA, a variety of asphalt subsets exists including Hot-Laid (HL), Stone Mastic Asphalt (SMA), Dense Friction Course (DFC), Open Graded Friction Course (OGFC), and Superpave. The asphalt pavement structure of a typical Canadian roadway cross-section is multi-layered. It consists of less than 150-mm asphalt pavement surface layer, with underlying layers of asphalt binder or leveling course layer, granular base and subbase. The other types of asphalt pavements are “deep strength” and “full depth”. Both types consist of 150-mm or more of asphalt, but “deep strength” is placed on permeable base and/or granular base and “full depth” is directly placed on the subgrade [Haas 97].

1.5 Types of Quiet Pavements

There is a need to reduce the overall noise generated from the tire-pavement interaction to improve the condition of area adjacent to major roadways. One method is to employ quiet pavements. Quiet pavement is defined as the pavement type that can reduce traffic noise when compared with dense-graded or conventional asphalt pavements. Several quiet asphalt pavement mixes are currently being adopted worldwide and they are categorized as follows: Rubberized Asphalt, Open Graded Friction Course (OGFC), and Stone Mastic Asphalt (SMA).

Many transportation agencies use rubberized asphalt pavement in order to achieve a significant environmental benefit of reducing tire waste and recycling old tires instead of directing them to landfills. An example of a rubberized asphalt mix is Rubberized Open Graded Friction Course (rOGFC). OGFC is a designed to reduce tire splash/spray in wet weather due to the permeable nature of the design, but its open texture can also reduce traffic noise. SMA is utilized as a surface course with relatively coarse surface texture, low permeability, and high rutting resistance. Its coarse texture can reduce tire splash/spray in wet weather and reduce traffic noise.

1.6 Types of Acoustical Measurements

Two internationally accepted sound level measurement techniques are commonly used for traffic sound level evaluations. This includes the Pass-By Method (PBM) and the Close-Proximity (CPX) Method. Two types of PBMs, Statistical Pass-By (SPB) and Controlled Pass-By (CPB) Methods, are used to measure roadside traffic noise that includes noise generated by aerodynamics, powertrain of vehicle, and the interaction between the vehicle tire and pavement [ISO 97, Bernhard 05b]. The CPX Method attempts to solely measure tire and pavement interaction noise by mounting microphone(s) close to the tire and pavement interface [ISO 00, Bernhard 05b].

For a given roadway, the amount of perceived traffic noise depends on the pavement properties. In fact, sound absorption coefficient of the pavement surface will influence the level of noise adjacent to a roadway. This parameter can be measured using the following two methods: Impedance Tube Method and Reverberation Time Method. The Impedance Tube Method determines the normal incident sound absorption coefficient over various frequencies [ASTM 98, ISO 98]. The Reverberation Time Method determines the random incident sound absorption coefficient over various frequencies [ASTM 02, Bies 03].

1.7 Scope and Objectives of Research

The objective of this research is to determine the sound attenuation ability of various types of asphalt pavements that are commonly used in Ontario. The overall methodology used in this research is illustrated in Figure 1.2.

Key stakeholders of this research include:

- The Regional Municipality of Waterloo (RMOW), Ontario, Canada
- The Centre for Pavement and Transportation Technology (CPATT), University of Waterloo (UW), Ontario, Canada

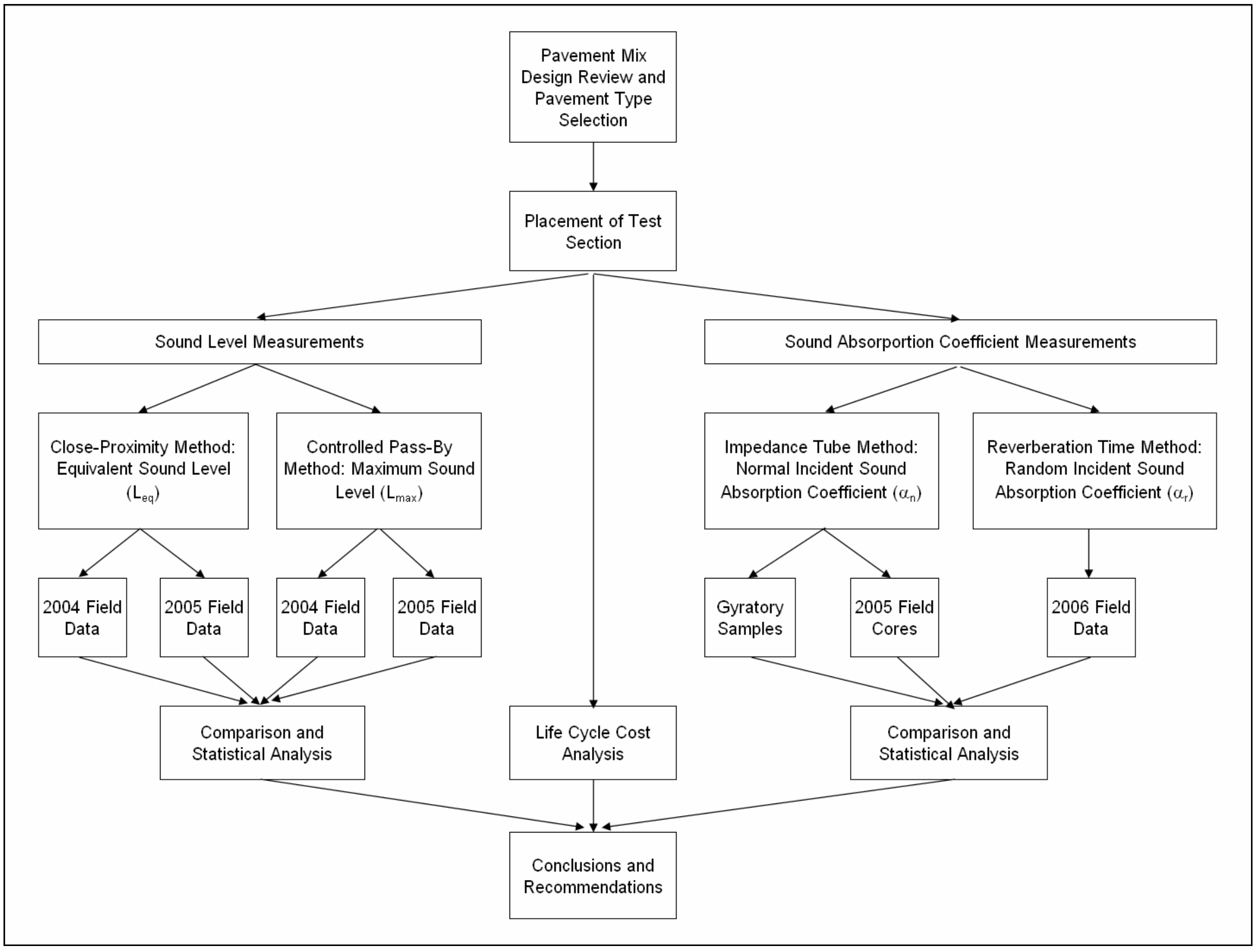

Figure 1.2 – Overview of Research

An investigation comparing the sound attenuation ability of various asphalt mixes with conventional mix was performed. The following provides a summary of the asphalt mixes employed in the research:

- Rubberized open-graded friction course (rOGFC)
    - Premium Aggregate Mix (rOFC)
    - Local Aggregate Mix (rOGC)
- Stone mastic asphalt (SMA)
- Hot-Laid 3 (HL-3) – Control Mix

Two rOGFC pavements were employed in this research. One rOGFC consists of premium aggregate and the other is composed of local aggregate. Premium aggregate meets higher quality standards in the physical property test methods when compared to local aggregates [MTO 02]. The purpose of using different aggregates is to determine whether the quality of the aggregate affects the sound attenuation ability.

Four types of asphalt pavement surface courses were placed on a two-lane regional road in August 2004. The purpose of placing all four pavements mixes in the same area is to increase the accuracy of evaluating the field measurement results because all four pavements are under the same traffic, environmental, and geographical conditions.

Field sound level measurements, CPB and CPX Methods were performed to determine the amount of sound attenuation level of each asphalt mix relative to the control mix in 2004 and 2005. Two sets of sound level measurements were obtained in order to evaluate any changes in the noise reduction abilities of the asphalt mixes over time:

- One month after construction
- 14 months after construction

Sound absorption property of each asphalt mix design was measured. Two sound absorption coefficient measurement techniques were adopted in this study: Impedance Tube Method and Reverberation Time Method. Gyratory samples using in-situ mixes and field cores samples in 2006 were used and subjected to the Impedance Tube Method to quantify sound absorption properties of mixes. The Reverberation Time Method was performed in the field for each asphalt mix test section in 2006. Comparisons between the studied mixes and the control mix, and between the two rOGFC were established. A statistical analysis was performed to determine whether there are significant differences between the various mixes. Additionally, a life cycle cost analysis is presented including the initial construction, maintenance, and rehabilitation costs. Finally, the conclusions of this research and recommendations for future work are provided.

1.8 Organization of Thesis

The purpose of this section is to provide a summary of the objectives in each chapter.

Chapter One provides a brief background of the research. In addition, the scope, objectives, and overview of the research are summarized.

Chapter Two provides a background of tire-pavement noise, a summary of HMA mix design methods, and common types of HMA used in Ontario.

Chapter Three details the methodology employed to determine the sound attenuation ability of the studied asphalt pavements.

Chapter Four summarizes the results obtained from the methodology employed in Chapter Three.

Chapter Five presents the statistical analysis of the asphalt pavements and provides insight on the significance of the findings.

Chapter Six provides the life cycle cost analysis with respect to the asphalt pavements studied in this research.

Chapter Seven provides the conclusions of this research and provides recommendations for future work.

CHAPTER 2: LITERATURE REVIEW

Chapter Two provides a fundamental concept of tire-pavement noise, a summary of HMA mix design methods, and common types of HMA used in Ontario.

2.1 Fundamental of Tire-Pavement Noise

2.1.1 Sound Measurement Unit

Sound can be determined by two characteristics: frequency and amplitude. Frequency is a measure of the number of vibrations that occur in one second. Frequency is measured in Hertz (Hz) and is known as pitch. The wavelength of any sound is the measurement of shortest repetition length for sound waves or the distance from rarefaction to rarefaction or compression to compression. The relationship between frequency and wavelength depends on the speed of sound in air, which is indicated in Equation 2.1.

$$c = f\lambda \qquad \text{[Equation 2.1]}$$

where f and λ represent frequency (Hz) and wavelength (m), respectively. c (m/s) represents the speed of sound in air. The speed of sound depends on the air temperature (^{o}C), T, which is indicated in Equation 2.2. For instance, the speed of sound at 20 °C is approximately 343 m/s.

$$c = 331.4 + 0.6T \qquad \text{[Equation 2.2]}$$

The amplitude of a sound wave refers to the loudness or the sound pressure level and it is measured in decibels (dB). Decibel is a logarithmic scale that is based on the logarithm of a ratio of the pressure to a reference pressure. The sound pressure level is also referred to the sound level or the noise level that is shown in Equation 2.3:

$$L_p = 20 \cdot \log_{10}\left(\frac{p}{p_o}\right) \qquad \text{[Equation 2.3]}$$

where L_p represents the sound pressure level (dB). The reference pressure, p_o, refers to a typical threshold of human hearing, 2×10^{-5} N/m^2. p refers to the air pressure level (N/m^2) caused by the vibration object.

Typically, a human with good hearing can perceive sound between 20 Hz to 20,000 Hz. However, human ears are not equally sensitive to all frequencies. Thus, three sound level weighting networks were introduced in order to simulate the human perception of sounds. These three weighting networks are A-weighting [dBA or dB(A)], B-weighting [dBB or dB(B)], and C-weighting [dBC or dB(C)]. These curves are shown in Figure 2.1 [Bies 03].

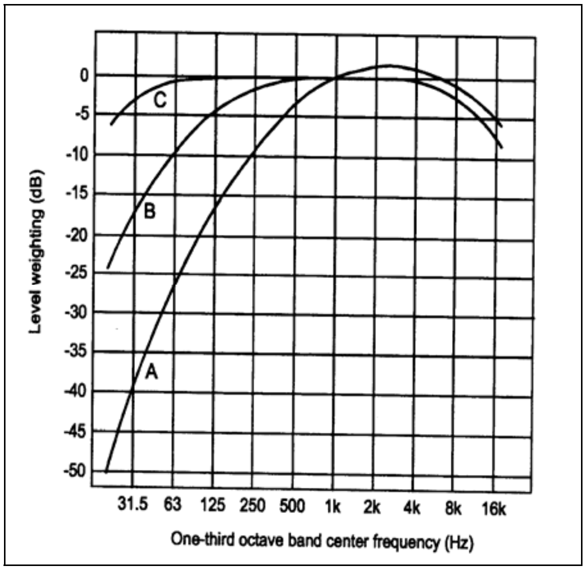

Figure 2.1 – A-, B- and C-weighting Curves for Sound Level Meters [Bies 03]

The A-weighting network is designed to approximate the response of the human ear, at moderate amplitudes, to typical environmental noise. The A-weighting network has been widely adopted for noise measurement standards and in many sound level meters to mimic the response of the human ear to sound. B-weighting and C-weighting networks are available for weighting sound at higher amplitudes than are typical of environmental noise (e.g. industrial noise).

The decibel scale ranges from threshold of hearing 0 dBA to the pain threshold 140 dBA approximately. It is not simple to quantify loudness without an actual measurement. Therefore, Table 2.1 demonstrates the sound level for typical sources, including various transportation noise sources. For instance, the perceived noise level of a passenger vehicle travelling at 80 km/h at a distance of 15 m away is 65 dBA. Similarly, a diesel truck travelling at 70 km/h is 75 dBA.

Table 2.1 – Noise Level Associated with Common Activities [Bies 03]

Activities	Noise Level
Power Lawnmower at Operator’s Ear	95 dBA
Milling Machine at 1.2 m	82 dBA
Diesel Truck, 70 km/h at 15 m	75 dBA
Vacuum Cleaner	70 dBA
Passenger Car, 80 km/h at 15 m	65 dBA
Whisper Speech	45 dBA
Quiet Room	40 dBA

Since the sound level is measured on a logarithmic scale, it cannot be added arithmetically. The formula used to add multiple sources of sound is shown in Equation 2.4.

$$dBA_{TOTAL} = 10 \times \log[10^{(\frac{dBA_1}{10})} + 10^{(\frac{dBA_2}{10})} + \ldots + 10^{(\frac{dBAn}{10})}] \qquad \text{[Equation 2.4]}$$

where dBA_{TOTAL} represents the sum of the addition from multiple sound sources dBA_n. For example, the summation of two 70 dBA sound sources side-by-side (i.e. dBA_1 and dBA_2), does not equal to 140 dBA, but equals to 73 dBA (i.e. dBA_{TOTAL}). This means that if the number of vehicles in a traffic flow is doubled, assuming all other factors being equal, the sound level will increase by 3 dBA.

2.1.2 Propagation of Noise

A sound source can be categorized into two types: point and line. Sound propagates spherically from a point. In other words, a noise source radiates sound equally in all directions [Bies 03]. A line source propagates sound cylindrically. That is, equal sound power output per unit length [Bies 03]. According to the Ontario Road Noise Analysis Method for Environment and Transportation (ORNAMENT) and the U.S. Federal Highway Administration (FHWA) Manual, traffic noise is classified as a line source since an endless chain of vehicles travel along the entire length of roadway. [Hanson 04, FHWA 80, and Schroter 89].

The sound level does not only depend on the loudness of the source, but also depends on other external factors such as ground surface characteristics and the distance between the source and the receiver [Schroter 89]. Equations 2.5 and 2.6 are used to calculate the sound level with respect to the road characteristic and the distance between the source and the receiver, for both point and line sources. Since traffic noise is considered as line source, ORNAMENT and FHWA Manual use Equation 2.6 to predict the amount of sound level changes.

$$\text{Point Source:} \quad A_d = 20 \times \log_{10}(\frac{d_2}{d_1})^{1+\alpha} \quad \text{[Equation 2.5]}$$

$$\text{Line Source:} \quad A_d = 10 \times \log_{10}(\frac{d_2}{d_1})^{1+\alpha} \quad \text{[Equation 2.6]}$$

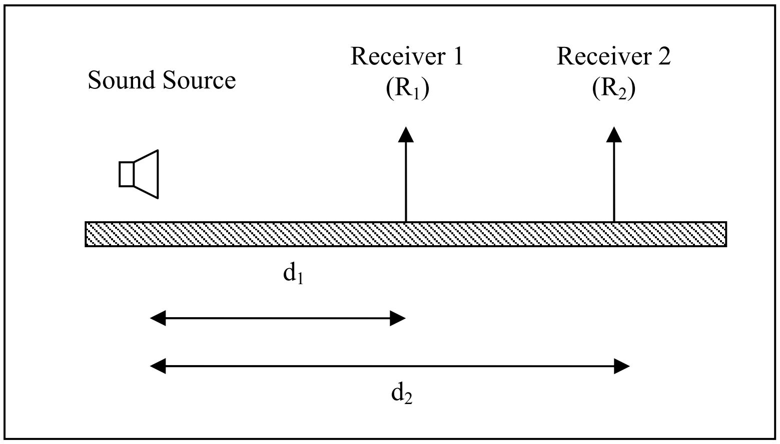

Figure 2.2 – Diagram of the Distance between Sound Source and Receivers

where α represents the ground absorption coefficient (dimensionless) that equals to zero for reflective surface (hard ground) and non-zero for the absorptive surface (soft ground) according to the ORNAMENT [Schroter 89]. d_1 and d_2 are the distances from the first and the second points of interest to the sound source respectively, which is demonstrated in Figure 2.2. A_d is the amount of sound level changed from d_1 and d_2 with a unit of dBA. Figures 2.3 and 2.4 demonstrate the set-back distance (d_2 subtracts d_1) in terms of point and line sources graphically, those are corresponding to the change of sound level (A_d) if assuming the d_1 is at 15 metre away from the noise source and with a hard ground surface (α=0).

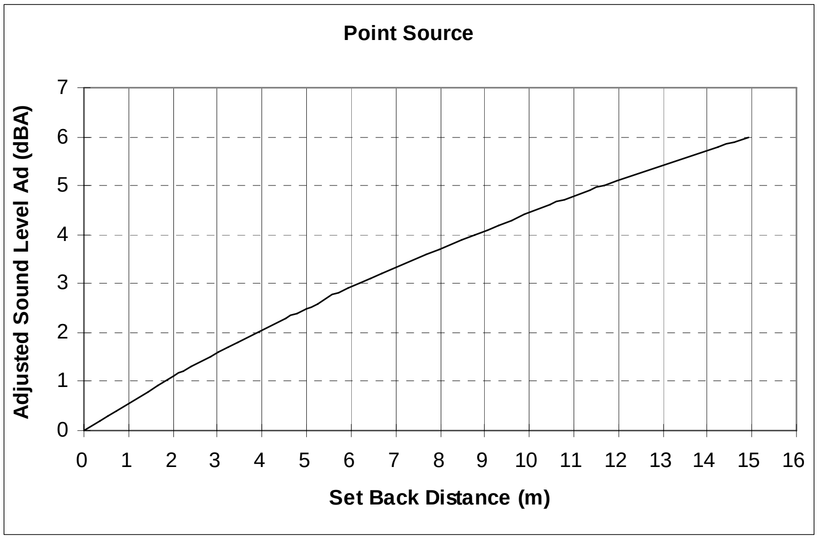

Figure 2.3 – Adjusted Sound Level vs. Set-Back Distance with Point Source

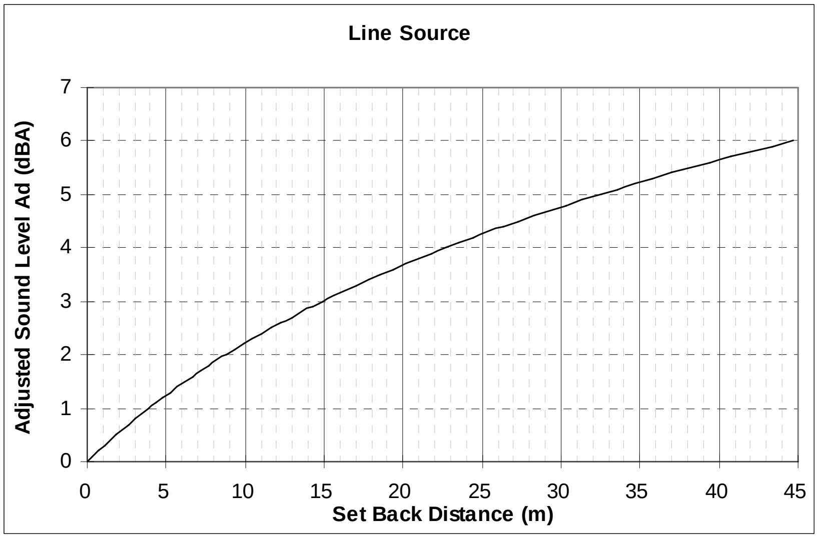

Figure 2.4 – Adjusted Sound Level vs. Set-Back Distance with Line Source

For example, the sound level decreases by 6 dBA from a point source and 3 dBA from a line source if the receiver moves 15 m further away from the original position and assuming the ground is hard (α=0).

According to the FHWA, studies have shown that average human can notice the change of the sound pressure level starting at 3 dBA [FHWA 95, Rayburn 04]. However, noise is also perceived psychologically. A recent research in Germany reveals that residents perceive sound level reductions as small as 0.3 dB to 1.5 dB as considerable improvements [SMILE 03].

2.1.3 Traffic Noise Mitigation Policies

The Regional Municipality of Waterloo (RMOW), Ontario, Canada, has implemented a guideline for noise policies to control excessive road traffic sound levels. This Implementation Guideline describes the process for assessing noise impacts, the responsibilities of the various parties, and the procedure for implementing sound attenuation requirements [RMOW 04]. These noise level criteria for sensitive land usage in the RMOW are generally consistent with the criteria established by the Ontario Ministry of the Environment (MOE) Canada (refer to Table 1.1 in Chapter One), through publication "LU-131, Noise Assessment Criteria in Land Use Planning" [MOE 97].

The sound level is typically measured by time-averaging (L_{eq}) or by capturing the maximum (L_{max}) value of an event. The selection between averaging and maximum response is dependent on the nature of the event. The A-weighted L_{eq} is commonly used in most noise policies. The allowable traffic sound level for outdoor living area varies among different countries. Physical noise mitigation methods are recommended if the outdoor living area sound level exceeds the values in Table 2.2 [FHWA 05a].

Table 2.2 – Allowable Daytime Outdoor Living Area Sound Levels

Locations	Allowable Daytime Outdoor Sound Level (L_{eq})
United States	67 dBA
Ontario, Canada	55 dBA
France	60 dBA
Denmark	55 dBA
Netherlands	50 dBA
United Kingdom	63 dBA

The most common physical mitigation methods include the construction of noise barriers (i.e. vertical noise barriers and earthberms), upgrade building façade components, and install central air conditioning units. Noise barrier walls and earthberms are presently found along most of the major highways and roads in North America. The European countries are using more comprehensive strategies to address excessive traffic noise level than United States (U.S.) and Canada. They are using a combination of installing noise barriers, investigating quiet pavement technologies, and implementing noise reduction technologies for vehicles. Furthermore, the European Union countries have agreed to track and map areas of noise along all existing roadways by 2007. Each country will then develop an action plan to address problems identified by this noise map [FHWA 05b].

There are advantages and disadvantages of using current noise mitigation methods. Acoustical improvement of building façade components, such as using thicker windows or brick exterior wall, constitute another way to control traffic noise level inside a dwelling. However, this method only reduces the indoor living area sound level from the traffic noise and it is only efficient with closed windows and doors. Another option is to install central air conditioning unit in the building if the indoor sound level exceed the sound level criteria. These upgrades will increase the construction cost and directly affect the cost to the users.

Earthberms have often been the preferred method because their natural appearance and potentially lower costs than noise barrier to control the outdoor living area sound level, but these require a substantial area (footprint) of land to install.

According to the RMOW Implementation Guidelines for Noise Policies, the noise barrier will be designed to achieve a 5 dBA or more reduction in the Daytime Outdoor Living Area noise level and to reduce the noise level to 60 dBA or less. The proposed height, location, and design to achieve these objectives will be reviewed by residents, Area Municipal Council and Regional Council with Regional Council having the final decision concerning the funding and installation of a proposed noise barrier in conjunction with the road design approval [RMOW 04]. Noise barriers can be built out of wood, stucco, concrete, masonry, metal, and other materials. In order to make the barrier effective in mitigating noise, the dimension of the noise barrier should be adequate to block the view of the road. Noise barriers are expensive. In some areas, homes are too far apart to permit noise barriers to be built at a reasonable cost. According to the FHWA, the cost of the noise barrier is in the range from USD\$160/m^2 to USD\$215/m^2 [FHWA 95]. Also, any openings at noise barriers for driveway connections or intersecting streets reduce the effectiveness of noise barriers [NCDOT 05].

2.1.4 Tire-Pavement Noise Generation Mechanism

Tire-pavement noise generation mechanisms can be divided into two main groups: mechanical vibrations of the tire and aerodynamical phenomena [Sandberg 02]. Noise generated by the mechanical vibration of the tire is known as structure-borne noise, which include the impact and adhesion mechanisms. Aerodynamical phenomena include air displacement is air-borne noise [Sandberg 02].

Impact Mechanism

- The impact between the tire tread block and the pavement surface causes radial vibrations and also causes tangential vibrations in both the tire tread and tire belt.

Adhesion Mechanism

- When a tire rolls over the pavement, the tire tread block can adhere to the pavement surface then snap and/or slip before breaking away of the pavement surface. These stick-snap and stick-slip phenomena cause the tire to vibrate and generate sound after the tire releases from the pavement.

Air Displacement Mechanism

- It is related to the air movement around the tire. Air is pumped into the cavities between the tire tread and road surface, compressed by the tire weight, and then pumped out from cavities during the rolling movement. The compression-release of air acts as a pump that generates sound, also known as air pumping.

The geometry of the tire and pavement can also enhance noise generation. This is similar to sound generated by musical instruments. For instance, the geometry of the tire above the pavement acts as a horn to amplify noise generated by the air pumping and the tread vibration. Small cavities in the tread pattern also amplify sound by acting as Helmholtz resonators. Air in the tread cavity vibrates and produces sound similar to a whistle.

Tire-pavement noise can also be reduced or attenuated by the surface texture and sound absorption properties of the pavement mix. A porous pavement surface creates more noise than a smooth pavement surface, but it also absorbs more noise than the smooth surface. This absorption results from the fact that air is squeezed into void spaces in the pavement rather than being compressed, reducing the quantity of noise that can propagate to a far field receiver [DDCL 06].

2.1.5 Traffic Sound Level Measuring Method

The quality of road surfaces, in terms of sound attenuation ability, can be quantified by measuring the traffic sound level. Close Proximity (CPX) Method and Pass-By Method (PBM) are standardized sound level measurement techniques for measuring traffic sound levels in the field.

In fact, the size of the vehicle in a traffic stream affects the traffic sound level. Generally, sizes of vehicles are categorized by the number of axles and the weight. A larger vehicle will cause a higher traffic sound level. A summary of the vehicle category for the International Organization for Standardization (ISO), the Ontario Ministry of the Environment (MOE), and the U.S. Federal Highway Administration (FHWA) is shown in Table 2.3 [ISO 97, Schroter 89, Lee 96].

Table 2.3 – Vehicle Categories

Specifications	Vehicle Category		
	MOE	ISO	FHWA
2-axle, 4 wheels, ≤ 9 passengers, ≤ 4500 kg	Car/Light	Car	Automobiles
2-axle, 6 wheels, 4500 to 12000 kg	Medium	Heavy	Medium
≥ 3-axle, design for hauling cargo, ≥ 12000 kg	Heavy		Heavy

Diesel truck and passenger car from the Table 2.1 of Section 2.1 are considered in the heavy and car categories according to the MOE and ISO classifications.

2.1.5.1 Pass-By Method

The PBM is a mean of assessing noise or sound at a distance. This method is conducted by placing a sound measurement system (i.e. microphone and sound level meter or similar instrument) at a defined distance from the vehicle path offset from the centreline. It measures the A-weighted maximum sound pressure level (L_{max}, in dBA) of vehicle passing by. The measured sound level includes all noise generated by the vehicle, including noise generated by the tire-pavement, powertrain, and aerodynamic.

Two pass-by methods are used to measure the roadside traffic sound level: the Statistical Pass-By (SPB) Method and the Controlled Pass-By (CPB) Method. The purpose of these two methods is to compare or evaluate traffic noise on different road surfaces.

2.1.5.1.1 Statistical Pass-By (SPB) Method

The Statistical Pass-By (SPB) Method procedures are defined by both the International Organization for Standardization ISO: 11819-1:1997 "Acoustics – Measurement of the Influence of Road Surface on Traffic Noise – Part 1: Statistical Pass-By Method" and the FHWA Measurement of Highway-Related Noise Manual. The SPB Method is used to measure the roadside sound level from a variety of road traffic (i.e. the free-flowing traffic condition). In addition, the pavement quality, such as condition, age, or the condition before and after resurfacing, can be monitored and evaluated.

In the SPB Method, the maximum A-weighted sound pressure level (L_{max}) is measured at a specified road-side location which is indicated in Figure 2.5.

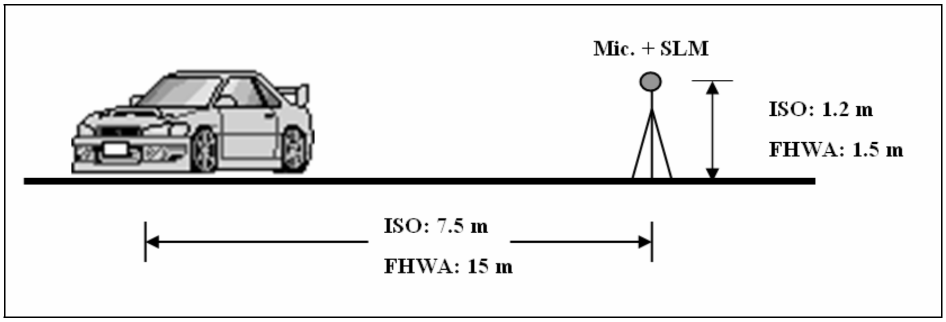

Figure 2.5 – Microphone Position for the Pass-By Method

The ISO standard suggests locating the microphone 7.5 m away from the centerline of the travel lane horizontally and 1.2 m above the plane of the road lane [ISO 97]. FHWA manual suggests placing the microphone 15 m (50 ft) away and 1.5 m (5 ft) above the ground. Both standards require recording the traffic count, vehicle speeds and sizes during the measurement. These data are used to compute a Statistical Pass-By Index (SPBI) and that Index is used to compare the sound level of various pavement types at different locations. Usually, the traffic data collection is recorded by a traffic counting device, video camera, and speed radar [Lee 96].

The ISO standard requires 180 vehicles which includes 100 cars and 80 heavy vehicles and their speeds. FHWA manual does not specify the number of vehicles required for the measurement. However, the FHWA provides some guidance in the minimum sample size. For instance, if the traffic speed is between 82 km/h (50 mph) and 96.5 km/h (60 mph), the minimum number of samples is 200.

The following is a summary of major considerations and limitations that are required for the selection of field site and operation during the SPB Method measurement [ISO 97, Lee 96]:

- Each road test section should be in a good condition and be homogeneous over the entire test section. The length of the test section shall be at least 30 m for the low speed road and 50 m for the high-speed road on both approaches to the microphone location.
- The test section shall be essentially level and straight. Roads with slight bends or with gradient ≤ 1% may be considered as valid test sites.
- Locate the microphone in the acoustical free field condition (i.e. at least 25 m of space around the microphone free of any reflecting objects other than the ground).
- Measured maximum A-weighted sound pressure level (L_{max}) using a microphone with a windscreen and a sound level meter.
- Calibration of acoustic instrumentation must be performed before and after the measurement.
- Included the frequency range of 50 Hz to 10000 Hz with centre-frequencies of one-third-octave bands during the measurement, but not mandatory.
- Minimize background noise, sound reflective objects, or terrain that might affect the measurement.
- Background noise levels must be 10 dBA below the maximum sound level during pass-bys.

Although the SPB Method measures the actual traffic noise emission, this method is labour and time intensive.

2.1.5.1.2 Controlled Pass-By (CPB) Method

The Controlled Pass-By (CPB) Method has the same measurement setup as the SPB Method as mentioned in Section 2.1.5.1.1. However, the difference is that it measures the sound level produced by a single vehicle or multiple selected vehicles, rather than from the normal free-flowing traffic stream. Currently, there is no international CPB Method standard in English, although a national French standard is available, NF S 31-119-2 [Sandberg 02].

The CPB Method is appropriate for:

- Comparing sound level between pavements
- Evaluating long-term performance of pavement

However, the disadvantage of the CPB Method is that it requires the temporary closure of the road during testing. This will affect the short-term traffic flow, especially in urban areas. Therefore, SPB Method is favourable to be used in urban areas, while the CPB Method is preferred in rural areas.

2.1.5.2 Close-Proximity Method

The Close-Proximity (CPX) Method, previously called the Trailer Method, is still under development by ISO at ISO/CD: 11819-2:1997 “Acoustical – Measurement of the Influence of Road Surface on Traffic Noise – Part 2: The Close Proximity Method”. The purpose of this method is to measure the equivalent sound pressure (L_{eq}, in dBA) generated directly from the tire-pavement interaction while the test vehicle travels along the test section. However, this method can only be used when tire-pavement noise dominates and powertrain noise may be neglected [ISO 00]. This technique is being routinely used in Europe and it is a good method to measure the sound level of the homogeneous road surface over a long distance and under a variety of conditions [HMAT 05]. It is suggested to use at least two microphones located close to the tire on a moving test vehicle which is illustrated in Figure 2.6.

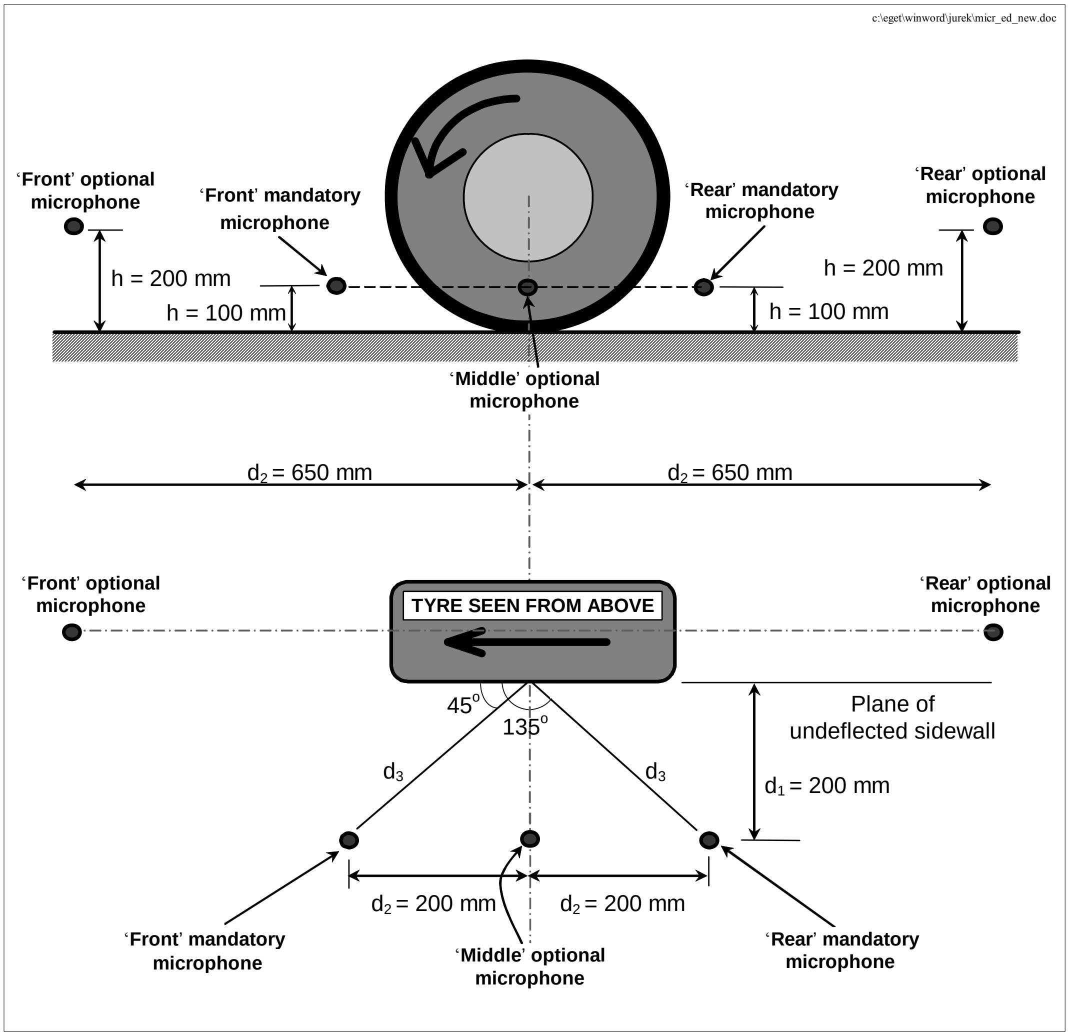

Figure 2.6 – Microphone Positions for the CPX Method [ISO 00]

Two mandatory microphones (i.e. front and rear) shall be mounted 0.1 m above the pavement level and 0.2 m away from the plane of the tire sidewall. The ISO draft standard does not recommend a position farther away form the test tire than the positions specified in Figure 2.6 [ISO 00].

In 2002, the National Center for Asphalt Technology (NCAT) at Auburn University in the U.S. constructed two Close-Proximity Trailers in accordance with the draft ISO procedures for the Arizona Department of Transportation (ADOT) and NCAT to measure tire-pavement noise. A test tire and microphones are located inside the trailer to isolate sound from passing traffic. The trailer or the shielding is required to prevent capturing sound from other directions [HMAT 05].

Another CPX Method was being promoted by the California Department of Transportation (Caltrans) is General Motors (GM) Sound Intensity Device. The advantage of the sound intensity approach is this device requires one microphone only. It can be simply attached to the lug nut of a tire rim and does not require a trailer [Scofield 05]. Figure 2.7 shows pictures of NCAT Trailer and GM Sound Intensity Device.


NCAT Trailer
GM Sound Intensity Device

Figure 2.7 – CPX System

The ISO draft standard consists of two types of CPX Method approaches: Investigatory Method and Survey Method, which depends on the purpose of the measurement. The Investigatory Method is the main method of CPX standard which intended to be used in all cases where the number of measurements or the distance travelled during all measurements is not exceptionally high. The ISO draft standard recommends using four different reference tires with different tread patterns (Types A, B, C, and D) for this measurement method. These reference tires, illustrated in Figure 2.8, are sufficient to represent typical tires used in a normal traffic condition. The Survey Method is an optional method which intended to be used in cases where the number of measurements or the distance travelled during all measurements is exceptionally high. In this case, only two out of four reference tires (Types A and D) are required to be tested.

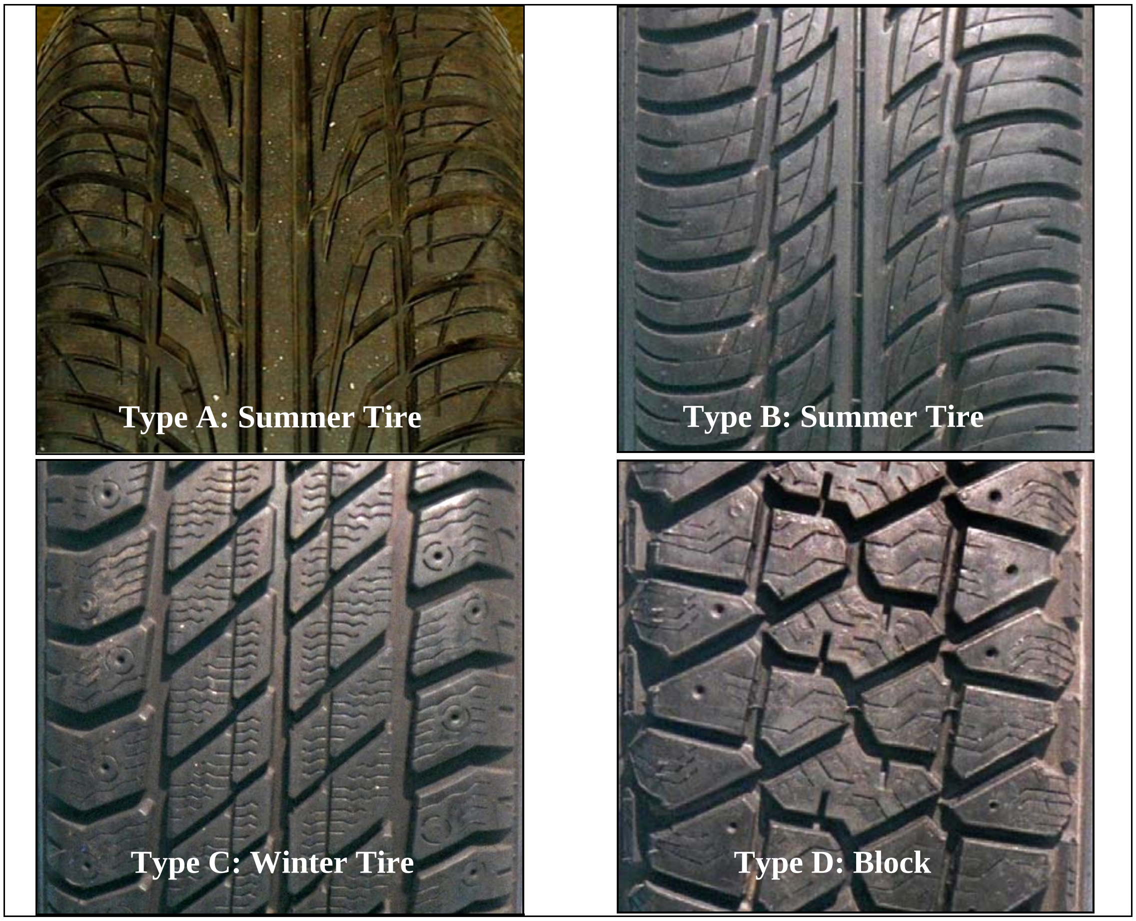

Figure 2.8 – Reference Tires Tread Pattern [ISO 00]

Types A and B reference tires are intended for use mainly at the air temperature above 0 ^{o}C. These tread patterns are commonly used in passenger vehicle tire design. Type C reference tire is a popular tire design used in areas where the average air temperature is below 0 ^{o}C (i.e. in conditions that may include snow and ice on the road). Type D reference tire is designed for trucks and originally intended for mud and snow use [ISO 00].

The following is a summary of major considerations and limitations that are required for the selection of field site and operation during the CPX Method measurement [ISO 00]:

- Each road test section should be in good condition and be homogeneous over the entire test section. The length of the pavement test section has to be at least 100 m. If the available test section length is only 20 m – 100 m, the number of runs shall be sufficient to give a total measured distance of at least 200 m.

- The test section shall be essentially level and straight. Roads with slight bends may be considered as valid test sites.
- Measured the average A-weighted sound pressure level using two microphones with windscreens and a sound level meter are recommended.
- Calibration of acoustic instrumentation must be performed at least before and after measurement.
- Included the frequency range of 315 Hz to 4000 Hz with centre-frequencies of one-third-octave bands during the measurement, but not mandatory.
- Background noise levels must be 10 dBA below the average sound level during the measurement.

2.1.6 Sound Absorption Coefficient Measuring Method

A vehicle traveling on different types of pavements produces unique sound levels due to the unique sound absorption property of each pavement type. Pavement sound absorption property is related to the pavement porosity. A connected network of pores allows sound waves to pass through and dissipate inside the pavement, thereby reducing the reflected noise. Porosity is influenced by the pavement thickness, the air void content, the airflow resistance, and the tortuosity. Some studies refer the air void content as the porosity [Sandberg 02]. These parameters are quantified by its sound absorption coefficient, a function of frequency, and it varies with the frequency of sound. For high speed roads (greater than 85 km/h), the critical frequency is 1000 Hz. For low speed roads (about 50 km/h), the critical frequency is 600 Hz [Sandberg 02, von Meier 92, Leung 06].

The sound absorption coefficient has a value between “zero” and “one”. A “zero” sound absorption coefficient represents the material that reflects all incident sound waves, or in other words: the material does not absorb sound. A “one” represents a material that absorbs all incident sound waves, or in other words: the material does not reflect sound. For example, absorption coefficient of 0.3 represents 100% of sound waves enters the pavement surface and 30% of sound waves are absorbed and 70% of sound waves are reflected, as illustrated in Figure 2.9. Absorption coefficients are usually measured over a range of frequencies.

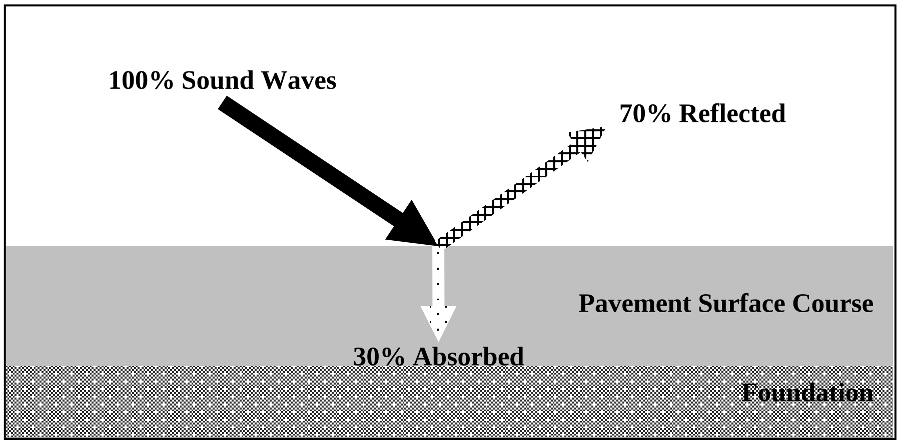

Figure 2.9 – Example of Sound Absorption and Reflection on Pavement Surface

The air flow resistance, *R*, is defined as the resistance to air passing through open pores in the pavement. A study in France shows that *R* influences the curves of the sound absorption coefficients versus frequencies. The increase of *R* tends to decrease the peak of absorption coefficient and increase the minimum absorption coefficient. The tortuosity, *K*, is an artificial parameter that describes the shape of pore in the pavement. It has no influence on the value of the peak absorption coefficient. However, an increase in K narrows the width of the curve and lowers the peak frequency.

The asphalt binder content is a factor that affects the shape of the pores as it affects the direction and section of the connection between pores. The thickness of the pavement has a large effect on the sharpness of the peak; the thicker pavement will have a broader peak shape, a lower peak frequency and a lower absorption coefficient. Air void content has no influence on the value of the peak absorption coefficient and the peak frequency. However, increasing the air void content will widen the curve in the vicinity of the peak value and increase the minimum value [Berengier 90, Sandberg 02, Crocker 04, Hamet 90].

The material sound absorption coefficient can be determined by two methods: Impedance Tube Method and Reverberation Time Method. The Impedance Tube Method is suitable for small samples and commonly adapted by the transportation agencies or researchers to determine the pavement normal incident sound absorption coefficient in various frequencies. The National Center for Asphalt Technology in the U.S. is currently using the Impedance Tube Method to measure the pavement sound absorption coefficient. The Reverberation Time Method determines the random incident sound absorption coefficient at various frequencies and suitable for large objects. These two measurement methods are described at the following sections.

2.1.6.1 Impedance Tube

The Impedance Tube Method is a laboratory testing method that is used to determine material acoustical properties. It is described in two common standards: ISO 10534-2:1998 and ASTM E1050-98. This method uses an impedance tube, two microphones, a sound source (i.e. loudspeaker), and a digital frequency analysis system to determine normal incidence sound absorption coefficient of material. The schematic of the Impedance Tube System is shown in Figure 2.10. A loudspeaker is connected to one end and the testing material is mounted at the other end of the tube.

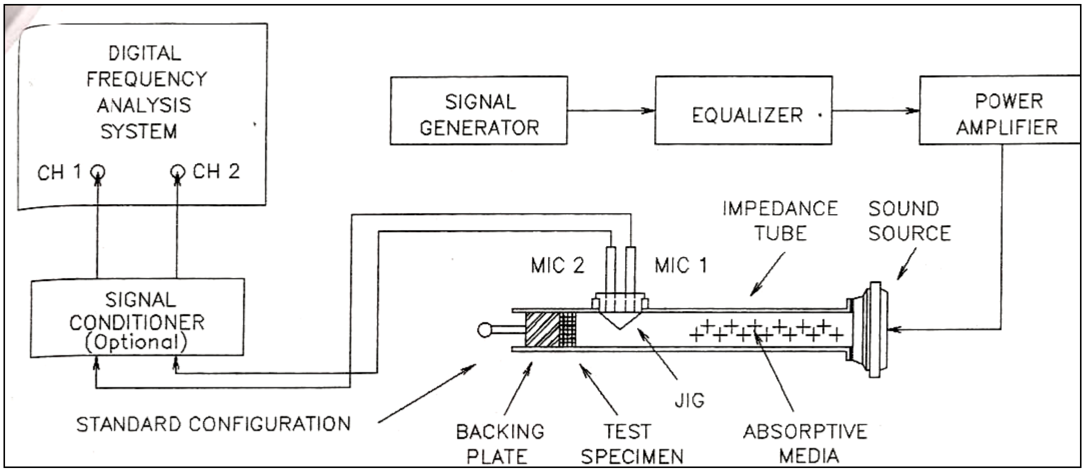

Figure 2.10 – Impedance Tube Setup Schematic [ASTM 98]

In this testing method, plane waves are generated in a tube as a stationary random signal with a flat spectral density (White Noise) within a specified frequency range. The decomposition of the stationary sound wave pattern into forward- and backward-traveling components are achieved by measuring sound pressures simultaneously at two fixed locations using wall-mounted microphones. The normal incident absorption coefficient within specified frequencies for the testing material is then calculated by processing the complex acoustic transfer function [ASTM 98, ISO 98].

The dimensions of the impedance tube will determine the working frequency range of the Impedance Tube Method. The lower working frequency is a function of the microphone spacing and the accuracy of the analysis system. ASTM and ISO standards recommend that the microphone spacing exceeds one and five percent (β) of the wavelength corresponding to the lower frequency of interest, respectively [Equation 2.7].

$$s > \beta\lambda \quad \text{where} \quad \lambda = \frac{c}{f_l} \quad \text{[Equation 2.7]}$$

where s represents the distance (m) between two microphones. λ is the wavelength (m) corresponding to the lower frequency of interest (Hz), f_l. c represents the speed of sound inside the tube (m/s). The upper working frequency limit, f_u, is a function of the tube diameter (m) and the speed of sound (m/s) inside the tube [Equation 2.8].

$$f_u < \frac{Kc}{d} \qquad \text{[Equation 2.8]}$$

where K equals 0.586 or 0.58 according to the ASTM standard or ISO standard, respectively. d represents the tube diameter (m) and c is the speed of sound (m/s) inside the tube.

Each testing sample should fit snugly in the sample holder. It is recommended to seal any peripheral cracks or gaps with Vaseline or plasticine, if necessary, taping and greasing the entire edge to prevent unwanted air gaps. If the sample has an uneven or irregular back, which would introduce an unintended backing air space behind the sample, a layer of putty-like material should be placed between the sample and the rigid termination [ASTM 98, ISO 98].

Two types of errors may occur on the Impedance Tube Method: Bias and Random Errors. A minimum of two samples are required and tested with the same mounting conditions. When the original sample has a non-uniform surface, additional samples should be tested to adequately represent the all regions of the pavement surface. In all cases, the results should be averaged [ASTM 98, ISO 98].

Bias error may occur on the Impedance Tube Method. The primary source of bias error is an insufficient frequency spectral resolution. Frequency spectral resolution is the frequency interval that the digital analyzer will measure. In order to minimize bias error, Bodén and

Åbom suggest the following guidelines for frequency resolution (refers to Equations 2.9 and 2.10) [Stevens 03, Bodén 86]:

$$\Delta f < \frac{8}{L} \qquad \text{[Equation 2.9]}$$

$$\Delta f < \frac{5.5}{l} \qquad \text{[Equation 2.10]}$$

where L is the overall length of the impedance tube (m). Δf represents the frequency resolution (Hz) which based on the dimensions of the impedance tube. l represents the distance (m) from the face of the sample to the further of two microphones. Random error is usually induced from processing random noise records of finite length, but may also involve electric noise in the instrumentation or extraneous acoustic signals. Typically, a product of frequency bandwidth and total averaging time of 50 to 100 seconds can keep random error low [ISO 98].

The NCAT has constructed two impedance tubes as illustrated in Figure 2.11, which can fit typical pavement coring sample sizes (100-mm and 150-mm diameter), to measure the pavement sound absorption coefficients [Crocker 04].

Figure 2.11 – NCAT Impedance Tubes [Crocker 04]

According to Equation 2.8, the theoretical upper frequency limits for 100-mm and 150-mm diameter tubes are 1318 Hz and 1978 Hz, respectively. Based on the NCAT experience, the upper working frequencies are 2000 Hz for 100-mm tube and 1250 Hz for 150-mm tube [Crocker 04]. Both impedance tubes can measure a frequency as low as 200 Hz.

Derivatives of sound absorption tests that NCAT has performed include studying asphalt slabs of the studied asphalt pavements with the impedance tube mounted vertically on the slab and cored the samples from the slabs with the impedance tube mounted horizontally. Since sound leakage or air space inside the tube will cause measurement error, NCAT inserted three O-rings around the inner wall of the tube to hold the sample and avoid the creation of any extraneous air pockets. Steel rigid back plate was also used behind the samples to provide a hard sound reflective termination, it is also known as the rigid termination.

The results from the NCAT study illustrate the peak sound absorption frequencies of the fine aggregate samples are slightly lower than that of coarse aggregate samples. In addition, the peaks for fine aggregate samples are boarder. The thickness of the sample also affects the peak frequency. In fact, the thinner the sample, the higher the peak frequency. Figures 2.12 and 2.13 show the 150-mm (6-in) impedance tube results from the NCAT study.

The peak frequency of SMA (76.2-mm thick and 3% air void content) is around 700 Hz and the peak absorption coefficient is about 0.12. For both fine and coarse 50-mm (2-in) OGFC, the peak absorption coefficient is 0.8 at 900 Hz. For both fine and coarse 38-mm (1.5-in) OGFC, the peak absorption is also about 0.8, but at 1100 Hz [Crocker 04].

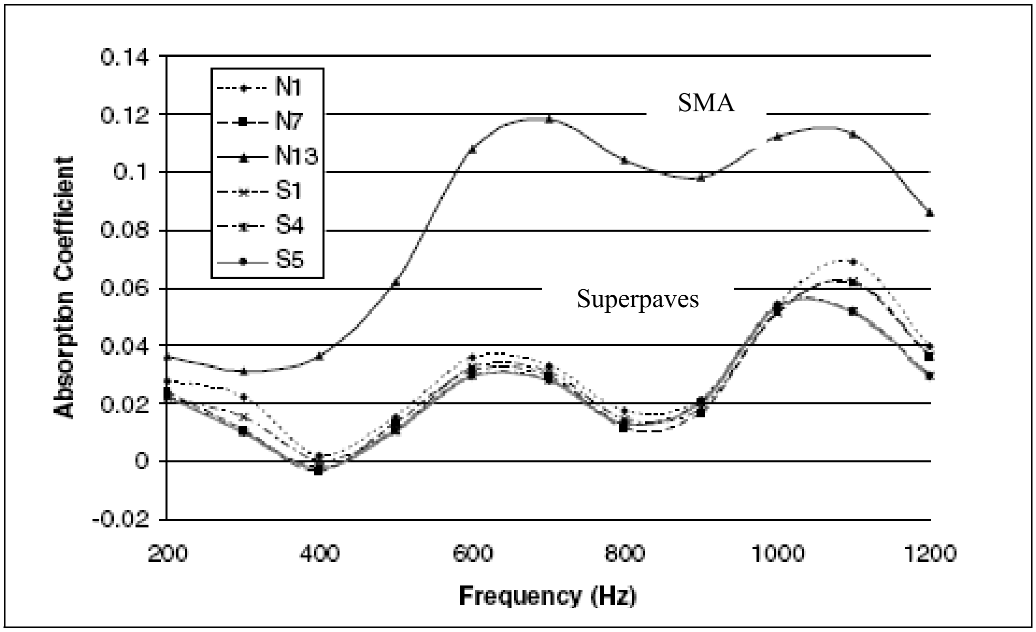

Figure 2.12 – NCAT 150-mm (6-in) Impedance Tube Result for SMA and Superpave [Crocker 04]

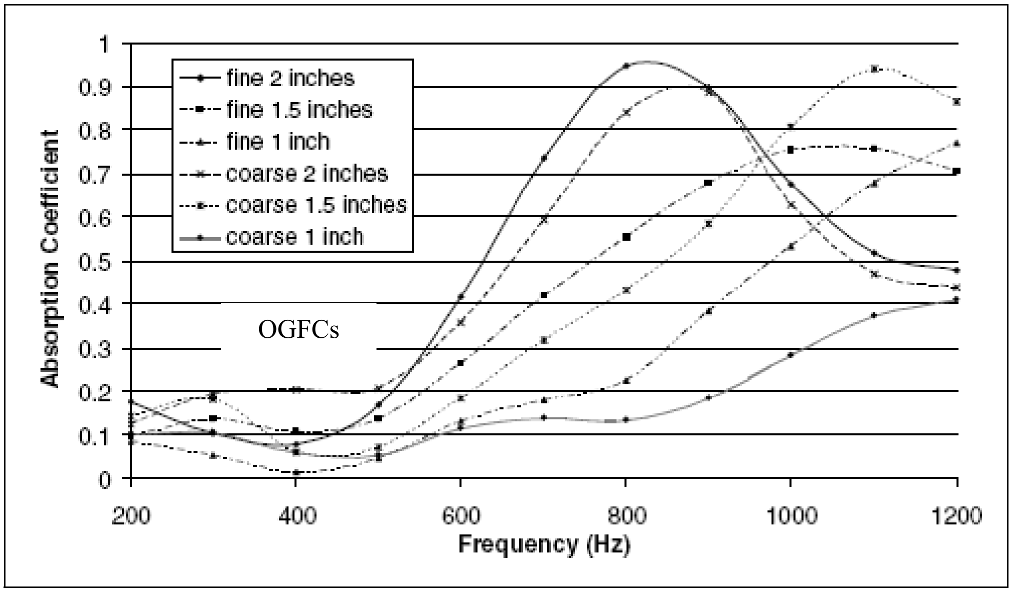

Figure 2.13 – NCAT 150-mm (6-in) Impedance Tube Result for OGFCs [Crocker 04]

2.1.6.2 Reverberation Time Method

Sound waves travel to the human ear by either a direct or an indirect path. The indirect sound wave is known as reverberation. It takes a little longer time to reach the ear than the direct sound wave because it travels a longer distance than the direct sound wave. For instance, sound was produced in a room by clapping hands. The indirect path is the sound waves reflected off from the wall, ceiling, floor, or other surface for more than one time before arriving at the ear.

The direct path is the sound waves reach the human ear directly without reflected off from any objects. The energy of the indirect sound wave is weaker and dissipated because the reflected surface will absorb part of the energy.

The Reverberation Time Method is used to measure the required time for a sound wave to dissipate energy after the sound source stopped in an enclosed room in a specified frequency. This method was developed by a pioneer in architectural acoustics, Wallace Clement Sabine. He investigated the impact of the absorption on the reverberation time in the Fogg lecture room at Harvard a century ago. In 1989, he discovered the relationship between the material absorption and reverberation time. Therefore the absorption coefficient measured by the Reverberation Time Method is also known as Sabine Absorption Coefficient [AE 06]. The calculation of the Sabine Absorption Coefficient, using the Sabine formula is described in Equations 2.11 and 2.12.

$$\bar{\alpha} = \frac{55.25V}{Sc(RT_{60})} \qquad \text{[Equation 2.11]}$$

$$\bar{\alpha} = \frac{\sum_{i=1}^{q} s_i \alpha_i}{\sum_{i=1}^{q} s_i} \qquad \text{[Equation 2.12]}$$

where V represents the volume of the reverberation room (m^3) and c is the speed of sound (m/s). $\bar{\alpha}$ and α_i represent the Average Sabine Absorption Coefficients of all materials (dimensionless) and the Absorption Coefficient of a particular material inside the chamber (dimensionless). S and s_i represent the total surface area (m^2) and the surface area of a particular material inside the chamber (m^2). The reverberation time 60, RT_{60}, is quantified in seconds represents the time required for the sound pressure level to decay by 60 dB from its initial value [Bies 03]. In most cases, the decay level between the initial level and the background level is less than 60 dB; therefore, extrapolation must be used to determine the RT_{60} from the linear portion of the decay curve. Once RT_{60} is obtained, the absorption coefficient can be calculated using Equations 2.11 and 2.12 [Bies 03].

Sabine Reverberation Time Method is listed on ASTM standard C423-02a "Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method". The absorption coefficient of a test specimen is calculated by measuring the reverberation time of both before and after placing that specimen in a room. The ASTM standard recommends the volume of the reverberation room shall be no less than 125 m^3. The level of the background noise in each frequency band shall be at least 15 dB below the lowest level used to calculate the decay rate [ASTM 02].

This method is implemented by sending a band of random noise signal (Pink Noise) into the empty enclosed room with a loudspeaker. Pink noise has the following characteristics [NI 06]:

- Used for acoustic applications
- Flat spectrum when viewed on a third-octave spectrum analyzer
- Flat spectrum when viewed on an analyzer whose bandwidth is a constant percentage of the center frequency of the filter.

Then, examining the decay of the sound pressure level as a function of time (i.e. reverberation time) using a microphone and real-time analyzer after shutting down the loudspeaker. The test specimen is then placed in the room and the reverberation time is measured again. Figure 2.14 demonstrates set-up of the Reverberation Time Method.

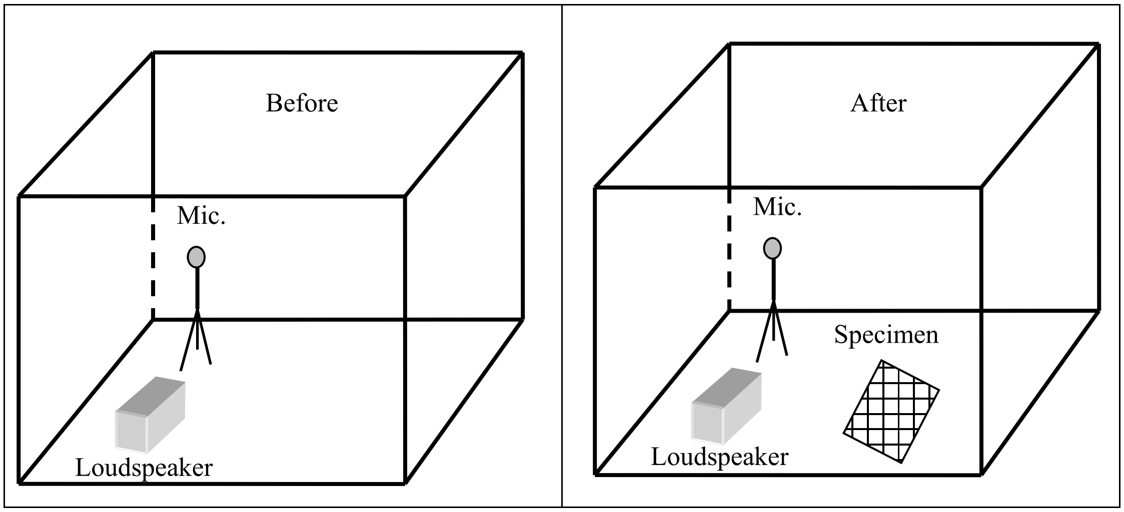

Figure 2.14 – Reverberation Time Method Measurement

Once RT_{60} is obtained, the absorption coefficient can be calculated using Equations 2.11 and 2.12 [Bies 03]. From these two reverberation times (before and after specimen placement), absorption coefficient can be determined by Equations 2.13, 2.14, and 2.15.

$$A = 0.9210\frac{Vd}{c} \qquad \text{[Equation 2.13]}$$

$$A = A_2 - A_1 \qquad \text{[Equation 2.14]}$$

$$\alpha = \frac{A_2 - A_1}{S} + \alpha_1 \qquad \text{[Equation 2.15]}$$

where A and d represent the sound absorption (m^2) and decay rate (dB/s), respectively. V and c represent the volume of reverberation room (m^3) and the speed of sound (m/s). A_1 and A_2 are the sound absorption of the room (m^2) before and after placing the specimen. S represents the area of the test specimen (m^2). α and α_1 are the absorption coefficient of the test specimen (dimensionless) and the absorption coefficient of the surface covered by the specimen (dimensionless), respectively. Equations 2.13 is a combination form of Equations 2.11 and 2.12, which uses decay rate rather than RT_{60}.

Based on the Equation 2.11, the Sabine absorption coefficient and reverberation time has an inversely proportional relationship. Therefore, highly reflective materials (e.g. smooth concrete floor, brick wall, and window) will have longer reverberation time and lower absorption coefficient than absorptive materials (e.g. heavy carpet and fibre glass). The sound absorption properties of materials vary with frequencies. According to the ASTM standard, 1/3 octave centre frequencies: 125, 250, 500, 1000, 2000, and 4000 Hz have to be included. For example, the Sabine absorption coefficient of typical concrete floor is 0.01 at frequencies of 125, 250, and 500 Hz and 0.02 at 1000, 2000, and 4000 Hz [Bies 03].

2.2 Fundamental of Hot Mix Asphalt

Hot Mix Asphalt (HMA) mainly consists of two basic ingredients: aggregate and asphalt binder. HMA performance properties include [WAPA 02]:

- Stiffness
- Stability
- Durability

- Permeability
- Workability
- Fatigue resistance
- Skid resistance
- Moisture damage resistance

The selection of aggregates and asphalt binder are significant to the performance of HMA. Combining aggregate and asphalt binder together yields a HMA mix design. Several different HMA mix design methods are commonly used including:

- Hveem
- Marshall
- Superior Performing Asphalt Pavement (Superpave)

2.2.1 Aggregates

Aggregate is a collective term for sand, gravel and crushed stone which is processed either from quarries or from naturally occurring granular sources. Aggregates provide the HMA with structural strength and frictional resistance [MTO 90]. A number of different aggregates are available for HMA. The selection of a specific aggregate depends on the traffic, economics, and performance [MTO 90].

Aggregates are categorized based on their grain size distribution (i.e. gradation) and physical properties. The gradation and physical requirements of the coarse and fine aggregates are specified separately in order to control their quality and mix proportions [MTO 90]. Several standard test methods have been used to determine the physical properties of aggregates, including Los Angeles Abrasion, Magnesium Sulphate Soundness, Water Absorption, Aggregate Angularity, Loss by Washing, Petrographic Analysis, Flat and Elongated Particles, and Percentage Crushed [Haas 97, MTO 90]. These methods can be found in Standard Specifications of typical provincial highway in Canada and other transportation agencies [Haas 97].

Typically, the quality of the aggregate may be classified into two types: 1) Premium Aggregate, and 2) Local Aggregate. Premium aggregate meets higher quality standards in the physical property testing methods when compared to local aggregates [MTO 02]. Aggregate physical property means an inherent attribute or feature of aggregate. The physical property tests are carried out to determine aggregate's resistance to weathering or degradation or both [MTO 02]. Therefore, premium aggregate is typically used in more heavily trafficked areas where higher strength and fictional resistance are required. Since the quality of the local aggregate is relatively lower, the cost of the local aggregate is also lower compared to the premium aggregate.

The particle size distribution, also known as gradation, is influential in determining HMA performance properties [WAPA 02]. Thus, most agencies specify allowable gradation. Generally, aggregate gradation is divided into four main groups: dense or well-graded, gap graded, open graded, and uniformly graded.

Dense or well-graded refers to a gradation that is near maximum density. Gap graded is a gradation contains only a small percentage of aggregate particles in the mid-size range (the gradation curve is flat in the mid-size range). Open graded contains a small percentage of small-size range (the gradation curve is flat and near-zero in the small size range). Uniformly graded is a gradation that all particles are the same size and falls into a very narrow size range (the gradation curve is steep) [WAPA 02].

2.2.2 Asphalt Binder

Asphalt binder is a complex hydrocarbon found as a residue from the process of petroleum fractional distillation [Haas 97, WAPA 02]. It is dark brown to black in color and highly viscous, which acts as a binding agent in HMA. Asphalt binders are commonly graded in accordance with its hardness rather than physical properties [Haas 97]. Two major asphalt binder grading systems are 1) Penetration Grading, 2) Superpave Performance Grading (PG).

In Penetration Grading System, it is assumed that the less viscous the asphalt, the deeper the needle will penetrate leading to a higher penetration number [WSDOT 06]. This penetration depth is correlated with asphalt binder performance. Asphalt binder with a high penetration number is used for cold climates. Similarly, asphalt binder with a low penetration number is used for warmer climates. However, sufficient knowledge to select an appropriate penetration graded asphalt binder given specific temperature and traffic conditions are required [Haas 97]. For larger provincial or state and local agencies, this knowledge or expertise will likely exist in-house. However, smaller agencies may employ private firms to determine the appropriate asphalt binder to use for a specific scenario [Haas 97].

Superpave Performance Grading (PG) System is popular as the binder can be selected based on the expected low and high pavement service temperature on site [Haas 97]. For example, an asphalt binder identified as PG 64-22 must meet performance criteria at an average 7-day maximum pavement design temperature of 64 ^{o}C, and also at a minimum pavement design temperature of –22 ^{o}C. In 1997, the Ministry of Transportation of Ontario (MTO) began to use the Performance Graded system to select the appropriate type of asphalt binder. This PG system was fully implemented in 2001 [Tam 05].

The addition of modifiers in the asphalt binder improves the performance of HMA by changing the properties of the asphalt binder. Examples of modifiers include:

- Filler
- Extender
- Polymer (rubber and plastic)
- Fibre
- (Anti)-Oxidant
- Hydrocarbon
- Anti-stripping agent

In general, the purposes of using modifiers are to adjust the binder to achieve the following types of improvement [WSDOT 06]:

- Lower stiffness at high temperatures during construction to increase workability and compatibility
- Higher stiffness at high service temperature to reduce rutting and shoving

- Lower stiffness at low service temperature to reduce thermal cracking
- Increase adhesion between the asphalt binder and the aggregate in the presence of moisture

2.2.3 HMA Mix Design

The procedures of all mix design methods consist of three basic steps, 1) Aggregate Selection, 2) Asphalt Binder Selection, and 3) Aggregate to Asphalt Binder Ratio Selection [WAPA 02]. Once the aggregate and the binder are selected, HMA mix samples are made using a specific mix design procedure and specifications.

One of the primary differences between the mix design procedures is the method of compaction [AI 01]. The Hveem Method uses a California Kneading Compactor. The Superpave Method uses a Superpave Gyratory Compactor. The Marshall Method, traditionally used by the MTO, uses a Marshall Drop Hammer. Many engineers believe that the impact compaction used with the Marshall Method does not simulate mixture densification as it occurs in the field [AI 01]. Superpave and Hveem Compaction Methods represent the compaction of asphalt pavement in the field [AI 01]. Marshall Mix Design is the traditional design method using in the MTO. However, Superpave is a new rational approach to design that result in extending the pavement service life. Therefore, the MTO has carried out parallel testing to study the impact of Superpave specifications on MTO contracts [Tam 05]. In 2002, 10% of the contracts were designed using the Superpave Mix Design Method. Beyond 2005, all MTO contracts were exclusively using Superpave Method [Tam 05]. Some agencies and private laboratories continue to use the Marshall Design Method [WAPA 02].

The recommended ratio of aggregate to binder for the HMA mix design is often referred to as the Job Mix Formula (JMF). Targets values of aggregate gradation and asphalt binder content are specified based on the JMF along with allowable specification bands to allow for inherent material and production variability [WAPA 02]. However, it is expected the manufacturer produce the aggregate gradation closely to the JMF during production.

2.3 The Use of HMA Surface Course Types in Ontario

The current MTO asphalt pavement surface course directive provides suggested asphalt mixes for the use on Ontario Highways. This list is based on the Annual Average Daily Traffic (AADT) or Equivalent Single-Axle Load (ESAL) criteria [MTO 06]. Table 2.4 summaries the list of the selection MTO surface course type for provincial highways.

Table 2.4 – Selection of Surface Course Types for Provincial Highways [MTO 06]

ESALS/Design Lane/Year (or AADT/lane)	Surface Course Types
AADT < 500	HL4
AADT 500-2500	HL3 or Superpave 12.5
AADT 2500-5000	HL1 or Superpave 12.5 FC 1
1<ESAL<3 Million or AADT > 5000	DFC, OFC or Superpave 12.5 FC 2
ESAL > 3 Million	SMA

Basically, the selection of surface course in different traffic volume depends on the aggregate quality. The aggregate quality requirement is listed on Ontario Provincial Standard Specification 1003 (OPSS 1003) [MTO 02]. HL-4, HL-3 and Superpave 12.5 contain local fine and coarse aggregates. Typically, these asphalt types are used in low volume roads where high fictional resistance may not be required. In fact, HL-3 and Superpave 12.5 are virtually the same; with the only difference is mix design procedure. HL-3 uses Marshall Mix Design and Superpave 12.5 uses Superpave mix design.

Both HL-1 and Superpave 12.5 FC 1 consist of premium coarse aggregate. DFC (Dense Fiction Course), OFC (Open Friction Course), and Superpave 12.5 FC 2 employ premium fine and coarse aggregates to accommodate high traffic volumes and improved friction properties. Both fine and coarse aggregate of SMA (Stone Mastic Asphalt) are also in premium qualities.

Asphalt mix types of HL-1, HL-3, HL-4, and DFC are dense-graded surface course mixes which are relatively impermeable in comparison to the gap graded and open graded surface courses. Gradations of HL-3 and DFC have an identical gradation to HL-1, but with different quality of aggregates as mentioned above. HL-4 is mainly used in Northern Ontario and in some parts of Southern Ontario as a surface of binder course [MTO 90]. Since HL-3 is used in the area with

AADT between 500 and 2500, many municipalities in Ontario use HL-3 as a primary mix for residential streets and arterials.

2.3.1 Rubberized Asphalt

Rubberized asphalt is a process of incorporating crumb rubber with asphalt paving material. Some agencies claim that rubberized asphalt pavement could reduce tire-pavement noise. In fact, the original purpose of using rubberized asphalt is neither for tire recycle nor traffic sound attenuation.

In the early 1960s, a material engineer, Charles McDonald from Sahuaro Petroleum from Phoenix, Arizona, used crumb rubber modifier (CRM) to enhance the elastic properties of the binder. The intent was to increase the resistance to bleeding in hot weather and reflective cracking in cold weather [Heitzman 92]. In the mid-1970s, Arizona Refinery Company developed a similar CRM by replacing a portion of the crumb rubber with devulcanized recycled rubber.

CRM can be incorporated using a wet process (i.e. McDonald Process) or a dry process. In the wet process, crumb rubber acts as an asphalt binder modifier. It requires that a finely ground rubber be blended into the asphalt binder at an elevated temperature prior to the asphalt binder being mixed with aggregate [ARTS 06]. The dry process incorporates crumb rubber is used as a portion of the fine aggregate [FWHA 06]. It refers to replacing some portion of aggregates with crumb rubbers and mixing them prior to addition to asphalt binder, which was developed in the late 1960s in Sweden [Heitzman 92].

In the early 1990s, the MTO discovered that dry process rubberized asphalt exhibits poor short-term performance under moderate to heavy traffic loadings. More specifically, the dry crumb rubber tends to segregate and pop out from the asphalt matrix causing premature failure at the surface of the mat. Review of past performance information indicates that wet process rubberized asphalt can result in good pavements if designed and constructed properly. The MTO had a successful experience using wet process rubberized asphalt in the mid-1990s [MacDonald 04]. Currently, the California Department of Transportation (Caltrans) approves rubberized asphalt produced using only wet process for new projects and dry process for the rehabilitation projects [Caltrans 05].

Many studies have proven that rubberized asphalt can reduce a significant level of traffic noise. For Instance, Sacramento County Department of Environmental and Bollard and Brennan Inc. have conducted a study which looked at the difference in noise levels between rubberized asphalt and conventional asphalt. The study concluded that rubberized asphalt provides 4 dBA sound attenuation [BBI 99].

Rubberized asphalt pavement is typically designed as open-graded or gap-graded mix [Way 98]. The following two sections present the sound attenuation results obtained in Canada, the U.S., and other countries around the world using both open- and gap-graded mixes.

2.3.2 Open Graded Friction Course Asphalt

Open Graded Friction Course (OGFC), is known as Open Friction Course (OFC) in Ontario. This surface course mix is designated for urban highways with heavy traffic where a porous, skid resistant, and sound absorbent material are required. It is used on highways such as the Toronto By-pass, the Ottawa Queensway (Hwy 417), and the Queens Elizabeth Way (QEW) in Canada.

OGFC is a hot mix open graded friction mix, which refers to an aggregate gradation that incorporates a skeleton of uniform aggregate size with a small percentage of aggregate particles in the small range. This can increase the proportion of air voids because there are not enough small particles to fill in the voids between the larger particles.

In most cases, transportation agencies do not specify the minimum air void content of OGFC, but 18% to 22% air voids is typically used in Europe [Kuennen 04]. Due to this open texture characteristic, OGFC has superior drainage ability than the conventional asphalt pavement (i.e. dense-graded asphalt pavement). It improves driving safety by reducing water pooling on the surface and increases pavement skid resistance under heavy rain conditions. Many studies conducted by transportation agencies proved that OGFC also reduces a significant amount of traffic noise generated by the interaction between tire and pavement. Both Spain and New

Zealand found that OGFC reduces the sound level by 2 dBA [Jackson 03, Garcia 04]. However, the open texture of OGFC would cause a problem of clogging, especially OGFC located in areas with snow and ice. It is because de-icing materials (i.e sand and salt) will flush down in void and clog the void. This clogging issue may increase the noise level by 1-2 dBA over time [Karlsson 06].

The Ministry of Transportation and Highways of British Columbia, Canada conducted a three-year program to study the noise reduction performance on Open-Graded Asphalt Pavement in 1995. It was found that OGFC pavement attenuates 4.9 dBA compared to conventional asphalt pavements. After three years of service, the OGFC continues to reduce traffic noise between 3.5 to 4 dBA. Also, no excess physical wear or deterioration of the OGFC was observed over the first three years of service [Wakefield 99].

As mentioned in Section 2.3.1, rubberized asphalt is commonly used with open graded mix. The Arizona Department of Transportation (ADOT) experienced that the initial average sound attenuation level of the rubberized open-graded friction course overlay is 5 to 8 dBA compared to PCC pavement [Scofield 05]. In addition to the sound attenuation ability, rubberized open-graded friction courses also provide smoother rides for the road users. Citizens in Arizona are satisfied with the rOGFC characteristics [Kuennen 04].

2.3.3 Stone Mastic Asphalt

Stone mastic asphalt (SMA), or stone matrix asphalt, was developed about 30 years ago in Germany. It has been used in Canada since 1990 and in the U.S. since 1991 [Scherocman 05]. SMA is a gap-graded asphalt mix, which has a high proportion of coarse aggregate that interlocks to form a stone-on-stone skeleton to resist permanent deformation. SMA contains a high asphalt content that increases fatigue resistance and it is suitable for the area with high traffic volume. Its popularity in Canada and the U.S. is ever increasing [Haas 97]. The MTO recommends SMA pavements for the roadways with traffic loadings in excess of three million equivalent single axle loads per year.

Although SMA has excellent frictional properties, plastic deformation resistance, and durability, it requires detailed attention during the production and placement process. Draindown (i.e. “fat spot”) is one of the biggest problems that occur in the pavement of the SMA Mix. It may occur if the mixing temperature or asphalt content is too high, or both are too high [Scherocman 05]. Therefore, extra care during the production and placement process is necessary.

Voids between the coarse aggregates in SMA are filled with mineral filler and asphalt binder. Since SMA contains a high asphalt binder content and lacks of medium-sized aggregate, the air void content is reduced. Typically, the SMA air void content is about 3.5% to 5%. The compacted SMA has a surface texture appearance similar to open graded asphalt, but SMA is non-permeable, resists water intrusion, and also has a lower air void content that is similar to dense-graded asphalt.

Research studies showed that the air void content of pavement affects traffic noise levels. Therefore, noise generated on SMA should be slightly higher than open graded asphalt. But since SMA has a lower air void content and non-permeable, clogging is less likely occurred when compared to open graded asphalt. As a result, SMA should provide more constant performance than open graded asphalt in terms of the traffic noise level.

A municipal resurfacing contract in Mississauga, Ontario, revealed that SMA can provide up to 2 dB sound attenuation compared to conventional asphalt mix [Bateman 02]. However, some studies showed that SMA does not attenuate traffic noise when compared with dense graded asphalt. In the state of Indiana, SMA with 4% air void appears louder than conventional hot-mix asphalt (HMA) by 1.2 to 1.7 dBA, depending on the vehicle types, speeds, and measurement methods [McDaniel 05]. A research project in Valencia in Spain concludes that some SMA mixes are louder than dense graded asphalt [Garcia 04].

CHAPTER 3: METHODOLOGY

Chapter Three details the methodology employed in determining the sound attenuation ability of the studied asphalt pavements. This chapter also includes the descriptions of studied pavements, test section location, sound level measurement and sound absorption coefficient measurement methodologies.

3.1 Description of Studied Pavements

Two rubberized Open Graded Friction Courses (rOGFC) and Stone Mastic Asphalt (SMA) were chosen to be the studied asphalt pavements. These were selected as being the most promising while not being overly risky. In short, there was concern these asphalt mixes might fail. So although other mixes could have been selected, given that Waterloo is highly susceptible to freeze thaw, it was determined to use these more conservative designs. These three asphalt pavements will be compared to a commonly used mix in municipalities across Ontario - Hot-Laid 3 (HL-3). HL-3 is a dense-graded surface mix which consists of 15% recycled asphalt pavement (RAP). The design thickness of each pavement type is approximately 40 mm. The asphalt binder for all studied pavements used is of PG 64-28. It means the binder is designed to comply with the performance criteria at an average 7-day maximum pavement design temperature of 64 ^{o}C and at a minimum pavement design temperature of -28 ^{o}C. The gradation, aggregate quality, and basic mix design properties are summarized in Figure 3.1 and Table 3.1.

The mix designs and gradations of both rOFC and rOGC are similar and contain blended recycled tire rubber particles in asphalt binder using wet process, but one uses premium aggregate and the other uses local aggregate. Typically, OGFC contains 100% crushed premium fine and coarse aggregates that provide high rut and skid resistances. Also, premium aggregates meet much higher standards during aggregate physical tests. However, premium aggregates have a higher cost than local aggregates. Therefore, it is beneficial to evaluate the sound attenuation ability of rOGFC using local aggregates. In order to distinguish the difference between these two rOGFCs, the rOGFC with premium aggregate is named Rubberized Open Friction Course (rOFC) and the rOGFC with local aggregate is named

Rubberized Open Graded Course (rOGC) in this study. SMA, the third type of asphalt mix in this study, uses premium graded fine and coarse aggregates and is typically used in the areas of heavy traffic in Canada.

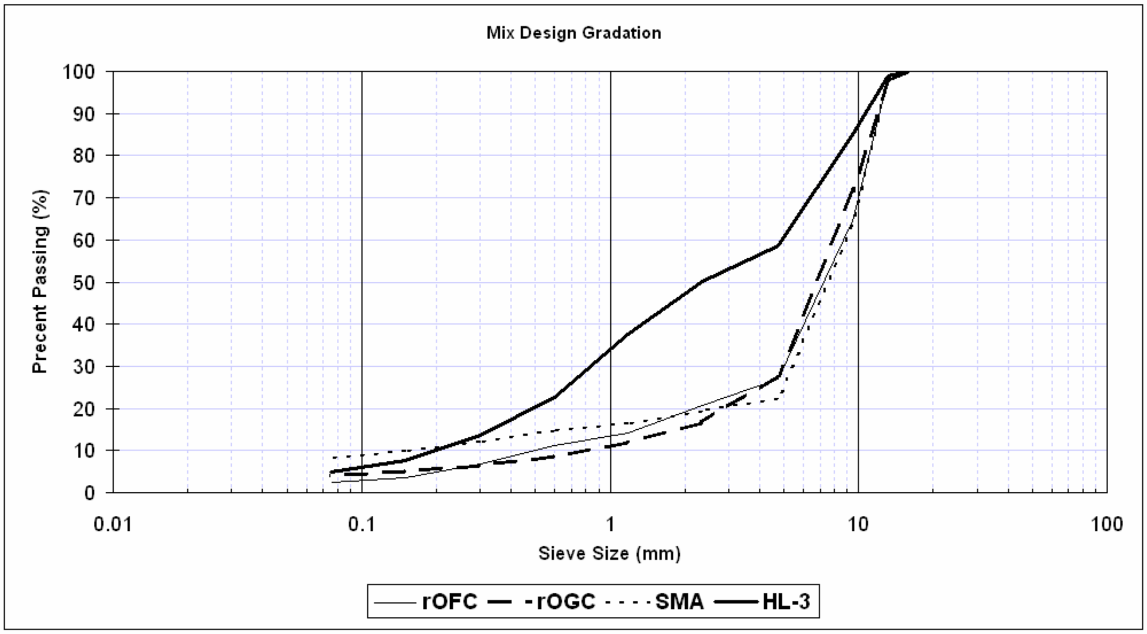

Figure 3.1 – Mix Design Gradation

Table 3.1 – Basic Mix Design Properties

Requirements	Job Mix Formula			
	rOFC	rOGC	SMA	HL-3
Type of Aggregates (Fine and Coarse)	Premium	Local	Premium	Local
Asphalt Contents (%)	5.6	5.8	5.7	5.0
Air Voids (%)	6.9	8.6	3.9	3.7
VMA (%)	18.3	19.3	16.9	15.4
Stability (N)	7397	6234	N/A	14111
Flow (0.25 mm)	13.0	16.1	N/A	10.6
BRD	2.281	2.286	2.355	2.400
MRD	2.450	2.501	2.451	2.493

Many studies have claimed that a high air void content of pavement mix results in a high sound absorption but the high air void content also causes a clogging problem, especially for the areas within a snow belt where sand and/or salt are used for the snow removal. Since Ontario is located within a freeze-thaw environment, winter road maintenance using sand and/or salt is inevitable. In order to minimize the level of air void clogging, air void contents of rOFC and rOGC have been designed to 6.9% and 8.6%, which is lower than the typical air void percentage of open graded mixes.

3.2 Site Description

Four types of asphalt pavement surface courses were placed over a four-day period in August 2004 on William-Hasting Line (Road 11), between Manser Road and Chalmers Forrest Road in Waterloo, Ontario, Canada as shown in Figures 3.2 and 3.3.

The test site was selected because it is located in a rural area surrounded by farmlands, which provides less ambient noise activity than in an urban area. Also, the site provides a long and straight horizontal alignment with uniform vertical grade, which allows placing of all four pavements mixes at the same area. This was beneficial since it increased the accuracy of comparing the noise measurement results between pavements since all four pavements were tested under the same scenario, which included geographic location, background noise, and other environmental factors (e.g., temperature and humidity).

William-Hasting Road is a two-lane regional road which had an Annual Average Daily Traffic (AADT) of 3,012 in 2002. The AADT expected for 2006 is 3,260 with an estimated 2% growth every year after. In the winter of 2005/2006, the Regional Municipality of Waterloo winter maintenance crew salted/sanded 101 times on this road. The 2004/2005 winter maintenance schedule was not available, but it will be assumed that the schedule was similar to 2005/2006.

Figure 3.2 – Map of Waterloo, Ontario (Adopted from www.mapquest.ca)

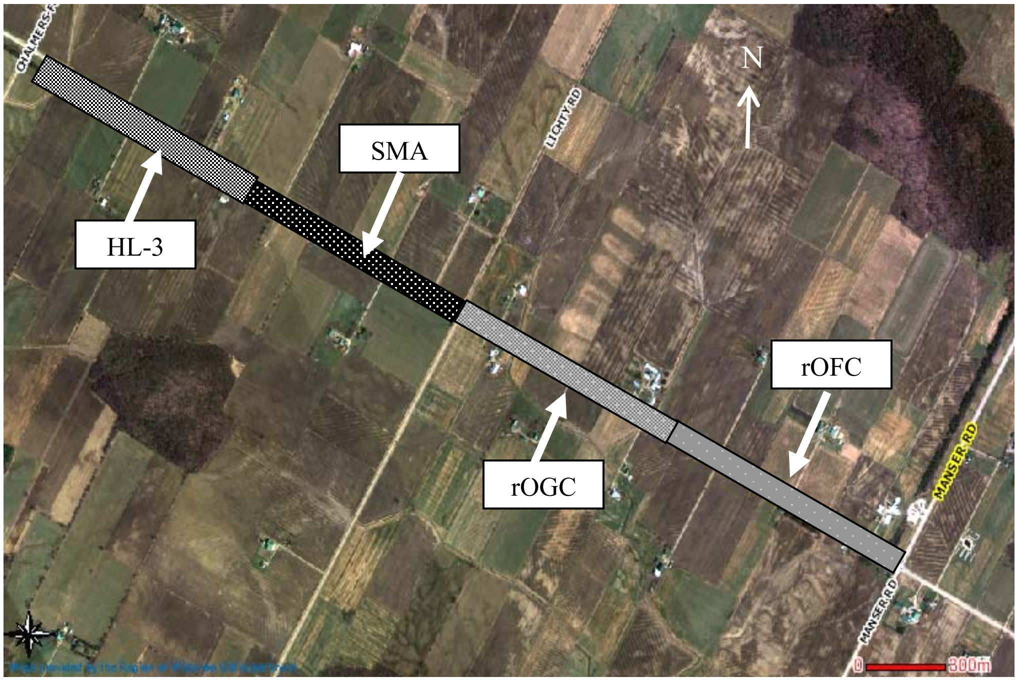

Figure 3.3 – Aerial Photograph of the Site

A 40-mm thick cold-in-place recycled layer was placed throughout the test section areas as the binder or lower course. Pavement surface courses were placed in an order of rOFC, rOGC, SMA, and HL-3 from east to west. The length of each type of pavement section is approximately 600 m which is in line with ISO standards. Figure 3.4 shows close-up photographs of the studied pavements placed on the test section.

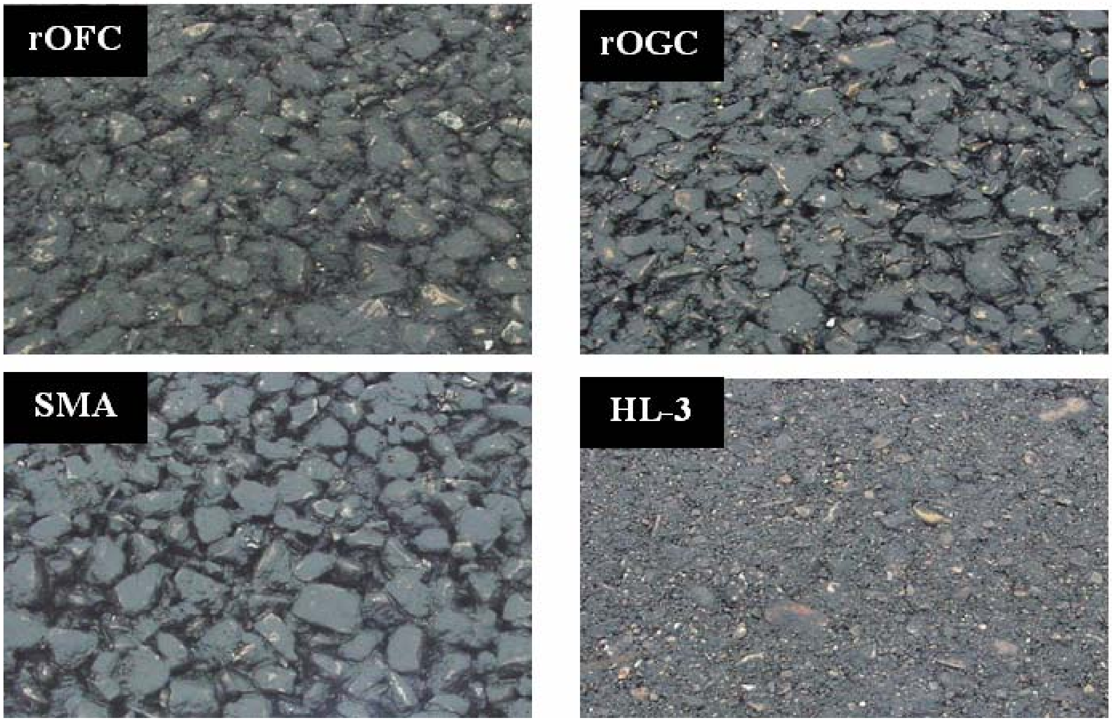

Figure 3.4 – Photographs of the Studied Pavements

Both rOFC and rOGC are rubberized open graded friction courses and have similar mix design and gradation; therefore, the appearances of both mixes are similar. SMA is a gap-graded asphalt mix, but its appearance also looks very similar to OGFC. HL-3 is a dense-graded mix which is commonly used in municipalities in Ontario; therefore, it becomes the control pavement in this study.

AMEC Earth & Environmental carried out skid resistance measurements at the test site in September 2004. AMEC measured approximately 26 locations on the rOFC and rOGC sections and 30 locations on the SMA section. The measurement results show that all three mixes had excellent early skid resistance. On average, the skid resistances of rOFC and rOGC were 69 and 65 [AMEC 05]. It was expected that the skid resistance level of rOGC would be slightly lower than the level of rOFC because the aggregate quality of rOGC is lower than that of rOFC. SMA also had an excellent skid resistance performance measured at 65 which was the same as of rOGC [AMEC 05]. However, some fat spots (i.e. bleeding, high percentage of asphalt content) were found on the SMA section which had skid resistance levels of 51. AMEC suggests that if the SMA fat spot areas exhibit cracking or deficiencies during the noise study monitoring period, then SMA at that areas should be removed. AMEC did not perform a skid resistance test on the control HL-3 section.

3.3 Sound Level Measurement Methodologies

Two sound level measurement techniques were utilized in this study: the Controlled Pass-By (CPB) Method and the Close-Proximity (CPX) Method. The purpose of these two methods is to compare the measured traffic sound level on the studied pavements with the typical municipal pavement mix, HL-3. Both sound level measurements were taken by RWDI AIR Inc. in September 2004 and October 2005, which are about one month and 14 months after the pavement was placed, respectively.

The entire test site, about 3.6 km on William Hasting Line from Manser Road to Chalmers Forrest Road, was closed during the measurements. The closure distance was longer than the test section distance because the testing vehicle required extra distances for acceleration and deceleration. Since the entire test site was closed during the measurements and it is located in a rural area, the ambient noise is minimized and constant during the sound level measurements.

There were thirteen test vehicles used for the first noise measurement and seven test vehicles for the second measurement. The test vehicles were divided into three categories according to the ORNAMENT: light, medium, and heavy vehicles, which are listed in Table 3.2.

Table 3.2 – Description of Test Vehicles

Vehicle Size	Vehicles Type	
	September 2004	October 2005
Car/ Light Truck	2 cars, 1 mini van, 2 light trucks	1 car, 1 mini van, 1 light truck
Medium Truck	2 city buses, 3 city work trucks	1 city bus, 1 city work truck, 1 small snow plow truck
Heavy Truck	3 dump trucks	1 dump truck

Three light vehicles (i.e. one car, one mini van, and one light truck) and one medium vehicle (i.e. one city work truck) from 2004 measurement have been used again in 2005 measurements. The two city buses used in 2004 measurement are the same model as the bus which used in 2005 measurement. Also, two of the dump trucks used in 2004 measurement are the same model as the dump truck used in 2005 measurement.

Each noise measurement consisted of a single test vehicle passing through the test site. The set-up is illustrated in Figure 3.5. Four stationary (CPB Method) microphones used to measure pass-by noise were setup on the side of the road for each pavement section. Each station was set-up at the midway point of each asphalt pavement section as pictured in Figure 3.6. All vehicle tire types are all-season tires, which is sufficient to represent typical tires used in Southern Ontario. Another microphone (CPX Method), used to measure tire-pavement interaction noise, was mounted on the test vehicle as shown in Figure 3.7.

Both CPB and CPX Method measurements were performed simultaneously while the test vehicle was travelling along the test section. The driver of the test vehicle drove through the centerline of the test road at constant speeds of 60 km/h, 70 km/h, 80 km/h, and 90 km/h from east to west and then made a return trip. Thus two measurements for each speed were taken for each vehicle: 1) from East to West, and 2) from West to East. Since the driving directions of the two measurements are different, they are considered as individual measurement.

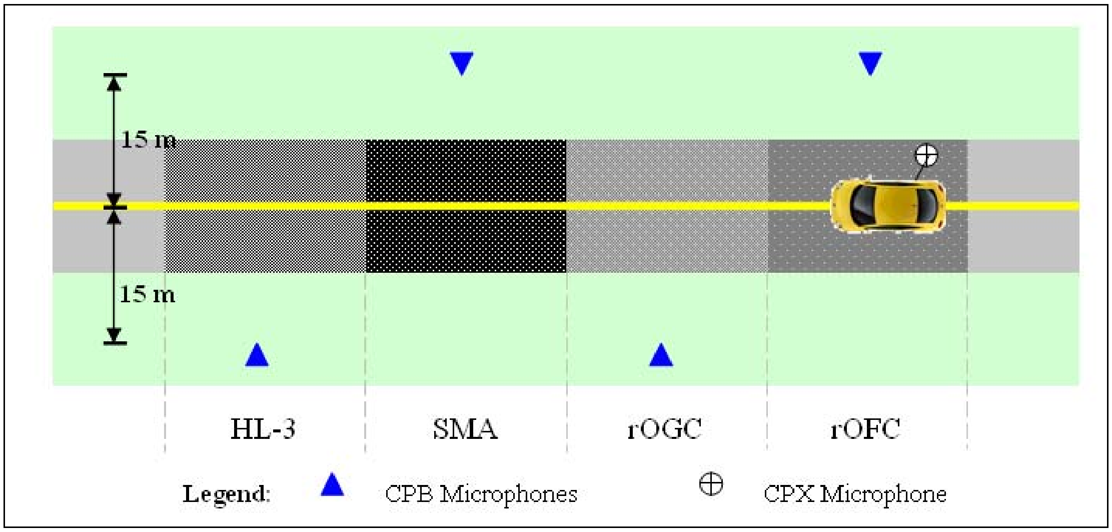

Figure 3.5 – Sound Level Measurement Set-up

Figure 3.6 – Controlled Pass-by Method Monitoring Station Set-up

Figure 3.7 – Close-Proximity Method Microphone Set-up

3.3.1 Controlled Pass-By Method

The Controlled Pass-by (CPB) Method measures the sound as a vehicles travels past a stationary microphone with a constant vehicle speed. Each monitoring station was located 15 m away from the centreline of the road, a microphone with a windscreen and sound level meter were located 1.5 m above the level of pavement, and was monitored by a technician. The windscreen was used to remove excessive wind noise. The A-weighted maximum sound level, L_{max} was measured using this method. The maximum sound level, L_{max}, identifies the maximum sound level produced when the test vehicle passes by. Calibration of the testing equipment was performed constantly during the test period to minimize deviation. Frequency spectrum for each pass-by measurement was also recorded.

3.3.2 Close-Proximity Method

The Close-Proximity (CPX) Method can give a good acoustic quality estimation of a homogeneous road surface over a long distance and under a variety of conditions. In this project, a microphone with two windscreens was secured by a simple truss structure that extended approximately 45 cm (18 inches) to 50 cm (20 inches) away from the centre of the front or rear wheel of a test vehicle. The windscreens here were designed to remove wind noise while the test vehicle is moving.

The purpose of this set-up was to ensure that the CPX measurement would measure the noise generated between the tire and pavement interface and to avoid measuring the engine noise generated from the test vehicle. The A-weighted equivalent sound pressure, L_{eq}, was measured on each pavement section. L_{eq} represents the average sound levels in a given period that corresponding to the required vehicle travel time on each pavement section. Since each pavement section is approximately 600 m long, it is believed that the measured L_{eq} will be a good representation of pavement-tire noise for each pavement section. Frequency spectrum was not recorded in this method.

3.4 Pavement Sound Absorption Measurement Method

Two pavement sound absorption properties measurements, the Impedance Tube Method and Reverberation Time Method, were carried out by the CPATT. These measurements were utilized to determine the pavement normal (Sabine) and random incident sound absorption coefficients in various frequencies.

3.4.1 Impedance Tube Method

The Impedance Tube Method is a commonly use to determine the material normal incident sound absorption coefficient in various frequencies. This method uses an impedance tube with a sound source (i.e., loudspeaker) connected to one end and a test sample mounted in the tube at the other end. In this study, the test sample refers to the asphalt pavement sample.

The diameter of the asphalt pavement sample is 150 mm (6 inches); therefore, a 150-mm diameter impedance tube was used in this study. However, a 150-mm diameter commercial impedance tube was not available on the market. For that reason, CPATT purchased a 150-mm diameter (6-inch) impedance tube from the National Centre of Asphalt Technology (NCAT) in 2005. The design of the NCAT impedance tube is in accordance with ISO and ASTM standards, as illustrated in Figure 3.8. Figures 3.9 and 3.10 illustrate the impedance tube measurement set-up and procedure.

The dimensions of the impedance tube determine the measured frequency range of the tube. In terms of frequency, the lower limit is a function of the microphone spacing and the upper limit is a function of the tube diameter. According to the tube design, the theoretical lower and upper frequency limits using the formula stated on the ISO standard are 170 Hz and 1335 Hz, respectively. The actual working frequencies are determined according to the testing results.

Two types of samples were tested in the Impedance Tube Method:

- Asphalt gyratory samples were compacted using the Superpave Gyratory Compactor. The mixes used for the gyratory samples are from the test site in August 2004.
- Asphalt core samples were cored directly from the test site in March 2006.

Figure 3.8 – NCAT 150-mm diameter Impedance Tube

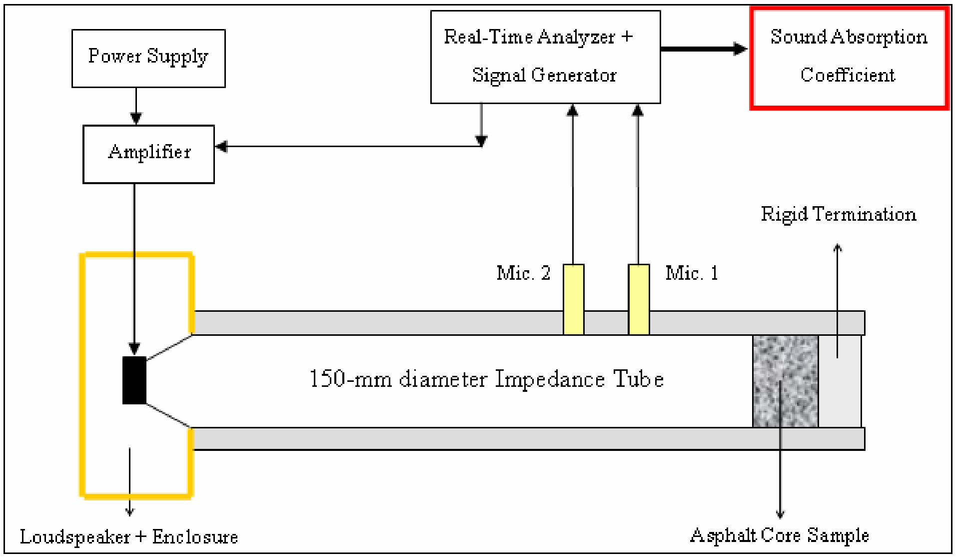

Figure 3.9 – Impedance Tube Setup Schematic

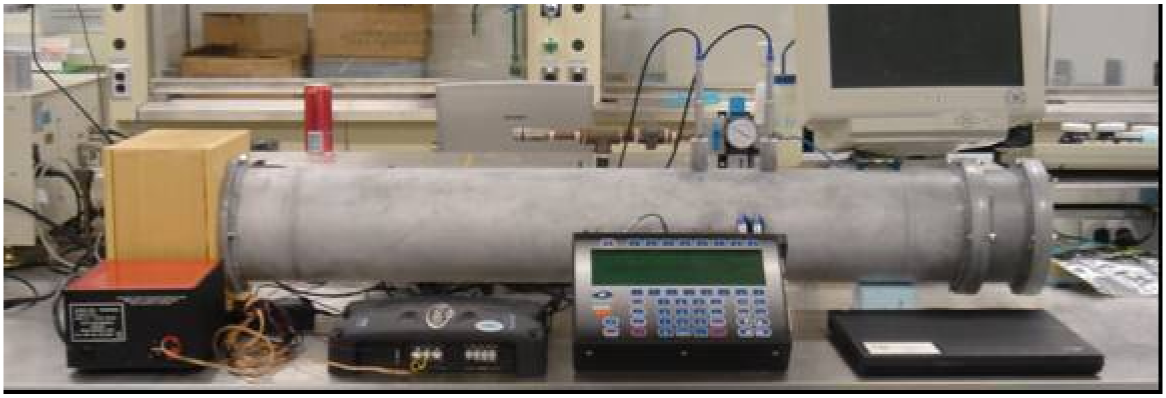

Figure 3.10 – Picture of the Impedance Tube Measurement System

During the testing, plane waves were generated in a tube through a loudspeaker using broadband white noise from the signal generation feature of a Larson Davis Real Time Analyzer (Model: 3000+). White noise is a type of noise that consists of all audible frequencies with equal intensity. Frequency spectral resolution (i.e., frequency interval) of the digital analyzer was set to be 3.125 Hz in order to minimize the bias error during the measurement. Total averaging time of 64 seconds was used to keep the random error low. The decomposition of the interference field is achieved by the measurement of acoustic pressures using two Larson Davis half-inch free-field microphones. A real time analyzer is also used to calculate the complex acoustic transfer function for the use of determining the absorption coefficient from the ACUPRO software. The ACUPRO Version 2.1 "Measurement of Acoustical Properties of Materials and Systems" software is utilized to calculate the normal incidence absorption coefficient.

Samples are shown in Figure 3.11. Since the back of the sample surfaces were not smooth which would induce unwanted air gaps between the back of the sample and the rigid termination, all samples were saw-cut into approximately 40-mm thick samples in order to create a smooth back surface and increase the accuracy when averaging the results. Furthermore, 40-mm corresponds to the mix design thickness.

The circumference of the samples was wrapped with closed-cell weather stripping foams before being inserted into the sample holder. The close-cell weather stripping foam prevents air gaps between the sample and the sample holder that may cause measurement errors. A 27-mm (approximately one-inch) thick steel plunger was used as the rigid termination in order to provide a hard reflective surface. The steel plunger was also wrapped with closed-cell weather stripping foams before inserting into the sample holder at the Impedance Tube system also shown in Figure 3.12.

Since the testing surfaces of asphalt samples are not homogeneous, one sample cannot represent the sound absorption property of the material. Therefore five samples of each type of asphalt pavement mix were tested and averaged, in order to include representative regions of the surface. Eight random positions with the same mounting condition were measured and averaged in each sample to provide measurement consistency and repeatability.

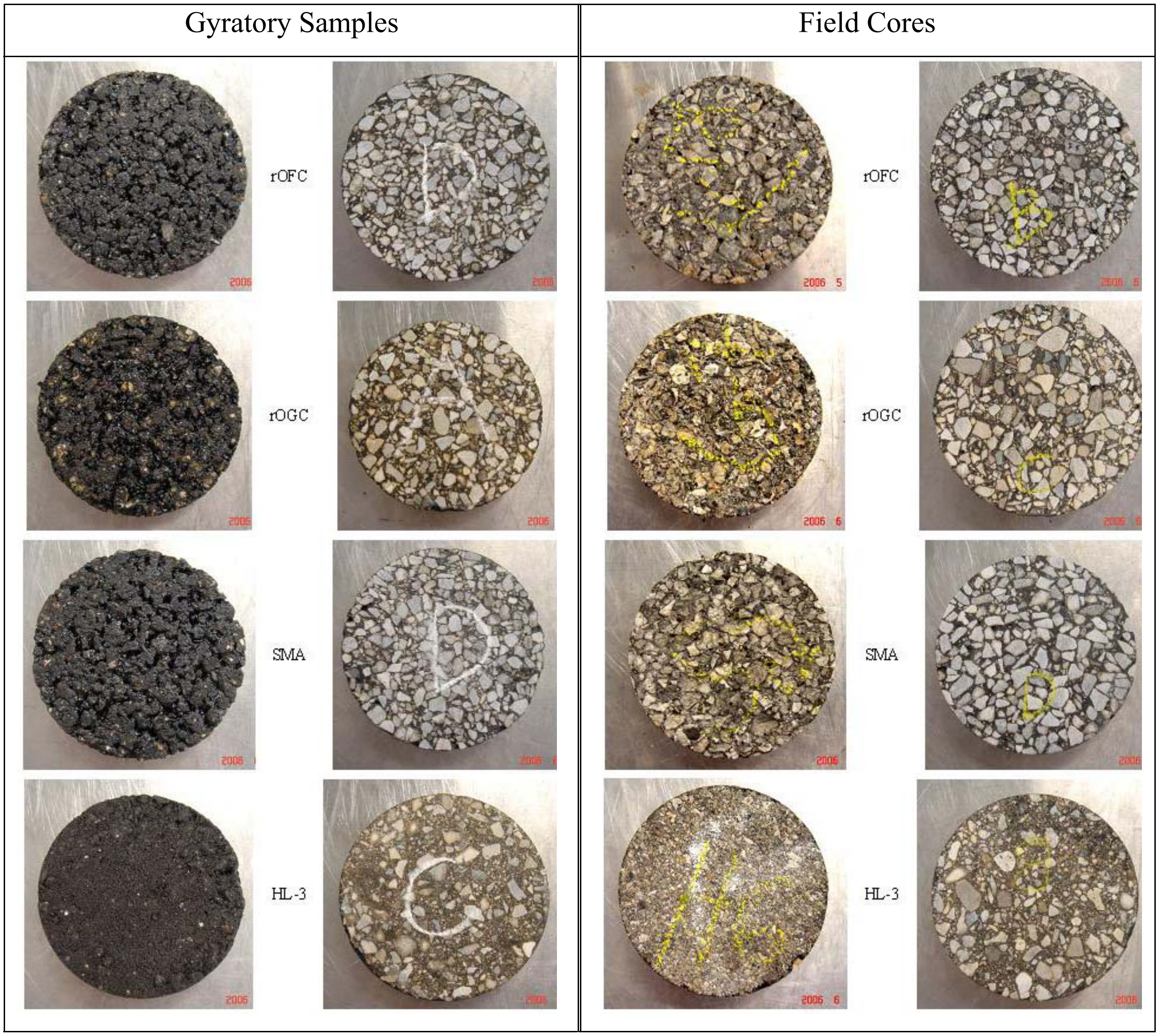

Figure 3.11 – Samples for Impedance Tube Testing

Figure 3.12 – Sample and Steel Plunger wrapped with Closed-Cell Weather Stripping Foams

3.4.2 Reverberation Time Method

Reverberation Time Method was utilized in this study in order to find the Sabine absorption coefficient of the studied pavements. According to the ASTM standard, the volume of the reverberation room is usually no less than 125 m^3 [ASTM 02]. However, it is not feasible to build a 125 m^3 mobile reverberation room to find the absorption properties of pavement surfaces in the field or to compact a large studied asphalt pavement slab. Therefore, as part of this research CPATT/UW worked with RWDI Air Inc. to design a smaller scale of the reverberation time chamber (0.8 m^3 approximately), which can be utilized in the field. The reverberation time chamber was constructed by the University of Waterloo Workshop, as shown in Figure 3.13.

The modified reverberation time chamber is an open-based, flat-topped pyramid, and built with surface spray sealed medium density fibreboard (MDF). The top openings are for the placement of a microphone and a loudspeaker with tweeter. The edges of the open base were placed with close-cell weather stripping foams in order to avoid sound leakage from the bottom edge during the measurement. Figures 3.14 and 3.15 illustrate the Reverberation Time Method setup and procedure.

During the testing, a band of random noise signal (Pink Noise: equal acoustic power per 1/3 octave bandwidth) was generated by the signal generation feature from the Larson Davis Real Time Analyzer (Model: 3000+) and was sent through the loudspeaker for 7.5 seconds. Once the loudspeaker stopped after 7.5 seconds, the sound pressure level was measured continuously for three seconds using a half-inch free-field microphone. Reverberation Time 60, RT_{60}, with various frequencies was calculated by the Larson Davis Real Time Analyzer. Finally, the average Sabine absorption coefficient in various frequencies can be calculated according to the Equation 2.11 from Chapter 2.

The UW attempted to find absorption coefficients of the reverberation chamber material (i.e. MDF) by placing the chamber on a MDF panel. The purpose of using the MDF panel is to create a homogeneous interior surface material environment assuming the surface areas of the speaker and microphone are negligible. The average Sabine absorption coefficient in various frequencies of MDF is then calculated using Equation 2.11. Since the absorption coefficients of the MDF are known, the absorption coefficients of the in-situ pavement type can be calculated using Equation 2.12 after measuring the RT_{60} on site. However, some of the calculated absorption coefficients of the in-situ pavement are negative values which are illogical. This phenomenon maybe because the bottom of the chamber is supported by a hard surface underneath, but the sides of the chamber are not supported by anything during measurement. This means the sides of the chamber would undertake more structural-borne vibration than the bottom. Also, the reverberation chamber is small which produces smaller values of RT_{60} in the chamber and any errors maybe magnified. Therefore, average Sabine absorption coefficients of the whole chamber were used instead of solely calculating the absorption coefficient of the pavement surface in order to avoid negative sound absorption coefficients. The calculated average Sabine absorption coefficient of the whole chamber represents the average Sabine absorption coefficient of all materials inside the chamber which include the MDF, in-situ pavement surface, loudspeaker, and microphone.

Figure 3.13 – Reverberation Time Chamber designed by RWDI Air Inc.

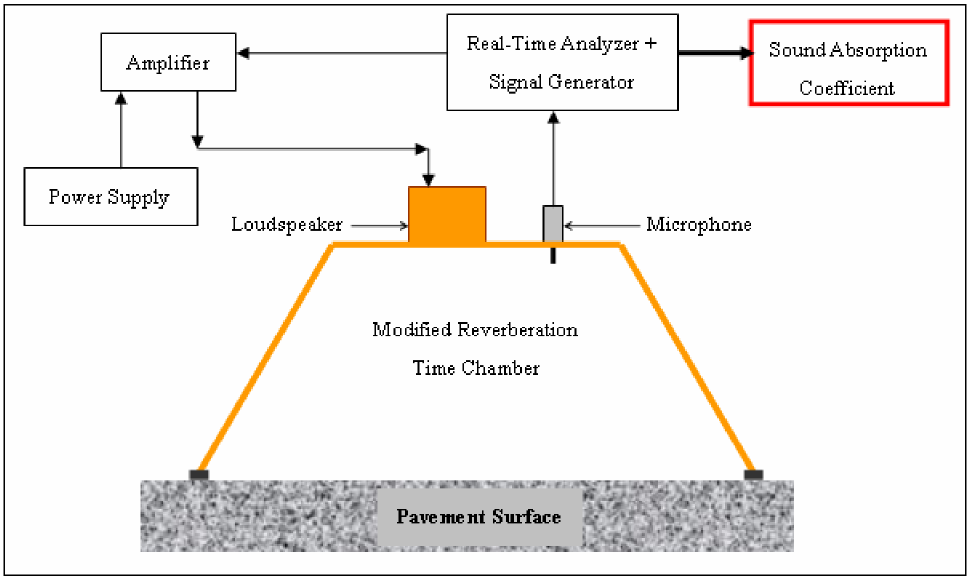

Figure 3.14 – Modified Reverberation Time Chamber Setup Schematic

Figure 3.15 – Picture of Reverberation Time Measurement System

The University of Waterloo carried out field reverberation time measurements on June 2, 2006. Two traffic control personnel from the Regional Municipality of Waterloo with slow/stop signs were on site to control traffic flow during the measurement. Five random locations of each pavement type were selected in this measurement. Sample pavement surface of each pavement is shown in Figure 3.16. Ten RT_{60} measurements were taken in each location. Some measurements were discarded because of the chamber vibration caused by the vehicle pass-by (air-borne and structure-borne).

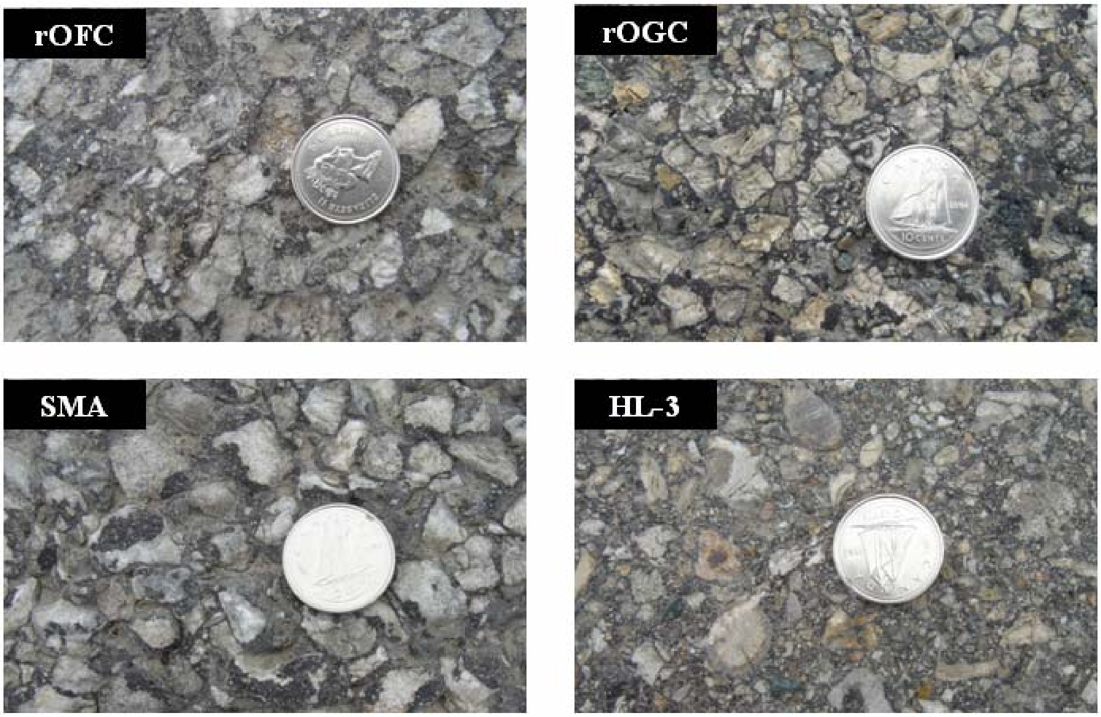

Figure 3.16 – Sample Pavement Surface for Reverberation Time Testing

Since the modified reverberation chamber is a pilot study in measuring pavement absorption properties, it must be validated. Experimental errors such as sound leakage from the edge or vibrating chamber must be taken into account. However, the results presented should be sufficient for comparison purposes since all measurements taken were all recorded under same conditions.

CHAPTER 4: MEASUREMENT RESULTS

Chapter Four summarizes the results obtained from the sound level and sound absorption coefficient measurements. The sound level measurements are the Controlled Pass-By (CPB) Method and the Close Proximity (CPX) Method. The sound absorption coefficient measurements used in this study include the Impedance Tube Method and Reverberation Time Method.

4.1 Sound Level Measurements

Both data of CPB and CPX Methods are summarized in Appendix A and B, respectively. The CPB measurement data includes the measured sound level as a function of 1/3 octave band centre frequency. Some data points are missing due to the technical difficulties or were not tested.

4.1.1 Controlled Pass-By Method

The CPB Method measures noise generated from the tire/pavement, aerodynamics and powertrain. However, tire/pavement noise dominates when a vehicle travels at a steady speed over 50 km/h. Therefore, it can be assumed that the measurement in the CPB Method is mainly contributed by the tire/pavement interaction.

Figures A.1 to A.8 in Appendix A illustrate the sound level measurement versus each 1/3 octave band centre frequency for all test vehicle measurements in both measurement years of CPB Method. All test vehicles generated a similar trend of the frequency spectrum for each pavement mix in both years. Figure A.2, 2004 rOGC frequency spectrum, indicates five measurements are not consistent with the trend. The source of these inconsistencies is from the measurements of the Minivan and Pick-up Truck 1 that are most likely due to the measurement errors. Therefore they are eliminated for the further analysis.

The average frequency spectrum for each asphalt mix for both measurement years are shown in Figures A.9 to A.16. Each figure is categorized into All Vehicles, Vehicle Speeds, and Vehicle Sizes in order to determine whether the sound level and peak frequencies will be influenced by vehicle size and speed. The results show increases in sound level as vehicle size and speed increases throughout the frequency spectrum. However, vehicle sizes and speeds do not affect the location of the peak frequency range that the first peak frequency occurs in between 63 Hz and 80 Hz and second peak frequency occurs in between 630 Hz and 800 Hz for both 2004 and 2005 measurement years.

Figures 4.1 and 4.2 summarize the 2004 and 2005 average sound levels for all vehicles as a function of 1/3 octave centre band frequency for each pavement mix. Generally, it is observed that there are two peaks. Although tire/pavement noise should dominate at the speeds in this study, powertrain noise is observed at the low-frequency range of 50 Hz to 125 Hz which is indicated as the first peak. The second peak occurs at the mid-frequency range of 500 to 1250 Hz, generated by the dominant tire/pavement noise over 50 km/h (i.e. the vehicle speeds in this study).

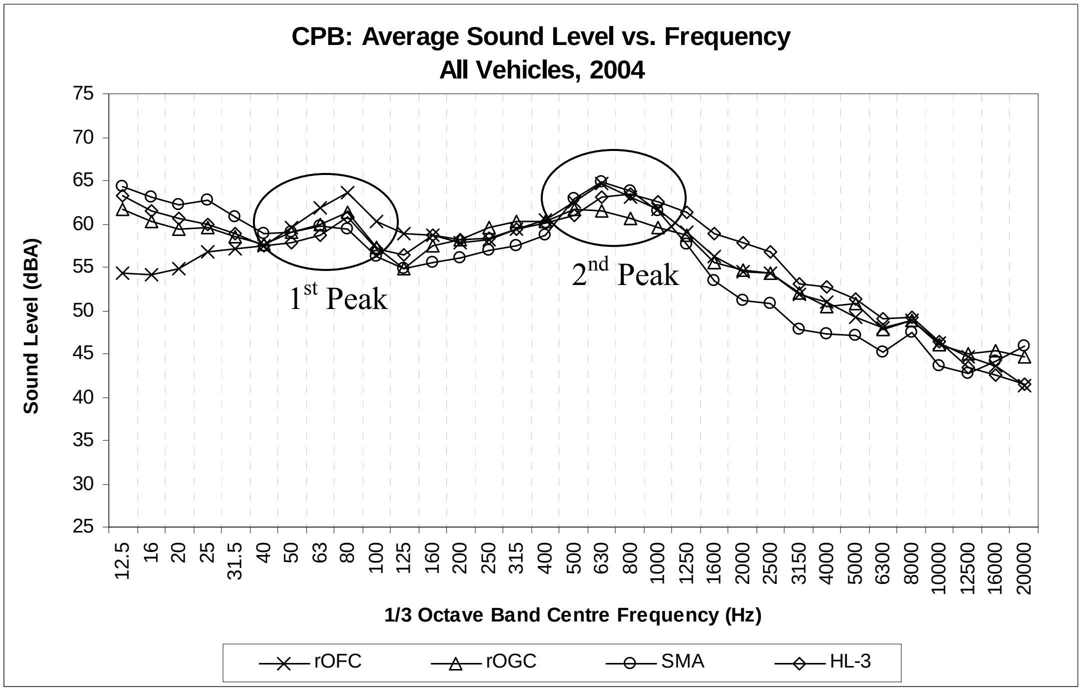

Figure 4.1 – 2004 Average Sound Level versus 1/3 Octave Band Centre Frequency

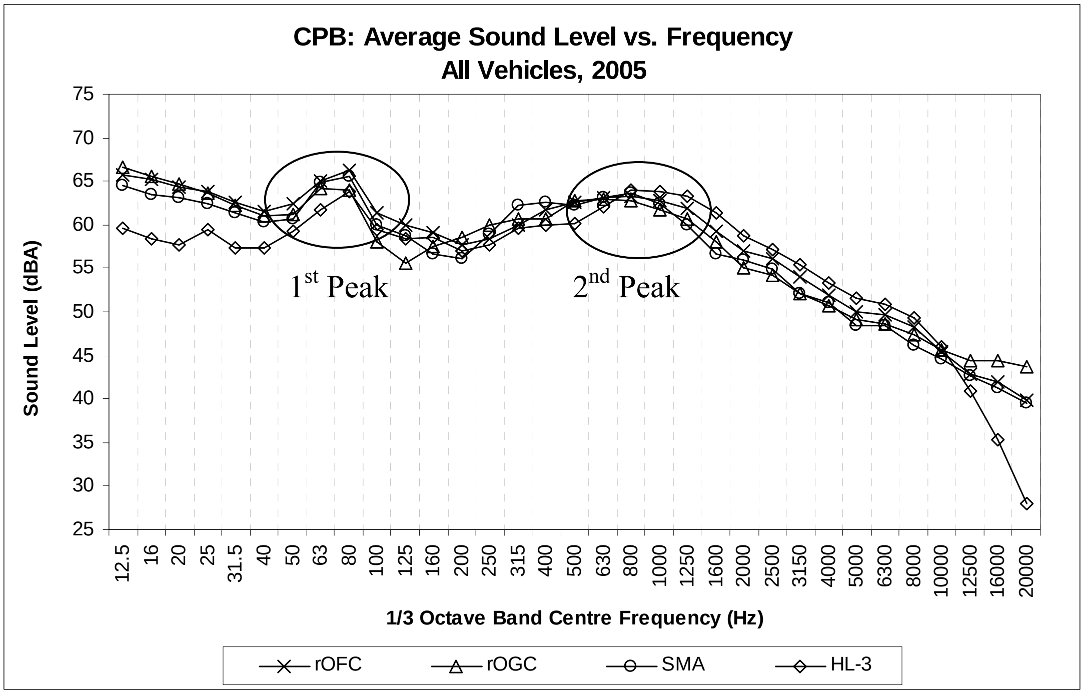

Figure 4.2 – 2005 Average Sound Level versus 1/3 Octave Band Centre Frequency

Figures 4.3 and 4.4 show the 2004 and 2005 CPB average measured sound level versus vehicle speeds presented in terms of vehicle size and pavement type. Table 4.1 summarizes the average measured sound level in a tabular form. Individual plots according to the vehicle sizes are shown in Figures A.17 to A.19.

The CPB measured sound level results have the consistent results with the result from the CPB frequency spectrum that the measured sound level increases as both the vehicle speed and size increased. It is notable that the light vehicles have similar performance while the medium vehicles and heavy vehicles are also clustered together.

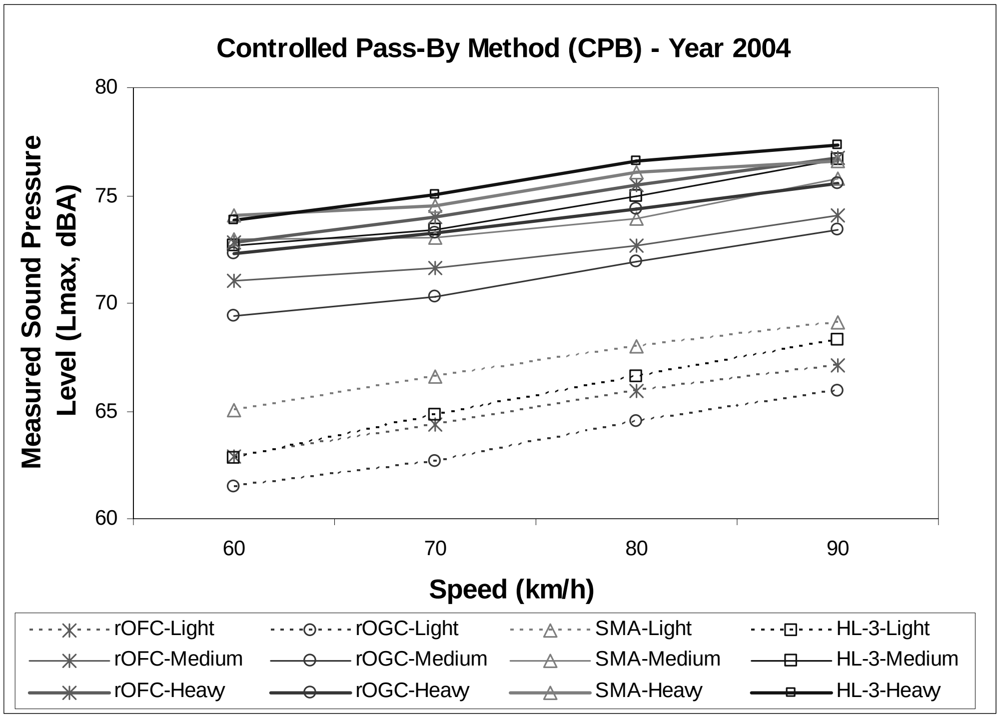

Figure 4.3 – CPB: 2004 Average Measured Sound level versus Vehicle Speeds

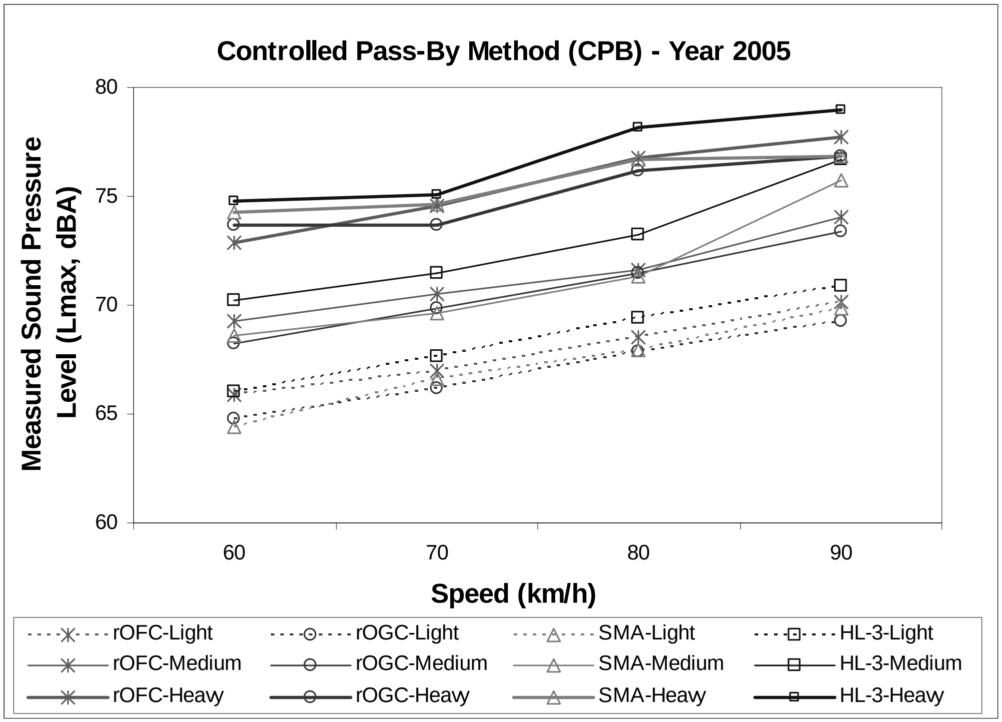

Figure 4.4 – CPB: 2005 Average Measured Sound level versus Vehicle Speeds

Table 4.1 – Summary of CPB Sound Level Measurements

Vehicle Size	Speed (km/h)	Measured Sound Level (dBA)							
		rOFC		rOGC		SMA		HL-3	
		2004	2005	2004	2005	2004	2005	2004	2005
Light	60	62.9	64.6	61.5	64.3	65.0	64.2	62.8	65.0
	70	64.4	66.2	62.7	66.1	66.6	66.1	64.8	67.4
	80	65.9	68.2	64.5	67.7	68.0	67.9	66.6	69.1
	90	67.1	69.7	66.0	69.1	69.1	69.3	68.3	71.0
Medium	60	71.0	70.5	69.4	68.7	73.0	69.7	72.6	71.3
	70	71.6	70.5	70.3	70.0	73.1	70.1	73.4	71.8
	80	72.7	71.9	71.9	71.7	73.9	71.4	75.0	73.5
	90	74.0	74.0	73.4	73.4	75.8	75.8	76.7	76.7
Heavy	60	72.8	72.9	72.3	73.7	74.1	74.3	73.9	74.8
	70	74.0	74.6	73.3	73.7	74.6	74.7	75.0	75.1
	80	75.5	76.8	74.4	76.2	76.1	76.7	76.6	78.2
	90	76.7	77.8	75.6	76.9	76.6	76.9	77.3	79.0

4.1.2 Close-Proximity Method

Figures 4.5 and 4.6 show the 2004 and 2005 CPX average measured sound level versus vehicle speed presented in terms of vehicle size and pavement type. Table 4.2 summarizes the average measured sound level in a tabular form. Individual plots according to the vehicle size are shown in Figures B.1 to B.3.

The results from both years show that the sound level increases as the vehicle speed and size increases for all pavement mixes. The results are similar to those observed for the CPB Method.

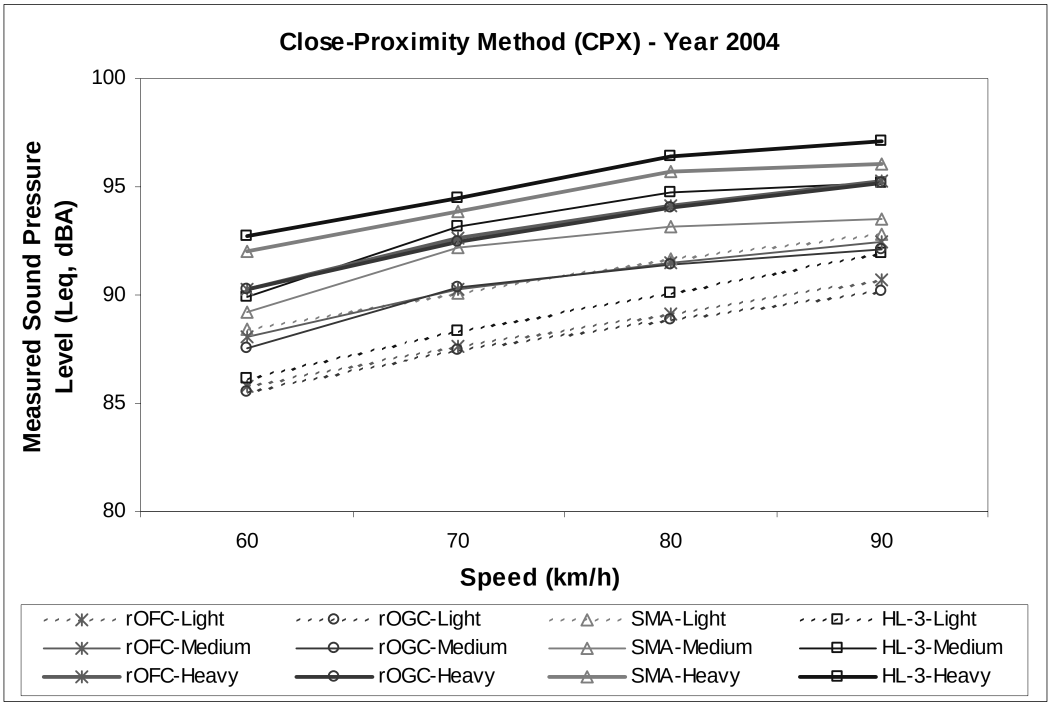

Figure 4.5 – CPX: 2004 Average Measured Sound level versus Vehicle Speeds

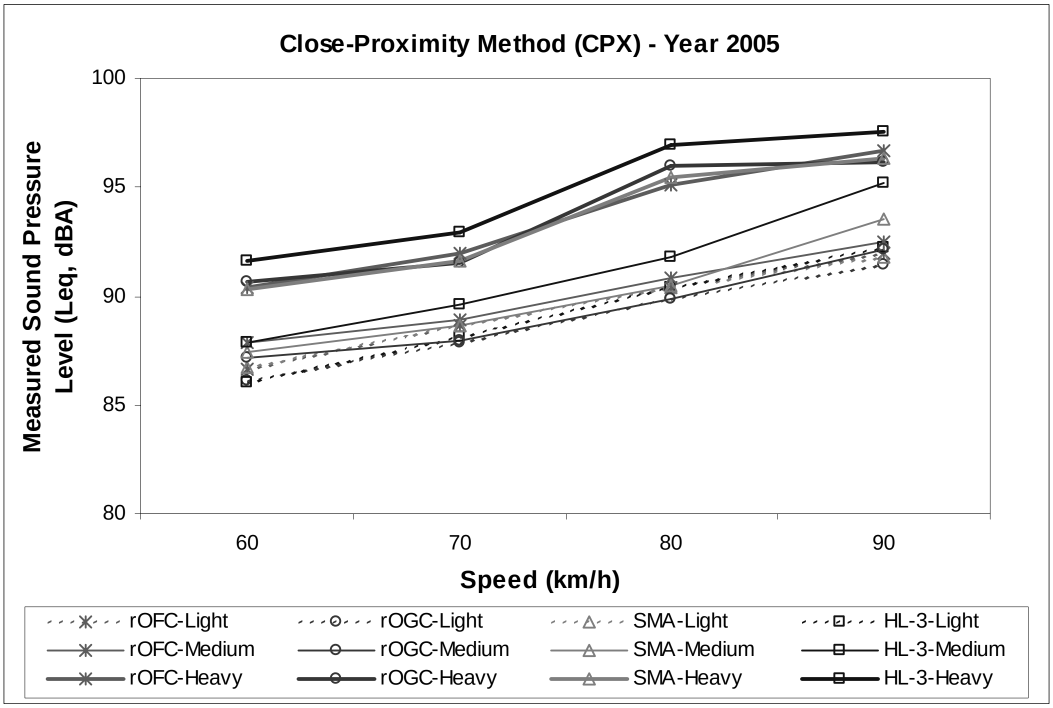

Figure 4.6 – CPX: 2005 Average Measured Sound level versus Vehicle Speeds

Table 4.2 – Summary of CPX Sound Level Measurements

Vehicle Size	Speed (km/h)	Measured Sound Level (dBA)							
		rOFC		rOGC		SMA		HL-3	
		2004	2005	2004	2005	2004	2005	2004	2005
Light	60	85.8	86.6	85.5	86.1	88.4	86.7	86.1	86.0
	70	87.7	88.6	87.5	87.9	90.1	88.6	88.3	88.1
	80	89.1	90.4	88.9	89.8	91.6	90.4	90.1	90.4
	90	90.7	91.9	90.1	91.4	92.9	91.8	91.9	92.2
Medium	60	88.1	87.9	87.5	87.2	89.2	87.4	89.9	87.8
	70	90.3	88.9	90.3	88.0	92.2	88.6	93.2	89.6
	80	91.5	90.8	91.4	89.9	93.2	90.5	94.7	91.8
	90	92.5	92.5	92.1	92.1	93.5	93.5	95.2	95.2
Heavy	60	90.3	90.4	90.3	90.7	92.0	90.3	92.8	91.6
	70	92.7	92.0	92.4	91.6	93.9	91.6	94.4	93.0
	80	94.1	95.1	94.0	96.0	95.7	95.5	96.4	97.0
	90	95.3	96.7	95.2	96.2	96.1	96.4	97.1	97.6

4.1.3 Mixes Ranking according to the Measured Sound Levels

This section ranks the asphalt mixes from the quietest to the noisiest according to the measured sound levels from 2004 and 2005. The quietest mix represents the mix has the lowest measured sound level among all mixes. The rankings are categorized in accordance with the average measured sound levels from both 2004 and 2005 in both sound measurement methods (i.e. CPB and CPX). The purpose of the categorization is to determine whether the sound level will be influenced by the vehicle sizes and vehicle types:

All Vehicles

Vehicle Sizes

- Light Vehicles
- Medium Vehicles
- Heavy Vehicles

Vehicle Speeds

- 60 km/h

- 70 km/h
- 80 km/h
- 90 km/h

Vehicle Sizes at a Particular Speed

- Light, Medium, and Heavy Vehicles at 60 km/h
- Light, Medium, and Heavy Vehicles at 70 km/h
- Light, Medium, and Heavy Vehicles at 80 km/h
- Light, Medium, and Heavy Vehicles at 90 km/h

4.1.3.1 Compared with All Vehicles

Table 4.3 shows the ranking from the quietest to the noisiest mix according to the average sound level from all results (i.e. both years and methods). The results show that the ranking from the CPB Method is the same as the CPX Method. The ranking indicates that rOGC is the quietest for both methods and years. Both methods used in 2004 show that rOFC is quieter than HL-3, while SMA is the noisiest mix. However, both methods in 2005 show that SMA is the second quietest mix and HL-3 becomes the nosiest mix.

Table 4.3 – Ranking of the Mixes: Compared with All Vehicles

Comparison		Controlled Pass-By (CPB)				Close-Proximity (CPX)			
Vehicle Type	Year	Quietest Mix < ---------- > Noisiest Mix				Quietest Mix < ---------- > Noisiest Mix			
All Vehicles	2004	rOGC	rOFC	HL-3	SMA	rOGC	rOFC	HL-3	SMA
	2005	rOGC	SMA	rOFC	HL-3	rOGC	SMA	rOFC	HL-3

4.1.3.2 Compared with Vehicle Sizes

Table 4.4 summarizes the ranking from the quietest to the noisiest mix, categorized by vehicle sizes. Generally, the results show that the ranking from the CPB Method is the same as the CPX Method. The ranking indicates that rOGC is the quietest mix and HL-3 is noisiest mix in both methods and years, regardless of the vehicle sizes. rOFC is quieter than SMA based on 2004 results, but SMA becomes better than rOFC in 2005.

Table 4.4 – Ranking of the Mixes: Compared with Vehicle Sizes

Comparison		Controlled Pass-By (CPB)				Close-Proximity (CPX)			
Vehicle Type	Year	Quietest Mix < ---------- > Noisiest Mix				Quietest Mix < ---------- > Noisiest Mix			
Light	2004	rOGC	rOFC	HL-3	SMA	rOGC	rOFC	HL-3	SMA
	2005	rOGC	SMA	rOFC	HL-3	rOGC	HL-3	SMA	rOFC
Medium	2004	rOGC	rOFC	SMA	HL-3	rOGC	rOFC	SMA	HL-3
	2005	rOGC	SMA	rOFC	HL-3	rOGC	SMA	rOFC	HL-3
Heavy	2004	rOGC	rOFC	SMA	HL-3	rOGC	rOFC	SMA	HL-3
	2005	rOGC	rOFC	SMA	HL-3	SMA	rOFC	rOGC	HL-3

4.1.3.3 Compared with Vehicle Speeds

Table 4.5 summarizes the ranking from the quietest to the noisiest mix, categorized by vehicle speeds. Generally, the results show that the ranking from the CPB Method is the same as the CPX Method. rOGC is the quietest mix regardless of the vehicle speeds in both measurement years and methods. Based on the speeds of 60 and 70 km/h in 2004 measurement, and rOFC is quieter than HL-3 and SMA is the nosiest mix. However, in 2005 measurement, HL-3 becomes the nosiest mix and SMA is quieter than rOFC. In terms of 80 and 90 km/h, HL-3 is the noisiest mix in both years. rOFC is quieter than SMA in 2004, but vice versa in 2005.

Table 4.5 – Ranking of the Mixes: Compared with Vehicle Speeds

Comparisons		Controlled Pass-By (CPB)				Close-Proximity (CPX)			
Vehicle Speed	Year	Quietest Mix < ---------- > Noisiest Mix				Quietest Mix < ---------- > Noisiest Mix			
60 km/h	2004	rOGC	rOFC	HL-3	SMA	rOGC	rOFC	HL-3	SMA
	2005	rOGC	SMA	rOFC	HL-3	rOGC	SMA	HL-3	rOFC
70 km/h	2004	rOGC	rOFC	HL-3	SMA	rOGC	rOFC	HL-3	SMA
	2005	rOGC	SMA	rOFC	HL-3	rOGC	SMA	rOFC	HL-3
80 km/h	2004	rOGC	rOFC	SMA	HL-3	rOGC	rOFC	SMA	HL-3
	2005	rOGC	SMA	rOFC	HL-3	rOGC	SMA	rOFC	HL-3
90 km/h	2004	rOGC	rOFC	SMA	HL-3	rOGC	rOFC	SMA	HL-3
	2005	rOGC	SMA	rOFC	HL-3	rOGC	SMA	rOFC	HL-3

4.1.3.4 Compared with Vehicle Sizes at 60 km/h

Table 4.6 summarizes the ranking from the quietest to the noisiest mix, categorized by the vehicle sizes at the speed of 60 km/h. The results show that the ranking from the CPB Method is difference than the ranking from CPX Method in both years.

In terms of light vehicle category in CPB and CPX Methods in 2004, rOGC and SMA is the quietest and the noisiest mix, respectively. HL-3 is quieter than rOFC in the CPB Method, but it is nosier than rOFC in the CPX Method. In 2005, SMA is the quietest mix in the CPB Method, but it is the noisiest mix in the CPX Method. HL-3 is the noisiest mix in CPB Method, but it is the quietest in the CPX Method in 2005. However, rOGC is quieter than rOFC in both methods in 2005.

In terms of medium vehicle category, rOGC is the quietest mix in both methods and years. rOFC and SMA are the second quietest mix in 2004 and 2005 methods, respectively. HL-3 is the noisiest mix in 2004 CPX Method and 2005 CPB Method. rOFC and SMA are the noisiest mix in 2005 CPX Method and 2004 CPB Method, respectively.

In terms of heavy vehicle category, rOGC is the quietest mix in both methods in 2004. rOFC becomes the quietest mix in both methods in 2005.

Table 4.6 – Ranking of the Mixes: Compared with Vehicle Sizes at 60 km/h

Comparison		Controlled Pass-By (CPB)				Close-Proximity (CPX)			
60 km/h	Year	Quietest Mix < ---------- > Noisiest Mix				Quietest Mix < ---------- > Noisiest Mix			
Light	2004	rOGC	HL-3	rOFC	SMA	rOGC	rOFC	HL-3	SMA
	2005	SMA	rOGC	rOFC	HL-3	HL-3	rOGC	rOFC	SMA
Medium	2004	rOGC	rOFC	HL-3	SMA	rOGC	rOFC	SMA	HL-3
	2005	rOGC	SMA	rOFC	HL-3	rOGC	SMA	HL-3	rOFC
Heavy	2004	rOGC	rOFC	HL-3	SMA	rOGC	SMA	HL-3	rOFC
	2005	rOFC	rOGC	SMA	HL-3	rOFC	rOGC	HL-3	SMA

4.1.3.5 Compared with Vehicle Sizes at 70 km/h

Table 4.7 summarizes the ranking from the quietest to the noisiest mix, categorized by the vehicle sizes at the speed of 70 km/h. Generally, the results show that the ranking from the CPB Method is the same as the CPX Method. rOGC is the quietest mix in both years. SMA is the nosiest mix in terms of light vehicle category, but HL-3 is the nosiest mix in terms of medium and heavy vehicle categories. In 2004, rOFC is quieter than SMA in both medium and heavy vehicle categories, but the ranking is reversed in 2005.

Table 4.7 – Ranking of the Mixes: Compared with Vehicle Sizes at 70 km/h

Comparison		Controlled Pass-By (CPB)				Close-Proximity (CPX)			
70 km/h	Year	Quietest Mix < ---------- > Noisiest Mix				Quietest Mix < ---------- > Noisiest Mix			
Light	2004	rOGC	rOFC	HL-3	SMA	rOGC	rOFC	HL-3	SMA
	2005	rOGC	SMA	rOFC	HL-3	rOGC	HL-3	rOFC	SMA
Medium	2004	rOGC	rOFC	SMA	HL-3	rOFC	rOGC	SMA	HL-3
	2005	rOGC	SMA	rOFC	HL-3	rOGC	SMA	rOFC	HL-3
Heavy	2004	rOGC	rOFC	SMA	HL-3	rOGC	rOFC	SMA	HL-3
	2005	rOGC	rOFC	SMA	HL-3	rOGC	SMA	rOFC	HL-3

4.1.3.6 Compared with Vehicle Sizes at 80 km/h

Table 4.8 summarizes the ranking from the quietest to the noisiest mix, categorized by the vehicle sizes at the speed of 80 km/h. Generally, the results show that the ranking from the CPB Method is the same as the CPX Method. rOGC is the quietest mix in both years. HL-3 is the nosiest mix in both years except in terms of light vehicle category in 2004. rOFC is quieter than SMA in both medium and heavy vehicle categories in 2004, but the ranking is reversed in 2005.

Table 4.8 – Ranking of the Mixes: Compared with Vehicle Sizes at 80 km/h

Comparison		Controlled Pass-By (CPB)				Close-Proximity (CPX)			
80 km/h	Year	Quietest Mix < ---------- > Noisiest Mix				Quietest Mix < ---------- > Noisiest Mix			
Light	2004	rOGC	rOFC	HL-3	SMA	rOGC	rOFC	HL-3	SMA
	2005	rOGC	SMA	rOFC	HL-3	rOGC	rOFC	SMA	HL-3
Medium	2004	rOGC	rOFC	SMA	HL-3	rOGC	rOFC	SMA	HL-3
	2005	SMA	rOGC	rOFC	HL-3	rOGC	SMA	rOFC	HL-3
Heavy	2004	rOGC	rOFC	SMA	HL-3	rOGC	rOFC	SMA	HL-3
	2005	rOGC	SMA	rOFC	HL-3	rOFC	SMA	rOGC	HL-3

4.1.3.7 Compared with Vehicle Sizes at 90 km/h

Table 4.9 summarizes the ranking from the quietest to the noisiest mix, categorized by vehicle sizes at the speed of 90 km/h. Generally, the results show that the ranking from the CPB Method is the same as the CPX Method. rOGC is the quietest mix in both years. HL-3 is the noisiest mix in both years except in terms of light vehicle category in 2004. rOFC is quieter than SMA in both medium and heavy vehicle categories in 2004, but the ranking is reversed in 2005.

Table 4.9 – Ranking of the Mixes: Compared with Vehicle Sizes at 90 km/h

Comparison		Controlled Pass-By (CPB)				Close-Proximity (CPX)			
80 km/h	Year	Quietest Mix < ---------- > Noisiest Mix				Quietest Mix < ---------- > Noisiest Mix			
Light	2004	rOGC	rOFC	HL-3	SMA	rOGC	rOFC	HL-3	SMA
	2005	rOGC	SMA	rOFC	HL-3	rOGC	SMA	rOFC	HL-3
Medium	2004	rOGC	rOFC	SMA	HL-3	rOGC	rOFC	SMA	HL-3
	2005	rOGC	SMA	rOFC	HL-3	rOGC	SMA	rOFC	HL-3
Heavy	2004	rOGC	SMA	rOFC	HL-3	rOGC	rOFC	SMA	HL-3
	2005	rOGC	SMA	rOFC	HL-3	rOGC	SMA	rOFC	HL-3

4.2 Sound Absorption Coefficient Measurements

Sound absorption coefficient data from both Impedance Tube Method and Reverberation Time Method are located in Appendix C and D, respectively. The following sections summarize the sound absorption coefficient of each pavement mix.

4.2.1 Impedance Tube Method

The Impedance Tube Method is used to determine the normal incident sound absorption coefficient at various frequencies. The Impedance Tube measurement results of each mix are illustrated in Appendix C. There are two types of samples that were tested: Gyratory and Field Core samples. Gyratory samples using the same mix from the test site were compacted by the Superpave Gyratory Compactor. Field core samples were taken directly from the test site in March 2006, approximately 20 months after construction. The trends of sample curves in each mix are very consistent in the Figures of Appendix C. Table 4.10 summarizes both gyratory and field core samples sound absorption coefficient results versus 1/3 octave band centre frequencies and the average sound absorption coefficient throughout the working frequency spectrum using Impedance Tube Method. According to the impedance tube design; the theoretical lower and upper frequencies that can be measured are 170 Hz and 1335 Hz, respectively. However, it is observed the actual working frequency range is between 200 Hz and 1200 Hz which is close to the working frequency that NCAT defined.

Table 4.10 – Summary of Impedance Tube Sound Absorption Coefficient

1/3 Octave Band Centre Frequency (Hz)	Impedance Tube – Sound Absorption Coefficient							
	rOFC		rOGC		SMA		HL-3	
	Gyratory	Core	Gyratory	Core	Gyratory	Core	Gyratory	Core
200	0.024	0.041	0.031	0.047	0.025	0.031	0.041	0.027
250	0.034	0.039	0.043	0.061	0.025	0.039	0.050	0.028
315	0.049	0.034	0.059	0.057	0.036	0.039	0.071	0.027
400	0.086	0.034	0.089	0.055	0.053	0.038	0.084	0.031
500	0.104	0.025	0.105	0.042	0.059	0.025	0.058	0.021
630	0.081	0.030	0.085	0.048	0.055	0.033	0.061	0.027
800	0.074	0.038	0.079	0.059	0.053	0.045	0.071	0.035
1000	0.089	0.034	0.103	0.056	0.058	0.038	0.078	0.032
1250	0.081	0.057	0.105	0.083	0.066	0.071	0.113	0.054
Overall	0.077	0.037	0.085	0.057	0.050	0.048	0.070	0.033

Figures 4.7 and 4.8 summarize the average sound absorption coefficient of the samples versus frequencies for both Gyratory and Field Core samples.

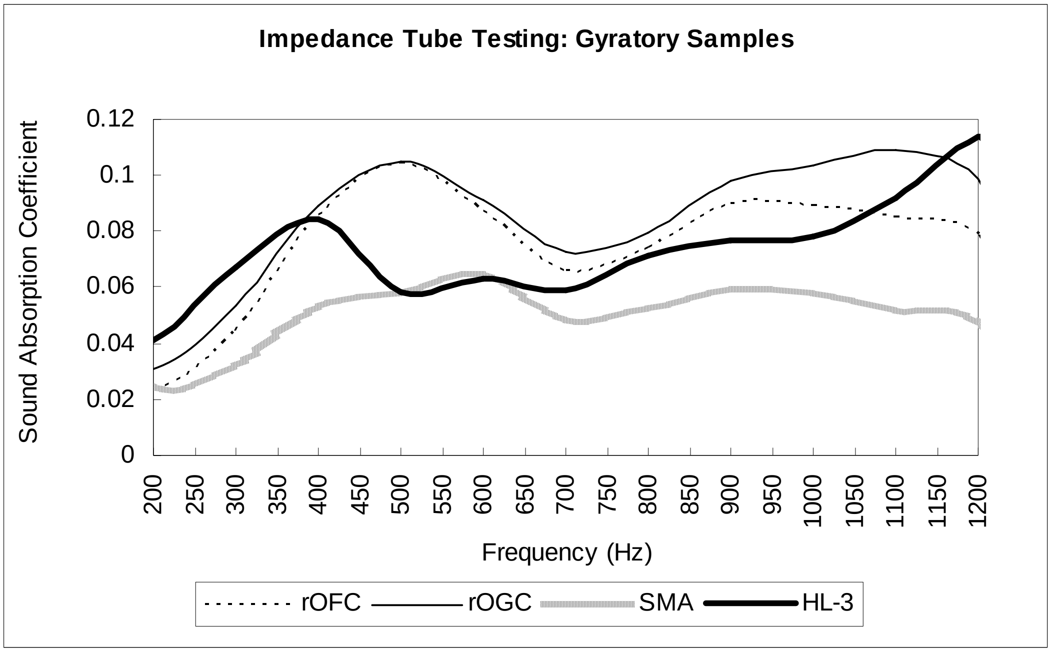

Figure 4.7 – Impedance Tube: Average Sound Absorption Coefficient vs. Frequency for Gyratory Samples

It is observed that peaks occurred in the gyratory samples in Figure 4.7. The first peak frequencies of rOFC and rOGC are within 450 Hz to 550 Hz. The first peak frequency of HL-3 occurs at a lower range than rOFC and rOGC between 350 Hz to 400 Hz. The first peak of SMA is boarder, lower, and as not as obvious as the other mixes. The second peak of all mixes is not shown as obvious as the first peaks. The trends of rOFC and rOGC are similar and they have a higher magnitude of sound absorption when compared to SMA and HL-3 in the frequency range of 350 Hz to 1100 Hz. The first peak absorption coefficients of rOFC and rOGC are about 0.1 at a frequency of 500 Hz. This absorption coefficient represents 10% of sound waves hitting the pavement surface are absorbed and 90% of sound waves are reflected. The first peak absorption coefficient of HL-3 is about 0.08 at 375 Hz whereby 8% of sound waves are absorbed and 92% of sound waves are reflected. For SMA, the highest sound absorption coefficient is about 0.06 at 600 Hz.

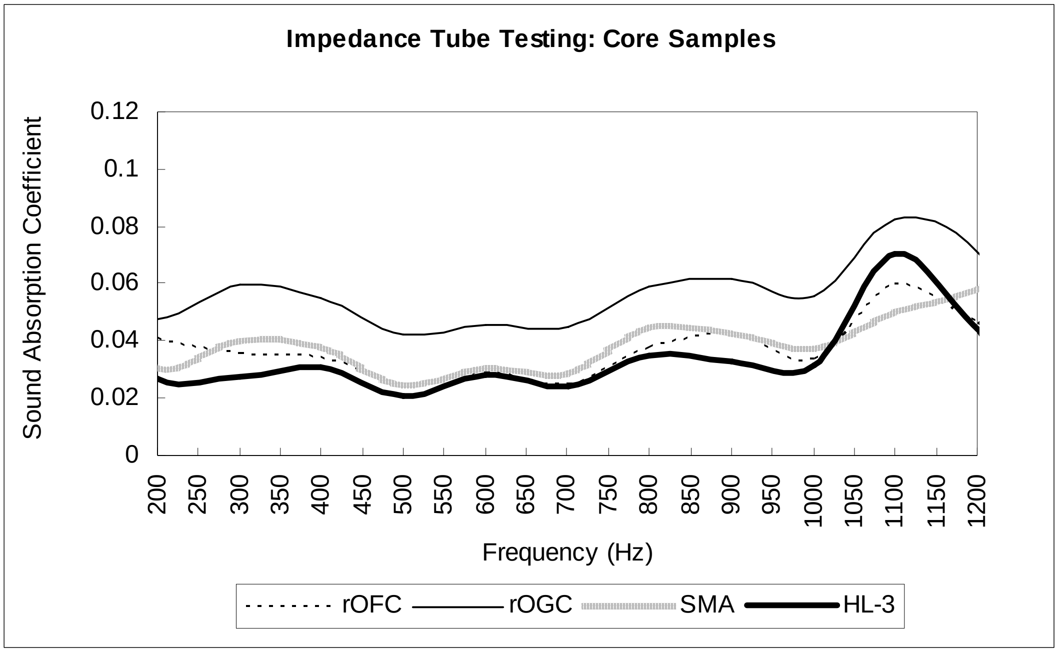

Figure 4.8 – Impedance Tube: Average Sound Absorption Coefficient vs. Frequency for Core Samples

Impedance Tube Testing results show that the trends and patterns of all field core samples are very similar in Figure 4.8. There are a few peaks occurred in each curve. The highest peaks are in the range of 1000 Hz to 1200 Hz. From that range, rOGC has the highest sound absorption coefficient of 0.08, HL-3 has the second highest (0.06), rOFC has the third highest (0.05) and SMA has the lowest (0.04). In terms of the rest of the working frequencies, the sound absorption coefficient of rOGC is higher than the others by 0.02 approximately.

4.2.2 Reverberation Time Method

The Reverberation Time Method is used to measure the required time for a sound wave to dissipate 60 dBA after the sound source stopped in an enclosed room at a specified frequency. This time is known as the Reverberation Time 60 (RT_{60}). The sound absorption coefficient is then calculated using the RT_{60} measured from the Reverberation Time Method. RT_{60} on each pavement mix was taken from the test site in May 2006, approximately 22 months after construction. RT_{60} versus frequency and calculated sound absorption coefficient versus frequency are shown in Appendix D. Table 4.11 summarizes the in-service pavement sound absorption coefficient results versus 1/3 octave band centre frequencies and the average sound absorption coefficient using Reverberation Time Method. As noted from Section 3.4.2, the calculated sound absorption coefficient in this study is the average sound absorption coefficient of the materials inside the reverberation chamber, which includes the MDF, the speaker, and the pavement surface, rather than simply the pavement surface. Therefore the results presented in this section are used for the comparison purposes only.

Table 4.11 – Summary of Reverberation Time Sound Absorption Coefficient

1/3 Octave Band Centre Frequency (Hz)	Reverberation Time – Sound Absorption Coefficient			
	rOFC	rOGC	SMA	HL-3
200	0.021	0.022	0.025	0.018
250	0.042	0.069	0.064	0.046
315	0.047	0.049	0.060	0.047
400	0.039	0.042	0.047	0.042
500	0.037	0.027	0.025	0.021
630	0.024	0.019	0.016	0.014
800	0.039	0.034	0.030	0.021
1000	0.031	0.030	0.031	0.020
1250	0.033	0.038	0.037	0.031
Overall	0.035	0.037	0.037	0.029

The average sound absorption coefficient of the reverberation chamber on each in-service pavement types versus frequencies is shown in Figure 4.9.

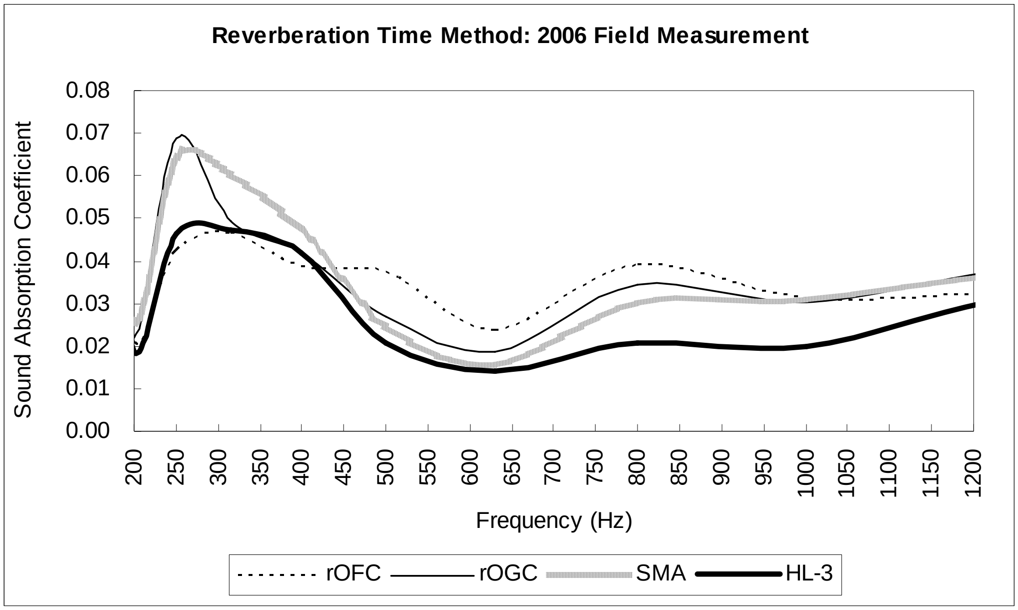

Figure 4.9 – Reverberation Time: Average Sound Absorption Coefficient vs. Frequency for In-Service Pavement

Reverberation Time Method results show that the trend of all field core mix samples are similar. Two peaks occurred on each pavement types. The first peak occurred at the lower frequency ranges of 250 Hz to 400 Hz. The second peak occurred at a frequency range of 750 Hz to 850 Hz. The first peak of sound absorption coefficients of rOFC and HL-3 mixes are 0.045. rOGC and SMA have similar first peak sound absorption coefficients at 0.65. From the observed second peak, the rOFC absorbs the largest amount of sound compared to other mixes, rOGC is better than SMA, and HL-3 absorbs the least amount of sound.

4.2.3 Mixes Ranking according to the Sound Absorption Coefficients

This section summarizes the sound absorption coefficient ranking of the asphalt mixes employed in this study according to the results from the Impedance Tube and Reverberation Time Methods. The mix with a high sound absorption coefficient means that mix absorbs more sound. The ranking is categorized into 1/3 octave band centre frequencies between 200 Hz and 1250 Hz.

Table 4.12 demonstrates the ranking of the gyratory samples according to the results from the Impedance Tube Method. rOGC has the highest sound absorption coefficient from 400 Hz to

1000 Hz of the 1/3 octave band centre frequencies. HL-3 has the highest sound absorption coefficient from 200 Hz to 315 Hz and 1250 Hz. SMA has the lowest sound absorption coefficient in most of the 1/3 octave band centre frequencies. The overall ranking is the same as the ranking from 400 to 1000 Hz 1/3 octave band centre frequencies. Although at 500 Hz, the ranking shows that SMA has a higher sound absorption coefficient than HL-3, the sound absorption coefficient difference is 0.001 only.

Table 4.12 – Ranking of the Mixes: Impedance Tube Gyratory Sample

1/3 Octave Band Centre Frequency (Hz)	Impedance Tube Gyratory Samples			
	Highest Sound Absorption Sample < ---- > Lowest Sound Absorption Sample			
200	HL-3	rOGC	SMA	rOFC
250	HL-3	rOGC	rOFC	SMA
315	HL-3	rOGC	rOFC	SMA
400	rOGC	rOFC	HL-3	SMA
500	rOGC	rOFC	SMA	HL-3
630	rOGC	rOFC	HL-3	SMA
800	rOGC	rOFC	HL-3	SMA
1000	rOGC	rOFC	HL-3	SMA
1250	HL-3	rOGC	rOFC	SMA
Overall	rOGC	rOFC	HL-3	SMA

Table 4.13 ranks the field core samples according to the results from the Impedance Tube Method. rOGC has the highest sound absorption coefficient at all 1/3 octave band centre frequencies. HL-3 has the lowest sound absorption coefficient at all 1/3 octave band centre frequencies. The overall ranking is the same as the ranking that from all 1/3 octave band centre frequencies except at 200 Hz.

Table 4.13 – Ranking of the Mixes: Impedance Tube Field Sample

1/3 Octave Band Centre Frequency (Hz)	Impedance Tube Field Core Samples			
	Highest Sound Absorption Sample < ---- > Lowest Sound Absorption Sample			
200	rOGC	rOFC	SMA	HL-3
250	rOGC	SMA[1]	rOFC[1]	HL-3
315	rOGC	SMA	rOFC	HL-3
400	rOGC	SMA	rOFC	HL-3
500	rOGC	SMA[2]	rOFC[2]	HL-3
630	rOGC	SMA	rOFC	HL-3
800	rOGC	SMA	rOFC	HL-3
1000	rOGC	SMA	rOFC	HL-3
1250	rOGC	SMA	rOFC	HL-3
Overall	rOGC	SMA	rOFC	HL-3

Note:

[1] The absorption coefficients of rOFC and SMA are the same to the nearest 1000th; therefore it is assumed that their ranking is inter-changeable

[2] The absorption coefficients of rOFC and SMA are the same to the nearest 1000th; therefore it is assumed that their ranking is inter-changeable

Table 4.14 summarizes the ranking of the in-service pavement according to the results from the Reverberation Time Method. rOFC and SMA have the highest sound absorption coefficient in most of the 1/3 octave band centre frequencies. rOGC places the second highest sound absorption coefficient in most of the 1/3 octave band centre frequencies. HL-3 has the second and lowest sound absorption coefficient in most of the 1/3 octave band centre frequencies. The overall ranking result from the Reverberation Time Method are consistent with the Impedance Tube overall ranking that rOGC has the highest sound absorption coefficient, SMA is better than rOFC, and HL-3 has the lowest sound absorption coefficient.

Table 4.14 – Ranking of the Mixes: Reverberation Time Method on In-Service Pavements

1/3 Octave Band Centre Frequency (Hz)	Reverberation Chamber on In-Service Pavement			
	Highest Sound Absorption Sample < ---- > Lowest Sound Absorption Sample			
200	SMA	rOGC	rOFC	HL-3
250	rOGC	SMA	HL-3	rOFC
315	SMA	rOGC	HL-3	rOFC
400	SMA	rOGC	HL-3	rOFC
500	rOFC	rOGC	SMA	HL-3
630	rOFC	rOGC	SMA	HL-3
800	rOFC	rOGC	SMA	HL-3
1000	rOFC[1]	SMA[1]	rOGC	HL-3
1250	rOGC	SMA	rOFC	HL-3
Overall	rOGC[2]	SMA[2]	rOFC	HL-3

Note:
[1] The absorption coefficients of rOFC and SMA are the same to the nearest 1000th; therefore it is assumed that their ranking is inter-changeable
[2] The absorption coefficients of rOGC and SMA are the same to the nearest 1000th; therefore it is assumed that their ranking is inter-changeable

4.3 Summary of Findings

The sound level measurement results indicate that sound level increases as the vehicle size and vehicle speed increases. However, the vehicle size and speed do not affect the pattern and trend of the frequency spectrum where the peaks occur at 63-80 Hz and 630-800 Hz. The asphalt mixes have also been ranked and analyzed based on vehicle type and speed in the sound level measurements and based on the 1/3 octave band centre frequencies in the sound absorption coefficient measurements. Table 4.15 summarizes the major rankings from all measurements and divides the rankings into two similar aged groups, “New” and “More than One Year of Service”, as follows:

New

- Sound level measurement data using the CPB and CPX Methods in September 2004 (i.e. one month after construction)
- Sound absorption coefficient of gyratory samples using Impedance Tube Method. The mixes used for the gyratory samples are from the test site in August 2004.

More than One Year of Service

- Sound level measurement data using the CPB and CPX Methods in October 2005 (i.e. 14 months after construction)
- Sound absorption coefficient of March 2006 (i.e. 22 months after construction) field core samples using Impedance Tube Method
- Sound absorption coefficient of in-service pavements using Reverberation Time method in May 2006 (i.e. 22 months after construction)

The major rankings include the average of all vehicle sound level measurements and the sound absorption coefficients at 630 Hz and 1000 Hz. The 600 Hz is the critical frequency for low speed roads (approximately 50 km/h) and the 1000 Hz is the critical frequency for high speed roads (greater than 85 km/h). Since the ranking is presented in terms of 1/3 octave band frequency spectrum, 630 Hz is used instead of 600 Hz for low speed roads.

Table 4.15 – Summary of Major Ranking of All Measurement Methods

Age Group	Measurement Method	Categories	Quietest Mix < ----------------- > Noisiest Mix			
New	CPB	All Vehicles	rOGC	rOFC	HL-3	SMA
	CPX	All Vehicles	rOGC	rOFC	HL-3	SMA
	Impedance Tube	Overall	rOGC	rOFC	HL-3	SMA
		630 Hz	rOGC	rOFC	HL-3	SMA
		1000 Hz	rOGC	rOFC	HL-3	SMA
More than One Year of Service	CPB	All Vehicles	rOGC	SMA	rOFC	HL-3
	CPX	All Vehicles	rOGC	SMA	rOFC	HL-3
	Impedance Tube	Overall	rOGC	SMA	rOFC	HL-3
		630 Hz	rOGC	SMA	rOFC	HL-3
		1000 Hz	rOGC	SMA	rOFC	HL-3
	Reverberation Time	Overall	rOGC[1]	SMA[1]	rOFC	HL-3
		630 Hz	rOFC	rOGC	SMA	HL-3
		1000 Hz	rOFC[2]	SMA[2]	rOGC	HL-3

Note:
[1] rOGC and SMA are inter-changeable according to Tables 4.11 and 4.14
[2] rOFC and SMA are inter-changeable according to Tables 4.11 and 4.14

The CPB Method is used to measure the sound level at a distance of 15 m away from the vehicle path, while the CPX Method is used to measure the sound level near the tire/pavement interface. The overall sound level measurement rankings of the CPB and CPX Methods are consistent. Both method results indicate that rOGC is the quietest followed by rOFC, the control HL-3, and SMA is the noisiest in the "New" age group. After the pavement mixes were put into service for more than a year (i.e. "More than One Year of Service" age group), rOGC remains the quietest mix ranking, but SMA becomes the second quietest mix and the control HL-3 is the noisiest.

The Impedance Tube and Reverberation Time Methods are used to measure the normal and random (i.e. Sabine) incidence sound absorption coefficient of the pavement types, respectively. Based on the results from the sound absorption coefficient measurements, certain pavement types have a higher performance at certain frequency bands than the others. However, the range of the entire dataset with respect to sound absorption coefficient is between 0.01 and 0.1, which is relatively small. The overall rankings from the Impedance Tube and Reverberation Time Methods are consistent with the rankings from the same age group of the sound level measurement results. The Impedance Tube Method ranking at 630 Hz and 1000 Hz are also consistent with the overall ranking, but not for the Reverberation Time Method ranking at 630 Hz and 1000 Hz. However the rankings at 630 Hz and 1000 Hz from the Reverberation Time Method also indicate that the control HL-3 is the noisiest mix.

CHAPTER 5: STATISTICAL ANALYSIS

A paired t-test statistical analysis was carried out to examine whether the asphalt mixes tested are significantly different. The analysis includes comparisons between studied mixes (i.e. rOFC, rOGC, and SMA) and the control mix (i.e. HL-3). A comparison between rOFC and rOGC is also included because these two pavement mixes have a similar mix design but have a major difference in the quality of the aggregates. At noted previously, rOFC utilizes premium aggregate while rOGC utilizes local aggregate which does not meet all the strict requirements. The purpose of using a paired t-test is to eliminate the variability present among vehicles when comparing the measured sound level between asphalt mixes and eliminate the variability present among frequencies when comparing the absorption coefficient measurement [Leung 07].

The hypothesis for the paired t-test is as follows:

- H_o: $\mu_D = 0$, there is no significant difference between the asphalt mixes
- H_1: $\mu_D \neq 0$, there is a significant difference between the asphalt mixes

where μ_D is the average of the sound level difference or sound absorption coefficient difference between each pair of asphalt mixes being compared. The null hypothesis (H_o) representing the average difference between each pair of asphalt mixes is 0 dBA in sound level comparison or zero in sound absorption coefficient comparison. The null hypothesis is rejected if the t_{value} calculated is greater than the $t_{critical}$ at the 5% level of significance or if the P-value is less than the 5% level of significance. In other words, the average value of the mean difference does not include zero at a 95% confidence interval resulting in the average value of the mean difference is statistically significant.

5.1 Sound Level Measurement

The average sound level differences and the statistical analysis results between the studied mixes for both CPB and CPX Methods and years are summarized in tabular form in Appendix E. The analysis is categorized into the following scenarios in order to determine whether the sound level is influenced by the vehicle sizes and/or speeds:

All Vehicles

Vehicle Sizes

- Light Vehicles
- Medium Vehicles
- Heavy Vehicles

Vehicle Speeds

- 60 km/h
- 70 km/h
- 80 km/h
- 90 km/h

Vehicle Sizes at a Particular Speed

- Light, Medium, and Heavy Vehicles at 60 km/h
- Light, Medium, and Heavy Vehicles at 70 km/h
- Light, Medium, and Heavy Vehicles at 80 km/h
- Light, Medium, and Heavy Vehicles at 90 km/h

From the analysis, a positive average sound level difference (i.e. mean) denotes that the average amount of sound level of the first mix is greater than the second mix (i.e. the second mix is quieter). A negative average sound level difference (i.e. mean) denotes that the average amount of sound level of the first mix is lower than the second mix (i.e. the first mix is quieter).

5.1.1 rOFC vs. HL-3

Figure 5.1 illustrates the change of sound level difference between rOFC and HL-3 for the CPB Method from 2004 to 2005. Overall, the CPB results show that rOFC is quieter than HL-3 when compared using all test vehicles at the same time in both measurement years. rOFC is also quieter than HL-3 in most of the categories, with the exception of the following category:

Vehicle Sizes at a Particular Speed

- Light Vehicles at 60 km/h in 2004

The sound attenuation ability of rOFC is similar in both measurement years in the CPB method.

Figure 5.2 shows the change of sound level difference between rOFC and HL-3 for the CPX Method from 2004 to 2005. Overall, the CPX results show that rOFC is quieter than HL-3 when compared using all test vehicles at the same time in both measurement years. rOFC is also quieter than HL-3 in most of the categories, with the exception of the following categories:

Vehicle Sizes

- Light Vehicles in 2005

Vehicle Speeds

- 60 km/h in 2005

Vehicle Sizes at a Particular Speed

- Light and Medium Vehicles at 60 km/h in 2005
- Light vehicle at 70 km/h in 2005

The results show that the sound attenuation ability of rOFC decreases from 2004 to 2005.

Figures 5.1 and 5.2 indicate that rOFC is quieter than HL-3 in many scenarios for both measurement methods. However, it is necessary to determine whether these sound level differences between rOFC and HL-3 are statistically significant.

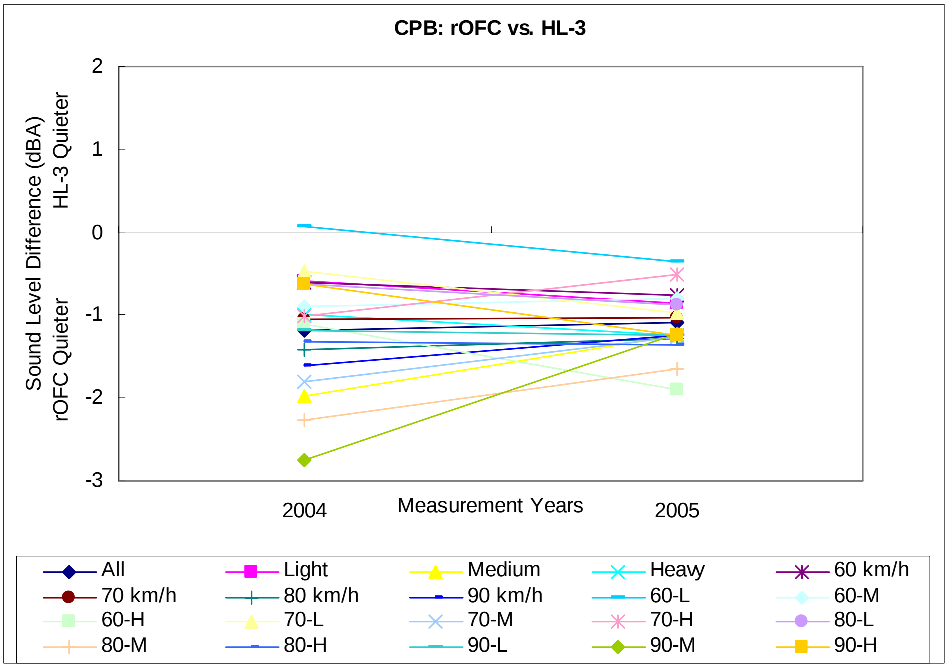

Figure 5.1 – CPB: Sound Level Difference between rOFC and HL-3

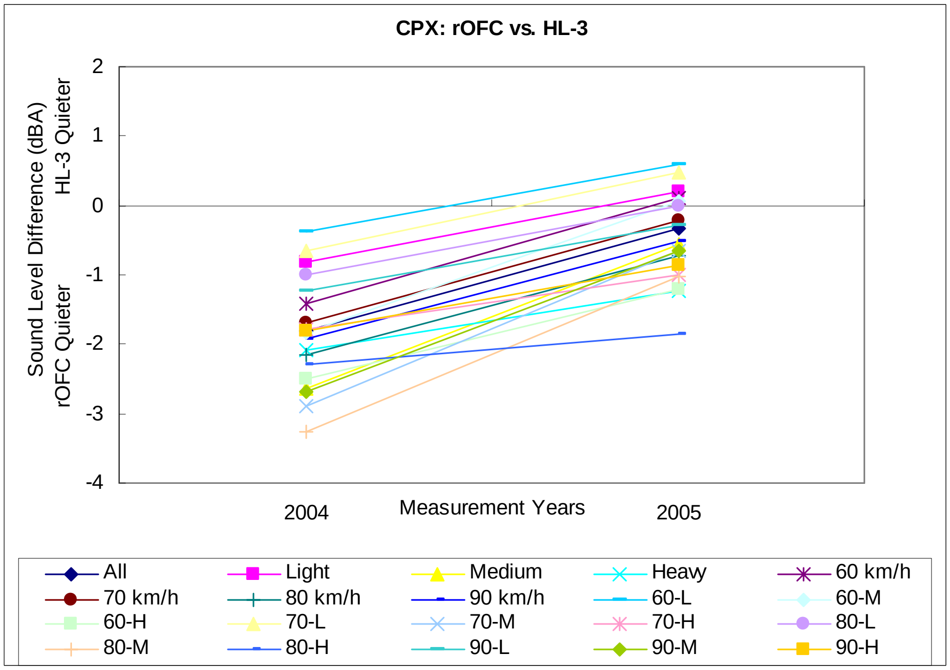

Figure 5.2 – CPX: Sound Level Difference between rOFC and HL-3

5.1.1.1 Compared with All Vehicles

Table 5.1 summarizes the comparison between rOFC and HL-3 in terms of all vehicles tested. The results indicate that rOFC is significantly different from HL-3 at a 95% confidence level. The sound attenuation level of rOFC remains relatively constant at about 1.2 dBA after one year in the CPB Method. The sound attenuation ability of rOFC is reduced (degrades) from 1.8 dBA to 0.3 dBA after one year based on the CPX Method.

Table 5.1 – Sound Level Statistical Analysis between rOFC and HL-3 (All Vehicles)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
Vehicle Type	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
All Vehicles	2004	-1.2	rOFC	Yes	-1.8	rOFC	Yes
	2005	-1.1	rOFC	Yes	-0.3	rOFC	Yes

5.1.1.2 Compared with Vehicle Sizes

Table 5.2 summarizes the comparison between rOFC and HL-3 in terms of vehicle sizes. rOFC is quieter than HL-3, with the exception of light vehicles in the 2005 CPX Method where HL-3 is quieter than rOFC by 0.2 dBA. However, this difference is not significant. The rest of the results from the CPB and CPX Methods show that rOFC is significantly different from HL-3 at a 95% confidence level.

Table 5.2 – Sound Level Statistical Analysis between rOFC and HL-3 (Vehicles Sizes)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
Vehicle Type	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
Light	2004	-0.6	rOFC	Yes	-0.8	rOFC	Yes
	2005	-0.9	rOFC	Yes	0.2	HL-3	No
Medium	2004	-2.0	rOFC	Yes	-2.7	rOFC	Yes
	2005	-1.2	rOFC	Yes	-0.6	rOFC	Yes
Heavy	2004	-1.0	rOFC	Yes	-2.1	rOFC	Yes
	2005	-1.3	rOFC	Yes	-1.2	rOFC	Yes

5.1.1.3 Compared with Vehicle Speeds

Table 5.3 summarizes the comparison between rOFC and HL-3 in terms of vehicle speeds. rOFC is quieter than HL-3 at most of the speeds in 2004 measurements. Their differences are also significant. In 2005, the results show that rOFC is still significantly different from HL-3 in the CPB Method, but not in the CPX Method with the exception of the speed of 80 km/h.

Table 5.3 – Sound Level Statistical Analysis between rOFC and HL-3 (Vehicles Speeds)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
Vehicle Speed	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
60 km/h	2004	-0.6	rOFC	No	-1.4	rOFC	Yes
	2005	-0.8	rOFC	Yes	0.1	HL-3	No
70 km/h	2004	-1.1	rOFC	Yes	-1.7	rOFC	Yes
	2005	-1.0	rOFC	Yes	-0.2	rOFC	No
80 km/h	2004	-1.4	rOFC	Yes	-2.2	rOFC	Yes
	2005	-1.3	rOFC	Yes	-0.7	rOFC	Yes
90 km/h	2004	-1.6	rOFC	Yes	-1.9	rOFC	Yes
	2005	-1.2	rOFC	Yes	-0.5	rOFC	No

5.1.1.4 Compared with Vehicle Sizes at 60 km/h

Table 5.4 summarizes the results between rOFC and HL-3 in terms of vehicle sizes at 60 km/h. In 2004, rOFC is quieter than HL-3 in most of the vehicle sizes. However, the differences between them are not significant other than the medium and heavy vehicles in the CPX Method. In 2005, statistical results show that rOFC is not significantly different from HL-3.

Table 5.4 – Sound Level Statistical Analysis between rOFC and HL-3 (Vehicles Sizes at 60 km/h)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
60 km/h	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
Light	2004	0.1	HL-3	No	-0.4	rOFC	No
	2005	-0.4	rOFC	No	0.6	HL-3	No
Medium	2004	-0.9	rOFC	No	-1.8	rOFC	Yes
	2005	-0.8	rOFC	No	0.1	HL-3	No
Heavy	2004	-1.1	rOFC	No	-2.5	rOFC	Yes
	2005	-1.9	rOFC	No	-1.2	rOFC	No

5.1.1.5 Compared with Vehicle Sizes at 70 km/h

Table 5.5 summarizes the results between rOFC and HL-3 in terms of vehicle sizes at 70 km/h. The results from both methods show that rOFC is quieter than HL-3, with the exception of the light vehicles at 70 km/h in the 2005 CPX Method. The analysis reveals that rOFC is significantly different from HL-3 in most of the scenarios, with the exception of the result from the light vehicles in the 2004 CPB Method, the heavy vehicles in the CPB Method of both measurement years, and the light and medium vehicles in the 2005 CPX Method. No statistical analysis is performed for the heavy vehicle in the 2005 CPX Method because the standard deviation between the data pairs is zero.

Table 5.5 – Sound Level Statistical Analysis between rOFC and HL-3 (Vehicles Sizes at 70 km/h)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
70 km/h	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
Light	2004	-0.5	rOFC	No	-0.7	rOFC	Yes
	2005	-1.0	rOFC	Yes	0.5	HL-3	No
Medium	2004	-1.8	rOFC	Yes	-2.9	rOFC	Yes
	2005	-1.3	rOFC	Yes	-0.7	rOFC	No
Heavy	2004	-1.0	rOFC	No	-1.8	rOFC	Yes
	2005	-0.5	rOFC	No	-1.0	rOFC	---

5.1.1.6 Compared with Vehicle Sizes at 80 km/h

Table 5.6 summarizes the results between rOFC and HL-3 in terms of vehicle sizes at 80 km/h. The results from both methods show that rOFC is quieter than HL-3. The analysis reveals that rOFC is significantly different from HL-3 in most of the scenarios, with the exception of the result from the light vehicles in the 2004 CPB Method, the heavy vehicles in the CPB Method of both measurement years, and the light vehicles in the 2005 CPX Method.

Table 5.6 – Sound Level Statistical Analysis between rOFC and HL-3 (Vehicles Sizes at 80 km/h)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
80 km/h	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
Light	2004	-0.6	rOFC	No	-1.0	rOFC	Yes
	2005	-0.9	rOFC	Yes	-0.0	rOFC	No
Medium	2004	-2.3	rOFC	Yes	-3.3	rOFC	Yes
	2005	-1.7	rOFC	Yes	-1.0	rOFC	Yes
Heavy	2004	-1.3	rOFC	No	-2.3	rOFC	Yes
	2005	-1.4	rOFC	No	-1.9	rOFC	Yes

5.1.1.7 Compared with Vehicle Sizes at 90 km/h

Table 5.7 summarizes the results between rOFC and HL-3 in terms of vehicle size at 90 km/h. The results indicate that rOFC is quieter than HL-3. In terms of light vehicles, rOFC is not significantly different from HL-3 in the 2005 CPX Method, but rOFC is significantly different from HL-3 in other measurements. In terms of medium vehicles, rOFC is significantly different from HL-3 in 2004 methods, but not in 2005 methods. In terms of heavy vehicles, rOFC is significantly different from HL-3 in the 2004 CPX Method, but not in other measurements.

Table 5.7 – Sound Level Statistical Analysis between rOFC and HL-3 (Vehicles Sizes at 90 km/h)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
90 km/h	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
Light	2004	-1.2	rOFC	Yes	-1.2	rOFC	Yes
	2005	-1.3	rOFC	Yes	-0.3	rOFC	No
Medium	2004	-2.8	rOFC	Yes	-2.7	rOFC	Yes
	2005	-1.2	rOFC	No	-0.7	rOFC	No
Heavy	2004	-0.6	rOFC	No	-1.8	rOFC	Yes
	2005	-1.3	rOFC	No	-0.9	rOFC	No

5.1.2 rOGC vs. HL-3

Figure 5.3 illustrates the change of sound level difference between rOGC and HL-3 for the CPB Method from 2004 to 2005. Overall, the CPB results show that rOFC is quieter than HL-3 when compared using all test vehicles at the same time in both measurement years. rOFC is also quieter than HL-3 for the rest of the categories. The sound attenuation ability of rOGC is about the same in both measurement years in the CPB Method.

Figure 5.4 shows the change of sound level difference between rOGC and HL-3 for CPX Method from 2004 to 2005. Overall, the CPX results show that rOFC is quieter than HL-3 when compared using all test vehicles at the same time in both measurement years. rOFC is also quieter than HL-3 in most of the categories, with the exception of the following category:

Vehicle Sizes at a Particular Speed

- Light Vehicles at 60 km/h in 2005

Figures 5.3 and 5.4 indicate that the sound attenuation ability of rOGC decreases from 2004 to 2005 and the rOGC is quieter than HL-3 in many scenarios for both measurement methods. However, it is necessary to determine whether these sound level differences between rOGC and HL-3 are statistically significant.

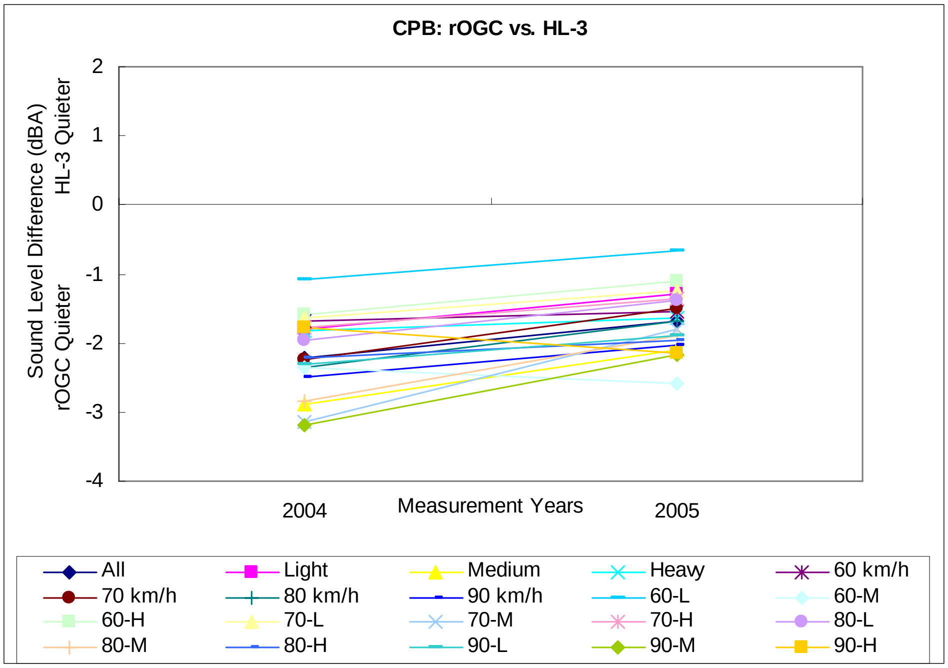

Figure 5.3 – CPB: Sound Level Difference between rOGC and HL-3

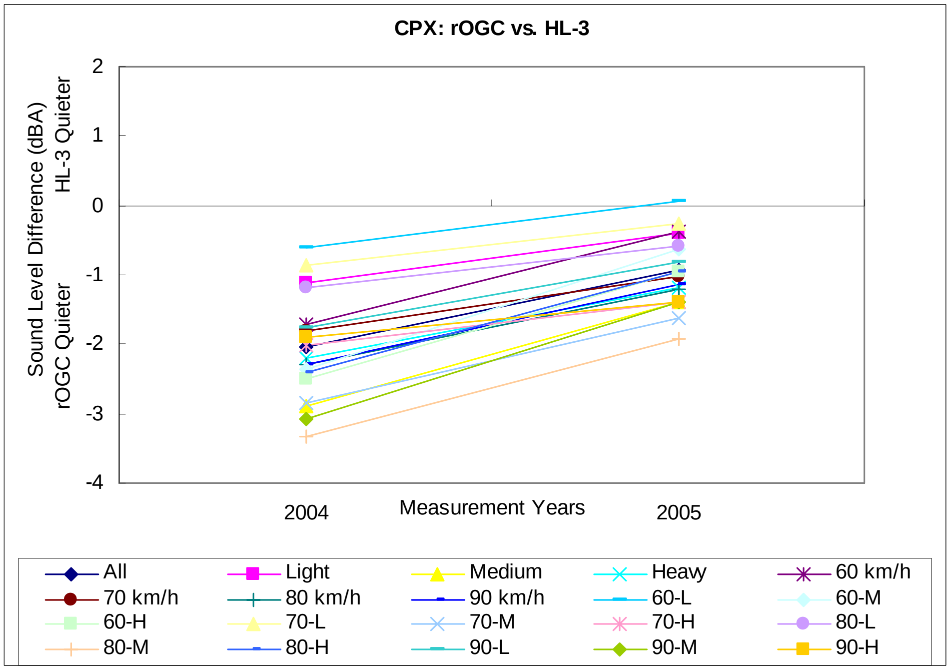

Figure 5.4 – CPX: Sound Level Difference between rOGC and HL-3

5.1.2.1 Compared with All Vehicles

Table 5.8 summarizes the comparison between rOGC and HL-3 in terms of all vehicles tested. The results indicate that rOGC is significantly different from HL-3 in both measurement methods and years. The sound attenuation ability of rOGC decreases after one year from 2.2 dBA to 1.7dBA based on the CPB Method. The sound attenuation ability of rOGC is reduced (degrades) from 2.0 dBA to 0.9 dBA after one year based on the CPX Method.

Table 5.8 – Sound Level Statistical Analysis between rOGC and HL-3 (All Vehicles)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
Vehicle Type	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
All Vehicles	2004	-2.2	rOGC	Yes	-2.0	rOGC	Yes
	2005	-1.7	rOGC	Yes	-0.9	rOGC	Yes

5.1.2.2 Compared with Vehicle Sizes

Table 5.9 summarizes the comparison between rOGC and HL-3 in terms of vehicle sizes. rOGC is quieter than HL-3 in both measurement methods and years. The statistical analysis shows that rOGC is significantly different from HL-3 in terms of vehicle sizes in both measurement methods and years.

Table 5.9 – Sound Level Statistical Analysis between rOGC and HL-3 (Vehicles Sizes)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
Vehicle Type	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
Light	2004	-1.8	rOGC	Yes	-1.1	rOGC	Yes
	2005	-1.3	rOGC	Yes	-0.4	rOGC	Yes
Medium	2004	-2.9	rOGC	Yes	-2.9	rOGC	Yes
	2005	-2.1	rOGC	Yes	-1.4	rOGC	Yes
Heavy	2004	-1.8	rOGC	Yes	-2.2	rOGC	Yes
	2005	-1.6	rOGC	Yes	-1.2	rOGC	Yes

5.1.2.3 Compared with Vehicle Speeds

Table 5.10 summarizes the comparison between rOGC and HL-3 in terms of vehicle speeds. rOGC is quieter than HL-3 in both measurement methods and years. The statistical analysis shows that the rOGC is significantly different from HL-3 in terms of vehicle speeds in both measurement methods and years, with the exception of the 60 km/h category in the 2005 CPX Method.

Table 5.10 – Sound Level Statistical Analysis between rOGC and HL-3 (Vehicles Speeds)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
Vehicle Speed	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
60 km/h	2004	-1.7	rOGC	Yes	-1.7	rOGC	Yes
	2005	-1.6	rOGC	Yes	-0.4	rOGC	No
70 km/h	2004	-2.2	rOGC	Yes	-1.8	rOGC	Yes
	2005	-1.5	rOGC	Yes	-1.0	rOGC	Yes
80 km/h	2004	-2.4	rOGC	Yes	-2.3	rOGC	Yes
	2005	-1.7	rOGC	Yes	-1.2	rOGC	Yes
90 km/h	2004	-2.5	rOGC	Yes	-2.3	rOGC	Yes
	2005	-2.0	rOGC	Yes	-1.1	rOGC	Yes

5.1.2.4 Compared with Vehicle Sizes at 60 km/h

Table 5.11 summarizes the results between rOGC and HL-3 in terms of vehicle sizes at 60 km/h. rOGC is quieter than HL-3 in both measurement method and years, with the exception of the light vehicles in the 2005 CPX Method. The statistical analysis shows that rOFC is significantly different from HL-3 in both methods in 2004. However rOGC is not significantly different from HL-3 in 2005 results, with the exception of the medium vehicles in the CPB Method.

Table 5.11 – Sound Level Statistical Analysis between rOGC and HL-3 (Vehicles Sizes at 60 km/h)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
60 km/h	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
Light	2004	-1.1	rOGC	Yes	-0.6	rOGC	Yes
	2005	-0.7	rOGC	No	0.1	HL-3	No
Medium	2004	-2.4	rOGC	Yes	-2.4	rOGC	Yes
	2005	-2.6	rOGC	Yes	-0.6	rOGC	No
Heavy	2004	-1.6	rOGC	Yes	-2.5	rOGC	Yes
	2005	-1.1	rOGC	No	-1.0	rOGC	No

5.1.2.5 Compared with Vehicle Sizes at 70 km/h

Table 5.12 summarizes the results between rOGC and HL-3 in terms of vehicle sizes at 70 km/h. rOGC is quieter than HL-3 in both measurement methods and years. The analysis reveals that rOGC is significantly different from HL-3 in all cases, with the exception of the light vehicles in the 2005 CPX Method and heavy vehicles in the 2005 CPB Method.

Table 5.12 – Sound Level Statistical Analysis between rOGC and HL-3 (Vehicles Sizes at 70 km/h)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
70 km/h	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
Light	2004	-1.6	rOGC	Yes	-0.9	rOGC	Yes
	2005	-1.3	rOGC	Yes	-0.3	rOGC	No
Medium	2004	-3.1	rOGC	Yes	-2.8	rOGC	Yes
	2005	-1.8	rOGC	Yes	-1.6	rOGC	Yes
Heavy	2004	-1.8	rOGC	Yes	-2.0	rOGC	Yes
	2005	-1.4	rOGC	No	-1.4	rOGC	Yes

5.1.2.6 Compared with Vehicle Sizes at 80 km/h

Table 5.13 summarizes the results between rOGC and HL-3 in terms of vehicle sizes at 80 km/h. rOGC is quieter than HL-3 in both measurement methods and years. The analysis reveals that rOGC is significantly different from HL-3 in all vehicle sizes at 80 km/h in the 2004 measurements. It also reveals that rOGC is significantly different from HL-3 in the 2005 measurements, with the exception of the light vehicles in the CPX Method and the heavy vehicles in both CPB and CPX Methods.

Table 5.13 – Sound Level Statistical Analysis between rOGC and HL-3 (Vehicles Sizes at 80 km/h)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
80 km/h	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
Light	2004	-2.0	rOGC	Yes	-1.2	rOGC	Yes
	2005	-1.4	rOGC	Yes	-0.6	rOGC	No
Medium	2004	-2.8	rOGC	Yes	-3.3	rOGC	Yes
	2005	-1.9	rOGC	Yes	-1.9	rOGC	Yes
Heavy	2004	-2.2	rOGC	Yes	-2.4	rOGC	Yes
	2005	-2.0	rOGC	No	-1.0	rOGC	No

5.1.2.7 Compared with Vehicle Sizes at 90 km/h

Table 5.14 summarizes the results between rOGC and HL-3 in terms of vehicle sizes at 90 km/h. rOGC is quieter than HL-3 in both measurement methods and years. The analysis reveals that rOGC is significantly different from HL-3 in all vehicle sizes of 80 km/h in the 2004 measurements. It also reveals that rOGC is significantly different from HL-3 in the 2005 measurements, with the exception of the light vehicles in the CPX Method and the heavy vehicles in both CPB and CPX Methods.

Table 5.14 – Sound Level Statistical Analysis between rOGC and HL-3 (Vehicles Sizes at 90 km/h)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
90 km/h	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
Light	2004	-2.3	rOGC	Yes	-1.8	rOGC	Yes
	2005	-1.9	rOGC	Yes	-0.8	rOGC	No
Medium	2004	-3.2	rOGC	Yes	-3.1	rOGC	Yes
	2005	-2.2	rOGC	Yes	-1.4	rOGC	Yes
Heavy	2004	-1.8	rOGC	Yes	-1.9	rOGC	Yes
	2005	-2.2	rOGC	No	-1.4	rOGC	No

5.1.3 SMA vs. HL-3

Figure 5.5 illustrates the change of sound level difference between SMA and HL-3 for the CPB Method from 2004 to 2005. Overall, the CPB results show that SMA is noisier than HL-3 when compared using all test vehicles at the same time in both measurement years. However, SMA is quieter than HL-3 in most of the other categories, with the exception of the following categories:

Vehicle Sizes

- Light Vehicles in 2004

Vehicle Speeds

- 60 km/h in 2004
- 70 km/h in 2004

Vehicle Size at a Particular Speed

- Light and Heavy Vehicles at 60 km/h in 2004
- Light vehicle at 70 km/h in 2004
- Light vehicle at 80 km/h in 2004
- Light vehicle at 90 km/h in 2004

Figure 5.6 shows the change of sound level difference between SMA and HL-3 for CPX Method from 2004 to 2005. Overall, the CPX results show that SMA is noisier than HL-3 when compared using all test vehicles at the same time in both measurement years. However, SMA is quieter than HL-3 in most of the other categories, with the exception of the following categories:

Vehicle Sizes

- Light Vehicles in 2004 and 2005

Vehicle Speeds

- 60 km/h in 2004
- 70 km/h in 2004

Vehicle Sizes at a Particular Speed

- Light Vehicles at 60 km/h in 2004 and 2005
- Light Vehicle at 70 km/h in 2004 and 2005
- Light Vehicle at 80 km/h in 2004 and 2005
- Light Vehicle at 90 km/h in 2004

Figures 5.5 and 5.6 indicate that the sound attenuation ability of SMA increases from 2004 to 2005 and some scenarios show SMA is noisier HL-3 and some of them show SMA is quieter than HL-3. However, it is necessary to determine whether these sound level differences between SMA and HL-3 are statistically significant.

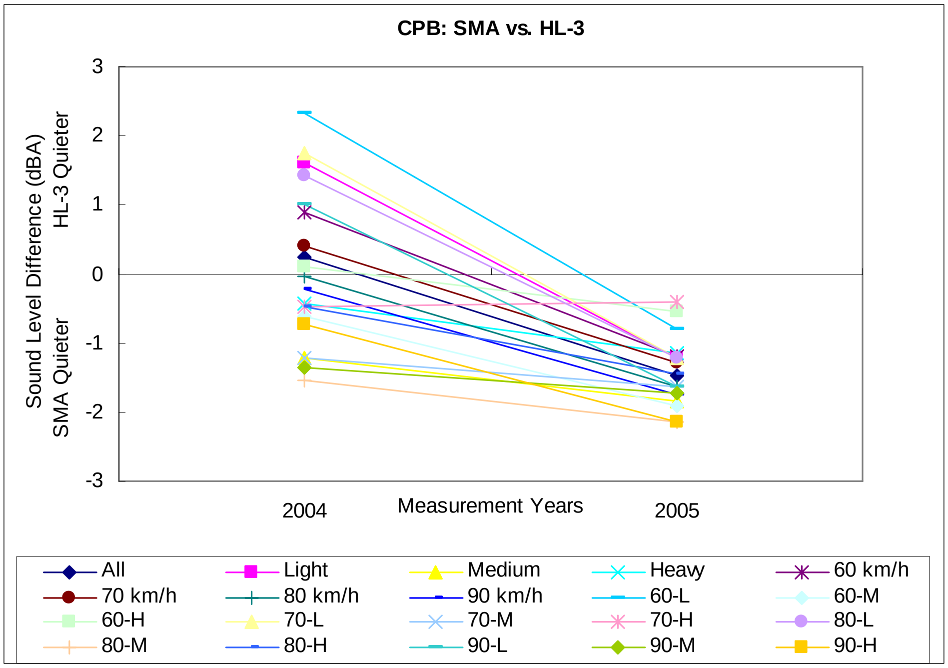

Figure 5.5 – CPB: Sound Level Difference between SMA and HL-3

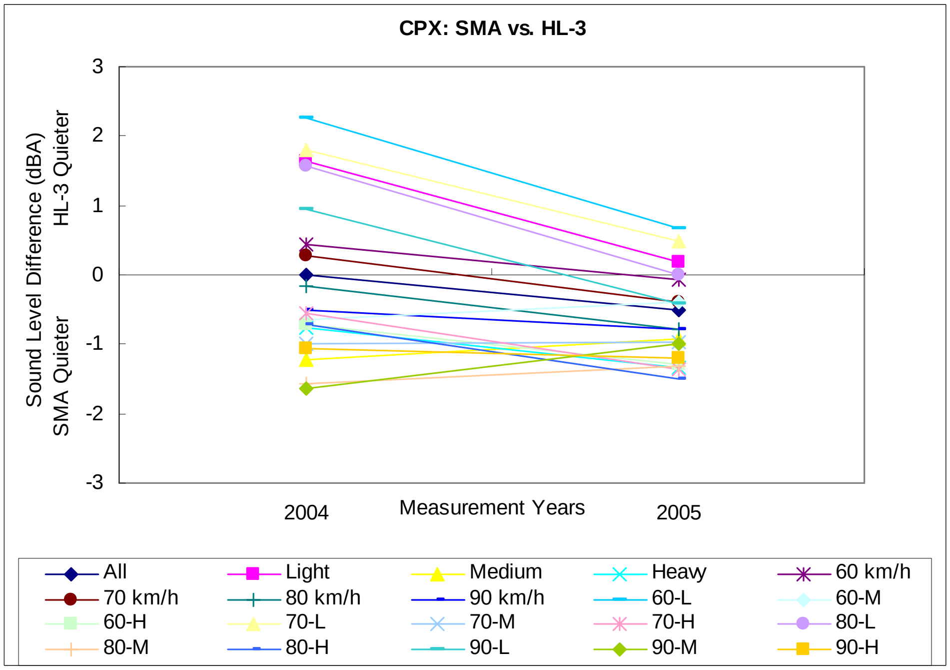

Figure 5.6 – CPX: Sound Level Difference between SMA and HL-3

5.1.3.1 Compared with All Vehicles

Table 5.15 summarizes the comparison between SMA and HL-3 in terms of all vehicles tested. The results indicate that SMA is 0.2 dBA higher than HL-3 in the 2004 CPB Method. However, statistic analysis results show that these noise level differences are not significant at a 95% confidence level. After one year, SMA becomes quieter than HL-3 by 1.5 dBA and 0.5 dBA in CPB and CPX Methods, respectively. Statistical analysis results show that these sound level differences are significant.

Table 5.15 – Sound Level Statistical Analysis between SMA and HL-3 (All Vehicles)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
Vehicle Type	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
All Vehicles	2004	0.2	HL-3	No	0.0	HL-3	No
	2005	-1.5	SMA	Yes	-0.5	SMA	Yes

5.1.3.2 Compared with Vehicle Sizes

Table 5.16 summarizes the comparison between SMA and HL-3 in terms of vehicle sizes. SMA is quieter than HL-3 in both medium and heavy vehicles and these differences are significant, with the exception of heavy vehicles in 2004 CPB Method. In terms of the light vehicles, SMA is noisier than HL-3, with an exception of the result from the 2005 CPB Method. Statistical analysis shows that the difference between SMA and HL-3 is significant, with the exception in the 2005 CPX Method.

Table 5.16 – Sound Level Statistical Analysis between SMA and HL-3 (Vehicles Sizes)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
Vehicle Type	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
Light	2004	1.6	HL-3	Yes	1.6	HL-3	Yes
	2005	-1.2	SMA	Yes	0.2	HL-3	No
Medium	2004	-1.2	SMA	Yes	-1.2	SMA	Yes
	2005	-1.9	SMA	Yes	-0.9	SMA	Yes
Heavy	2004	-0.4	SMA	No	-0.8	SMA	Yes
	2005	-1.1	SMA	Yes	-1.3	SMA	Yes

5.1.3.3 Compared with Vehicle Speeds

Table 5.17 summarizes the comparison between SMA and HL-3 in terms of <u>vehicle speeds</u>. In the speeds of 60 km/h and 70 km/h in 2004, HL-3 is quieter than SMA, but sound level difference between SMA and HL-3 is not significant, with the exception of 2004 CPB Method at 60 km/h. The speeds of 80 km/h and 90 km/h in both methods and years show that SMA is quieter than HL-3 and statistical analysis also shows that the sound level difference between SMA and HL-3 is not significant in 2004, but is significant in 2005.

Table 5.17 – Sound Level Statistical Analysis between SMA and HL-3 (Vehicles Speeds)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
Vehicle Speed	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
60 km/h	2004	0.9	HL-3	Yes	0.5	HL-3	No
	2005	-1.2	SMA	Yes	-0.1	SMA	No
70 km/h	2004	0.4	HL-3	No	0.3	HL-3	No
	2005	-1.3	SMA	Yes	-0.4	SMA	No
80 km/h	2004	-0.0	SMA	No	-0.2	SMA	No
	2005	-1.6	SMA	Yes	-0.8	SMA	Yes
90 km/h	2004	-0.22	SMA	No	-0.5	SMA	No
	2005	-1.7	SMA	Yes	-0.8	SMA	Yes

5.1.3.4 Compared with Vehicle Sizes at 60 km/h

Table 5.18 summarizes the results between SMA and HL-3 in terms of <u>vehicle sizes at 60 km/h</u>. When comparing light vehicles at 60 km/h, HL-3 is quieter than SMA in both methods in 2004 and the differences are significant. After one year, HL-3 is quieter than SMA in the CPB Method, but the difference is not significant. However, HL-3 is noisier than SMA in the CPX Method and the difference is significant. When comparing the medium vehicles at 60 km/h, SMA is quieter than HL-3 in both measurement methods and years, but statistical analysis shows that SMA is not significantly different from HL-3 in the 2004 CPB Method, but they are in 2005. The statistical analysis shows that SMA is significant different from HL-3 in the 2004 CPX Method, but not in the 2005 CPX Method. In heavy vehicle at 60 km/h, SMA is not significantly different from HL-3, except in 2004 using the CPX Method.

Table 5.18 – Sound Level Statistical Analysis between SMA and HL-3 (Vehicles Sizes at 60 km/h)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
60 km/h	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
Light	2004	2.3	HL-3	Yes	2.3	HL-3	Yes
	2005	-0.8	SMA	Yes	0.7	HL-3	No
Medium	2004	-0.6	SMA	No	-0.7	SMA	Yes
	2005	-1.9	SMA	Yes	-0.4	SMA	No
Heavy	2004	0.1	HL-3	No	-0.7	SMA	No
	2005	-0.6	SMA	No	-1.3	SMA	Yes

5.1.3.5 Compared with Vehicle Sizes at 70 km/h

Table 5.19 summarizes the results between SMA and HL-3 in terms of vehicle sizes at 70 km/h. Both medium and heavy vehicles in both methods and years show that SMA is quieter than HL-3, but statistical analysis shows that these sound level differences are not significant, with an exception of the medium vehicles in both 2005 methods. In terms of light vehicle of 70 km/h, HL-3 is quieter than SMA, but not in the 2005 CPB Method. However, the statistical analysis suggests that SMA is not significantly different from HL-3 in 2005 CPX Method.

Table 5.19 – Sound Level Statistical Analysis between SMA and HL-3 (Vehicles Sizes at 70 km/h)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
70 km/h	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
Light	2004	1.7	HL-3	Yes	1.8	HL-3	Yes
	2005	-1.2	SMA	Yes	0.5	HL-3	No
Medium	2004	-1.2	SMA	No	-1.0	SMA	No
	2005	-1.6	SMA	Yes	-1.0	SMA	Yes
Heavy	2004	-0.5	SMA	No	-0.6	SMA	No
	2005	-0.40	SMA	No	-1.4	SMA	No

5.1.3.6 Compared with Vehicle Sizes at 80 km/h

Table 5.20 summarizes the results between SMA and HL-3 in terms of vehicle sizes at 80 km/h. The results of both methods show that SMA is quieter than HL-3 in both medium and heavy vehicles. Statistical analysis shows that the difference between SMA and HL-3 is significant for medium vehicles, but not for heavy vehicles. There is no statistical analysis for 2005 using the CPX Method in heavy vehicle because the standard deviation of the paired data is zero. The result shows that SMA is significant different from HL-3 in the light vehicle, and that HL-3 is quieter than SMA in 2004 measurements, and SMA is quieter than HL-3 in 2005 measurement.

Table 5.20 – Sound Level Statistical Analysis between SMA and HL-3 (Vehicles Sizes at 80 km/h)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
80 km/h	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
Light	2004	1.4	HL-3	Yes	1.6	HL-3	Yes
	2005	-1.2	SMA	Yes	0.0	Same	No
Medium	2004	-1.5	SMA	Yes	-1.6	SMA	Yes
	2005	-2.1	SMA	Yes	-1.3	SMA	Yes
Heavy	2004	-0.5	SMA	No	-0.7	SMA	No
	2005	-1.5	SMA	No	-1.5	SMA	---

5.1.3.7 Compared with Vehicle Sizes at 90 km/h

Table 5.21 summarizes the results between SMA and HL-3 in terms of vehicle sizes at 90 km/h. In terms of light vehicle category, HL-3 is quieter than SMA in both 2004 methods and their difference is significant. After one year, SMA is quieter than HL-3, but the statistics show that the difference is significant in the CPB Method, but not in the CPX Method. In terms of medium and heavy vehicles, the results indicate that SMA is quieter than HL-3. Statistical analysis also shows that when SMA is significant different from HL-3 in one method, the results from the other method show they are not significant, or vice versa.

Table 5.21 – Sound Level Statistical Analysis between SMA and HL-3 (Vehicles Sizes at 90 km/h)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
90 km/h	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
Light	2004	1.0	HL-3	Yes	1.0	HL-3	Yes
	2005	-1.6	SMA	Yes	-0.4	SMA	No
Medium	2004	-1.4	SMA	No	-1.6	SMA	Yes
	2005	-1.7	SMA	Yes	-1.0	SMA	No
Heavy	2004	-0.7	SMA	No	-1.1	SMA	Yes
	2005	-2.2	SMA	Yes	-1.2	SMA	No

5.1.4 rOFC vs. rOGC

Figure 5.7 illustrates the change of sound level difference between rOFC and rOGC for the CPB Method from 2004 to 2005. Overall, the CPB results show that rOGC is quieter than rOFC when compared using all test vehicles at the same time in both measurement years. rOGC is also quieter than rOFC for the rest of the categories, with an exception of the following category:

Vehicle Size at a Particular Speed

- Heavy Vehicles at 60 km/h in 2005

Figure 5.8 shows the change of sound level difference between rOFC and rOGC for the CPX Method from 2004 to 2005. Overall, the CPX results show that rOGC is quieter than rOFC when compared using all test vehicles at the same time in both measurement years. rOGC is also quieter than rOFC in most of the categories, with the exception of the following categories:

Vehicle Size

- Heavy Vehicles in 2005

Vehicle Size at a Particular Speed

- Heavy Vehicles at 60 km/h in 2005
- Medium Vehicle at 70 km/h in 2004
- Heavy Vehichle at 80 km/h in 2005

The sound attenuation ability of rOGC decreases from 2004 to 2005 in the CPB Method, but most of the scenarios of noise attenuation abilities of rOGC increases from 2004 to 2005 in the CPX Method. Generally, rOGC is quieter than rOFC in many scenarios for both methods. However, it is necessary to determine whether these sound level differences between rOFC and rOGC are statistically significant.

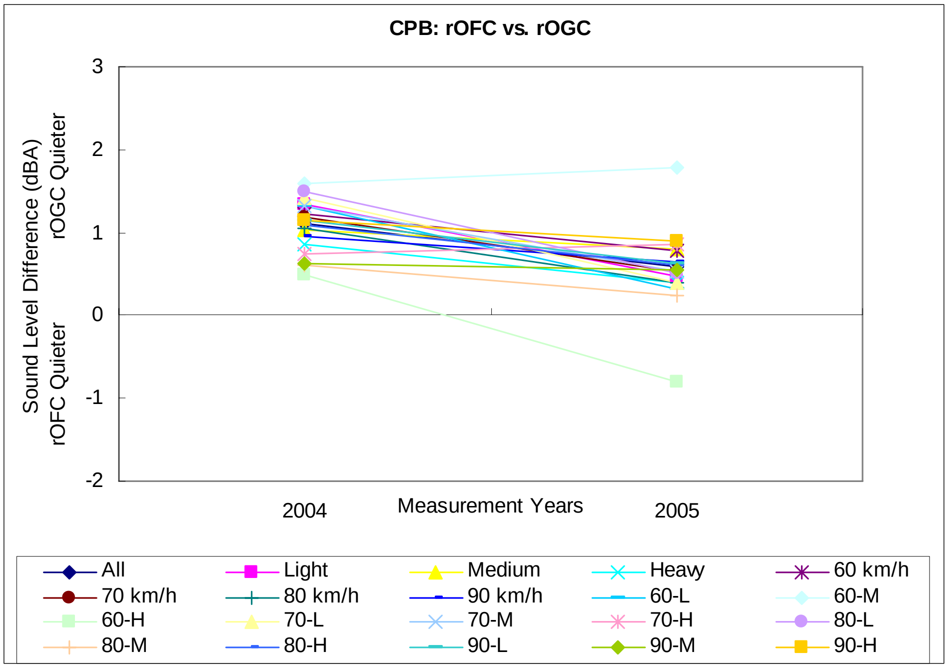

Figure 5.7 – CPB: Sound Level Difference between rOFC and rOGC

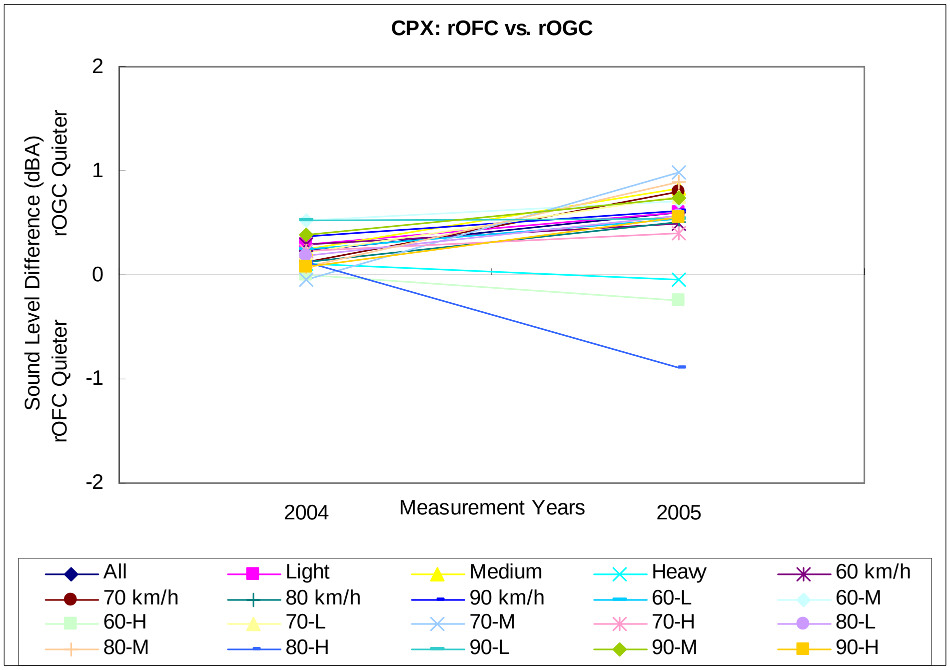

Figure 5.8 – CPX: Sound Level Difference between rOFC and rOGC

5.1.4.1 Compared with All Vehicles

Table 5.22 summarizes the comparison between rOFC and rOGC in terms of all vehicles tested. The results indicate that rOGC is quieter than rOFC. The sound attenuation level of rOGC decreases after one year from 1.1 dBA to 0.6 dBA based on the CPB Method. The sound attenuation level of rOGC increases from 0.2 dBA to 0.6 dBA after one year based on the CPX Method. Statistical analysis shows that rOFC is significantly different from rOGC at a 95% confidence level.

Table 5.22 – Sound Level Statistical Analysis between rOFC and rOGC (All Vehicles)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
Vehicle Type	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
All Vehicles	2004	1.1	rOGC	Yes	0.2	rOGC	Yes
	2005	0.6	rOGC	Yes	0.6	rOGC	Yes

5.1.4.2 Compared with Vehicle Sizes

Table 5.23 summarizes the comparison between rOFC and rOGC in terms of vehicle size. rOGC is quieter than rOFC in both measurement method and years, with an exception of 2005 CPX Method in the heavy vehicles. The statistical analysis shows that rOFC is significantly different from rOGC in light and medium vehicles, but not in the heavy vehicle.

Table 5.23 – Sound Level Statistical Analysis between rOFC and rOGC (Vehicles Sizes)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
Vehicle Type	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
Light	2004	1.3	rOGC	Yes	0.3	rOGC	Yes
	2005	0.5	rOGC	Yes	0.6	rOGC	Yes
Medium	2004	1.0	rOGC	Yes	0.3	rOGC	Yes
	2005	0.8	rOGC	Yes	0.8	rOGC	Yes
Heavy	2004	0.9	rOGC	No	0.1	rOGC	No
	2005	0.4	rOGC	No	-0.1	rOFC	No

5.1.4.3 Compared with Vehicle Speeds

Table 5.24 summarizes the comparison between rOFC and rOGC in terms of vehicle speeds. rOGC is quieter than rOFC in both measurement methods and years. In 2004, the statistical analysis results show that rOFC is significantly different from rOGC at all speeds in the CPB Method, but only show that their differences are significant in 60 km/h and 90 km/h in the CPX Method. In 2005, statistical analysis results show that rOGC is not significantly different from OFC at the speed of 60 km/h, 70 km/h, and 80 km/h in the CPB Method. However, their differences are significant at all speeds in the CPX Method.

Table 5.24 – Sound Level Statistical Analysis between rOFC and rOGC (Vehicles Speeds)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
Vehicle Speed	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
60 km/h	2004	1.2	rOGC	Yes	0.3	rOGC	Yes
	2005	0.8	rOGC	No	0.5	rOGC	Yes
70 km/h	2004	1.2	rOGC	Yes	0.1	rOGC	No
	2005	0.5	rOGC	No	0.8	rOGC	Yes
80 km/h	2004	1.1	rOGC	Yes	0.1	rOGC	No
	2005	0.4	rOGC	No	0.5	rOGC	Yes
90 km/h	2004	1.0	rOGC	Yes	0.4	rOGC	Yes
	2005	0.7	rOGC	Yes	0.6	rOGC	Yes

5.1.4.4 Compared with Vehicle Sizes at 60 km/h

Table 5.25 summarizes the results between rOFC and rOGC in terms of vehicle sizes at 60 km/h. rOGC is quieter than the rOFC in all vehicle sizes at 60 km/h, with the exception of heavy vehicles in 2005 measurements. In 2004, results show that rOFC is significantly different from rOGC in light and medium vehicles in the CPB Method, but not in the CPX Method. After one year, rOGC is significantly different from rOFC, with the exception of light vehicles in the 2005 CPB Method. In terms of heavy vehicles, rOFC is not significantly different from rOGC in both measurement years and methods.

Table 5.25 – Sound Level Statistical Analysis between rOFC and rOGC (Vehicles Sizes at 60 km/h)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
60 km/h	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
Light	2004	1.3	rOGC	Yes	0.2	rOGC	No
	2005	0.3	rOGC	No	0.5	rOGC	Yes
Medium	2004	1.6	rOGC	Yes	0.5	rOGC	No
	2005	1.8	rOGC	Yes	0.7	rOGC	Yes
Heavy	2004	0.5	rOGC	No	0.0	rOGC	No
	2005	-0.8	rOFC	No	-0.3	rOFC	No

5.1.4.5 Compared with Vehicle Sizes at 70 km/h

Table 5.26 summarizes the results between rOFC and rOGC in terms of vehicle sizes at 70 km/h. rOGC is quieter than HL-3 in both measurement methods and years, with an exception of medium vehicle in the 2004 CPX Method. However, the statistical analysis shows that this exception is not significant. Other than that, the result shows that rOGC is not significantly different from rOFC in most of the situations other than light vehicles in the 2004 CPB Method, light and medium in the 2005 CPX Method.

Table 5.26 – Sound Level Statistical Analysis between rOFC and rOGC (Vehicles Sizes at 70 km/h)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
70 km/h	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
Light	2004	1.4	rOGC	Yes	0.2	rOGC	No
	2005	0.4	rOGC	No	0.8	rOGC	Yes
Medium	2004	1.3	rOGC	No	-0.1	rOFC	No
	2005	0.5	rOGC	No	1.0	rOGC	Yes
Heavy	2004	0.8	rOGC	No	0.2	rOGC	No
	2005	0.9	rOGC	No	0.4	rOGC	No

5.1.4.6 Compared with Vehicle Sizes at 80 km/h

Table 5.27 summarizes the results between rOFC and rOGC in terms of vehicle sizes at 80 km/h. rOGC is quieter than rOFC in both measurement methods and years, with an exception of heavy vehicle in the 2004 CPX Method. Although rOGC is quieter than rOFC, statistical analysis shows that rOGC is not significantly different from rOFC in most of the situations, other than light vehicles in the 2004 CPB Method, and both light and medium vehicles in the 2005 CPX Method.

Table 5.27 – Sound Level Statistical Analysis between rOFC and rOGC (Vehicles Sizes at 80 km/h)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
80 km/h	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
Light	2004	1.5	rOGC	Yes	0.2	rOGC	No
	2005	0.5	rOGC	No	0.6	rOGC	Yes
Medium	2004	0.6	rOGC	No	0.1	rOGC	No
	2005	0.2	rOGC	No	0.9	rOGC	Yes
Heavy	2004	1.1	rOGC	No	0.1	rOGC	No
	2005	0.6	rOGC	No	-0.9	rOFC	No

5.1.4.7 Compared with Vehicle Sizes at 90 km/h

Table 5.28 summarizes the results between rOFC and rOGC in terms of vehicle size at 90 km/h. rOGC is quieter than rOFC in both measurement methods and years. Although rOGC is quieter than rOFC, statistical analysis shows that rOGC is not significantly different from rOFC in most of the situations, other than light vehicles in both CPB and CPX Methods in 2004, and both light and medium vehicles in the 2005 CPX Method.

Table 5.28 – Sound Level Statistical Analysis between rOFC and rOGC (Vehicles Sizes at 90 km/h)

Comparison		Controlled Pass-By (CPB)			Close-Proximity (CPX)		
90 km/h	Year	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?	Sound Level Difference (dBA)	Quieter Mix	Significant Difference?
Light	2004	1.1	rOGC	Yes	0.5	rOGC	Yes
	2005	0.6	rOGC	No	0.5	rOGC	Yes
Medium	2004	0.6	rOGC	No	0.4	rOGC	No
	2005	0.6	rOGC	No	0.7	rOGC	Yes
Heavy	2004	1.2	rOGC	No	0.1	rOGC	No
	2005	0.9	rOGC	No	0.6	rOGC	No

5.2 Sound Absorption Coefficient Measurement

Average sound absorption coefficient differences and the statistical analysis between the studied mixes for both Impedance Tube Method and Reverberation Time Method are summarized in a tabular form in Appendix E.

Positive average absorption coefficient difference (i.e. mean) denotes the average amount of absorption coefficient of the first mix is greater than the second mix (i.e. the second mix absorbs more sound). Negative average absorption coefficient difference (i.e. mean) denotes the average amount of absorption coefficient of the first mix is lower than the second mix (i.e. the first mix absorbs more sound).

5.2.1 rOFC vs. HL-3

Table 5.29 summarizes the results of the sound absorption coefficient comparison and statistical analysis between rOFC and HL-3. Results from the sound absorption coefficient testing methods show that rOFC has a higher average sound absorption coefficient than HL-3. On average, the sound absorption coefficient of rOFC is higher than HL-3 by 0.007 from the gyratory samples and 0.004 from the 2006 field core samples in the Impedance Tube Method. Statistical analysis also shows that rOFC is significantly different from HL-3 in both gyratory and 2006 field core samples at a 95 % confidence interval. The sound absorption coefficient of rOFC is higher than HL-3 by 0.006 from the 2006 field samples in the Reverberation Time Method; however, their differences are not significant at a 95 % confidence interval.

Table 5.29 – Sound Absorption Coefficient Statistical Analysis between rOFC and HL-3

Methods	Impedance Tube		Reverberation Time
Sample	Gyratory	2006 Field Core	2006 Field
Sound Absorption Coefficient Difference	0.007	0.004	0.006
Higher Absorption Coefficient Mix	rOFC	rOFC	rOFC
Significant Difference?	Yes	Yes	No

5.2.2 rOGC vs. HL-3

Table 5.30 summarizes the results of the sound absorption coefficient comparison and statistical analysis between rOGC and HL-3. Results from the sound absorption coefficient testing method show that rOGC has a higher average sound absorption coefficient than HL-3. On average, the sound absorption coefficient of rOGC is higher than HL-3 by 0.015 from the gyratory samples and 0.024 from the 2006 field core samples in the Impedance Tube Method, and 0.008 from the 2006 field samples in the Reverberation Time Method. All statistical analysis results show that rOGC is significantly different from HL-3 at a 95% confidence interval.

Table 5.30 – Sound Absorption Coefficient Statistical Analysis between rOGC and HL-3

Methods	Impedance Tube		Reverberation Time
Sample	Gyratory	2006 Field Core	2006 Field
Sound Absorption Coefficient Difference	0.015	0.024	0.008
Higher Absorption Coefficient Mix	rOGC	rOGC	rOGC
Significant Difference?	Yes	Yes	Yes

5.2.3 SMA vs. HL-3

Table 5.31 summarizes the results of the sound absorption coefficient comparison and statistical analysis between SMA and HL-3. Statistical analysis result shows that SMA is significantly different from HL-3 at a 95% confidence interval. Both 2006 field samples results show that SMA has a higher average sound absorption coefficient than HL-3 by 0.015 and 0.008 in the Impedance Tube Method and Reverberation Time Method, respectively. However, from the gyratory samples, the average sound absorption coefficient of HL-3 is higher than SMA by 0.002.

Table 5.31 – Sound Absorption Coefficient Statistical Analysis between SMA and HL-3

Methods	Impedance Tube		Reverberation Time
Sample	Gyratory	2006 Field Core	2006 Field
Sound Absorption Coefficient Difference	-0.020	0.015	0.008
Higher Absorption Coefficient Mix	HL-3	SMA	SMA
Significant Difference?	Yes	Yes	Yes

5.2.4 rOFC vs. rOGC

Table 5.32 summarizes the results of the sound absorption coefficient comparison and statistical analysis between rOFC and rOGC. Results of the sound absorption coefficient testing methods show that rOGC has a higher average sound absorption coefficient than rOFC. On average, the sound absorption coefficient of rOGC is higher than rOFC by 0.008 from the gyratory samples and 0.019 from the 2006 field core samples in the Impedance Tube Method, and 0.002 from the 2006 field samples in the Reverberation Time Method. Statistical analysis results show that rOGC is significantly different from rOFC at a 95% confidence interval in the Impedance Tube Method result, but not significantly different in the Reverberation Time Method result.

Table 5.32 – Sound Absorption Coefficient Statistical Analysis between rOFC and rOGC

Methods	Impedance Tube		Reverberation Time
Sample	Gyratory	2006 Field Core	2006 Field
Sound Absorption Coefficient Difference	-0.008	-0.019	-0.002
Higher Absorption Coefficient Mix	rOGC	rOGC	rOGC
Significant Difference?	Yes	Yes	No

5.3 Summary of Findings

This chapter has summarized average value differences and the statistical analysis results between studied mixes for the sound level and the sound absorption coefficient measurements.

The overall results show that average sound levels measured from both rOFC and rOGC are lower than the control mix HL-3, which means both rOFC and rOGC are quieter than the control mix HL-3. The sound level difference increases as the vehicle size and speed increases. Average sound level differences between either rOFC or rOGC and HL-3 are in a range of 0 dBA to 3 dBA in both CPB and CPX Methods in 2004. However, the difference decreases after one year, when the highest sound level difference drops from 3 dBA to 2 dBA approximately. This decrease maybe caused by a clogging problem due to the porous characteristic in rOFC and rOGC, while HL-3 does not have a clogging problem. The statistical analysis results show rOFC and rOGC are significantly different from HL-3 a 95% confidence level. In terms of the set-back distance in accordance with the Figure 2.4 in Chapter 2 "Adjusted Sound Level vs. Set-Back Distance with Line Source", the highest amount of noise reduction from rOFC and rOGC to the HL-3 is about 3 dBA in 2004 and 2 dBA in 2005, which is equivalent to a person moving 15 metres and 9 metres farther away from the noise source respectively, assuming the original position was 15 meters away from the noise source with a hard ground surface. Although measured sound levels between the rOFC and rOGC are very similar, statistical analysis result shows that sound level differences between them are significant at a 95% confidence level. The overall result shows that the rOGC is quieter than the rOFC by about 0 dBA to 1 dBA and that these differences decrease over time.

The overall result shows that HL-3 is quieter than SMA in the 2004 sound level measurement, but that the differences are not significant at a 95% confidence level. After one year of service, the result shows that SMA is quieter than HL-3 by 0.5 dBA to 2 dBA and the statistical analysis result shows that these differences are significant. These differences are equivalent to a set-back distance from two metres to 9 metres farther away from the noise source.

The Impedance Tube statistical analysis results show that average sound absorption coefficient differences between rOFC, rOGC, or SMA are significantly different from the control mix HL-3 at a 95% confidence level even though their differences are relatively small. The Reverberation Time statistical analysis results show that rOFC is not significantly different from HL-3, but rOGC and SMA are significantly different from HL-3 at a 95% confidence level.

When rOFC is compared with rOGC, the Impedance Tube statistical analysis indicates that the average absorption coefficient differences between these two mixes are significant, but are not significant in the Reverberation Time Method.

CHAPTER 6: LIFE CYCLE COST ANALYSIS

Life Cycle Cost Analysis (LCCA) is a process for evaluating and comparing the total economic worth of alternative projects by analyzing their initial costs and discounted future costs over the life of the project or over a selected analysis period. Chapter 6 summaries the cost effectiveness of the study mixes and control mix over a selected analysis period using both deterministic and probabilistic-based LCCA techniques. A sensitivity analysis for the probabilistic approach was also performed.

6.1 Input Parameters

Life cycle cost (LCC) can be analyzed with two techniques: Deterministic and Probabilistic. The deterministic approach uses the recommend mean values for all input parameters in the LCCA to determine a mean overall LCC, while probabilistic approach uses mean, standard deviation, and probability distribution of each input parameters in the LCCA to determine the statistic distribution of the total LCC. The probabilistic approach is recommended in most of the current LCCA practices, such as the MTO. It is because this approach considers the uncertainties and variability of the highway construction and pavement performance. Recommended input parameter values are given in Table F-1 in Appendix F. The probabilistic LCC can be carried out using a statistical software package. Crystal Ball® developed by Decisioneering Inc. is the statistical software package that recommended by the MTO [Lane 05]. The following parameters are typical inputs in the LCCA:

- Initial Pavement Service Life and Construction Cost
- Timing, Service Life, and Maintenance Cost
- Timing, Service Life, and Rehabilitation Cost
- Discount Rate
- Analysis Period
- Salvage Value
- User Cost

Typically, costs, service life, and timing associated with the alternatives are estimated or based on the pervious construction, maintenance, and rehabilitation performance. As a rule of thumb, the analysis period should be long enough to incorporate at least one rehabilitation activity

[Walls 98]. The LCCA guideline from the MTO recommends a 50-year analysis period be used for high-volume roadways with greater than 1 million Equivalent Single Axel Loads (ESALs) per year and a 30-year analysis period is used for a roadway with less than 1 million ESALs [Lane 05].

Reasonable unit price estimates are needed to ensure a fair assessment of life cycle costs. There are several sources of cost data are available at the MTO to determine the unit costs for use in LCCA. These sources include the MTO Highway Costing (HiCo) database, the MTO Estimating Office, and the MTO Maintenance Office. The HiCo database is commonly used in the MTO, which represents the average of the three lowest bid prices for each contract for the past 5 years. Caution should be taken when using costs from the HiCo Database. Each cost within this database is specific to a particular contract and may have specific circumstances related to its magnitude.

Salvage value is the economic value of a pavement at the end of the analysis period. The purpose of using the salvage value is to compare the alternative equitably over the specified analysis period even though the alternatives have different service lives. Salvage value is determined by dividing the remaining service life of the last rehabilitation treatment by the expected life of that treatment and multiplied by the cost of the last rehabilitation, refers to Equation 6.1.

$$SV = \frac{L_{rem}}{L_{\exp}} C_{rehab} \qquad \text{[Equation 6.1]}$$

where SV represents the salvage value at the end of the analysis period. L_{rem} and L_{exp} represent the remaining service life and expected service life of last rehabilitation treatments (years) at the end of the analysis period, respectively. C_{rehab} represents the cost of the last rehabilitation treatment.

User costs, which can be considered in pavement LCCA, include vehicle operating cost (VOC) and user delay cost (UDC). VOC is influenced by pavement condition and UDC is due to delays experienced by motorists during the construction, maintenance and rehabilitation treatments. However, these costs are not considered in the MTO LCCA because these are virtual costs that do not directly influence the values within the LCCA [Agarwal 97].

6.2 Present Worth Calculation

A present worth (PW) calculation is commonly used to determine the total life cycle cost of a pavement alternative. This method converts all associated costs for an alternative to today's dollars, refers to Equation 6.2.

$$PW = F\frac{1}{(1+i)^n} \qquad \text{[Equation 6.2]}$$

where PW represents the present worth cost ($) and F represents the future cost in present-day terms ($) occurring at year n. F includes the costs of the maintenance, rehabilitation, and salvage value after initial construction within the analysis periods. i and n represent the discount rate and the year until cost F is incurred.

According to the MTO guideline, the mean discount rate used in the PW method is 5.3% with a standard deviation of 0.52%. This discount rate is a "social" discount rate that reflects the social benefits foregone by not investing the funds elsewhere in the economy [Lane 05].

6.3 Maintenance and Rehabilitation Treatment Schedules

Two open graded friction courses (i.e. rOFC and rOGC), stone mastic asphalt (SMA), and Hot-Laid 3 (HL-3) were examined in this study. Routine maintenance treatments (such as pothole filling) were not included in this analysis. However, the major maintenance treatments such as rout and seal and sectional patching were included.

The service life and schedule of rOFC are based on the MTO Central Region experience. The mix designs of rOGC and rOFC are similar with the only difference is the aggregate quality but it does not affect the service life. Therefore, rOGC has the same service life and schedule as rOFC. Since these two mixes consist of open porous characteristics, freeze-thaw cycles will result in a more rapid deterioration of the asphalt layer compared to other asphalt mixes. Therefore, it is assumed that rOFC and rOGC will have 12 years of initial service life and milling (removal) of the surface and binder courses (i.e. two-lift) during the rehabilitation will be performed.

The service life and schedule of SMA are obtained from the MTO "Guidelines for the Use of Life Cycle Cost Analysis on MTO Freeway Projects", which is established based on the MTO pavement performance recorded and models.

The service life and schedule of HL-3 are based on the strategy of the municipal arterial functional category from the MTO "Impact on the Highway Infrastructure of Existing and Alternative Vehicle Configurations and Weight Limits Technical Report in 1997" [Agarwal 97]. Although the report suggested using HL-1 for the municipal arterial roads, the mix design of HL-1 and HL-3 are similar with the only difference in the quality of coarse aggregate, which does not affect the service life. Therefore, the strategy of HL-1 is used for the HL-3 in this study.

In this study, the costs of the surface course layers are obtained from the Regional Municipality of Waterloo in 2004. The unit costs of the other pavement layers, maintenance and rehabilitation treatments were obtained from the MTO "Guidelines for the Use of Life Cycle Cost Analysis on MTO Freeway Projects". The cost given for each items is the average unit cost, based on the three lowest bids for each project over a 5-year period ending in 1998. An inflation rate of 2.12% is applied for the costs in the MTO guideline in order to bring the 1998 unit costs to the value in 2004 for the LCCA [GOC 07].

6.4 Results of LCCA

Two 3.5 m wide lanes with AADT of 3260, representing the test site, were used to calculate the quantities for the materials required during the construction, maintenance and rehabilitation. The complete life cycle cost analysis of each pavement mix using both deterministic and probabilistic techniques are demonstrated in Appendix F. The deterministic LCC was calculated using the mean of all input parameters, while the probabilistic LCC was calculated using the mean, standard deviation, and probability distribution of input parameters with the Crystal Ball® statistical analysis software. Normal probability distributions are recommended for all input parameters in current MTO practice. Since the cost in the LCCA cannot be negative, some studies believe that lognormal probability distribution is better suited to describe the input cost parameters because the values of the random variable with the lognormal variables are always positive [Tighe 01]. Thus, both normal and lognormal probability distributions for the cost parameters are presented in this study. The following assumptions are used in the probabilistic LCCA approach:

- The lower limits of all input cost parameters in the normal probability distribution were assumed to be zero dollar
- The lower limits of all service lives were assumed to be three years
- The timing of each major maintenance treatment was assumed to be an equally distributed between rehabilitations
- Monte Carlo simulation with 100,000 iterations were performed

6.4.1 Deterministic Approach

Table 6.1 summarizes the initial construction, maintenance, rehabilitation, and total life cycle cost per lane per km for each pavement mix using a deterministic approach with 30 year analysis period. The value inside the bracket represents the cost ratio relative to the control mix, HL-3.

Table 6.1 – Life Cycle Cost using Deterministic Approach

Net Present Worth	Pavement Types			
	rOFC	rOGC*	SMA	HL-3
Initial Construction Cost	$ 111,999 (1.2)	$ 102,841 (1.1)	$ 111,999 (1.2)	$ 93,271 (1.0)
Maintenance and Rehabilitation Cost	$ 56,345 (3.4)	$ 48,477 (2.9)	$ 19,899 (1.2)	$ 16,656 (1.0)
Total Life Cycle Cost	$ 165,909 (1.6)	$149,271 (1.4)	$129,424 (1.2)	$ 106,973 (1.0)
* Conservative estimates have been applied to this mix as it has not been commonly used; therefore, long term performance data is not available.				

The initial construction cost for both rOFC and SMA are the same and both mixes have the highest initial cost due to the premium quality of aggregates. Although the mix designs of rOFC and rOGC are similar, rOGC consists of local aggregate rather than premium aggregate. Therefore, the cost of rOGC is lower. The initial construction cost of HL-3 is the lowest among all mixes because it is also using local aggregate and less asphalt binder. The differences between the initial construction costs of the studied mixes with the control mix are 20% more in rOFC and SMA and 10% in rOGC.

The maintenance and rehabilitation cost of rOFC is the highest among all mixes at about 3.4 times more than the cost of HL-3. This is due to:

- Cost of rOFC surface layer is high because rOFC is a premium aggregate mix
- rOFC service life is short, therefore required to perform more rehabilitations during the analysis period
- Resurface two lifts rather than one lift during rehabilitation

The cost of the maintenance and rehabilitation of rOGC is slightly lower than rOFC due to the use of local aggregate. However, its cost is 2.9 times more than HL-3. Although SMA uses premium aggregates, its service life is 21 years, much longer than the other mixes. Therefore, the maintenance and rehabilitation costs of SMA are only 0.2 times more than HL-3.

The total life cycle cost (LCC) of the control mix (i.e. HL-3) is \$106,973 per lane kilometre which is also the most economical mix among rOFC, rOGC and SMA. The LCC of SMA is \$129,424 that is the second economical mix and it is about 20% more expensive than HL-3. The LCC of rOFC is \$165,909 which is the highest LCC among all mixes and its cost is about 50% more than HL-3. The LCC of rOGC is \$149,271, which is slightly cheaper than rOFC, but its cost is about 30% more than HL-3.

6.4.2 Probabilistic Approach

Figure 6.1 demonstrates the life cycle cost frequency distribution of each pavement type in the form of histogram using a probabilistic LCCA approach. The curve shows the variability about the mean. The mean and standard deviation of the total life cycle cost per lane per km for each pavement mix are summarized in Table 6.2. The number inside the bracket represents the cost ratio relative to the control mix, HL-3. Two probability distributions were assumed in the cost input parameters in the probabilistic LCCA, Normal and Lognormal. The service life input parameters and the discount rate were assumed as normal probability distributions.

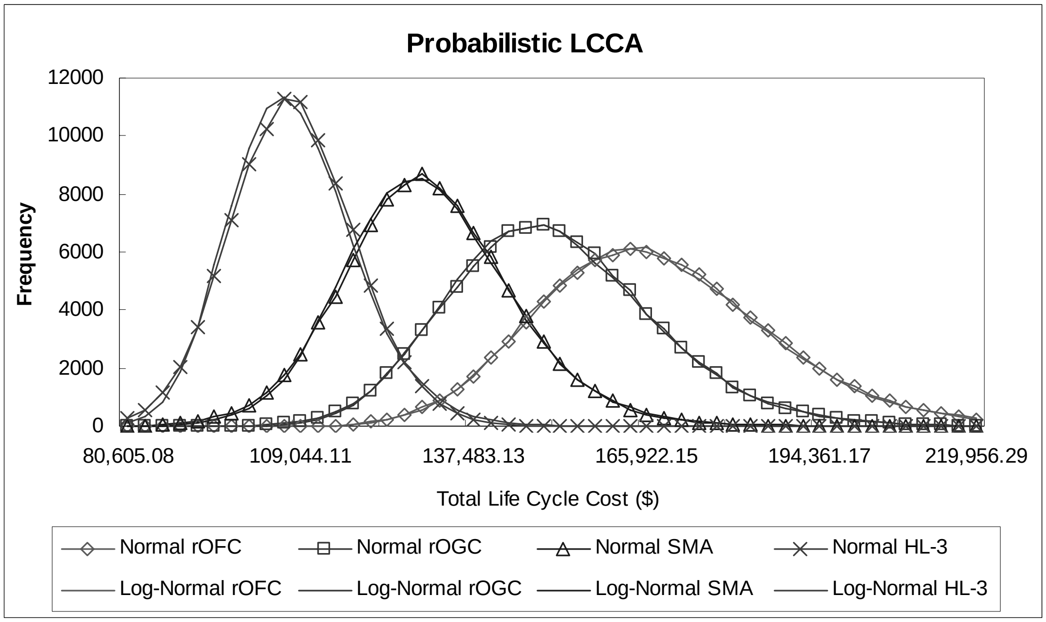

Figure 6.1 – Probabilistic LCCA Frequency Distribution

Table 6.2 – Life Cycle Cost using Probabilistic Approach

Life Cycle Cost	Probability Distribution*	Pavement Type			
		rOFC	rOGC	SMA	HL-3
Mean	Normal	$167,518 (1.6)	$150,566 (1.4)	$130,070 (1.2)	$107,749 (1.0)
	Lognormal	$167,395 (1.6)	$150,514 (1.4)	$130,112 (1.2)	$107,789 (1.0)
Standard Deviation	Normal	$19,236 (1.9)	$16,835 (1.7)	$14,003 (1.4)	$10,202 (1.0)
	Lognormal	$19,267 (1.9)	$16,881 (1.6)	$13,949 (1.4)	$10,253 (1.0)
* The probability distribution type refers to the cost input parameters only, the other input parameters are assumed as normal distributions					

The probabilistic LCCA results shows that probability distribution types of cost input parameters do not affect the distribution of the pavement total life cycle cost. The mean values in the probabilistic results are consistent with the deterministic result in that HL-3 is the most economical mix and rOFC is the most expensive mix. SMA is more economical than rOGC. The analysis shows that rOFC is not only the most expensive mix, and also its LCC is the most uncertain among the mixes since the wider the distribution is the greater the variability. The analysis shows that the more expensive the mix is, the greater the variability.

Figure 6.2 shows the cumulative probability of the LCC for each pavement mix. The mean LCC of each curve is located at the 50% cumulative probability. This means there is close to 0% of chance that costs for rOFC, rOGC, and SMA are less than the mean of the HL-3 LCC. When compared the maximum LCC of HL-3 with the others, there are about 50%, 10%, and 2% of chances that SMA, rOGC, and rOFC are less than the maximum LCC of HL-3, respectively. When compared rOFC with rOGC, there is only about 18% probability that cost for the rOFC is less than the mean of the LCC of rOGC.

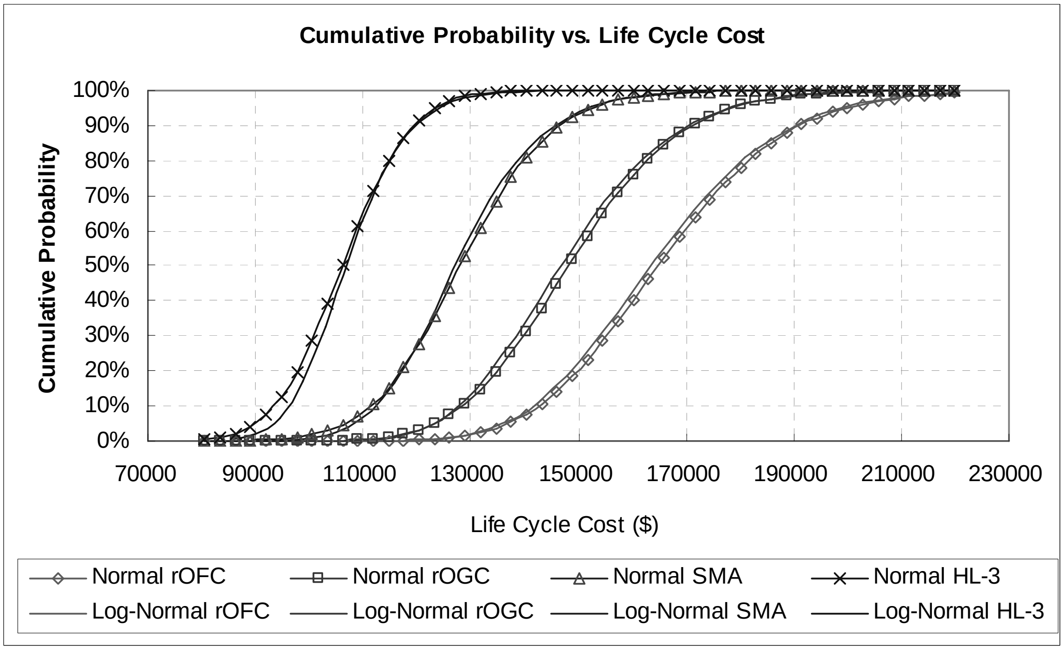

Figure 6.2 – Probabilistic LCCA Cumulative Probability Distribution

Sensitivity analysis is also performed in the probabilistic LCCA and the results are shown in Appendix F. This analysis identifies the important input parameters when determining the LCC distributions. The results of this sensitivity analysis for both normal and log-normal distributions are the same and they are presented as input parameters versus correlation coefficients in Appendix F. The higher the correlation coefficient, the more important the input parameter in determining the output result [Walls 98]. According to FHWA, the input parameters having correlation coefficients less than 0.6 are insignificant [Walls 98]. Basically, there was only one input parameter for each pavement mix with a correlation coefficient higher than 0.6. The initial service lives of the rOFC, rOGC, and SMA were the most sensitive input parameters. Their correlation coefficients are approximately -0.64, which represents if the initial service life of the pavement increase one standard deviation, then the net present worth of the pavement LCC will decrease 0.64 of a standard deviation, or vice versa. For HL-3, the most sensitive input parameter is the Granular B cost which has a correlation coefficient of +0.7. It indicates that if the cost of the Granular B increases 0.7 of standard deviation, then the net present worth of the HL-3 LCC will increase 0.7 of a standard deviation, or vice versa.

6.5 Summary of Findings

Both deterministic and probabilistic LCCA approaches were performed in this chapter. Two probability distributions of input cost parameters were assumed in the probabilistic approach: Normal and Log-Normal. The rest of the input parameters were assumed as normal probability distributions. The results show that the both input parameter probability distributions do not affect the output LCC probability distribution.

Both deterministic and probabilistic LCCA results show that HL-3 is the most economical mix, rOFC are the least economical mix, and SMA is more economical than rOGC. Basically the ranking from the most to the least uncertain LCC is the same as the ranking from the most to the least economical LCC. Besides, the cumulative LCC probability distribution shows that no mixes are comparable with the cost of the HL-3. Based on the sensitivity analysis, initial service lives of the rOFC, rOGC, and SMA have a significant negative influence to their LCC, while the cost of the Granular B has a significant positive influence to the LCC of HL-3.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

This thesis involved the design and construction of four asphalt pavement test sections to examine their acoustic attenuation performance. In addition, laboratory equipment was designed, acquired, and setup to test both laboratory prepared and field core samples. The acoustic attenuation performance evaluation of four asphalt pavement mixes was performed using sound level (i.e. Close Proximity Method and Controlled Pass-By) and sound absorption coefficient (i.e. Impedance Tube and Reverberation Time) measurement methods. These four pavement types include rubberized premium Open Graded Fiction Course (rOFC) and rubberized local Open Graded Friction Course (rOGC), Stone Mastic Asphalt (SMA), and the control mix Hot-Laid 3 (HL-3). Comparisons between studied mixes were performed using the result from each measurement method. Statistical analysis using the result of each measurement method was performed in order to determine whether the result difference between mixes is significant. Life Cycle Cost Analysis was also performed for each pavement type in order to determine the cost effectiveness of each mix.

It is found that vehicle noise increases when the vehicle speed or size increases in the results from the CPB and CPX Methods. The type of pavement mix affects the degree of traffic sound levels. Measurements from the CPX, CPB, Impedance Tube, and Reverberation Time Methods indicate that they all have the same overall ranking, from the best to the worst acoustic attenuation ability of the studied mixes:

"New" Pavements:	rOGC > rOFC > HL-3 > SMA
"More than One Year of Service" Pavements:	rOGC > SMA > rOFC > HL-3

rOFC and rOGC sound attenuation abilities decrease after one year when compared with the control mix. This reduction maybe caused by clogging of the pavement voids since both rOFC and rOGC consists of a porous surface texture. Statistical analysis indicates rOFC is not significantly different from rOGC in the early age, but rOGC performs significantly better than rOFC after 14 months in service at a 95% confidence interval. rOGC attenuates approximately 2 dBA after the mix was placed for 14 months when compared with the control mix. This sound level attenuation is equivalent to a receiver move of nine metres away from a noise source, assuming the original distance from the receiver to the noise source is 15 m apart.

The sound level results indicate that the measured sound level on SMA is higher compared to the control mix in the early age, but the difference is not significant at a 95% confidence interval. After 14 months in service, SMA performs significantly better than HL-3 and rOFC by 0.5 dBA to 2 dBA.

According to the statistical analysis of the overall sound absorption coefficient results, rOFC, rOFC, and SMA are significantly different from HL-3 in both test samples of the Impedance Tube measurement (i.e. Gyratory and 2006 field core) at a 95% confidence interval. The statistical analysis result of the Reverberation Time measurement shows that rOGC and SMA are significantly different from HL-3, but rOFC are not significantly different from HL-3 at a 95% confidence interval. rOFC is significantly different from rOGC at a 95% confidence interval in the Impedance Tube measurement, but not in the Reverberation Time measurement.

Life Cycle Cost Analysis (LCCA) was performed over a 30-year analysis period using both deterministic and probabilistic approaches. Two types of probability distributions, Normal and Log-Normal, were assumed for input cost parameters during the LCCA. The results show that probability distributions of input cost parameters do not affect the LCC. Results of LCC probability distributions indicate that the mix has a higher LCCA ranking, has a higher variability. The ranking from the most to the least economical mixes is as follows:

HL-3 > SMA > rOGC > rOFC

The LCC of rOFC, rOGC, and SMA are 60%, 40%, and 20% higher (respectively) than the control mix HL-3. Note, however because there is limited long term performance data on rOGC, so conservative service lives have been applied. Over time, it is expected that the rOGC section will show good in service performance and will improve the LCC for the rOGC. Sensitivity analysis shows that initial service lives of the rOFC, rOGC, and SMA have a significant negative influence to their LCC, while the cost of the Granular B has a significant positive influence to the LCC of HL-3. Since HL-3 has about the same initial service life with SMA but using local aggregates, HL-3 is more economical than SMA. The initial service life of

SMA is about two times greater than rOFC and rOGC, therefore, SMA is more economical than rOGC and rOFC. Both rOGC and rOFC have a similar mix design, but rOGC uses local aggregate rather than premium aggregates which rOFC uses, therefore, rOGC is more economical than rOFC.

7.2 Recommendations

Based on the results provided in this research, it is recommended that rubberized open graded course (rOGC) is the best choice among all mixes in terms of acoustical attenuation ability. rOGC consistently reduces 2 dBA sound level on average when compared with HL-3 after 14 months and as noted earlier as more performance data becomes available, it will likely improve over time. This 2 dBA represents a six metre set-back distance which is sufficient to reduce the use of a physical mitigation method if the measured outdoor living area traffic sound level is less than or equal to 58 dBA, accordance with the noise policy from the Ontario Ministry of the Environment. Although the life cycle cost of rOGC is 40% more than the HL-3, the noise reduction benefit from the rOGC may reduce the overall LCC by reducing the use of physical noise mitigation methods.

This research presents only the first year acoustical attenuation ability of the studied pavement mixes. It is recommended that additional sound level measurements be carried out in the future to monitor the long term pavement acoustical performance. More investigation into the feasibility of developing a laboratory Reverberation Time Method is recommended to validate the result from the modified Reverberation Time Chamber in this research, such as re-examined the design by the other acoustic experts. Also it is recommended to investigate and develop a relationship between sound level and sound absorption coefficient measurement methods in order to minimize the cost and duration of the evaluation of the pavement acoustical attenuation ability. Conducting skid, roughness, and pavement distress measurements on each pavement section is recommended in order to evaluate the long term performance of the test sections. Finally, it is recommended to include the LCC of the required physical noise mitigation methods to determine the overall life cycle benefits.

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APPENDIX A: RESULTS OF THE CONTROLLED PASS-BY METHOD

Table A.1 – Controlled Pass-By Method – Year 2004 Measured Sound Level

Size	Vehicle	Speed (km/h)	Measured Sound Level (Leq, dBA)			
			rOFC	rOGC	SMA	HL-3
Light	Taurus	60	61.7	60.9	64.3	61.7
		60	61.3	60.1	64.2	-
		70	62.4	61.5	66.1	63.4
		70	62.1	61.6	65.5	63.3
		80	64.3	62.9	67	64.9
		80	64.4	63.5	66.6	64.9
		90	65	64.4	68.1	66.2
		90	65.2	64.9	68.4	66.7
Light	Mazda	60	-	61	63.8	61.4
		60	60.8	59.9	64.2	60.3
		70	63.7	61.8	65.4	62.5
		70	63.3	61.4	65.7	62.8
		80	65.4	63.4	67.2	64.3
		80	64.3	62.4	66.2	64.1
		90	65.8	64.9	68.8	66.4
		90	65.5	64.6	68.3	66.3
Light	Minivan	60	62.8	62.1	65.6	63.3
		60	62.2	61.4	65.7	63.4
		70	64.7	62.6	67	65
		70	63.8	67.9	66.2	65.2
		80	65.6	64.9	68.4	67.3
		80	65.4	68.7	68.3	67.5
		90	67.1	64.7	69.6	68
		90	66.7	67.4	68.5	68.8
Light	Pick-up Truck 1	60	65.4	62.9	67.1	64.5
		60	64	63.1	65.6	63.8
		70	67	65.2	68.1	66.6
		70	65.6	64.8	67.7	66.7
		80	67.7	66	69.5	68.2
		80	67.5	66.3	68.9	68
		90	69.2	67.5	70.4	69.8
		90	68.8	67.7	70	69.6
Light	Pick-up Truck 2	60	65	62.2	65.4	63.7
		60	62.5	67.6	64.5	63.2
		70	65.7	70	67.6	66.4
		70	65.2	66.3	66.4	66.4
		80	68	66.1	69.3	68.3
		80	66.8	65.1	68.5	68.2
		90	69.1	66.9	72.8	69.9
		90	68.5	66.5	69.8	71
Medium	City Bus 1	60	73.9	73.8	73.4	75
		60	74.7	72	74.6	73.5

		70	-	-	-	-
		70	-	-	-	-
		80	74	-	74.4	76.7
		80	75.9	75.4	74.2	75
		90	75.1	77.4	76.6	78.2
		90	78	74.2	78.3	76
Medium	City Bus 2	60	73	71.5	73.5	74.5
		60	73.9	71.3	73.2	73.4
		70	75.9	73	74.7	75.4
		70	75.2	74.1	74.4	75.3
		80	76.1	74.2	76.5	76.8
		80	75.8	75.4	76.5	77.5
		90	77.5	76.9	80	79.8
		90	76.7	79.1	77.7	80.2
Medium	Dump Box 1	60	68.3	66.8	-	-
		60	67	66.3	-	70.3
		70	70.3	67.3	-	71.4
		70	68.2	68.3	-	72
		80	70.9	68.8	-	72.8
		80	69.7	69.6	-	73.2
		90	72.1	70	-	74.8
		90	71.1	70.8	-	75.2
Medium	Dump Box 2	60	67.8	65.6	-	69.1
		60	67.7	64.9	-	-
		70	69	67.1	-	72.5
		70	68.8	67	69	72.1
		80	69.3	68.4	70.7	73.7
		80	70	68.3	71.1	72.8
		90	70.1	69.1	71.5	74.5
		90	70.9	69.9	71.8	74.6
Medium	Dump Box 3	60	73	70.4	72.1	72.3
		60	70.7	71.4	71.2	73
		70	74	71.9	74.4	74
		70	71.4	73.5	72.8	74.6
		80	73.9	73.5	74.5	75.3
		80	71.4	73.9	73.5	75.9
		90	75	72.6	75.3	-
		90	73.9	74.1	74.8	76.9
Heavy	Dump Truck 1	60	72	71.7	73.3	73
		60	72.3	72.4	73	73.4
		70	75.2	74.6	76.2	76.1
		70	72.9	72.9	74.9	76
		80	73.8	73.1	75.3	74.8
		80	-	74.3	75.1	75.6

		90	79.5	78.6	80.2	79.8
		90	75.7	76.6	76.5	77.2
Heavy	Dump Truck 2	60	74.8	71.6	-	73.4
		60	73.2	73.7	78.2	77.5
		70	75.9	72.7	75.3	75.1
		70	74.3	75.7	75.4	75.9
		80	76.5	73.2	76.5	76.4
		80	75.8	75.2	75.8	78.1
		90	76.8	74	76.3	77.7
		90	76.2	76	76.7	77.1
Heavy	Dump Truck 3	60	74	70.7	73.9	72.6
		60	70.4	73.7	72	73.4
		70	74.4	70.8	72.5	73.2
		70	71.3	72.8	73	73.8
		80	76.6	74.2	77.7	76.1
		80	74.6	76.2	76.2	78.5
		90	76.9	72.9	75.6	75.4
		90	75.2	75.3	74.3	76.8

Table A.2 – Controlled Pass-By Method – Year 2005 Measured Sound Level

Size	Vehicle	Speed (km/h)	Measured Sound Level (Leq, dBA)			
			rOFC	rOGC	SMA	HL-3
Light	Minivan	60	64.9	65.2	64.4	65.1
		60	64.9	64.5	65	65.3
		70	67.1	66.3	66.5	67.6
		70	66.2	66.1	66.7	67.7
		80	68.4	68.3	67.9	69.3
		80	68.1	68.1	68.1	68.5
		90	70.1	69.2	69.3	70.3
		90	69.1	69.2	69.4	70.4
Light	Taurus	60	64.1	63.1	62.5	63.8
		60	63.4	62.5	62.5	63.6
		70	65.5	65.1	64.6	66.4
		70	65.1	64.3	65.1	65.6
		80	67.5	66.3	66.2	68.4
		80	67	66.3	66.7	68.2
		90	69.2	67.1	67.5	69.9
		90	68.6	67.7	68.3	69.8
Light	Pick-up Truck 1	60	65.8	64.8	66.2	66.7
		60	64.7	65.8	64.5	65.4
		70	67.2	67.3	67.2	68.7
		70	-	67.5	66.7	68.1
		80	69.8	68.1	69.4	70.3
		80	68.4	69.1	68.9	69.8
		90	71.4	70.3	71	72.8

		90	69.9	71	70.5	72.6
Medium	City Bus	60	69.7	67.5	-	69.3
		60	68.1	65.9	67.7	68.9
		70	69	67.6	68.4	69.2
		70	68.8	67.8	68.5	69.5
		80	70.5	69.1	68.9	70.7
		80	69.5	69	69.8	71.2
		90	72.6	71.5	73.3	72.3
		90	71.1	70.8	71.2	72.7
Medium	Snow Plow	60	75.7	71.4	72.9	74.6
		60	72.7	72.2	72.1	74
		70	73.5	72.6	73.4	74.8
		70	71.9	74	71.9	73.1
		80	75	74.4	74	76.6
		80	73.6	74.9	72.9	75.1
		90	76.7	-	74.1	76.5
		90	75.5	-	74.1	76.6
Medium	Dump Box 1	60	69.1	67.2	68.4	70.7
		60	67.5	67.9	67.6	70.1
		70	70.6	68.5	69.4	72.4
		70	69.2	69.3	69.2	71.6
		80	72	71	71.4	73.9
		80	70.7	71.5	71.4	73.7
		90	72.9	71.7	72.7	75.2
		90	72.1	72.5	72.6	75
Heavy	Dump Truck	60	74.6	73	74.8	75.1
		60	71.2	74.4	73.7	74.5
		70	75.4	73.1	74.8	75.7
		70	73.7	74.3	74.5	74.4
		80	77.9	75.8	77.1	78.2
		80	75.7	76.6	76.3	78.1
		90	78.3	76.4	77.1	79.3
		90	77.2	77.3	76.6	78.7

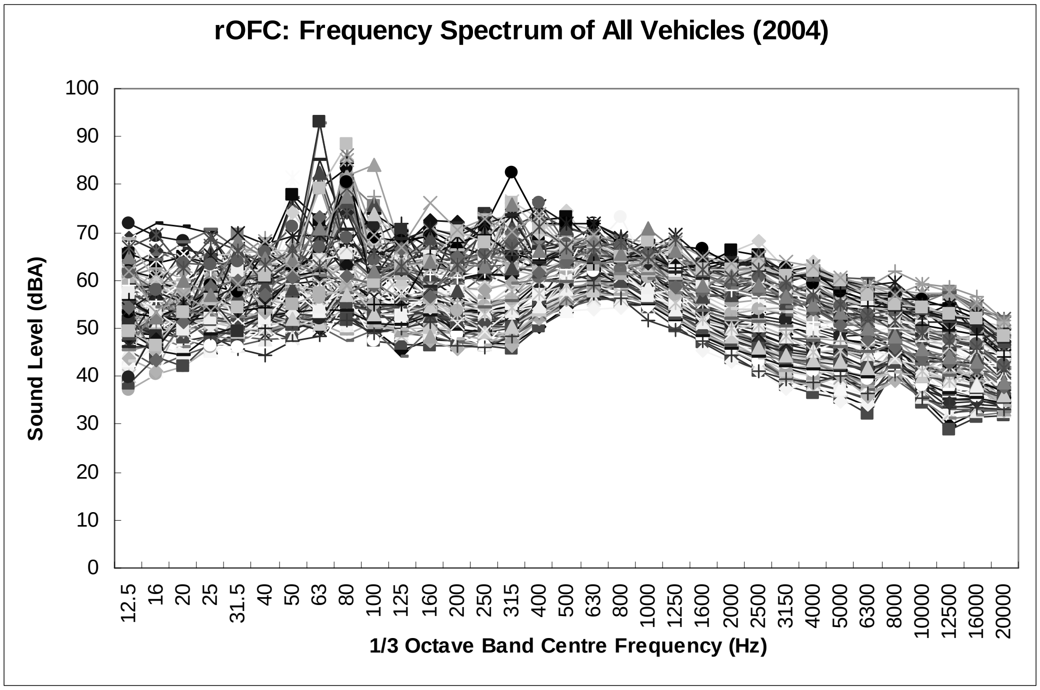


Figure A.1 – 2004 Frequency Spectrum: rOFC

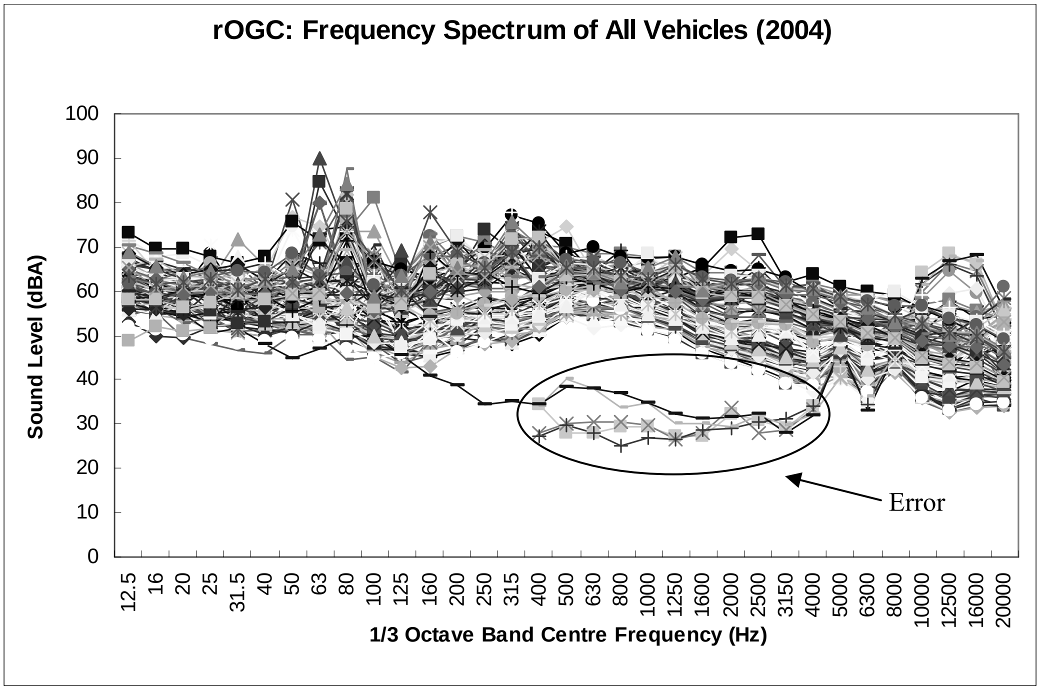


Figure A.2 – 2004 Frequency Spectrum: rOGC

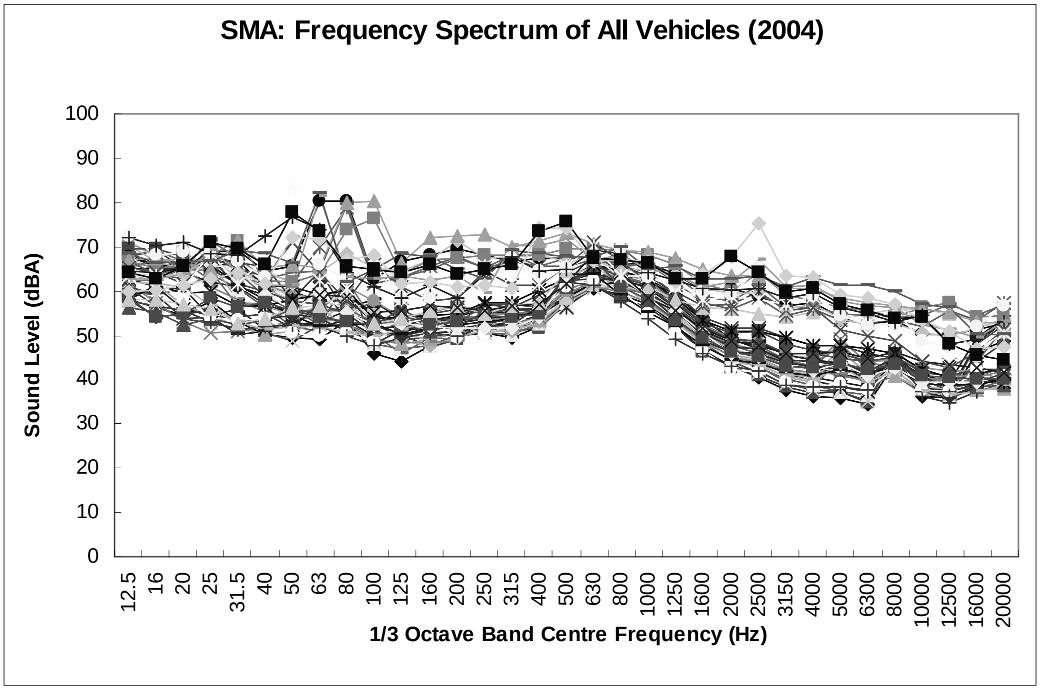


Figure A.3 – 2004 Frequency Spectrum: SMA

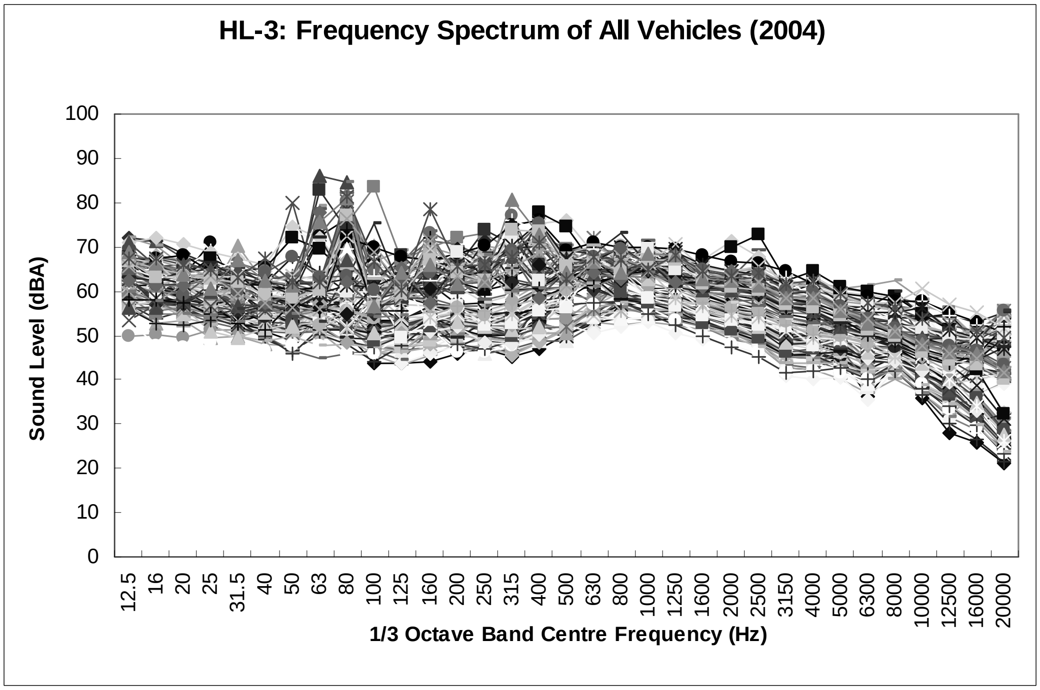


Figure A.4 – 2004 Frequency Spectrum: HL-3

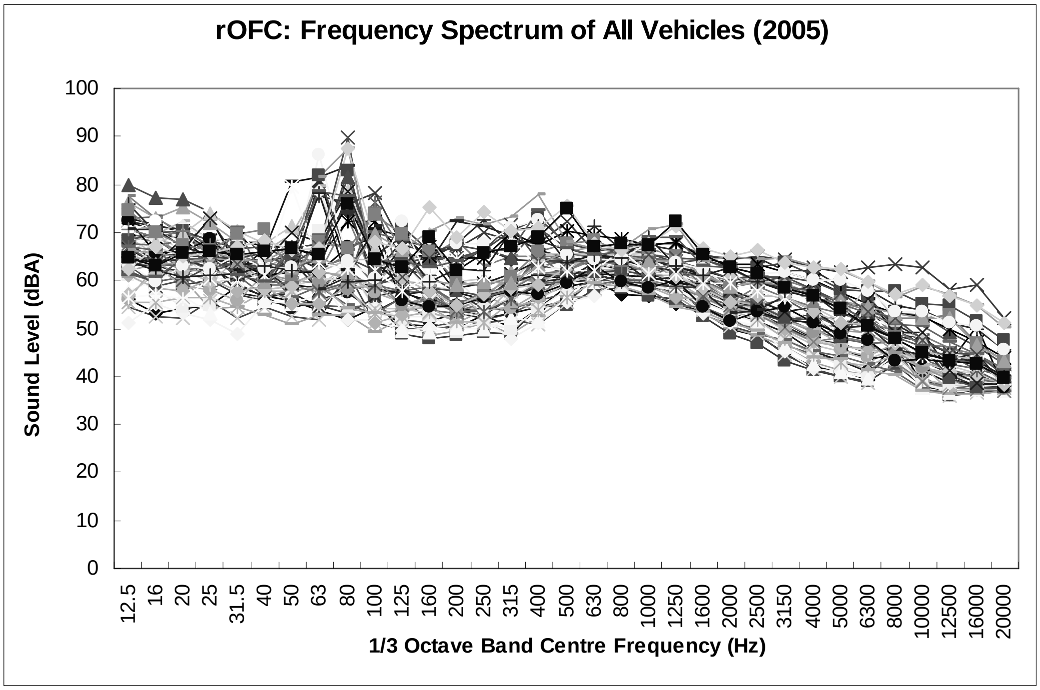


Figure A.5 – 2005 Frequency Spectrum: rOFC

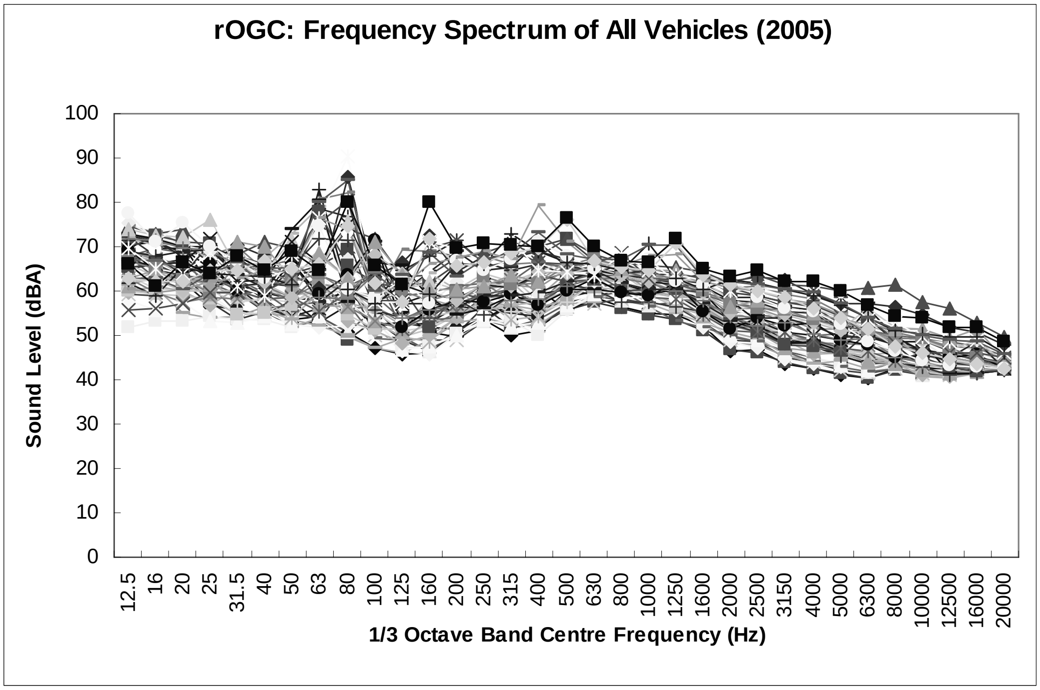


Figure A.6 – 2005 Frequency Spectrum: rOGC

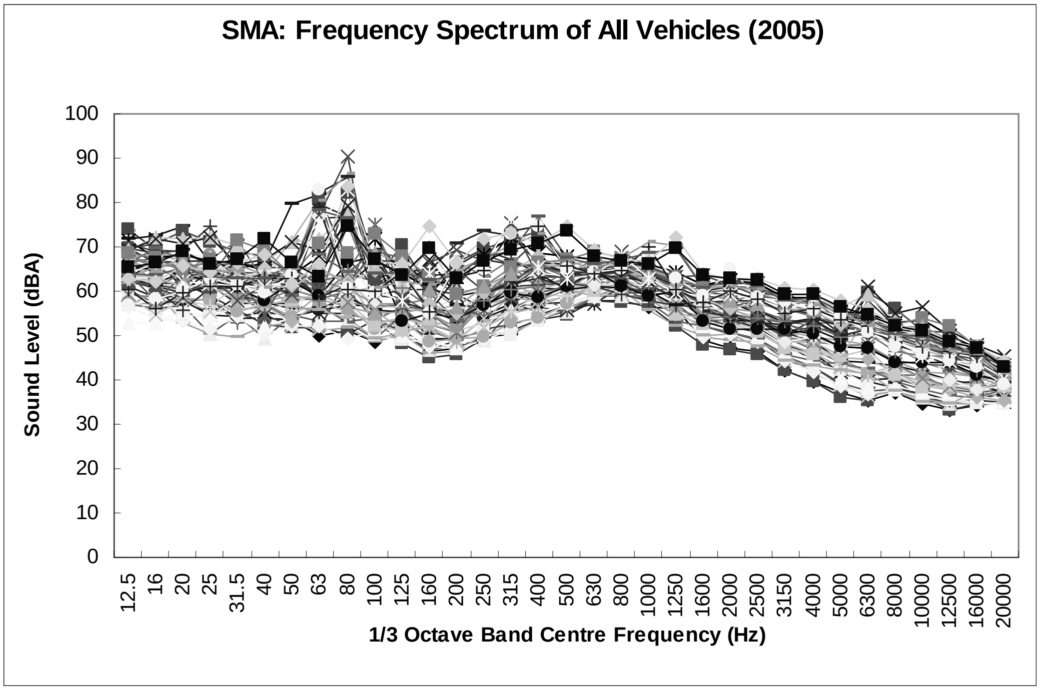


Figure A.7 – 2005 Frequency Spectrum: SMA

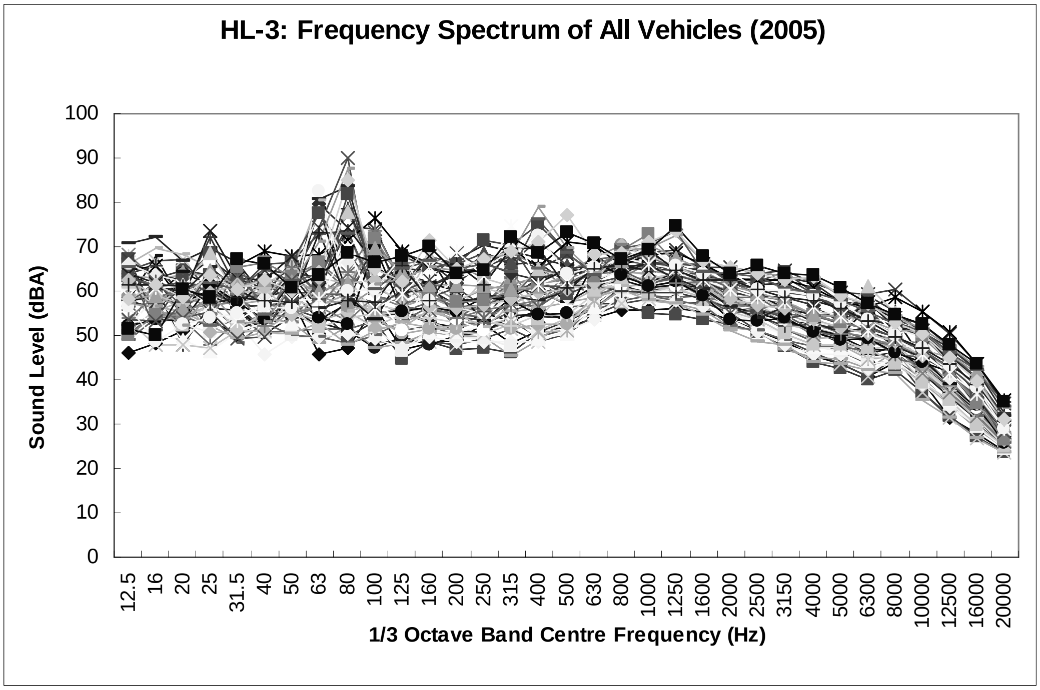


Figure A.8 – 2005 Frequency Spectrum: HL-3

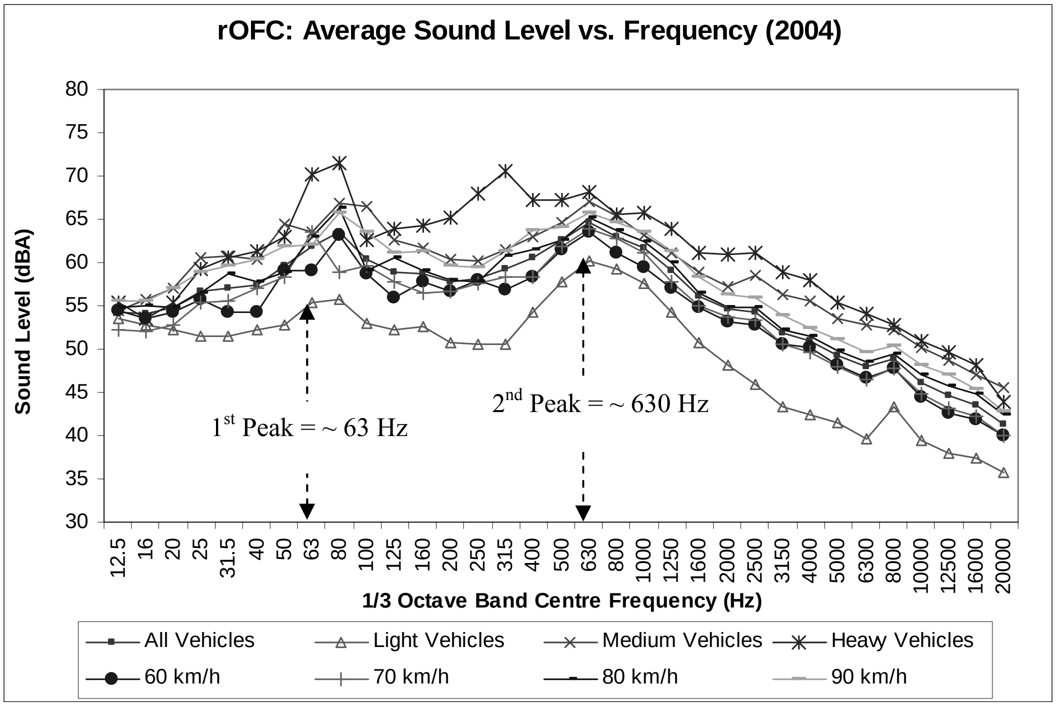


Figure A.9 – Average Frequency Spectrum of rOFC in 2004

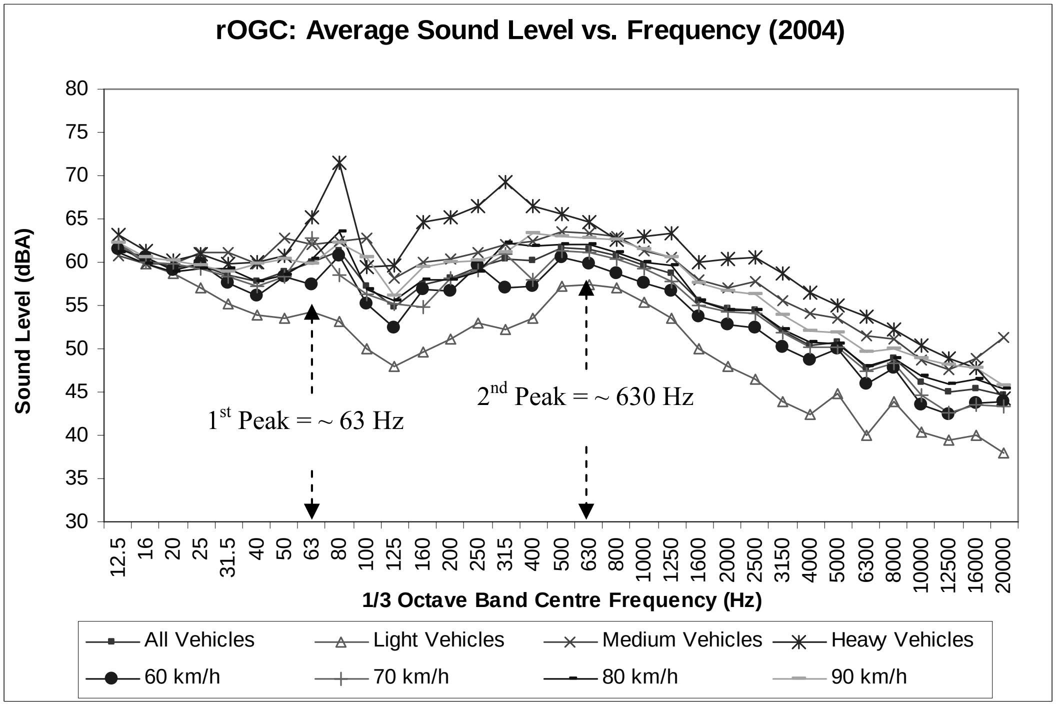


Figure A.10 – Average Frequency Spectrum of rOGC in 2004

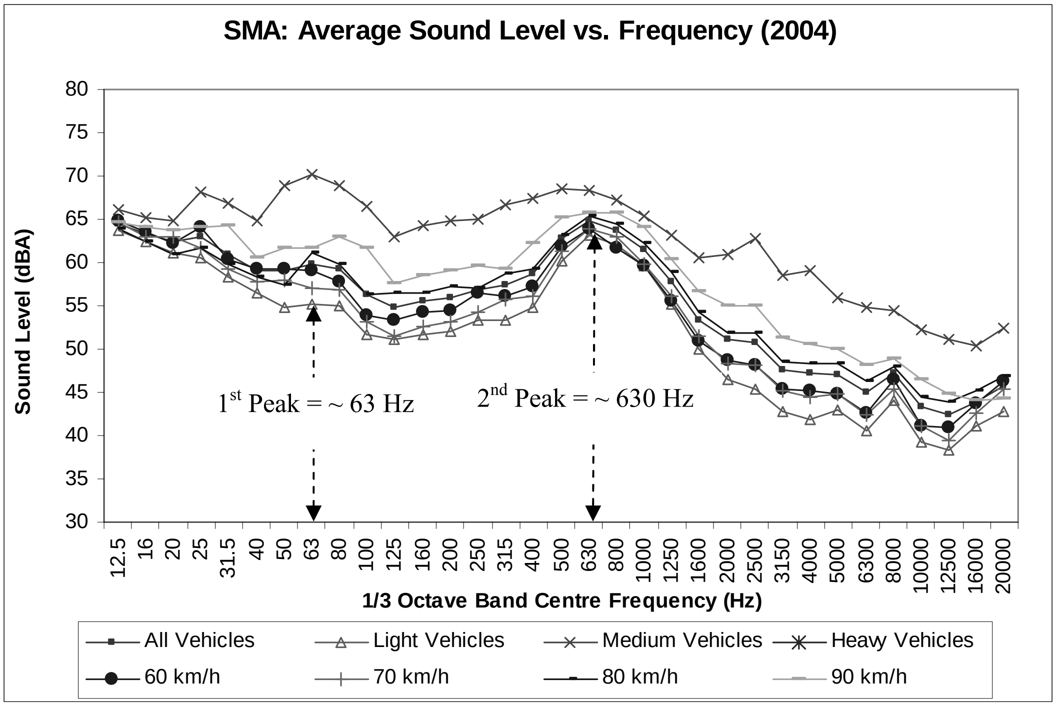


Figure A.11 – Average Frequency Spectrum of SMA in 2004

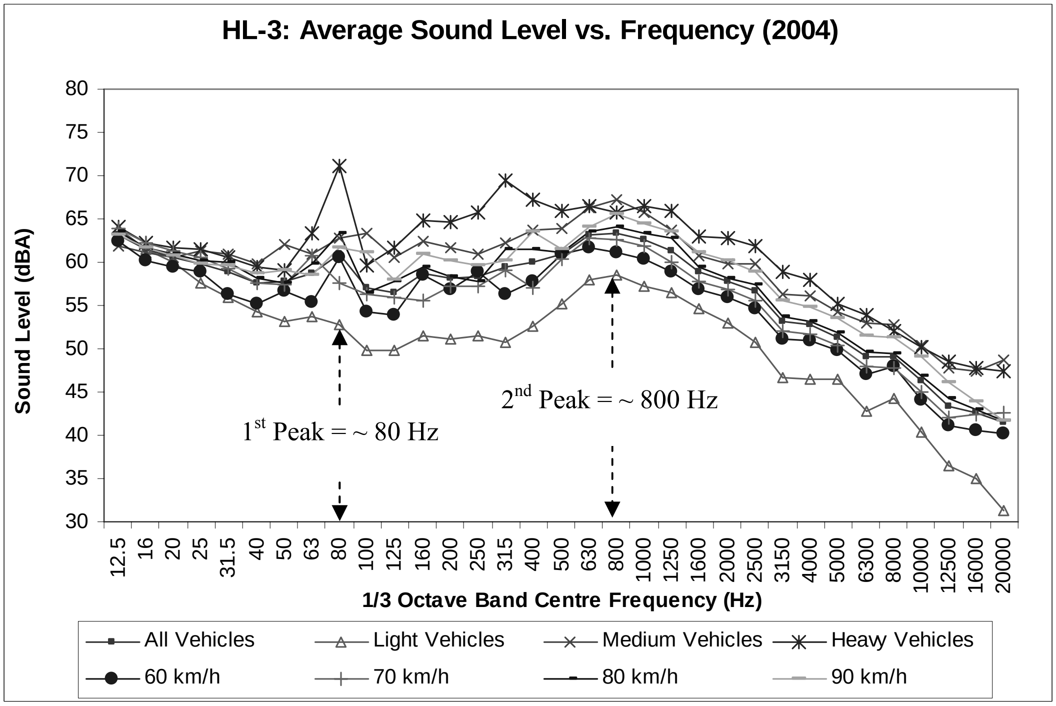


Figure A.12 – Average Frequency Spectrum of HL-3 in 2004

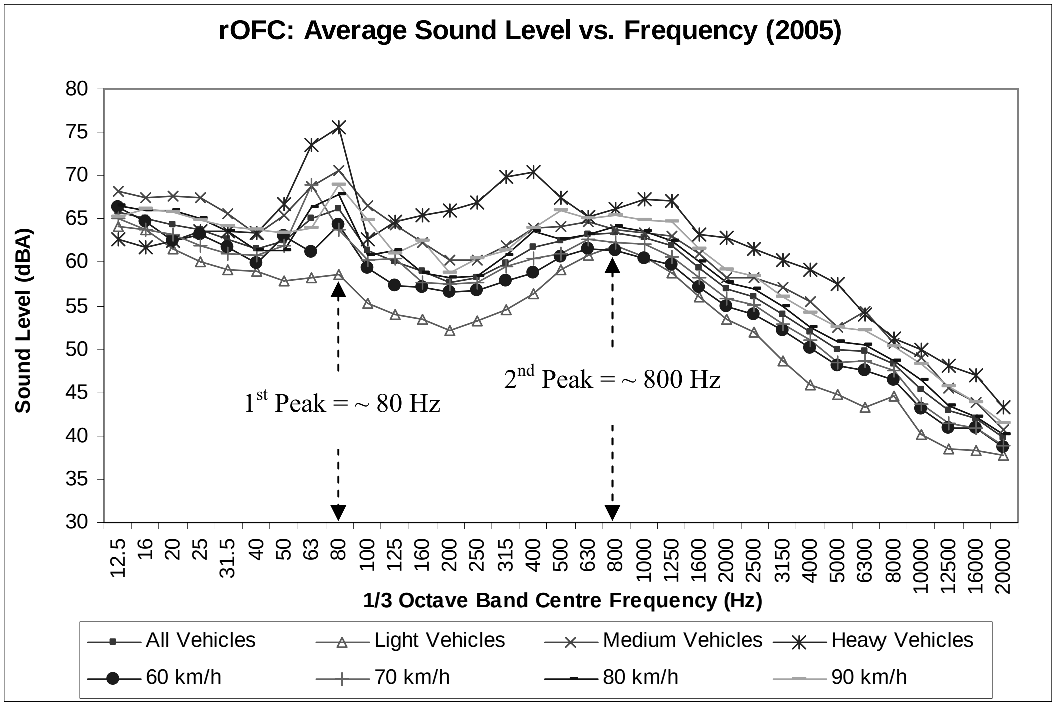


Figure A.13 – Average Frequency Spectrum of rOFC in 2005

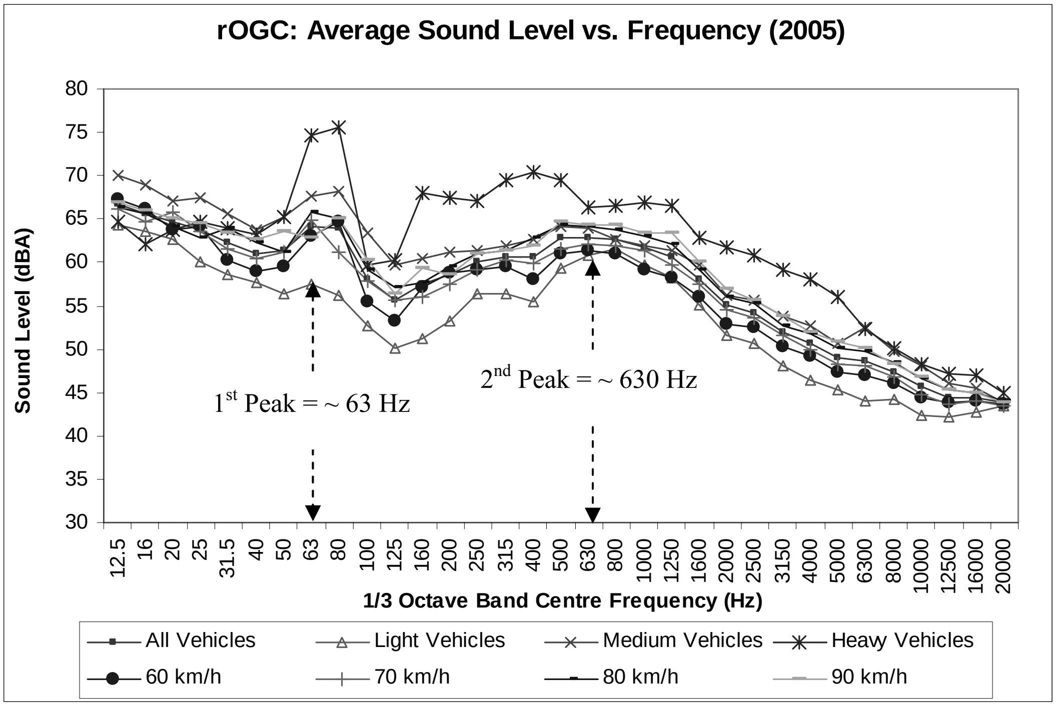


Figure A.14 – Average Frequency Spectrum of rOGC in 2005

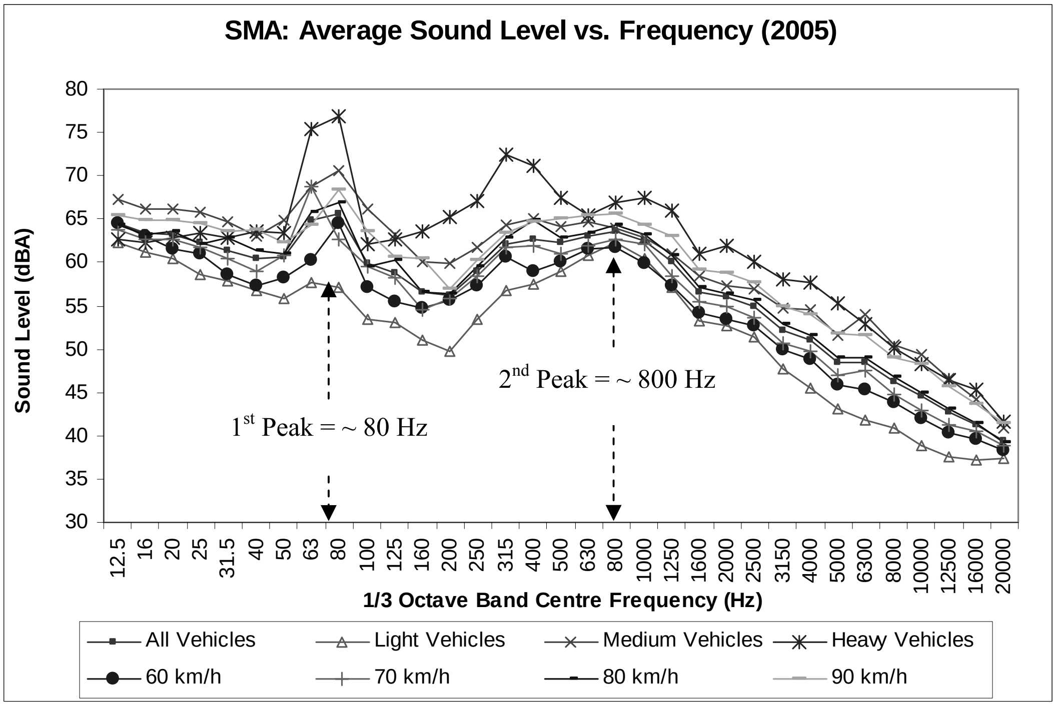


Figure A.15 – Average Frequency Spectrum of SMA in 2005

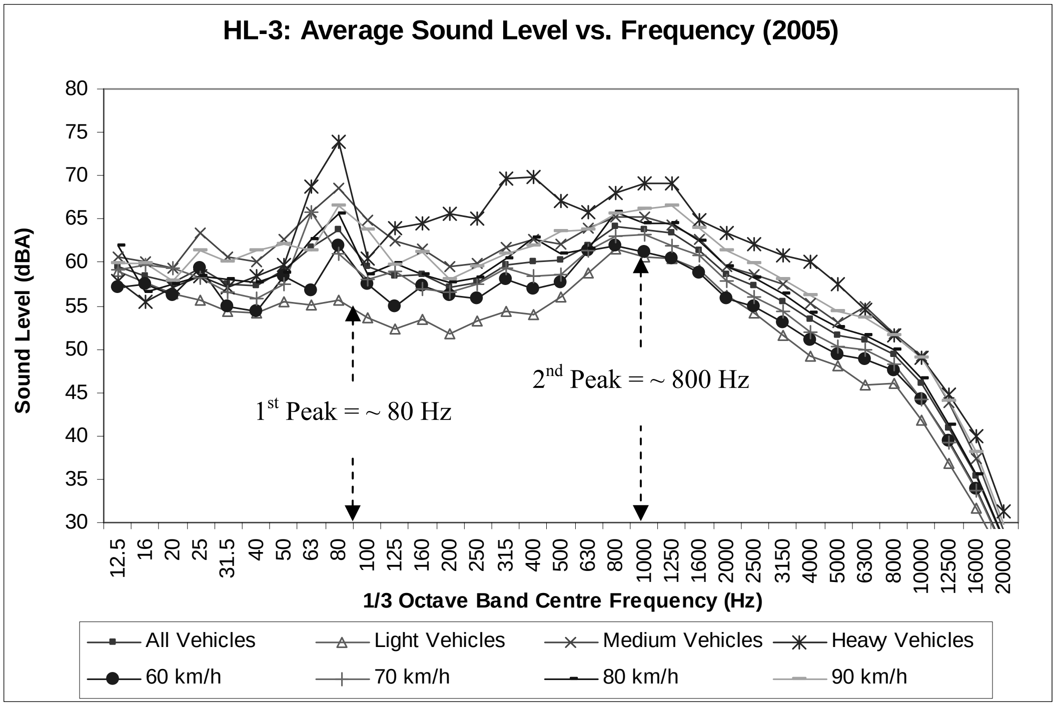
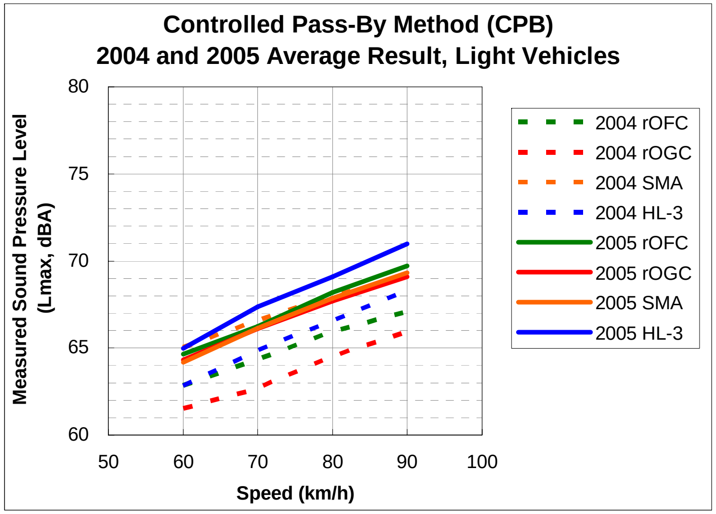


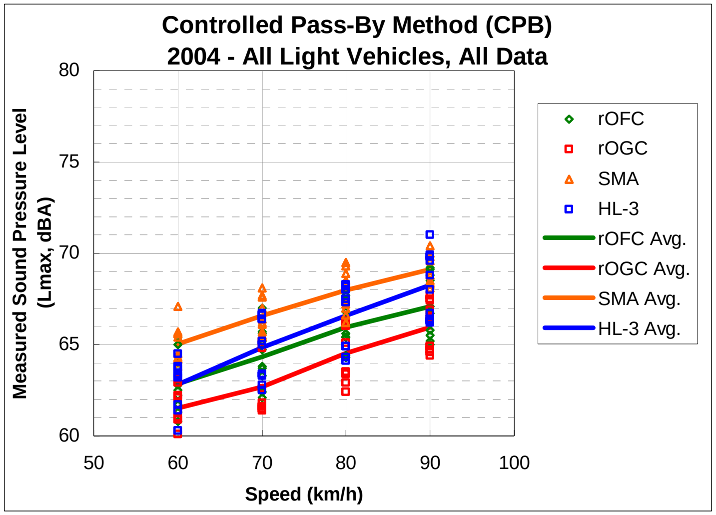
Figure A.16 – Average Frequency Spectrum of HL-3 in 2005

CPB Method: All Light Vehicle

2004	rOFC Avg.	rOGC Avg.	SMA Avg.	HL-3 Avg.
60	62.9	61.5	65.0	62.8
70	64.4	62.7	66.6	64.8
80	65.9	64.5	68.0	66.6
90	67.1	66.0	69.1	68.3

2005	rOFC Avg.	rOGC Avg.	SMA Avg.	HL-3 Avg.
60	64.6	64.3	64.2	65.0
70	66.2	66.1	66.1	67.4
80	68.2	67.7	67.9	69.1
90	69.7	69.1	69.3	71.0


Controlled Pass-By Method (CPB)
2004 and 2005 Average Result, Light Vehicles


Controlled Pass-By Method (CPB)
2004 - All Light Vehicles, All Data

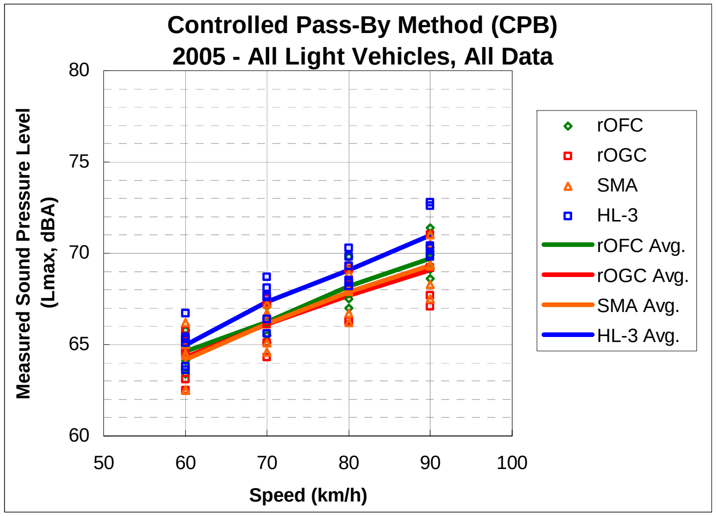
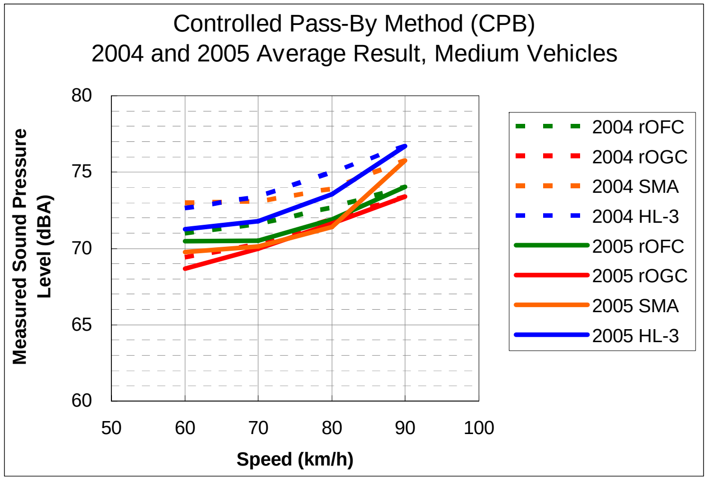

Controlled Pass-By Method (CPB)
2005 - All Light Vehicles, All Data

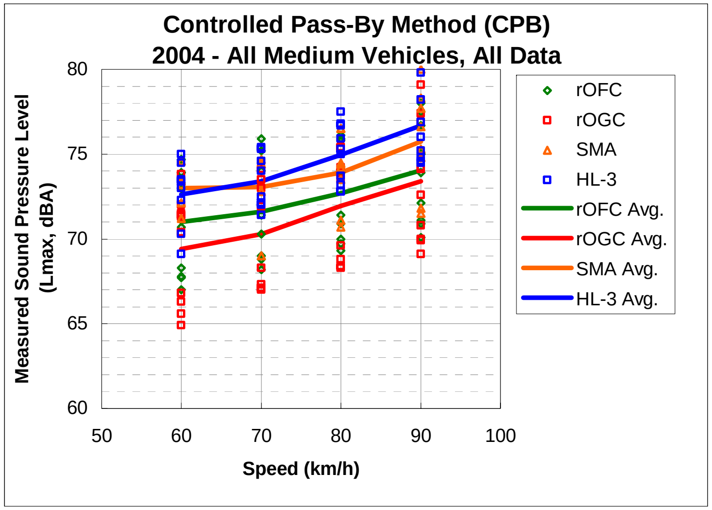
Figure A.17 – Controlled Pass-By Method Years 2004 and 2005 Results – Light Vehicles

CPB Method: All Medium Vehicle

2004	rOFC Avg.	rOGC Avg.	SMA Avg.	HL-3 Avg.
60	71.0	69.4	73.0	72.6
70	71.6	70.3	73.1	73.4
80	72.7	71.9	73.9	75.0
90	74.0	73.4	75.8	76.7

2005	rOFC Avg.	rOGC Avg.	SMA Avg.	HL-3 Avg.
60	70.5	68.7	69.7	71.3
70	70.5	70.0	70.1	71.8
80	71.9	71.7	71.4	73.5
90	74.0	73.4	75.8	76.7





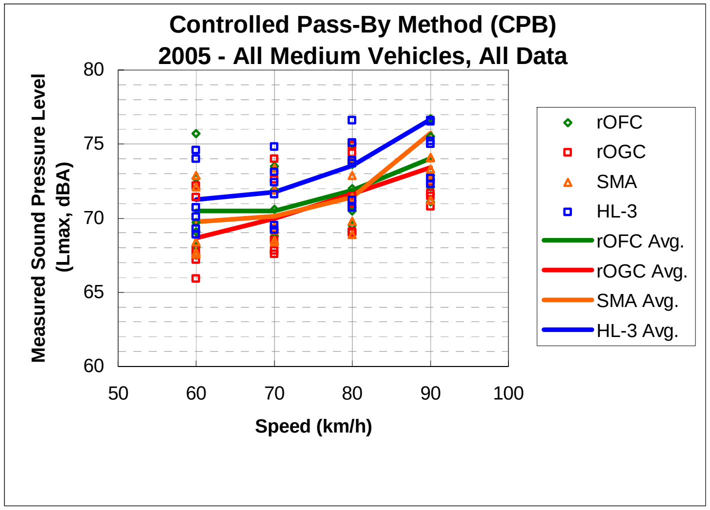
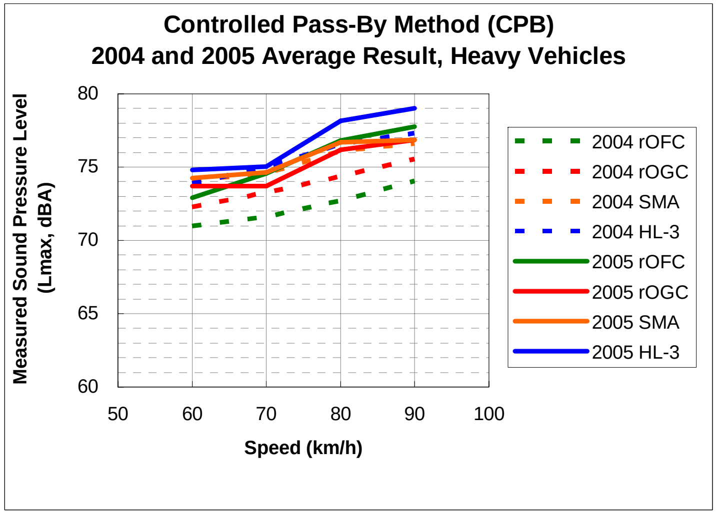


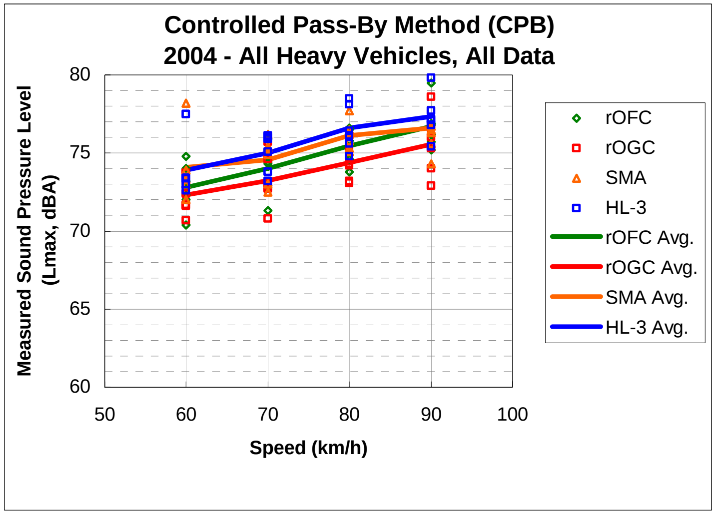
Figure A.18 – Controlled Pass-By Method Years 2004 and 2005 Results – Medium Vehicle

CPB Method: All Heavy Vehicle

2004	rOFC Avg.	rOGC Avg.	SMA Avg.	HL-3 Avg.
60	72.8	72.3	74.1	73.9
70	74.0	73.3	74.6	75.0
80	75.5	74.4	76.1	76.6
90	76.7	75.6	76.6	77.3

2005	rOFC Avg.	rOGC Avg.	SMA Avg.	HL-3 Avg.
60	72.9	73.7	74.3	74.8
70	74.6	73.7	74.7	75.1
80	76.8	76.2	76.7	78.2
90	77.8	76.9	76.9	79.0





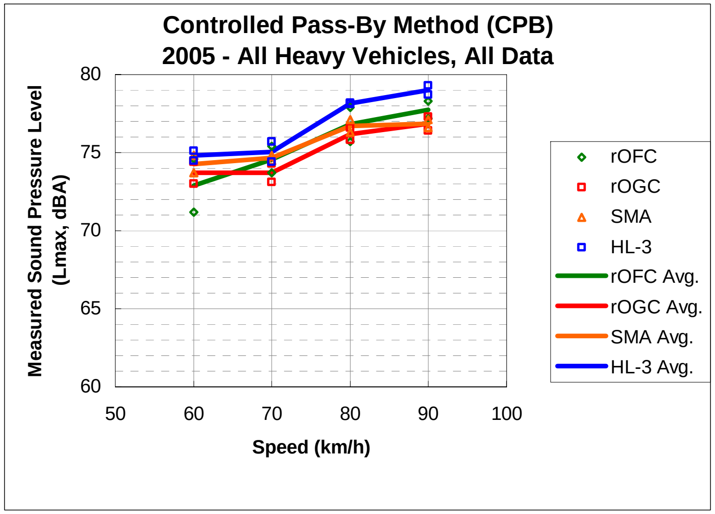


Figure A.19 – Controlled Pass-By Method Years 2004 and 2005 Results – Heavy Vehicles

APPENDIX B: RESULTS OF THE CLOSE-PROXIMITY METHOD

Table B.1 – Close-Proximity Method – Year 2004 Measured Sound Level

Size	Vehicle	Speed (km/h)	Measured Sound Level (Leq, dBA)			
			rOFC	rOGC	SMA	HL-3
Light	Taurus	60	85.1	84.9	88.2	84.7
		60	84.4	84.1	86.6	84.3
		70	85.9	86.4	89.5	86.4
		70	86.2	86.1	88.2	86.6
		80	87.2	87.6	90.8	88.2
		80	88	87.9	89.8	88.7
		90	88.9	88.4	91.9	90.8
		90	89.7	89.6	91.1	91.1
Light	Mazda	60	84.5	83.8	86.8	85.2
		60	83.4	83.5	87.7	83.9
		70	85.7	85.5	88.4	86.3
		70	86.8	85.5	89.4	86.7
		80	87.1	86.7	89.7	87.2
		80	88.1	86.5	90.5	87.8
		90	88.3	88.6	91.2	89.7
		90	89.8	88.9	91.9	89.5
Light	Minivan	60	86.6	86.8	88.6	87.1
		60	86.5	86.7	90	88
		70	88.2	87.2	90.3	88.5
		70	88	88	90.9	89.7
		80	89.3	89.3	91.9	91.4
		80	90.1	88.9	92.6	91.6
		90	91.4	89.7	93.1	92.3
		90	90.3	89.5	92.3	92.5
Light	Pick-up Truck 1	60	87	86.6	89.2	86.8
		60	86.7	86.6	88.9	86.6
		70	88.6	88.4	90.4	88.5
		70	88.6	88.4	91.1	88.9
		80	90.5	90.5	92.1	90.5
		80	89.9	90.2	92.9	91
		90	91.8	91.4	93.5	92.4
		90	91.5	91.9	94.2	92.7
Light	Pick-up Truck 2	60	87.1	86.2	88.8	87.6
		60	86.3	86	89	87.1
		70	89.2	89.5	91.6	91
		70	89.4	89.5	91.3	90.6
		80	90.2	90.6	92.8	92.4
		80	90.4	90.7	93.3	91.9
		90	92.2	91.8	94.6	93.9
		90	92.8	91.6	94.7	94.1
Medium	City Bus 1	60	84.1	84.6	86.4	86
		60	83.9	83.5	85.6	86

		70	-	-	-	-
		70	-	-	-	-
		80	87.9	87.8	90	90.2
		80	89.7	89.3	90	90.3
		90	88.9	88.3	90.9	90.7
		90	89.7	89.4	90.6	91
Medium	City Bus 2	60	85	85.3	87.4	87.3
		60	85.4	85.1	86.7	87.7
		70	87.6	88.4	89.5	89.2
		70	88	87.8	89.5	89.5
		80	90.7	91.4	92.3	93.8
		80	90.7	90.8	92.1	94.6
		90	92.1	93	93.6	94.8
		90	91.6	92.3	92.6	94.8
Medium	Dump Box 1	60	90.1	88.7	90.2	92.4
		60	88	87.4	89.8	90.8
		70	89.5	89.3	92	92.6
		70	89.8	89.4	91.4	92.7
		80	90.8	90.7	92.6	94.6
		80	91.3	90.8	93.3	94.5
		90	93.1	92.3	93.8	94.8
		90	93	92.5	94.3	95.6
Medium	Dump Box 2	60	91.8	90	93.6	94.6
		60	90.9	89.6	92.1	93.2
		70	92.1	91.4	93.8	97.1
		70	91.5	91.2	92.7	95.5
		80	93.2	92.5	94.8	97.9
		80	92.6	92.1	94	96.5
		90	94.4	93.1	95.1	97.4
		90	93.7	93.7	94.9	96.9
Medium	Dump Box 3	60	90.3	89.9	91.1	91.9
		60	91.1	91.2	89.4	88.9
		70	92.2	92.5	94.1	94.3
		70	91.4	92.5	94.3	94.3
		80	93.7	94.1	96.1	97.1
		80	94.1	94.5	96.5	97.8
		90	93.9	93.2	94.6	97.9
		90	94.5	93.2	95	97.8
Heavy	Dump Truck 1	60	88.7	89.4	90.7	92.7
		60	89.5	89.9	90.3	91.7
		70	93	93	93	95.7
		70	92.4	92	93.6	95.1
		80	94.2	93.5	94.4	96.2
		80	92.1	93.6	94.7	96

		90	95.8	95.8	96	97.7
		90	94.1	94.8	95	95.5
Heavy	Dump Truck 2	60	91.8	90.4	92.8	93.3
		60	91.3	90.7	94	94.4
		70	93.7	94	95.3	96.1
		70	94.1	93.5	95	95.2
		80	95.4	94.5	96.8	97.3
		80	94.2	94.2	96.9	96.6
		90	96.5	96.2	97.6	99.5
		90	96.1	95.9	97.2	98.2
Heavy	Dump Truck 3	60	90.9	90.7	92.4	92.7
		60	89.3	90.4	92	91.7
		70	91.7	90.8	92.9	92.6
		70	91	91.2	93.5	91.9
		80	94.4	94.1	95.4	95.8
		80	94.5	94.2	96	96.6
		90	94.3	93.6	95.5	95.8
		90	94.9	94.9	95	95.9

Table B.2 – Close-Proximity Method – Year 2005 Measured Sound Level

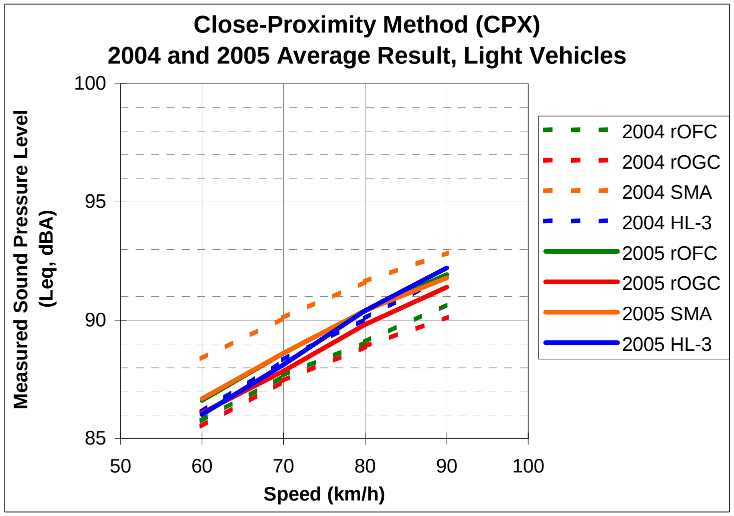
Size	Vehicle	Speed (km/h)	Measured Sound Level (Leq, dBA)			
			rOFC	rOGC	SMA	HL-3
Light	Minivan	60	88.1	87.6	88.4	86.5
		60	87.4	87.1	88.1	87.4
		70	89.8	88.8	90	88.2
		70	89.2	88.7	89.5	89.6
		80	90.7	90.3	91.1	89.8
		80	90.9	90.4	91	91.2
		90	92.4	91.6	92.1	91.2
		90	92.3	91.8	92.4	92.5
Light	Taurus	60	84.6	83.6	83.9	83.8
		60	84.4	83.6	84.7	83.3
		70	86.8	85.3	86.2	86
		70	86.6	85.7	86.9	85.4
		80	88.9	87.4	88.1	88.5
		80	88.2	87.6	88.7	87.6
		90	90.2	89.1	89.6	89.8
		90	90.2	89.6	90.3	89.4
Light	Pick-up Truck 1	60	87.8	87.4	87.8	87.8
		60	87.4	87.2	87.2	87.3
		70	89.8	89.4	89.4	89.6
		70	89.5	89.3	89.7	90
		80	91.9	91.5	91.6	92.6
		80	91.8	91.8	92	92.8

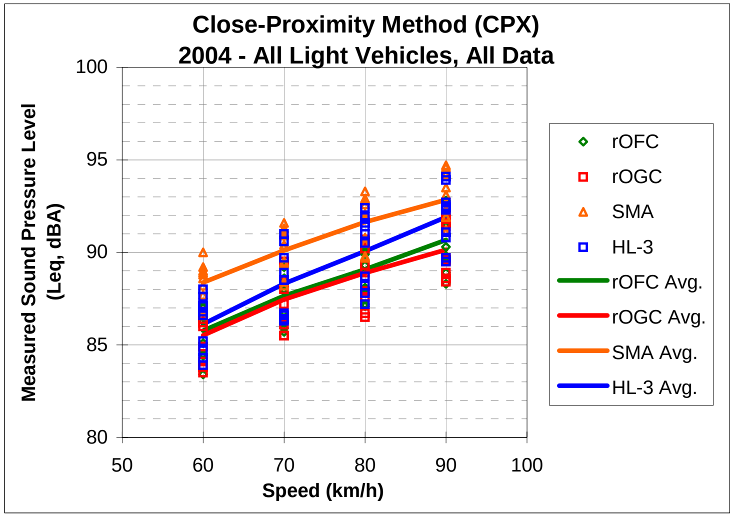
		90	93.2	92.7	93	94.6
		90	93.3	93.6	93.4	95.8
Medium	City Bus	60	87.2	86.9	86.5	85.3
		60	85.7	83.9	84.9	84.2
		70	87.9	86.6	87.5	87.8
		70	87.7	86.5	87.5	87.8
		80	89.7	88.2	88.7	90.6
		80	89.1	87.9	89	88.9
		90	92.2	91	92.7	91.8
		90	92.7	91.6	91.4	91.9
Medium	Snow Plow	60	89	88.8	88	89.4
		60	88	87.5	87.5	88.8
		70	88.4	88.1	88.5	90.1
		70	88.7	87.6	87.6	89.1
		80	90.9	90.5	90.6	92.2
		80	91	90.2	90.2	92.3
		90	93.5	93.2	93.1	95.1
		90	92.8	92.5	92.3	93.9
Medium	Dump Box 1	60	88.9	88.5	89.3	89.7
		60	88.5	87.5	88.3	89.5
		70	90.8	89.8	90.5	91.7
		70	90.1	89.1	90.1	91
		80	92.3	91.5	92.5	93.8
		80	91.8	91.1	92.1	93.2
		90	93.7	93	93.6	95
		90	93.9	93.1	93.6	95
Heavy	Dump Truck	60	90	90.8	90	91.4
		60	90.8	90.5	90.6	91.8
		70	91.9	91.4	91.7	92.9
		70	92	91.7	91.5	93
		80	95.3	95.9	95.7	97.2
		80	94.9	96.1	95.2	96.7
		90	96.2	95.5	95.8	96.7
		90	97.2	96.8	96.9	98.4

CPX Method: All Light Vehicle

2004	rOFC Avg.	rOGC Avg.	SMA Avg.	HL-3 Avg.
60	85.8	85.5	88.4	86.1
70	87.7	87.5	90.1	88.3
80	89.1	88.9	91.6	90.1
90	90.7	90.1	92.9	91.9

2005	rOFC Avg.	rOGC Avg.	SMA Avg.	HL-3 Avg.
60	86.6	86.1	86.7	86.0
70	88.6	87.9	88.6	88.1
80	90.4	89.8	90.4	90.4
90	91.9	91.4	91.8	92.2





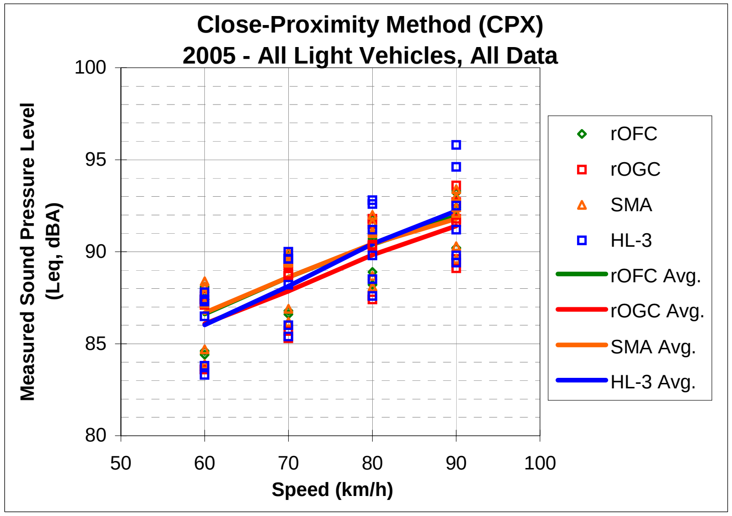
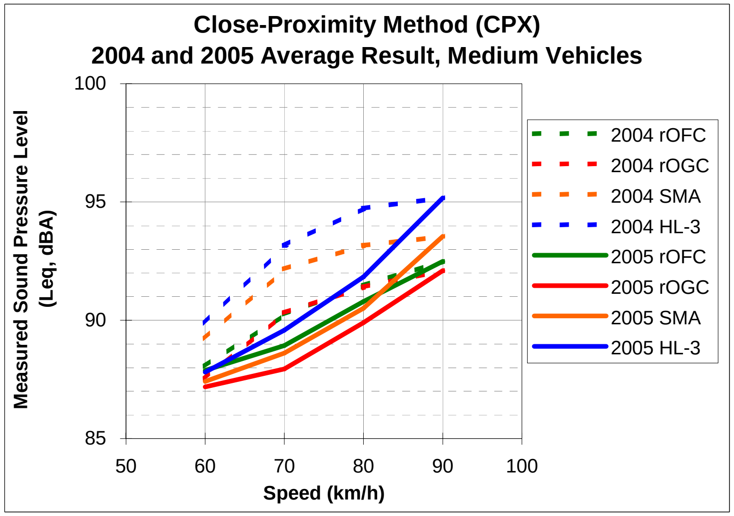


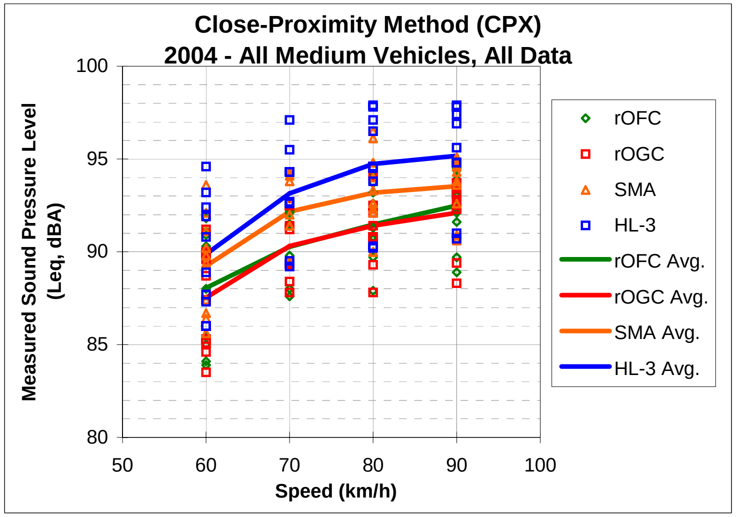
Figure B.1 – Close-Proximity Method Years 2004 and 2005 Results – Light Vehicles

CPX Method: All Medium Vehicle

2004	rOFC Avg.	rOGC Avg.	SMA Avg.	HL-3 Avg.
60	88.1	87.5	89.2	89.9
70	90.3	90.3	92.2	93.2
80	91.5	91.4	93.2	94.7
90	92.5	92.1	93.5	95.2

2005	rOFC Avg.	rOGC Avg.	SMA Avg.	HL-3 Avg.
60	87.9	87.2	87.4	87.8
70	88.9	88.0	88.6	89.6
80	90.8	89.9	90.5	91.8
90	92.5	92.1	93.5	95.2


Close-Proximity Method (CPX)
2004 and 2005 Average Result, Medium Vehicles


Close-Proximity Method (CPX)
2004 - All Medium Vehicles, All Data

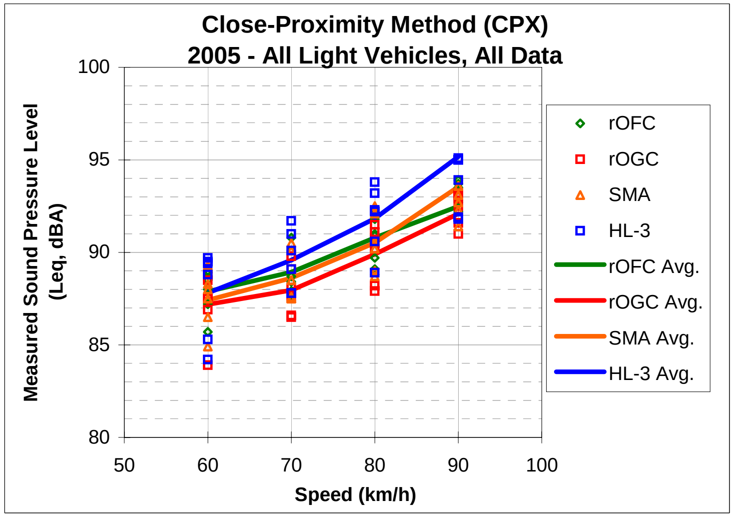
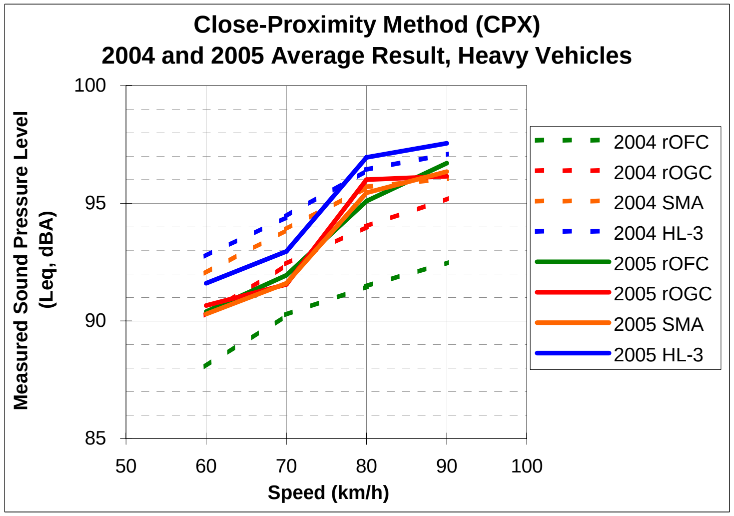

Close-Proximity Method (CPX)
2005 - All Light Vehicles, All Data

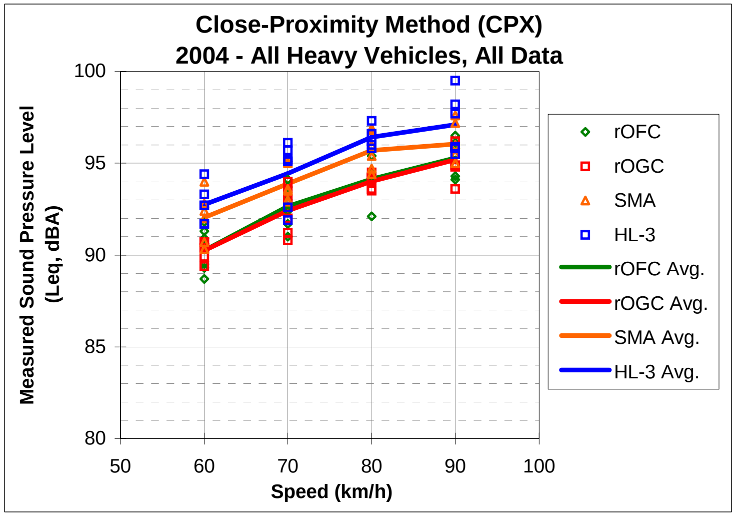
Figure B.2 – Close-Proximity Method Years 2004 and 2005 Results – Medium Vehicles

CPX Method: All Heavy Vehicle

2004	rOFC Avg.	rOGC Avg.	SMA Avg.	HL-3 Avg.
60	90.3	90.3	92.0	92.8
70	92.7	92.4	93.9	94.4
80	94.1	94.0	95.7	96.4
90	95.3	95.2	96.1	97.1

2005	rOFC Avg.	rOGC Avg.	SMA Avg.	HL-3 Avg.
60	90.4	90.7	90.3	91.6
70	92.0	91.6	91.6	93.0
80	95.1	96.0	95.5	97.0
90	96.7	96.2	96.4	97.6





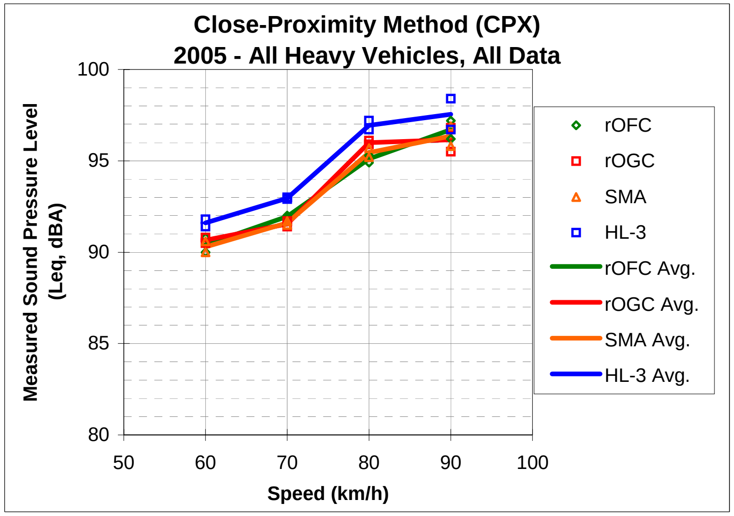
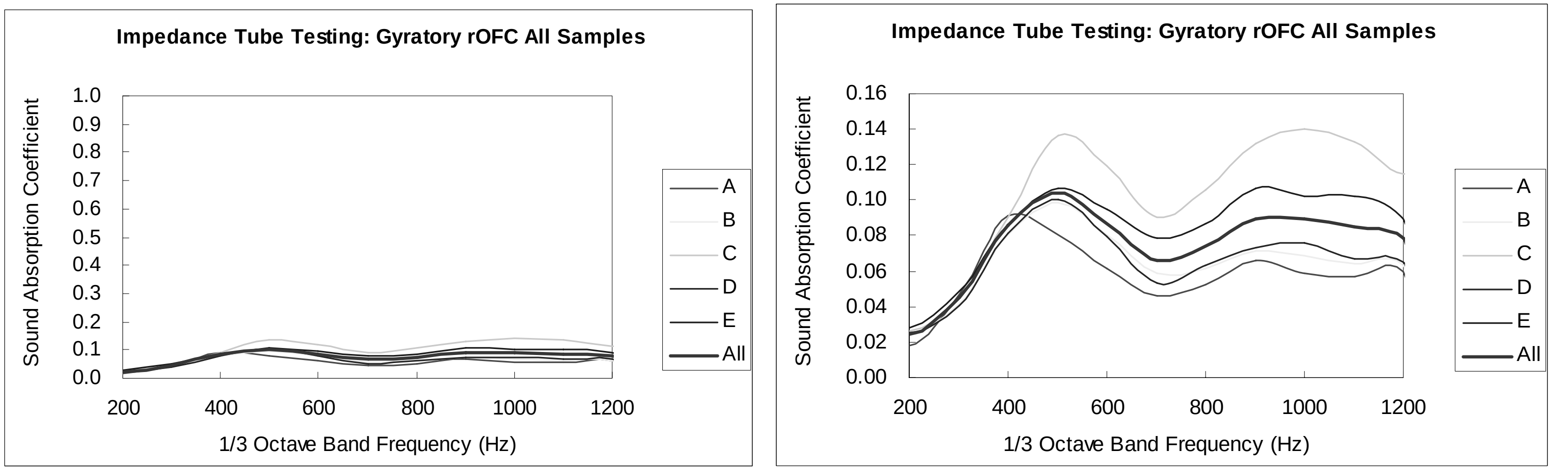


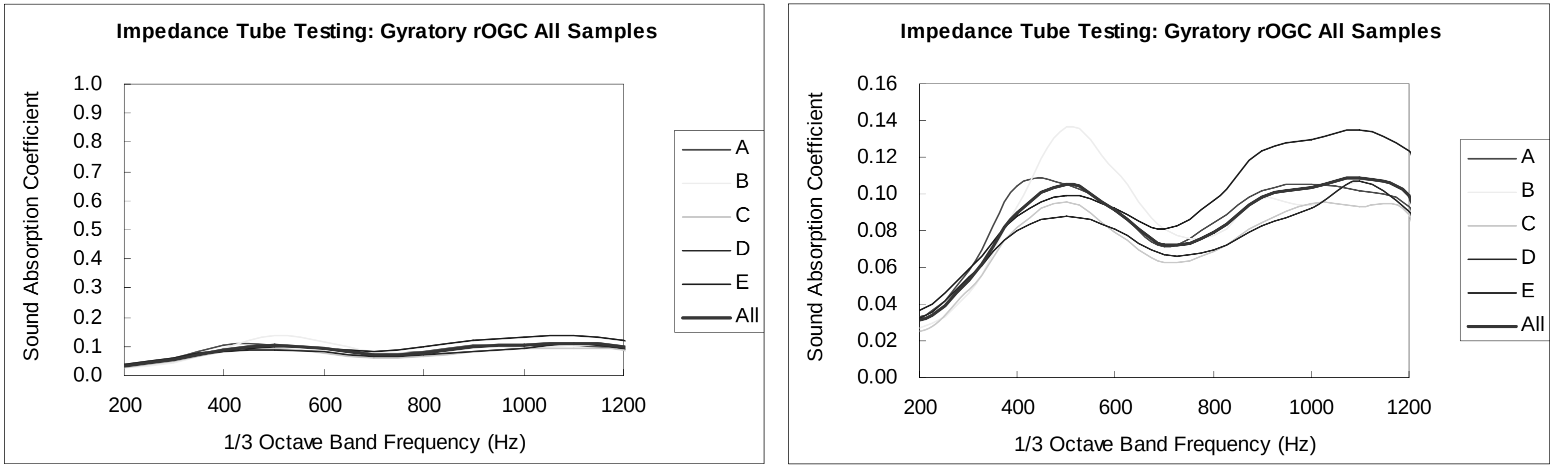
Figure B.3 – Close-Proximity Method Years 2004 and 2005 Results – Heavy Vehicles

APPENDIX C: RESULTS OF THE IMPEDANCE TUBE METHOD


Impedance Tube Testing: Gyratory rOFC All Samples

Impedance Tube Testing: Gyratory rOFC All Samples

Figure C.1 – Impedance Tube Method Result: rOFC Gyratory Samples


Impedance Tube Testing: Gyratory rOGC All Samples

Impedance Tube Testing: Gyratory rOGC All Samples

Figure C.2 – Impedance Tube Method Result: rOGC Gyratory Samples

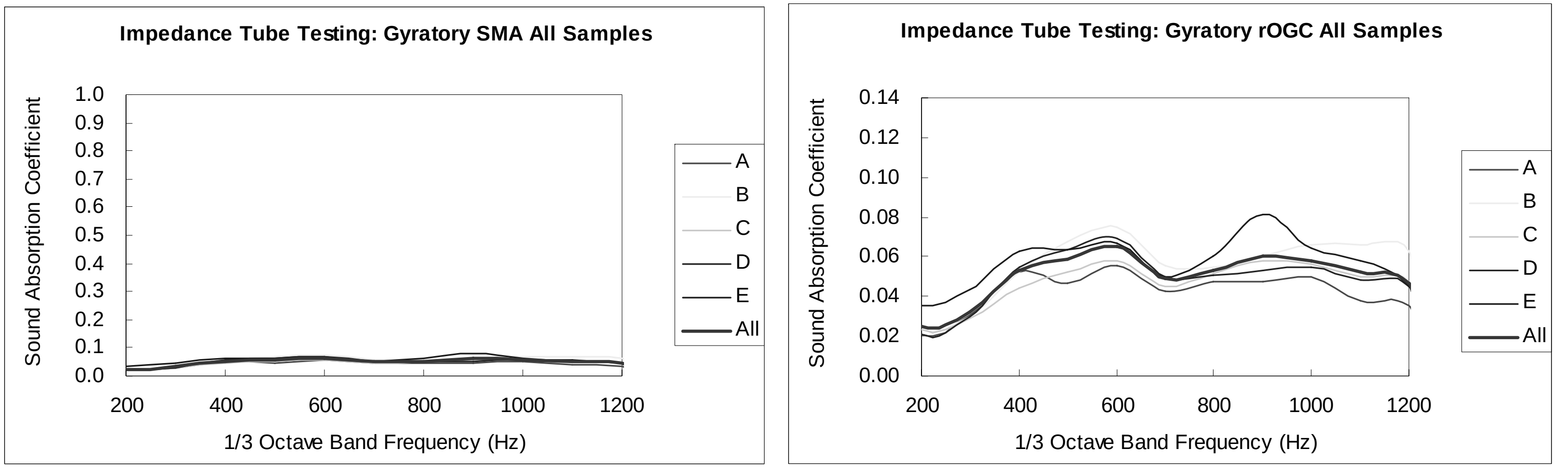


Figure C.3 – Impedance Tube Method Result: SMA Gyratory Samples

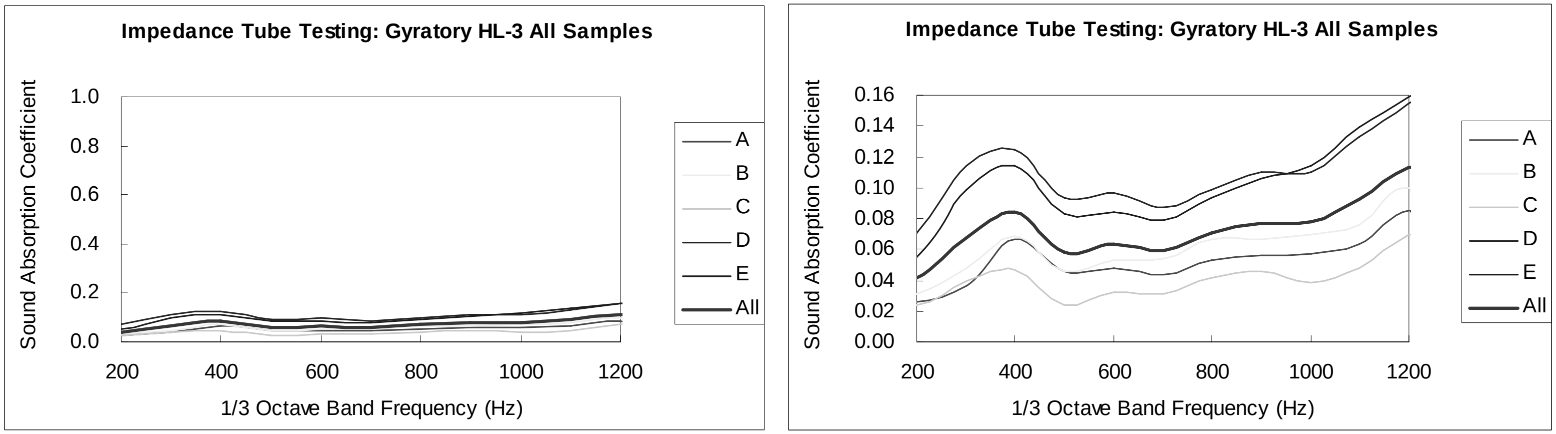


Figure C.4 – Impedance Tube Method Result: HL-3 Gyratory Samples

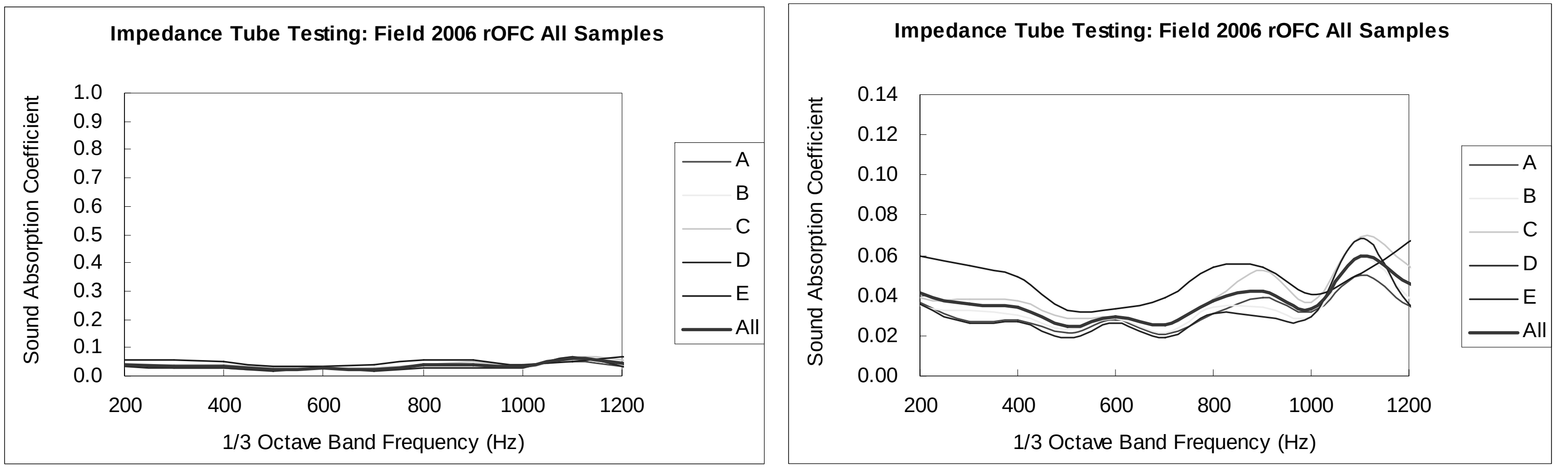


Figure C.5 – Impedance Tube Method Result: rOFC Field Core Samples

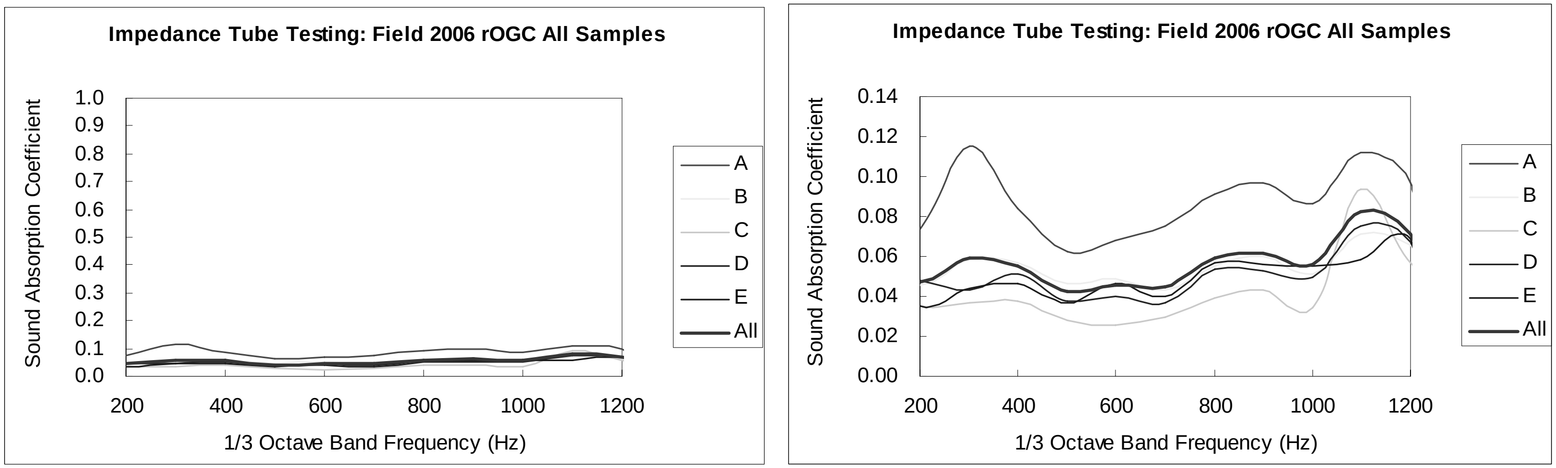


Figure C.6 – Impedance Tube Method Result: rOGC Field Core Samples

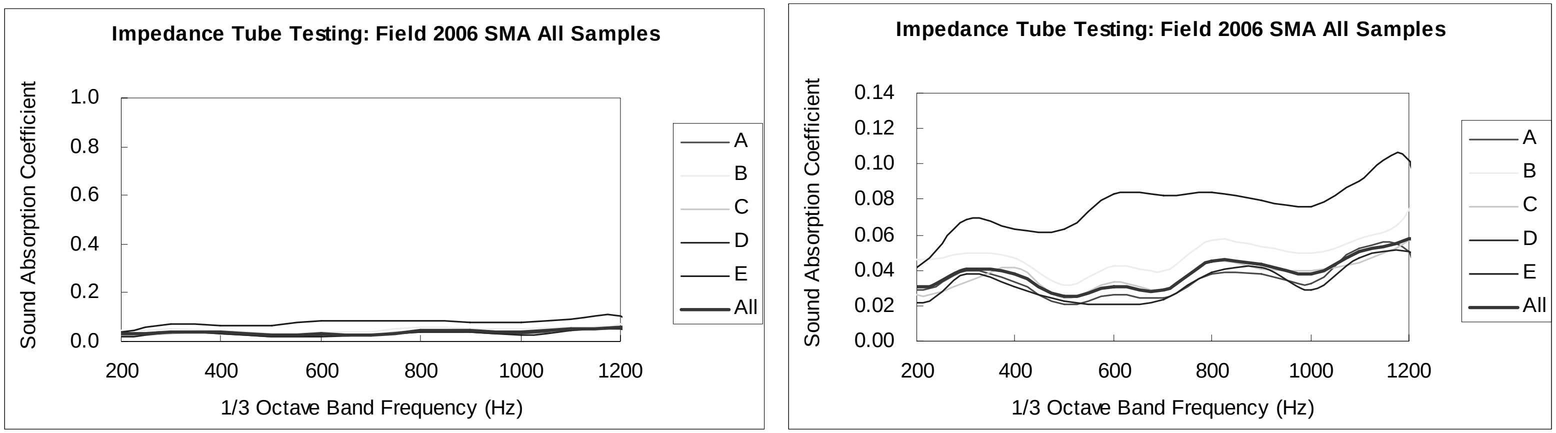


Figure C.7 – Impedance Tube Method Result: SMA Field Core Samples

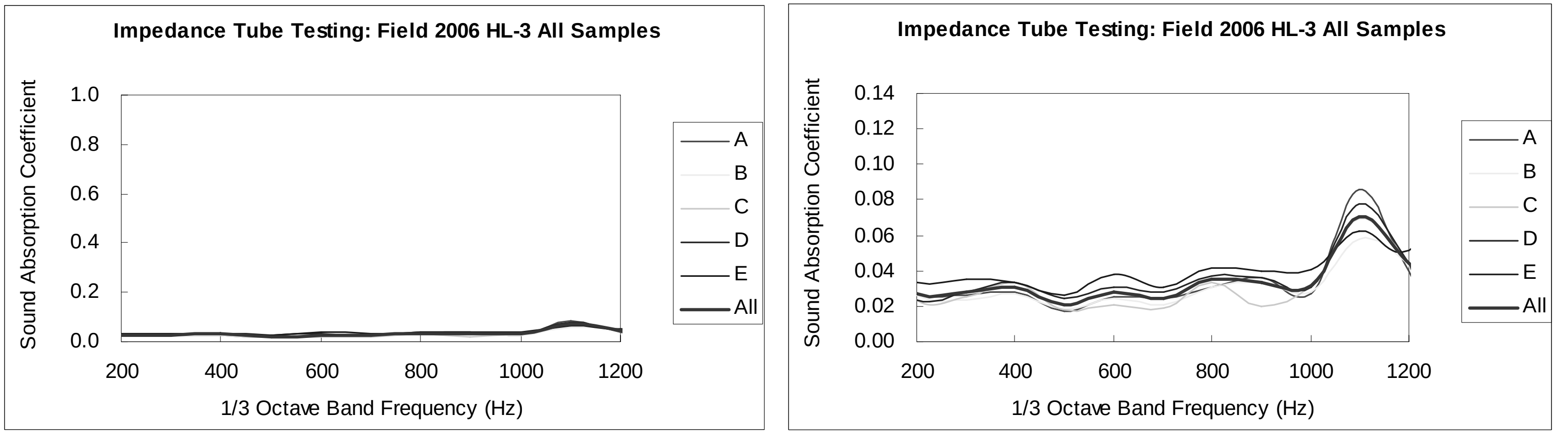


Figure C.8 – Impedance Tube Method Result: HL-3 Field Core Samples

APPENDIX D: RESULTS OF THE REVERBERATION TIME METHOD

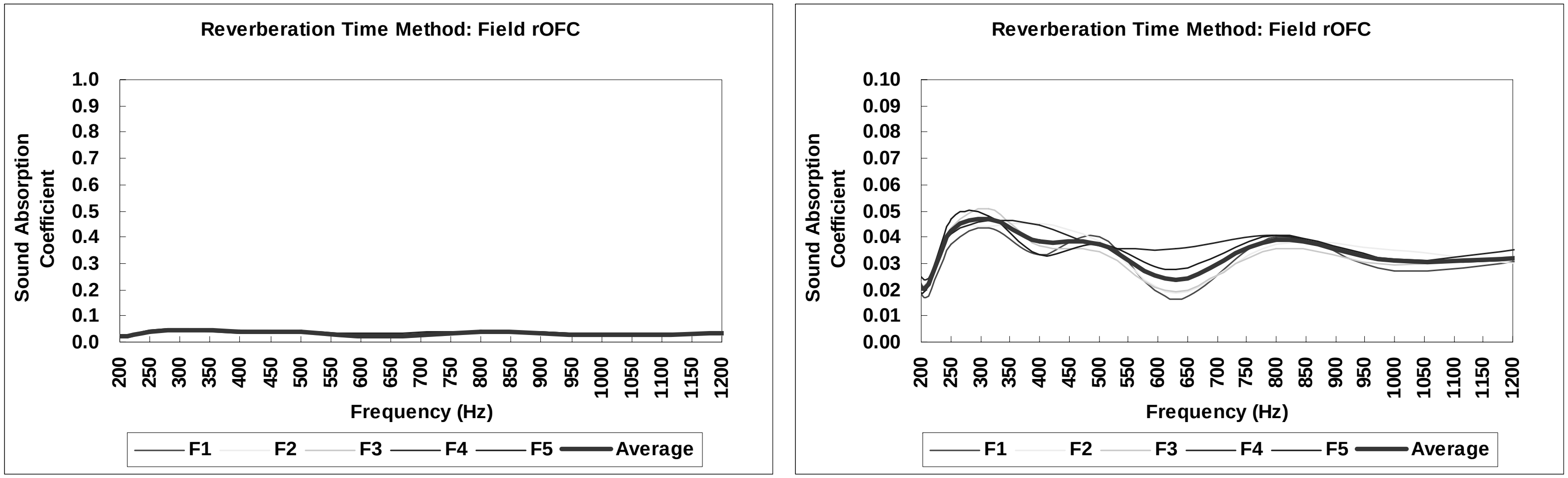


Figure D.1 – Reverberation Time Method Result: In-Service rOFC

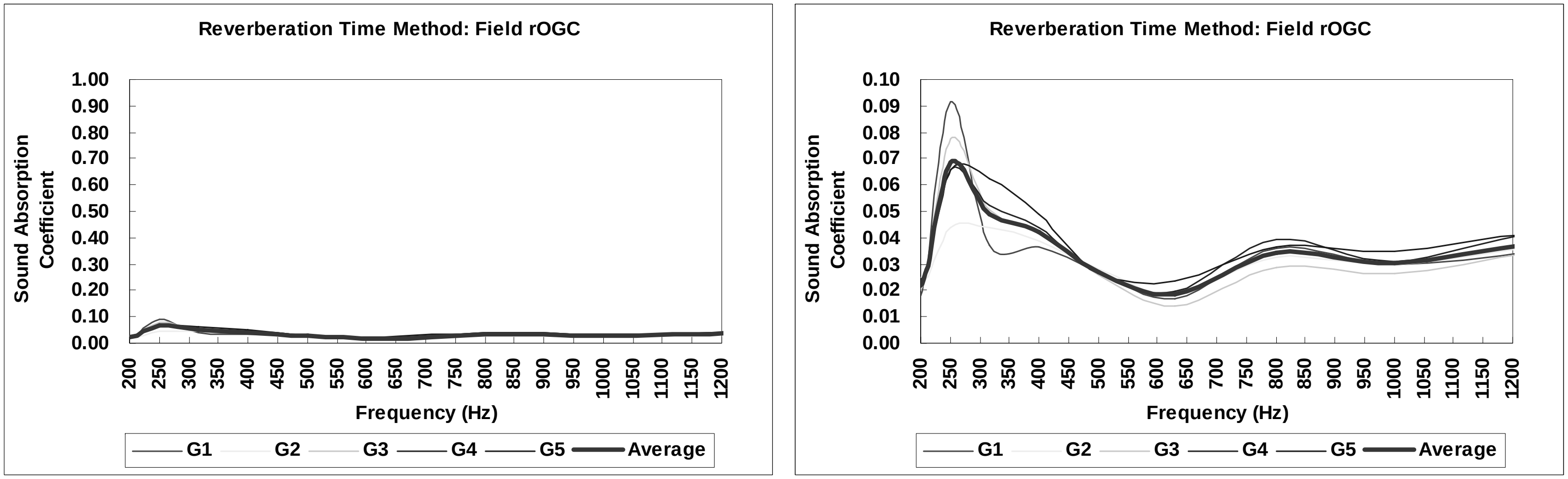
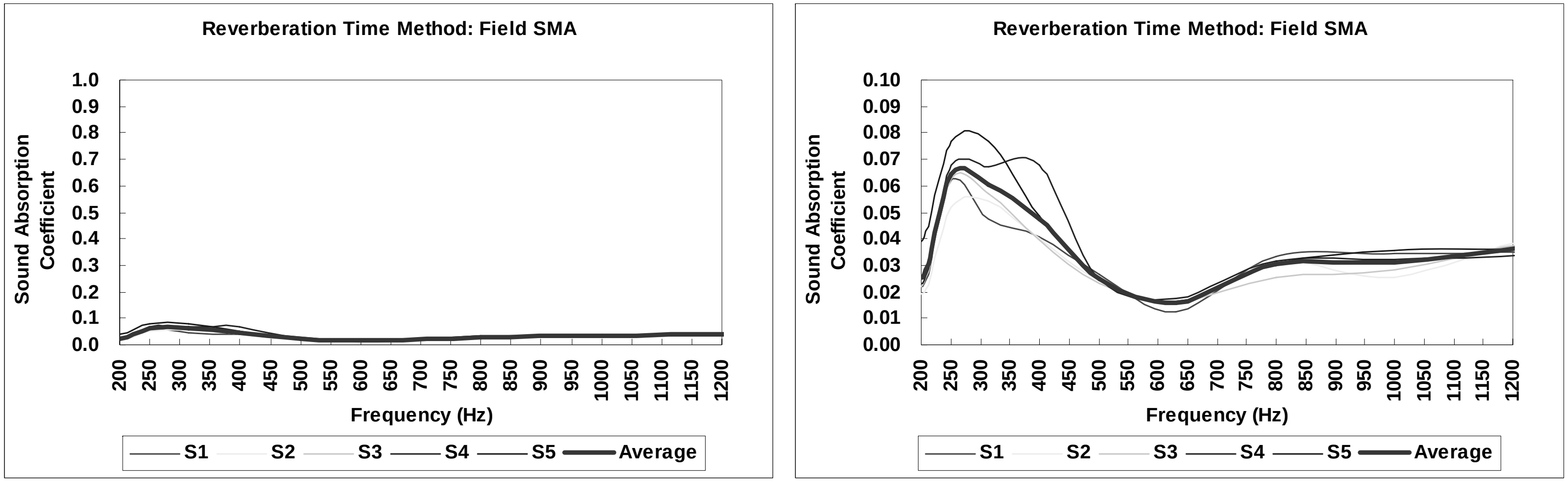
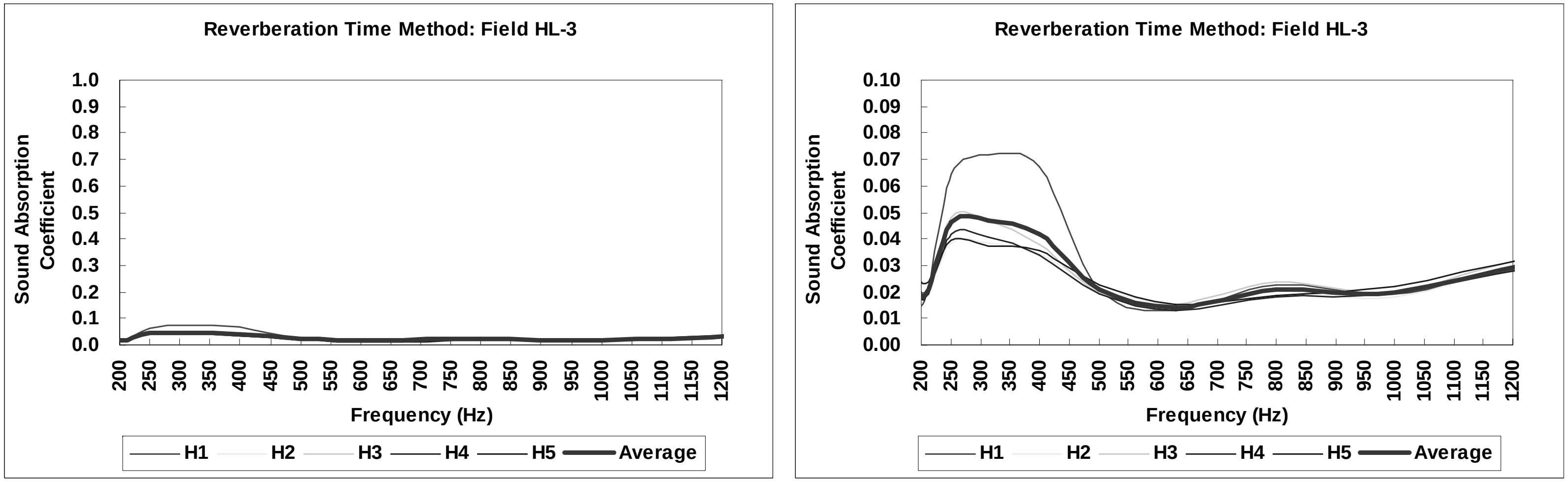


Figure D.2 – Reverberation Time Method Result: In-Service rOGC


Reverberation Time Method: Field SMA

Reverberation Time Method: Field SMA

Figure D.3 – Reverberation Time Method Result: In-Service SMA


Reverberation Time Method: Field HL-3

Reverberation Time Method: Field HL-3

Figure D.4 – Reverberation Time Method Result: In-Service HL-3

APPENDIX E: RESULTS OF THE STATISTICAL ANALYSIS

Table E.1 – Statistical Analysis of 2004 CPB Method

Categories	Statistical Analysis	Mixes Comparisons			
		rOFC/HL-3	rOGC/HL-3	SMA/HL-3	rOFC/rOGC
All Vehicles	Observations n	96	92	87	94
	Standard Deviation s	1.588	1.290	1.691	1.468
	Mean x_bar	-1.19	-2.21	0.23	1.10
	Degree of Freedom df	95	91	86	93
	t_{value}	7.357	16.400	1.293	7.265
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	1.985	1.986	1.988	1.986
	P(T<=t) two-tail	0.000	0.000	0.199	0.000
	Reject Ho?	Yes	Yes	No	Yes
Light Vehicles	Observations n	38	34	38	34
	Standard Deviation s	0.91	0.84	1.01	0.74
	Mean x_bar	-0.59	-1.79	1.62	1.33
	Degree of Freedom df	37	33	37	33
	t_{value}	3.986	12.363	9.847	10.492
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.026	2.035	2.026	2.035
	P(T<=t) two-tail	0.000	0.000	0.000	0.000
	Reject Ho?	Yes	Yes	Yes	Yes
Medium Vehicles	Observations n	35	34	26	37
	Standard Deviation s	1.80	1.54	1.34	1.58
	Mean x_bar	-1.97	-2.89	-1.22	1.04
	Degree of Freedom df	34	33	25	36
	t_{value}	6.481	10.956	4.635	3.990
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.032	2.035	2.060	2.028
	P(T<=t) two-tail	0.000	0.000	0.000	0.000
	Reject Ho?	Yes	Yes	Yes	Yes
Heavy Vehicle	Observations n	23	24	23	23
	Standard Deviation s	1.68	1.05	1.08	2.01
	Mean x_bar	-1.00	-1.83	-0.42	0.86
	Degree of Freedom df	22	23	22	22
	t_{value}	2.846	8.588	1.851	2.044
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.074	2.069	2.074	2.074
	P(T<=t) two-tail	0.009	0.000	0.078	0.053
	Reject Ho?	Yes	Yes	No	No
60 km/h	Observations n	22	22	20	24
	Standard Deviation s	1.61	1.10	1.62	1.53
	Mean x_bar	-0.60	-1.68	0.88	1.23
	Degree of Freedom df	21	21	19	23
	t_{value}	1.752	7.154	2.447	3.930
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.080	2.080	2.093	2.069
	P(T<=t) two-tail	0.094	0.000	0.024	0.001
	Reject Ho?	No	Yes	Yes	Yes
70 km/h	Observations n	24	21	21	21
	Standard Deviation s	1.52	1.37	1.61	1.56
	Mean x_bar	-1.06	-2.24	0.40	1.19
	Degree of Freedom df	23	20	20	20
	t_{value}	3.409	7.501	1.149	3.490
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.069	2.086	2.086	2.086
	P(T<=t) two-tail	0.002	0.000	0.264	0.002

	Reject Ho?	Yes	Yes	No	Yes
80 km/h	Observations n	25	24	24	23
	Standard Deviation s	1.57	1.20	1.67	1.25
	Mean x_bar	-1.42	-2.35	-0.04	1.06
	Degree of Freedom df	24	23	23	22
	t_{value}	4.521	9.603	0.122	4.038
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.064	2.069	2.069	2.074
	P(T<=t) two-tail	0.000	0.000	0.904	0.001
	Reject Ho?	Yes	Yes	No	Yes
90 km/h	Observations n	25	25	22	26
	Standard Deviation s	1.57	1.39	1.75	1.57
	Mean x_bar	-1.61	-2.50	-0.22	0.95
	Degree of Freedom df	24	24	21	25
	t_{value}	5.145	8.974	0.585	3.072
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.064	2.064	2.080	2.060
	P(T<=t) two-tail	0.000	0.000	0.565	0.005
	Reject Ho?	Yes	Yes	No	Yes
60 km/h - Light Vehicle	Observations n	8	8	9	8
	Standard Deviation s	0.84	0.59	0.74	0.83
	Mean x_bar	0.06	-1.08	2.32	1.33
	Degree of Freedom df	7	7	8	7
	t_{value}	0.210	5.134	9.442	4.491
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.365	2.365	2.306	2.365
	P(T<=t) two-tail	0.839	0.001	0.000	0.003
	Reject Ho?	No	Yes	Yes	Yes
60 km/h - Medium Vehicle	Observations n	8	8	6	10
	Standard Deviation s	1.57	1.02	1.08	1.22
	Mean x_bar	-0.89	-2.35	-0.62	1.60
	Degree of Freedom df	7	7	5	9
	t_{value}	1.601	6.491	1.401	4.150
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.365	2.365	2.571	2.262
	P(T<=t) two-tail	0.153	0.000	0.220	0.002
	Reject Ho?	No	Yes	No	Yes
60 km/h - Heavy Vehicle	Observations n	6	6	5	6
	Standard Deviation s	2.30	1.34	1.04	2.49
	Mean x_bar	-1.10	-1.58	0.10	0.48
	Degree of Freedom df	5	5	4	5
	t_{value}	1.173	2.886	0.215	0.476
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.571	2.571	2.776	2.571
	P(T<=t) two-tail	0.293	0.034	0.841	0.654
	Reject Ho?	No	Yes	No	No
70 km/h - Light Vehicle	Observations n	10	7	10	7
	Standard Deviation s	0.89	0.53	0.96	0.65
	Mean x_bar	-0.48	-1.63	1.74	1.41
	Degree of Freedom df	9	6	9	6
	t_{value}	1.700	8.061	5.708	5.719
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.262	2.447	2.262	2.447
	P(T<=t) two-tail	0.123	0.000	0.000	0.001
	Reject Ho?	No	Yes	Yes	Yes
70 km/h - Medium Vehicle	Observations n	8	8	5	8
	Standard Deviation s	1.81	1.68	1.31	1.70
	Mean x_bar	-1.81	-3.14	-1.22	1.33

	Degree of Freedom df	7	7	4	7
	t_{value}	2.828	5.285	2.082	2.203
	$t_{cri}=t_{df, 0.05}$ (two-tail)	2.365	2.365	2.776	2.365
	P(T<=t) two-tail	0.025	0.001	0.106	0.063
	Reject Ho?	Yes	Yes	No	No
70 km/h - Heavy Vehicle	Observations n	6	6	6	6
	Standard Deviation s	1.74	1.07	0.52	2.21
	Mean x_bar	-1.02	-1.77	-0.47	0.75
	Degree of Freedom df	5	5	5	5
	t_{value}	1.433	4.055	2.214	0.832
	$t_{cri}=t_{df, 0.05}$ (two-tail)	2.571	2.571	2.571	2.571
	P(T<=t) two-tail	0.211	0.010	0.078	0.443
	Reject Ho?	No	Yes	No	No
80 km/h - Light Vehicle	Observations n	10	9	10	9
	Standard Deviation s	0.93	0.63	0.77	0.47
	Mean x_bar	-0.63	-1.96	1.42	1.49
	Degree of Freedom df	9	8	9	8
	t_{value}	2.148	9.302	5.799	9.553
	$t_{cri}=t_{df, 0.05}$ (two-tail)	2.262	2.306	2.262	2.306
	P(T<=t) two-tail	0.060	0.000	0.000	0.000
	Reject Ho?	No	Yes	Yes	Yes
80 km/h - Medium Vehicle	Observations n	10	9	8	9
	Standard Deviation s	1.67	1.72	0.96	1.38
	Mean x_bar	-2.27	-2.83	-1.54	0.61
	Degree of Freedom df	9	8	7	8.000
	t_{value}	4.288	4.947	4.548	1.331
	$t_{cri}=t_{df, 0.05}$ (two-tail)	2.262	2.306	2.365	2.306
	P(T<=t) two-tail	0.002	0.001	0.003	0.220
	Reject Ho?	Yes	Yes	Yes	No
80 km/h - Heavy Vehicle	Observations n	5	6	6	5
	Standard Deviation s	1.81	0.73	1.57	1.89
	Mean x_bar	-1.32	-2.22	-0.48	1.08
	Degree of Freedom df	4	5	5	4
	t_{value}	1.634	7.461	0.756	1.280
	$t_{cri}=t_{df, 0.05}$ (two-tail)	2.776	2.571	2.571	2.776
	P(T<=t) two-tail	0.178	0.001	0.483	0.270
	Reject Ho?	No	Yes	No	No
90 km/h - Light Vehicle	Observations n	10	10	9	10
	Standard Deviation s	0.66	0.99	1.21	0.96
	Mean x_bar	-1.18	-2.32	1.01	1.14
	Degree of Freedom df	9	9	8	9
	t_{value}	5.686	7.421	2.512	3.762
	$t_{cri}=t_{df, 0.05}$ (two-tail)	2.262	2.262	2.306	2.262
	P(T<=t) two-tail	0.000	0.000	0.036	0.004
	Reject Ho?	Yes	Yes	Yes	Yes
90 km/h - Medium Vehicle	Observations n	9	9	7	10
	Standard Deviation s	1.90	1.71	1.94	1.95
	Mean x_bar	-2.76	-3.19	-1.36	0.63
	Degree of Freedom df	8	8	6	9
	t_{value}	4.345	5.585	1.854	1.022
	$t_{cri}=t_{df, 0.05}$ (two-tail)	2.306	2.306	2.447	2.262

	P(T<=t) two-tail	0.002	0.001	0.113	0.333
	Reject Ho?	Yes	Yes	No	No
90 km/h - Heavy Vehicle	Observations n	6	6	6	6
	Standard Deviation s	1.14	1.14	1.08	1.87
	Mean x_bar	-0.62	-1.77	-0.73	1.15
	Degree of Freedom df	5	5	5	5
	t_{value}	1.326	3.803	1.663	1.502
	$t_{cri}=t_{df, 0.05}$ (two-tail)	2.571	2.571	2.571	2.571
	P(T<=t) two-tail	0.242	0.013	0.157	0.193
	Reject Ho?	No	Yes	No	No

Table E.2 – Statistical Analysis of 2005 CPB Method

Categories	Statistical Analysis	Mixes Comparisons			
		rOFC/HL-3	rOGC/HL-3	SMA/HL-3	rOFC/rOGC
All Vehicles	Observations n	55	54	55	53
	Standard Deviation s	0.922	1.018	0.798	1.255
	Mean x_bar	-1.08	-1.68	-1.47	0.59
	Degree of Freedom df	54	53	54	52
	t_{value}	8.706	12.103	13.655	3.426
	$t_{cri}=t_{df, 0.05}$ (two-tail)	2.005	2.006	2.005	2.007
	P(T<=t) two-tail	0.000	0.000	0.000	0.001
	Reject Ho?	Yes	Yes	Yes	Yes
Light Vehicles	Observations n	23	24	24	23
	Standard Deviation s	0.630	0.780	0.568	0.813
	Mean x_bar	-0.86	-1.30	-1.22	0.47
	Degree of Freedom df	22	23	23	22
	t_{value}	6.552	8.140	10.499	2.745
	$t_{cri}=t_{df, 0.05}$ (two-tail)	2.074	2.069	2.069	2.074
	P(T<=t) two-tail	0.000	0.000	0.000	0.012
	Reject Ho?	Yes	Yes	Yes	Yes
Medium Vehicles	Observations n	24	22	23	22
	Standard Deviation s	1.081	1.097	0.862	1.374
	Mean x_bar	-1.24	-2.10	-1.85	0.80
	Degree of Freedom df	23	21	22	21
	t_{value}	5.608	9.002	10.277	2.715
	$t_{cri}=t_{df, 0.05}$ (two-tail)	2.069	2.080	2.074	2.080
	P(T<=t) two-tail	0.000	0.000	0.000	0.013
	Reject Ho?	Yes	Yes	Yes	Yes
Heavy Vehicle	Observations n	8	8	8	8
	Standard Deviation s	1.090	1.077	0.837	1.931
	Mean x_bar	-1.25	-1.64	-1.14	0.39
	Degree of Freedom df	7	7	7	7
	t_{value}	3.243	4.301	3.846	0.568
	$t_{cri}=t_{df, 0.05}$ (two-tail)	2.365	2.365	2.365	2.365
	P(T<=t) two-tail	0.014	0.004	0.006	0.588
	Reject Ho?	Yes	Yes	Yes	No
60 km/h	Observations n	14	14	13	14
	Standard Deviation s	1.164	1.231	0.723	1.768
	Mean x_bar	-0.76	-1.55	-1.19	0.79

	Degree of Freedom df	13	13	12	13
	t_{value}	2.457	4.709	5.948	1.663
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.160	2.160	2.179	2.160
	P(T<=t) two-tail	0.029	0.000	0.000	0.120
	Reject Ho?	Yes	Yes	Yes	No
70 km/h	Observations n	13	14	14	13
	Standard Deviation s	0.647	1.137	0.767	1.156
	Mean x_bar	-1.04	-1.50	-1.28	0.53
	Degree of Freedom df	12	13	13	12
	t_{value}	5.783	4.934	6.239	1.655
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.179	2.160	2.160	2.179
	P(T<=t) two-tail	0.000	0.000	0.000	0.124
	Reject Ho?	Yes	Yes	Yes	No
80 km/h	Observations n	14	14	14	14
	Standard Deviation s	0.820	0.814	0.670	1.045
	Mean x_bar	-1.28	-1.68	-1.64	0.40
	Degree of Freedom df	13	13	13	13
	t_{value}	5.833	7.720	9.176	1.432
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.160	2.160	2.160	2.160
	P(T<=t) two-tail	0.000	0.000	0.000	0.176
	Reject Ho?	Yes	Yes	Yes	No
90 km/h	Observations n	14	12	14	12
	Standard Deviation s	0.966	0.832	0.947	0.949
	Mean x_bar	-1.24	-2.03	-1.74	0.65
	Degree of Freedom df	13	11	13	11
	t_{value}	4.813	8.427	6.887	2.372
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.160	2.201	2.160	2.201
	P(T<=t) two-tail	0.000	0.000	0.000	0.037
	Reject Ho?	Yes	Yes	Yes	Yes
60 km/h - Light Vehicle	Observations n	6	6	6	6
	Standard Deviation s	0.423	0.831	0.374	0.857
	Mean x_bar	-0.35	-0.67	-0.80	0.32
	Degree of Freedom df	5	5	5	5
	t_{value}	2.026	1.965	5.237	0.906
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.571	2.571	2.571	2.571
	P(T<=t) two-tail	0.099	0.107	0.003	0.407
	Reject Ho?	No	No	Yes	No
60 km/h - Medium Vehicle	Observations n	6	6	5	6
	Standard Deviation s	1.355	0.744	0.512	1.619
	Mean x_bar	-0.80	-2.58	-1.92	1.78
	Degree of Freedom df	5	5	4	5
	t_{value}	1.446	8.504	8.388	2.698
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.571	2.571	2.776	2.571
	P(T<=t) two-tail	0.208	0.000	0.001	0.043
	Reject Ho?	No	Yes	Yes	Yes
60 km/h - Heavy Vehicle	Observations n	2	2	2	2
	Standard Deviation s	1.980	1.414	0.354	3.394
	Mean x_bar	-1.90	-1.10	-0.55	-0.80
	Degree of Freedom df	1	1	1	1
	t_{value}	1.357	1.100	2.200	0.333
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	12.706	12.706	12.706	12.706

	P(T<=t) two-tail	0.404	0.470	0.272	0.795
	Reject Ho?	No	No	No	No
70 km/h - Light Vehicle	Observations n	5	6	6	5
	Standard Deviation s	0.502	0.339	0.454	0.406
	Mean x_bar	-0.98	-1.25	-1.22	0.40
	Degree of Freedom df	4	5	5	4
	t_{value}	4.365	9.029	6.572	2.202
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.776	2.571	2.571	2.776
	P(T<=t) two-tail	0.012	0.000	0.001	0.092
	Reject Ho?	Yes	Yes	Yes	No
70 km/h - Medium Vehicle	Observations n	6	6	6	6
	Standard Deviation s	0.779	1.559	0.871	1.476
	Mean x_bar	-1.27	-1.80	-1.63	0.53
	Degree of Freedom df	5	5	5	5
	t_{value}	3.983	2.827	4.593	0.885
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.571	2.571	2.571	2.571
	P(T<=t) two-tail	0.010	0.037	0.006	0.417
	Reject Ho?	Yes	Yes	Yes	No
70 km/h - Heavy Vehicle	Observations n	2	2	2	2
	Standard Deviation s	0.283	1.768	0.707	2.051
	Mean x_bar	-0.50	-1.35	-0.40	0.85
	Degree of Freedom df	1	1	1	1
	t_{value}	2.500	1.080	0.800	0.586
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	12.706	12.706	12.706	12.706
	P(T<=t) two-tail	0.242	0.476	0.570	0.662
	Reject Ho?	No	No	No	No
80 km/h - Light Vehicle	Observations n	6	6	6	6
	Standard Deviation s	0.387	0.778	0.624	0.874
	Mean x_bar	-0.88	-1.38	-1.22	0.50
	Degree of Freedom df	5	5	5	5
	t_{value}	5.593	4.354	4.774	1.401
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.571	2.571	2.571	2.571
	P(T<=t) two-tail	0.003	0.007	0.005	0.220
	Reject Ho?	Yes	Yes	Yes	No
80 km/h - Medium Vehicle	Observations n	6	6	6	6
	Standard Deviation s	0.896	0.922	0.455	1.056
	Mean x_bar	-1.65	-1.88	-2.13	0.23
	Degree of Freedom df	5	5	5	5
	t_{value}	4.510	5.005	11.495	0.541
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.571	2.571	2.571	2.571
	P(T<=t) two-tail	0.006	0.004	0.000	0.612
	Reject Ho?	Yes	Yes	Yes	No
80 km/h - Heavy Vehicle	Observations n	2	2	2	2
	Standard Deviation s	1.485	0.636	0.495	2.121
	Mean x_bar	-1.35	-1.95	-1.45	0.60
	Degree of Freedom df	1	1	1	1
	t_{value}	1.286	4.333	4.143	0.400
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	12.706	12.706	12.706	12.706
	P(T<=t) two-tail	0.421	0.144	0.151	0.758
	Reject Ho?	No	No	No	No

90 km/h - Light Vehicle	Observations n	6	6	6	6
	Standard Deviation s	0.841	0.697	0.575	1.100
	Mean x_bar	-1.25	-1.88	-1.63	0.63
	Degree of Freedom df	5	5	5	5
	t_{value}	3.641	6.620	6.958	1.410
	$t_{cri}=t_{df, 0.05}$ (two-tail)	2.571	2.571	2.571	2.571
	P(T<=t) two-tail	0.015	0.001	0.001	0.218
	Reject Ho?	Yes	Yes	Yes	No
90 km/h - Medium Vehicle	Observations n	6	4	6	4
	Standard Deviation s	1.302	1.130	1.385	0.751
	Mean x_bar	-1.23	-2.18	-1.72	0.55
	Degree of Freedom df	5	3	5	3
	t_{value}	2.321	3.851	3.037	1.466
	$t_{cri}=t_{df, 0.05}$ (two-tail)	2.571	3.182	2.571	3.182
	P(T<=t) two-tail	0.068	0.031	0.029	0.239
	Reject Ho?	No	Yes	Yes	No
90 km/h - Heavy Vehicle	Observations n	2	2	2	2
	Standard Deviation s	0.354	1.061	0.071	1.414
	Mean x_bar	-1.25	-2.15	-2.15	0.90
	Degree of Freedom df	1	1	1	1
	t_{value}	5.000	2.867	43.000	0.900
	$t_{cri}=t_{df, 0.05}$ (two-tail)	12.706	12.706	12.706	12.706
	P(T<=t) two-tail	0.126	0.214	0.015	0.533
	Reject Ho?	No	No	Yes	No

Table E.3 – Statistical Analysis of 2004 CPX Method

Categories	Statistical Analysis	Mixes Comparisons			
		rOFC/HL-3	rOGC/HL-3	SMA/HL-3	rOFC/rOGC
All Vehicles	Observations n	102	102	102	102
	Standard Deviation s	1.282	1.356	1.650	0.633
	Mean x_bar	-1.80	-2.03	0.01	0.23
	Degree of Freedom df	101	101	101	101
	t_{value}	14.178	15.137	0.066	3.723
	$t_{cri}=t_{df, 0.05}$ (two-tail)	1.984	1.984	1.984	1.984
	P(T<=t) two-tail	0.000	0.000	0.947	0.000
	Reject Ho?	Yes	Yes	No	Yes
Light Vehicles	Observations n	40	40	40	40
	Standard Deviation s	0.76	0.83	0.91	0.57
	Mean x_bar	-0.81	-1.11	1.64	0.29
	Degree of Freedom df	39	39	39	39
	t_{value}	6.738	8.466	11.377	3.228
	$t_{cri}=t_{df, 0.05}$ (two-tail)	2.023	2.023	2.023	2.023
	P(T<=t) two-tail	0.000	0.000	0.000	0.003
	Reject Ho?	Yes	Yes	Yes	Yes
Medium Vehicles	Observations n	38	38	38	38
	Standard Deviation s	1.25	1.48	1.10	0.68
	Mean x_bar	-2.65	-2.90	-1.22	0.25
	Degree of Freedom df	37	37	37	37
	t_{value}	13.048	12.102	6.843	2.281

	$t_{cri}=t_{df,\,0.05}$ (two-tail)	2.026	2.026	2.026	2.026
	P(T<=t) two-tail	0.000	0.000	0.000	0.028
	Reject Ho?	Yes	Yes	Yes	Yes
Heavy Vehicle	Observations n	24	24	24	24
	Standard Deviation s	0.85	0.80	0.93	0.67
	Mean x_bar	-2.10	-2.20	-0.76	0.11
	Degree of Freedom df	23	23	23	23
	t_{value}	12.075	13.521	3.978	0.795
	$t_{cri}=t_{df,\,0.05}$ (two-tail)	2.069	2.069	2.069	2.069
	P(T<=t) two-tail	0.000	0.000	0.001	0.434
	Reject Ho?	Yes	Yes	Yes	No
60 km/h	Observations n	26	26	26	26
	Standard Deviation s	1.36	1.55	1.65	0.68
	Mean x_bar	-1.42	-1.72	0.45	0.30
	Degree of Freedom df	25	25	25	25
	t_{value}	5.338	5.635	1.387	2.205
	$t_{cri}=t_{df,\,0.05}$ (two-tail)	2.060	2.060	2.060	2.060
	P(T<=t) two-tail	0.000	0.000	0.178	0.037
	Reject Ho?	Yes	Yes	No	Yes
70 km/h	Observations n	24	24	24	24
	Standard Deviation s	1.32	1.36	1.74	0.55
	Mean x_bar	-1.68	-1.81	0.28	0.13
	Degree of Freedom df	23	23	23	23
	t_{value}	6.226	6.533	0.785	1.148
	$t_{cri}=t_{df,\,0.05}$ (two-tail)	2.069	2.069	2.069	2.069
	P(T<=t) two-tail	0.000	0.000	0.440	0.263
	Reject Ho?	Yes	Yes	No	No
80 km/h	Observations n	26	26	26	26
	Standard Deviation s	1.38	1.32	1.66	0.63
	Mean x_bar	-2.16	-2.29	-0.16	0.13
	Degree of Freedom df	25	25	25	25
	t_{value}	7.977	8.860	0.497	1.025
	$t_{cri}=t_{df,\,0.05}$ (two-tail)	2.060	2.060	2.060	2.060
	P(T<=t) two-tail	0.000	0.000	0.624	0.315
	Reject Ho?	Yes	Yes	No	No
90 km/h	Observations n	26	26	26	26
	Standard Deviation s	0.98	1.14	1.46	0.65
	Mean x_bar	-1.92	-2.30	-0.50	0.37
	Degree of Freedom df	25	25	25	25
	t_{value}	10.015	10.296	1.757	2.920
	$t_{cri}=t_{df,\,0.05}$ (two-tail)	2.060	2.060	2.060	2.060
	P(T<=t) two-tail	0.000	0.000	0.091	0.007
	Reject Ho?	Yes	Yes	No	Yes
60 km/h - Light Vehicle	Observations n	10	10	10	10
	Standard Deviation s	0.58	0.62	0.83	0.37
	Mean x_bar	-0.37	-0.61	2.25	0.24
	Degree of Freedom df	9	9	9	9
	t_{value}	2.033	3.107	8.528	2.075
	$t_{cri}=t_{df,\,0.05}$ (two-tail)	2.262	2.262	2.262	2.262
	P(T<=t) two-tail	0.073	0.013	0.000	0.068

	Reject Ho?	No	Yes	Yes	No
60 km/h - Medium Vehicle	Observations n	10	10	10	10
	Standard Deviation s	1.46	1.90	0.82	0.76
	Mean x_bar	-1.82	-2.35	-0.65	0.53
	Degree of Freedom df	9	9	9	9
	t_{value}	3.947	3.916	2.508	2.205
	$t_{cri}=t_{df, 0.05}$ (two-tail)	2.262	2.262	2.262	2.262
	P(T<=t) two-tail	0.003	0.004	0.033	0.055
	Reject Ho?	Yes	Yes	Yes	No
60 km/h - Heavy Vehicle	Observations n	6	6	6	6
	Standard Deviation s	0.92	0.94	0.83	0.92
	Mean x_bar	-2.50	-2.50	-0.72	0.00
	Degree of Freedom df	5	5	5	5
	t_{value}	6.682	6.513	2.108	0.000
	$t_{cri}=t_{df, 0.05}$ (two-tail)	2.571	2.571	2.571	2.571
	P(T<=t) two-tail	0.001	0.001	0.089	1.000
	Reject Ho?	Yes	Yes	No	No
70 km/h - Light Vehicle	Observations n	10	10	10	10
	Standard Deviation s	0.68	0.58	0.80	0.55
	Mean x_bar	-0.66	-0.87	1.79	0.21
	Degree of Freedom df	9	9	9	9
	t_{value}	3.061	4.717	7.046	1.206
	$t_{cri}=t_{df, 0.05}$ (two-tail)	2.262	2.262	2.262	2.262
	P(T<=t) two-tail	0.014	0.001	0.000	0.259
	Reject Ho?	Yes	Yes	Yes	No
70 km/h - Medium Vehicle	Observations n	8	8	8	8
	Standard Deviation s	1.19	1.62	1.37	0.63
	Mean x_bar	-2.89	-2.84	-0.99	-0.05
	Degree of Freedom df	7	7	7	7
	t_{value}	6.851	4.956	2.041	0.226
	$t_{cri}=t_{df, 0.05}$ (two-tail)	2.365	2.365	2.365	2.365
	P(T<=t) two-tail	0.000	0.002	0.081	0.828
	Reject Ho?	Yes	Yes	No	No
70 km/h - Heavy Vehicle	Observations n	6	6	6	6
	Standard Deviation s	0.90	0.84	1.49	0.48
	Mean x_bar	-1.78	-2.02	-0.55	0.23
	Degree of Freedom df	5	5	5	5
	t_{value}	4.831	5.880	0.906	1.200
	$t_{cri}=t_{df, 0.05}$ (two-tail)	2.571	2.571	2.571	2.571
	P(T<=t) two-tail	0.005	0.002	0.406	0.284
	Reject Ho?	Yes	Yes	No	No
80 km/h - Light Vehicle	Observations n	10	10	10	10
	Standard Deviation s	0.87	0.82	0.84	0.69
	Mean x_bar	-0.99	-1.18	1.57	0.19
	Degree of Freedom df	9	9	9	9
	t_{value}	3.615	4.556	5.887	0.868
	$t_{cri}=t_{df, 0.05}$ (two-tail)	2.262	2.262	2.262	2.262
	P(T<=t) two-tail	0.006	0.001	0.000	0.408
	Reject Ho?	Yes	Yes	Yes	No
Medium	Observations n	10	10	10	10

	Standard Deviation s	1.13	1.22	0.96	0.46
	Mean x_bar	-3.26	-3.33	-1.56	0.07
	Degree of Freedom df	9	9	9	9.000
	t_{value}	9.150	8.636	5.142	0.477
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.262	2.262	2.262	2.262
	P(T<=t) two-tail	0.000	0.000	0.001	0.645
	Reject Ho?	Yes	Yes	Yes	No
80 km/h - Heavy Vehicle	Observations n	6	6	6	6
	Standard Deviation s	0.86	0.38	0.74	0.85
	Mean x_bar	-2.28	-2.40	-0.72	0.12
	Degree of Freedom df	5	5	5	5
	t_{value}	6.530	15.281	2.385	0.335
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.571	2.571	2.571	2.571
	P(T<=t) two-tail	0.001	0.000	0.063	0.752
	Reject Ho?	Yes	Yes	No	No
90 km/h - Light Vehicle	Observations n	10	10	10	10
	Standard Deviation s	0.71	0.86	0.76	0.65
	Mean x_bar	-1.23	-1.76	0.95	0.53
	Degree of Freedom df	9	9	9	9
	t_{value}	5.488	6.468	3.958	2.579
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.262	2.262	2.262	2.262
	P(T<=t) two-tail	0.000	0.000	0.003	0.030
	Reject Ho?	Yes	Yes	Yes	Yes
90 km/h - Medium Vehicle	Observations n	10	10	10	10
	Standard Deviation s	0.84	1.13	1.09	0.74
	Mean x_bar	-2.68	-3.07	-1.63	0.39
	Degree of Freedom df	9	9	9	9
	t_{value}	10.037	8.626	4.745	1.656
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.262	2.262	2.262	2.262
	P(T<=t) two-tail	0.000	0.000	0.001	0.132
	Reject Ho?	Yes	Yes	Yes	No
90 km/h - Heavy Vehicle	Observations n	6	6	6	6
	Standard Deviation s	0.70	0.94	0.64	0.46
	Mean x_bar	-1.82	-1.90	-1.05	0.08
	Degree of Freedom df	5	5	5	5
	t_{value}	6.385	4.928	4.032	0.442
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.571	2.571	2.571	2.571
	P(T<=t) two-tail	0.001	0.004	0.010	0.677
	Reject Ho?	Yes	Yes	Yes	No

Table E.4 – Statistical Analysis of 2005 CPX Method

Categories	Statistical Analysis	Mixes Comparisons			
		rOFC/HL-3	rOGC/HL-3	SMA/HL-3	rOFC/rOGC
All Vehicles	Observations n	56	56	56	56
	Standard Deviation s	1.036	0.905	1.097	0.549
	Mean x_bar	-0.33	-0.94	-0.51	0.60
	Degree of Freedom df	55	55	55	55
	t_{value}	2.411	7.752	3.460	8.227

	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.004	2.004	2.004	2.004
	P(T<=t) two-tail	0.019	0.000	0.001	0.000
	Reject Ho?	Yes	Yes	Yes	Yes
Light Vehicles	Observations n	24	24	24	24
	Standard Deviation s	0.98	0.78	1.06	0.42
	Mean x_bar	0.20	-0.40	0.18	0.60
	Degree of Freedom df	23	23	23	23
	t_{value}	0.981	2.513	0.850	6.872
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.069	2.069	2.069	2.069
	P(T<=t) two-tail	0.337	0.019	0.404	0.000
	Reject Ho?	No	Yes	No	Yes
Medium Vehicles	Observations n	24	24	24	24
	Standard Deviation s	0.96	0.88	0.91	0.43
	Mean x_bar	-0.57	-1.40	-0.92	0.83
	Degree of Freedom df	23	23	23	23
	t_{value}	2.892	7.806	4.950	9.406
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.069	2.069	2.069	2.069
	P(T<=t) two-tail	0.008	0.000	0.000	0.000
	Reject Ho?	Yes	Yes	Yes	Yes
Heavy Vehicle	Observations n	8	8	8	8
	Standard Deviation s	0.46	0.38	0.22	0.71
	Mean x_bar	-1.23	-1.18	-1.34	-0.05
	Degree of Freedom df	7	7	7	7
	t_{value}	7.497	8.815	17.197	0.200
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.365	2.365	2.365	2.365
	P(T<=t) two-tail	0.000	0.000	0.000	0.847
	Reject Ho?	Yes	Yes	Yes	No
60 km/h	Observations n	14	14	14	14
	Standard Deviation s	1.09	0.95	1.13	0.57
	Mean x_bar	0.11	-0.38	-0.07	0.49
	Degree of Freedom df	13	13	13	13
	t_{value}	0.392	1.488	0.237	3.210
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.160	2.160	2.160	2.160
	P(T<=t) two-tail	0.702	0.161	0.817	0.007
	Reject Ho?	No	No	No	Yes
70 km/h	Observations n	14	14	14	14
	Standard Deviation s	0.93	0.80	1.05	0.42
	Mean x_bar	-0.21	-1.01	-0.40	0.80
	Degree of Freedom df	13	13	13	13
	t_{value}	0.866	4.716	1.424	7.086
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.160	2.160	2.160	2.160
	P(T<=t) two-tail	0.402	0.000	0.178	0.000
	Reject Ho?	No	Yes	No	Yes
80 km/h	Observations n	14	14	14	14
	Standard Deviation s	0.92	0.85	1.05	0.74
	Mean x_bar	-0.71	-1.21	-0.78	0.50
	Degree of Freedom df	13	13	13	13
	t_{value}	2.898	5.321	2.783	2.531
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.160	2.160	2.160	2.160
	P(T<=t) two-tail	0.012	0.000	0.016	0.025
	Reject Ho?	Yes	Yes	Yes	Yes

90 km/h	Observations n	14	14	14	14
	Standard Deviation s	1.10	0.84	1.11	0.39
	Mean x_bar	-0.52	-1.14	-0.78	0.62
	Degree of Freedom df	13	13	13	13
	t_{value}	1.767	5.068	2.617	5.923
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.160	2.160	2.160	2.160
	P(T<=t) two-tail	0.101	0.000	0.021	0.000
	Reject Ho?	No	Yes	Yes	Yes
60 km/h - Light Vehicle	Observations n	6	6	6	6
	Standard Deviation s	0.67	0.56	0.83	0.31
	Mean x_bar	0.60	0.07	0.67	0.53
	Degree of Freedom df	5	5	5	5
	t_{value}	2.186	0.291	1.976	4.246
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.571	2.571	2.571	2.571
	P(T<=t) two-tail	0.080	0.783	0.105	0.008
	Reject Ho?	No	No	No	Yes
60 km/h - Medium Vehicle	Observations n	6	6	6	6
	Standard Deviation s	1.29	1.24	1.12	0.61
	Mean x_bar	0.07	-0.63	-0.40	0.70
	Degree of Freedom df	5	5	5	5
	t_{value}	0.127	1.247	0.878	2.827
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.571	2.571	2.571	2.571
	P(T<=t) two-tail	0.904	0.267	0.420	0.037
	Reject Ho?	No	No	No	Yes
60 km/h - Heavy Vehicle	Observations n	2	2	2	2
	Standard Deviation s	0.28	0.49	0.14	0.78
	Mean x_bar	-1.20	-0.95	-1.30	-0.25
	Degree of Freedom df	1	1	1	1
	t_{value}	6.000	2.714	13.000	0.455
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	12.706	12.706	12.706	12.706
	P(T<=t) two-tail	0.105	0.225	0.049	0.728
	Reject Ho?	No	No	Yes	No
70 km/h - Light Vehicle	Observations n	6	6	6	6
	Standard Deviation s	0.86	0.61	0.92	0.48
	Mean x_bar	0.48	-0.27	0.48	0.75
	Degree of Freedom df	5	5	5	5
	t_{value}	1.378	1.073	1.281	3.856
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.571	2.571	2.571	2.571
	P(T<=t) two-tail	0.227	0.332	0.256	0.012
	Reject Ho?	No	No	No	Yes
70 km/h - Medium Vehicle	Observations n	6	6	6	6
	Standard Deviation s	0.66	0.34	0.57	0.35
	Mean x_bar	-0.65	-1.63	-0.97	0.98
	Degree of Freedom df	5	5	5	5
	t_{value}	2.425	11.614	4.143	6.795
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.571	2.571	2.571	2.571
	P(T<=t) two-tail	0.060	0.000	0.009	0.001
	Reject Ho?	No	Yes	Yes	Yes
km/h - Heavy Vehic	Observations n	2	2	2	2
	Standard Deviation s	0.00	0.14	0.21	0.14

	Mean x_bar	-1.00	-1.40	-1.35	0.40
	Degree of Freedom df	1	1	1	1
	t_{value}	---	14.000	9.000	4.000
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	12.706	12.706	12.706	12.706
	P(T<=t) two-tail	---	0.045	0.070	0.156
	Reject Ho?	---	Yes	No	No
80 km/h - Light Vehicle	Observations n	6	6	6	6
	Standard Deviation s	0.76	0.67	0.97	0.50
	Mean x_bar	-0.02	-0.58	0.00	0.57
	Degree of Freedom df	5	5	5	5
	t_{value}	0.054	2.121	0.000	2.772
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.571	2.571	2.571	2.571
	P(T<=t) two-tail	0.959	0.087	1.000	0.039
	Reject Ho?	No	No	No	Yes
80 km/h - Medium Vehicle	Observations n	6	6	6	6
	Standard Deviation s	0.64	0.52	0.79	0.39
	Mean x_bar	-1.03	-1.93	-1.32	0.90
	Degree of Freedom df	5	5	5	5.000
	t_{value}	3.969	9.171	4.104	5.655
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.571	2.571	2.571	2.571
	P(T<=t) two-tail	0.011	0.000	0.009	0.002
	Reject Ho?	Yes	Yes	Yes	Yes
80 km/h - Heavy Vehicle	Observations n	2	2	2	2
	Standard Deviation s	0.07	0.49	0.00	0.42
	Mean x_bar	-1.85	-0.95	-1.50	-0.90
	Degree of Freedom df	1	1	1	1
	t_{value}	37.000	2.714	---	3.000
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	12.706	12.706	12.706	12.706
	P(T<=t) two-tail	0.017	0.225	---	0.205
	Reject Ho?	Yes	No	---	No
90 km/h - Light Vehicle	Observations n	6	6	6	6
	Standard Deviation s	1.41	1.06	1.34	0.47
	Mean x_bar	-0.28	-0.82	-0.42	0.53
	Degree of Freedom df	5	5	5	5
	t_{value}	0.491	1.885	0.763	2.794
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.571	2.571	2.571	2.571
	P(T<=t) two-tail	0.645	0.118	0.480	0.038
	Reject Ho?	No	No	No	Yes
90 km/h - Medium Vehicle	Observations n	6	6	6	6
	Standard Deviation s	0.99	0.70	1.05	0.38
	Mean x_bar	-0.65	-1.38	-1.00	0.73
	Degree of Freedom df	5	5	5	5
	t_{value}	1.603	4.862	2.327	4.690
	$t_{cri}=t_{df,\ 0.05}$ (two-tail)	2.571	2.571	2.571	2.571
	P(T<=t) two-tail	0.170	0.005	0.067	0.005
	Reject Ho?	No	Yes	No	Yes
90 km/h - Heavy Vehicle	Observations n	2	2	2	2
	Standard Deviation s	0.49	0.28	0.42	0.21
	Mean x_bar	-0.85	-1.40	-1.20	0.55
	Degree of Freedom df	1	1	1	1
	t_{value}	2.429	7.000	4.000	3.667

	$t_{cri}=t_{df, 0.05}$ (two-tail)	12.706	12.706	12.706	12.706
	P(T<=t) two-tail	0.249	0.090	0.156	0.170
	Reject Ho?	No	No	No	No

Table E.5 – Statistical Analysis of Impedance Tube Method – Gyratory Samples

Frequency Range	Statistical Analysis	Mixes Comparisons			
		rOFC/HL-3	rOGC/HL-3	SMA/HL-3	rOFC/rOGC
200 Hz – 1200 Hz	Observations n	321	321	321	321
	Standard Deviation s	0.02	0.02	0.02	0.01
	Mean x_bar	0.007	0.015	-0.020	-0.008
	Degree of Freedom df	320	320	320	320
	t_{value}	6.240	16.551	23.342	22.648
	$t_{cri}=t_{df, 0.05}$ (two-tail)	1.967	1.967	1.967	1.967
	P(T<=t) two-tail	0.000	0.000	0.000	0.000
	Reject Ho?	Yes	Yes	Yes	Yes

Table E.6 – Statistical Analysis of Impedance Tube Method – 2006 Field Core Samples

Frequency Range	Statistical Analysis	Mixes Comparisons			
		rOFC/HL-3	rOGC/HL-3	SMA/HL-3	rOFC/rOGC
200 Hz – 1200 Hz	Observations n	321	321	321	321
	Standard Deviation s	0.00	0.00	0.01	0.00
	Mean x_bar	0.004	0.024	0.015	-0.019
	Degree of Freedom df	320	320	320	320
	t_{value}	21.876	92.947	49.855	95.771
	$t_{cri}=t_{df, 0.05}$ (two-tail)	1.967	1.967	1.967	1.967
	P(T<=t) two-tail	0.000	0.000	0.000	0.000
	Reject Ho?	Yes	Yes	Yes	Yes

Table E.7 – Statistical Analysis of Reverberation Time Method – 2006 Field Samples

Frequency Range	Statistical Analysis	Mixes Comparisons			
		rOFC/HL-3	rOGC/HL-3	SMA/HL-3	rOFC/rOGC
200 Hz – 1200 Hz	Observations n	9	9	9	9
	Standard Deviation s	0.008	0.007	0.005	0.010
	Mean x_bar	0.006	0.008	0.008	-0.002
	Degree of Freedom df	8	8	8	8
	t_{value}	2.027	3.359	4.923	0.606
	$t_{cri}=t_{df, 0.05}$ (two-tail)	2.306	2.306	2.306	2.306
	P(T<=t) two-tail	0.077	0.010	0.001	0.561
	Reject Ho?	No	Yes	Yes	No

APPENDIX F: RESULTS OF THE LIFE CYCLE COST ANALYSIS

Table F.1 – Input Parameters

Input Parameters	Mean	SD
Discount Rate, %	5.3%	0.52%
Service Life of rOFC, yrs	12	2.9
Life of 1st rOFC Rehab., yrs	10	2.2
Life of 2nd rOFC Rehab., yrs	10	2.2
Life of 3rd rOFC Rehab., yrs	10	2.2
Service Life of rOGC, yrs	12	2.9
Life of 1st rOGC Rehab., yrs	10	2.2
Life of 2nd rOGC Rehab., yrs	10	2.2
Life of 3rd rOGC Rehab., yrs	10	2.2
Service Life of SMA, yrs	21	5
Life of 1st SMA Rehab., yrs	13	2.8
Life of 2nd SMA Rehab., yrs	12	2.8
Life of 3rd SMA Rehab., yrs	11	2.8
Service Life of HL-3, yrs	15	3.6
Life of 1st HL-3 Rehab., yrs	12	2.6
Life of 2nd HL-3 Rehab., yrs	11	2.6
Life of 3rd HL-3 Rehab., yrs	10	2.6
rOFC, $/t	97.20	10.98
rOGC, $/t	70.50	7.97
SMA, $/t	97.20	10.98
HL-3, $/t	42.60	4.81
HL-8, $/t	43.66	4.93
Granular A, $/t	11.62	1.87
Granular B, $/t	8.11	1.76
Rout and Seal, $/m	2.04	0.23
Mill and Patch, $/m2	7.09	0.74
Milling, $/t	10.94	5.27
Tack Coat, $/m2	0.22	0.07

Table F.2 – rOFC Deterministic LCCA and Maintenance and Rehabilitation Strategy

Representative Pavement Type	**rOFC**
AADT (2-lane)	3260
Traffic Volume Category	Low Traffic
Analysis Period (years)	30
Discount Rate	5.3%

Initial Pavement Structure and Construction Costs

Thickness mm	Initial Pavement Structure	Quantity per km	Item Price	Cost per km	Total Initial Cost	Initial Cost per Lane-km	Expected Service Life
40	rOFC	686 t	$97.20 /t	$66,679.20	$223,997.36	$111,998.68	12
80	HL-8	1372 t	$43.66 /t	$59,907.29			
150	Granular A	2520 t	$11.62 /t	$29,294.71			
600	Granular B	8400 t	$8.11 /t	$68,116.16			

Maintenance and Rehabilitation Strategies and Costs

Scheduled Rehab. Year	Rehabilitation and Maintenance Treatment	Quantity per km	Item Price	Cost per km	Total Cost in Rehab. Year	Total Cost in Rehab. Year per Lane-km	Expected Service Life
4	Rout and Seal Cracks	500 m	$2.04 /m	$1,020.72	$1,020.72	$510.36	
8	Mill and patch 20 % spot repairs	1400 m2	$7.09 /m2	$9,923.68	$9,923.68	$4,961.84	
12	Mill 80 mm asphalt pavement	1372 t	$10.94 /t	$15,015.72	$114,665.37	$57,332.68	10
	Resurface rOFC - 40-mm	686 t	$97.20 /t	$66,679.20			
	Replace HL-8 - 40-mm	686 t	$43.66 /t	$29,953.65			
	Tack Coat (2 layers)	14000 m2	$0.22 /m2	$3,016.80			
15	Rout and Seal Cracks	500 m	$2.04 /m	$1,020.72	$1,020.72	$510.36	
19	Mill and patch 20 % spot repairs	1400 m2	$7.09 /m2	$9,923.68	$9,923.68	$4,961.84	
22	Mill 80 mm asphalt pavement	1372 t	$10.94 /t	$15,015.72	$114,665.37	$57,332.68	10
	Resurface rOFC - 40-mm	686 t	$97.20 /t	$66,679.20			
	Replace HL-8 - 40-mm	686 t	$43.66 /t	$29,953.65			
	Tack Coat (2 layers)	14000 m2	$0.22 /m2	$3,016.80			
25	Rout and Seal Cracks	500 m	$2.04 /m	$1,020.72	$1,020.72	$510.36	
29	Mill and patch 20 % spot repairs	1400 m2	$7.09 /m2	$9,923.68	$9,923.68	$4,961.84	
30	Salvage (Residual Life)				($22,933.07)	($11,466.54)	

Present Worth Life Cycle Cost Calculation

Year	Type of Cost	Cost per Lane-km	(P/F,I,N)	Present Worth Cost per Lane-km
0	Initial Construction	$111,998.68	1.00	$111,998.68
4	Rout and Seal	$510.36	0.81	$415.11
8	Mill and Patch	$4,961.84	0.66	$3,282.58
12	Rehabilitation	$57,332.68	0.54	$30,850.47
15	Rout and Seal	$510.36	0.45	$231.19
19	Mill and Patch	$4,961.84	0.38	$1,892.26
22	Rehabilitation	$57,332.68	0.32	$18,406.79
25	Rout and Seal	$510.36	0.27	$137.94
29	Mill and Patch	$4,961.84	0.23	$1,129.01
30	Salvage	($11,466.54)	0.21	($2,435.46)
			Initial Construction Cost for rOFC	$111,998.68
			Maintenance and Rehabilitation Cost for rOFC	$56,345.36
			Total LCC for rOFC	**$165,908.58**

Table F.3 – rOGC Deterministic LCCA and Maintenance and Rehabilitation Strategy

Representative Pavement Type	**rOGC**
AADT (2-lane)	3260
Traffic Volume Category	Low Traffic
Analysis Period (years)	30
Discount Rate	5.3%

Initial Pavement Structure and Construction Costs

Thickness mm	Initial Pavement Structure	Quantity per km	Item Price	Cost per km	Total Initial Cost	Initial Cost per Lane-km	Expected Service Life
40	rOGC	686 t	$70.50 /t	$48,363.00	$205,681.16	$102,840.58	12
80	HL-8	1372 t	$43.66 /t	$59,907.29			
150	Granular A	2520 t	$11.62 /t	$29,294.71			
600	Granular B	8400 t	$8.11 /t	$68,116.16			

Maintenance and Rehabilitation Strategies and Costs

Scheduled Rehab. Year	Rehabilitation and Maintenance Treatment	Quantity per km	Item Price	Cost per km	Total Cost in Rehab. Year	Total Cost in Rehab. Year per Lane-km	Expected Service Life
4	Rout and Seal Cracks	500 m	$2.04 /m	$1,020.72	$1,020.72	$510.36	
8	Mill and patch 20 % spot repairs	1400 m2	$7.09 /m2	$9,923.68	$9,923.68	$4,961.84	
12	Mill 80 mm asphalt pavement	1372 t	$10.94 /t	$15,015.72	$96,349.17	$48,174.58	10
	Resurface rOGC - 40-mm	686 t	$70.50 /t	$48,363.00			
	Replace HL-8 - 40-mm	686 t	$43.66 /t	$29,953.65			
	Tack Coat (2 layers)	14000 m2	$0.22 /m2	$3,016.80			
15	Rout and Seal Cracks	500 m	$2.04 /m	$1,020.72	$1,020.72	$510.36	
19	Mill and patch 20 % spot repairs	1400 m2	$7.09 /m2	$9,923.68	$9,923.68	$4,961.84	
22	Mill 80 mm asphalt pavement	1372 t	$10.94 /t	$15,015.72	$96,349.17	$48,174.58	10
	Resurface rOGC - 40-mm	686 t	$70.50 /t	$48,363.00			
	Replace HL-8 - 40-mm	686 t	$43.66 /t	$29,953.65			
	Tack Coat (2 layers)	14000 m2	$0.22 /m2	$3,016.80			
25	Rout and Seal Cracks	500 m	$2.04 /m	$1,020.72	$1,020.72	$510.36	
29	Mill and patch 20 % spot repairs	1400 m2	$7.09 /m2	$9,923.68	$9,923.68	$4,961.84	
30	Salvage (Residual Life)				($19,269.83)	($9,634.92)	

Present Worth Life Cycle Cost Calculation

Year	Type of Cost	Cost per Lane-km	(P/F,I,N)	Present Worth Cost per Lane-km
0	Initial Construction	$102,840.58	1.00	$102,840.58
4	Rout and Seal	$510.36	0.81	$415.11
8	Mill and Patch	$4,961.84	0.66	$3,282.58
12	Rehabilitation	$48,174.58	0.54	$25,922.54
15	Rout and Seal	$510.36	0.45	$231.19
19	Mill and Patch	$4,961.84	0.38	$1,892.26
22	Rehabilitation	$48,174.58	0.32	$15,466.56
25	Rout and Seal	$510.36	0.27	$137.94
29	Mill and Patch	$4,961.84	0.23	$1,129.01
30	Salvage	($9,634.92)	0.21	($2,046.43)
			Initial Construction Cost for rOGC	$102,840.58
			Maintenance and Rehabilitation Cost for rOGC	$48,477.19
			Total LCC for rOGC	$149,271.34

Table F.4 – SMA Deterministic LCCA and Maintenance and Rehabilitation Strategy

Representative Pavement Type	**SMA**
AADT (2-lane)	3260
Traffic Volume Category	Low Traffic
Analysis Period (years)	30
Discount Rate	5.3%

Initial Pavement Structure and Construction Costs

Thickness mm	Initial Pavement Structure	Quantity per km	Item Price	Cost per km	Total Initial Cost	Initial Cost per Lane-km	Expected Service Life
40	SMA	686 t	$97.20 /t	$66,679.20	$223,997.36	$111,998.68	21
80	HL-8	1372 t	$43.66 /t	$59,907.29			
150	Granular A	2520 t	$11.62 /t	$29,294.71			
600	Granular B	8400 t	$8.11 /t	$68,116.16			

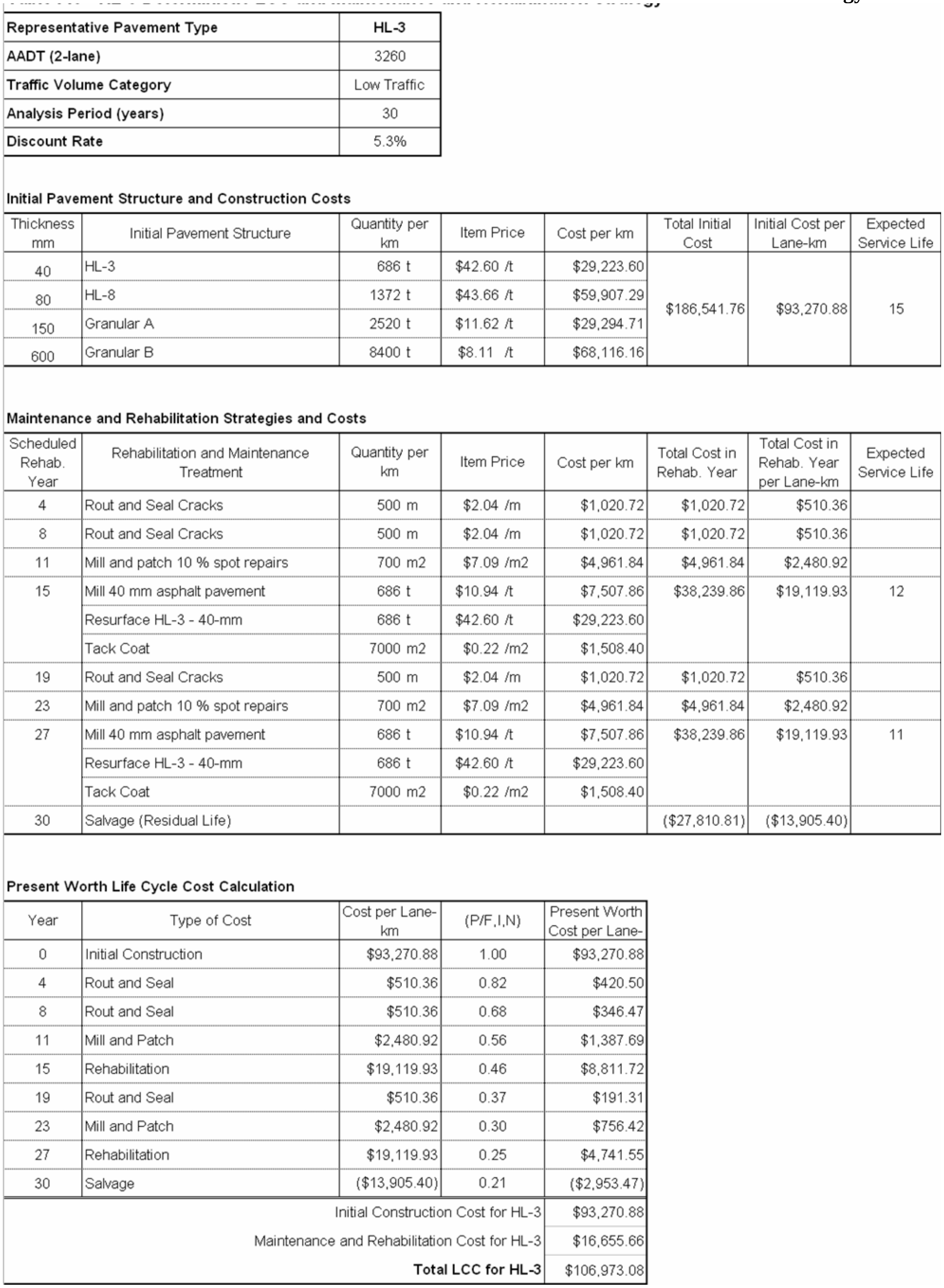
Maintenance and Rehabilitation Strategies and Costs

Scheduled Rehab. Year	Rehabilitation and Maintenance Treatment	Quantity per km	Item Price	Cost per km	Total Cost in Rehab. Year	Total Cost in Rehab. Year per Lane-km	Expected Service Life
4	Rout and Seal Cracks	500 m	$2.04 /m	$1,020.72	$1,020.72	$510.36	
8	Rout and Seal Cracks	500 m	$2.04 /m	$1,020.72	$3,501.64	$1,750.82	
	Mill and patch 5 % spot repairs	350 m2	$7.09 /m2	$2,480.92			
13	Rout and Seal Cracks	500 m	$2.04 /m	$1,020.72	$8,463.48	$4,231.74	
	Mill and patch 15 % spot repairs	1050 m2	$7.09 /m2	$7,442.76			
17	Rout and Seal Cracks	500 m	$2.04 /m	$1,020.72	$10,944.40	$5,472.20	
	Mill and patch 20% spot repairs	1400 m2	$7.09 /m2	$9,923.68			
21	Mill 40 mm asphalt pavement	686 t	$10.94 /t	$7,507.86	$75,695.46	$37,847.73	13
	Resurface SMA - 40-mm	686 t	$97.20 /t	$66,679.20			
	Tack Coat	7000 m2	$0.22 /m2	$1,508.40			
25	Rout and Seal Cracks	500 m	$2.04 /m	$1,020.72	$1,020.72	$510.36	
30	Rout and Seal Cracks	500 m	$2.04 /m	$1,020.72	$8,463.48	$4,231.74	
	Mill and patch 15 % spot repairs	1050 m2	$7.09 /m2	$7,442.76			
30	Salvage (Residual Life)				($23,290.91)	($11,645.46)	

Present Worth Life Cycle Cost Calculation

Year	Type of Cost	Cost per Lane-km	(P/F,I,N)	Present Worth Cost per Lane-km
0	Initial Construction	$111,998.68	1.00	$111,998.68
4	Rout and Seal	$510.36	0.81	$410.85
8	Rout and Seal, Mill and Patch	$1,750.82	0.65	$1,134.60
13	Rout and Seal, Mill and Patch	$4,231.74	0.52	$2,207.61
17	Rout and Seal, Mill and Patch	$5,472.20	0.42	$2,298.08
21	Rehabilitation	$37,847.73	0.34	$12,795.11
25	Rout and Seal	$510.36	0.27	$137.94
30	Rout and Seal, Mill and Patch	$4,231.74	0.22	$914.42
30	Salvage	($11,645.46)	0.21	($2,473.46)
			Initial Construction Cost for SMA	$111,998.68
			Maintenance and Rehabilitation Cost for SMA	$19,898.60
			Total LCC for SMA	$129,423.82

Table F.5 – HL-3 Deterministic LCCA and Maintenance and Rehabilitation Strategy



Representative Pavement Type	**HL-3**
AADT (2-lane)	3260
Traffic Volume Category	Low Traffic
Analysis Period (years)	30
Discount Rate	5.3%

Initial Pavement Structure and Construction Costs

Thickness mm	Initial Pavement Structure	Quantity per km	Item Price	Cost per km	Total Initial Cost	Initial Cost per Lane-km	Expected Service Life
40	HL-3	686 t	$42.60 /t	$29,223.60	$186,541.76	$93,270.88	15
80	HL-8	1372 t	$43.66 /t	$59,907.29			
150	Granular A	2520 t	$11.62 /t	$29,294.71			
600	Granular B	8400 t	$8.11 /t	$68,116.16			

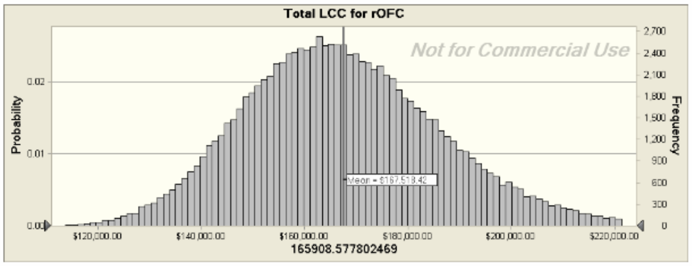
Maintenance and Rehabilitation Strategies and Costs

Scheduled Rehab. Year	Rehabilitation and Maintenance Treatment	Quantity per km	Item Price	Cost per km	Total Cost in Rehab. Year	Total Cost in Rehab. Year per Lane-km	Expected Service Life
4	Rout and Seal Cracks	500 m	$2.04 /m	$1,020.72	$1,020.72	$510.36	
8	Rout and Seal Cracks	500 m	$2.04 /m	$1,020.72	$1,020.72	$510.36	
11	Mill and patch 10 % spot repairs	700 m2	$7.09 /m2	$4,961.84	$4,961.84	$2,480.92	
15	Mill 40 mm asphalt pavement	686 t	$10.94 /t	$7,507.86	$38,239.86	$19,119.93	12
	Resurface HL-3 - 40-mm	686 t	$42.60 /t	$29,223.60			
	Tack Coat	7000 m2	$0.22 /m2	$1,508.40			
19	Rout and Seal Cracks	500 m	$2.04 /m	$1,020.72	$1,020.72	$510.36	
23	Mill and patch 10 % spot repairs	700 m2	$7.09 /m2	$4,961.84	$4,961.84	$2,480.92	
27	Mill 40 mm asphalt pavement	686 t	$10.94 /t	$7,507.86	$38,239.86	$19,119.93	11
	Resurface HL-3 - 40-mm	686 t	$42.60 /t	$29,223.60			
	Tack Coat	7000 m2	$0.22 /m2	$1,508.40			
30	Salvage (Residual Life)				($27,810.81)	($13,905.40)	

Present Worth Life Cycle Cost Calculation

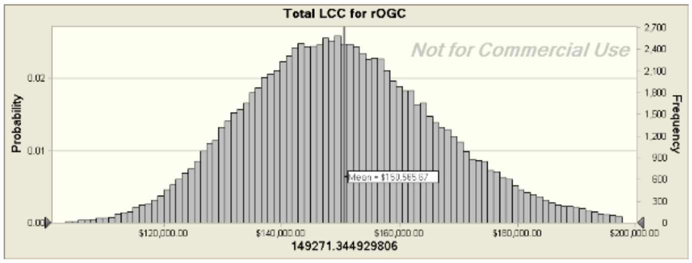
Year	Type of Cost	Cost per Lane-km	(P/F,I,N)	Present Worth Cost per Lane-
0	Initial Construction	$93,270.88	1.00	$93,270.88
4	Rout and Seal	$510.36	0.82	$420.50
8	Rout and Seal	$510.36	0.68	$346.47
11	Mill and Patch	$2,480.92	0.56	$1,387.69
15	Rehabilitation	$19,119.93	0.46	$8,811.72
19	Rout and Seal	$510.36	0.37	$191.31
23	Mill and Patch	$2,480.92	0.30	$756.42
27	Rehabilitation	$19,119.93	0.25	$4,741.55
30	Salvage	($13,905.40)	0.21	($2,953.47)
			Initial Construction Cost for HL-3	$93,270.88
			Maintenance and Rehabilitation Cost for HL-3	$16,655.66
			Total LCC for HL-3	$106,973.08

Forecast: Total LCC for rOFC
Summary:
Entire range is from $97,104.34 to $281,959.42
Base case is $165,908.58
After 100,000 trials, the std. error of the mean is $60.83



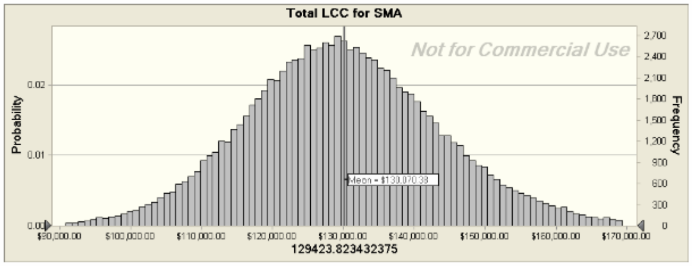
Statistics:	Forecast values
Trials	100,000
Mean	$167,518.42
Median	$166,204.44
Mode	—
Standard Deviation	$19,235.65
Variance	$370,010,311.22
Skewness	0.4188
Kurtosis	3.36
Coeff. of Variability	0.1148
Minimum	$97,104.34
Maximum	$281,959.42
Range Width	$184,855.07
Mean Std. Error	$60.83

Forecast: Total LCC for rOGC
Summary:
Entire range is from $90,529.59 to $246,534.22
Base case is $149,271.34
After 100,000 trials, the std. error of the mean is $53.24



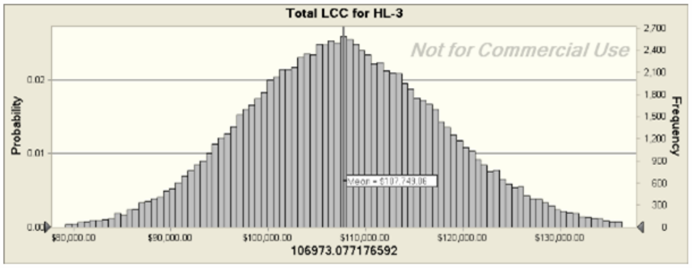
Statistics:	Forecast values
Trials	100,000
Mean	$150,565.67
Median	$149,582.78
Mode	—
Standard Deviation	$16,834.75
Variance	$283,408,811.14
Skewness	0.3744
Kurtosis	3.32
Coeff. of Variability	0.1118
Minimum	$90,529.59
Maximum	$246,534.22
Range Width	$156,004.63
Mean Std. Error	$53.24

Forecast: Total LCC for SMA
Summary:
Entire range is from $73,286.24 to $228,326.22
Base case is $129,423.82
After 100,000 trials, the std. error of the mean is $44.28



Statistics:	Forecast values
Trials	100,000
Mean	$130,070.38
Median	$129,508.95
Mode	—
Standard Deviation	$14,003.30
Variance	$196,092,344.99
Skewness	0.2793
Kurtosis	3.51
Coeff. of Variability	0.1077
Minimum	$73,286.24
Maximum	$228,326.22
Range Width	$155,039.99
Mean Std. Error	$44.28

Forecast: Total LCC for HL-3
Summary:
Entire range is from $66,330.56 to $162,080.82
Base case is $106,973.08
After 100,000 trials, the std. error of the mean is $32.26



Statistics:	Forecast values
Trials	100,000
Mean	$107,749.06
Median	$107,526.09
Mode	—
Standard Deviation	$10,202.12
Variance	$104,083,182.40
Skewness	0.1426
Kurtosis	3.09
Coeff. of Variability	0.0947
Minimum	$66,330.56
Maximum	$162,080.82
Range Width	$95,750.25
Mean Std. Error	$32.26

Figure F.1 – Probabilistic LCCA Using Normal Distribution Cost Input Parameters

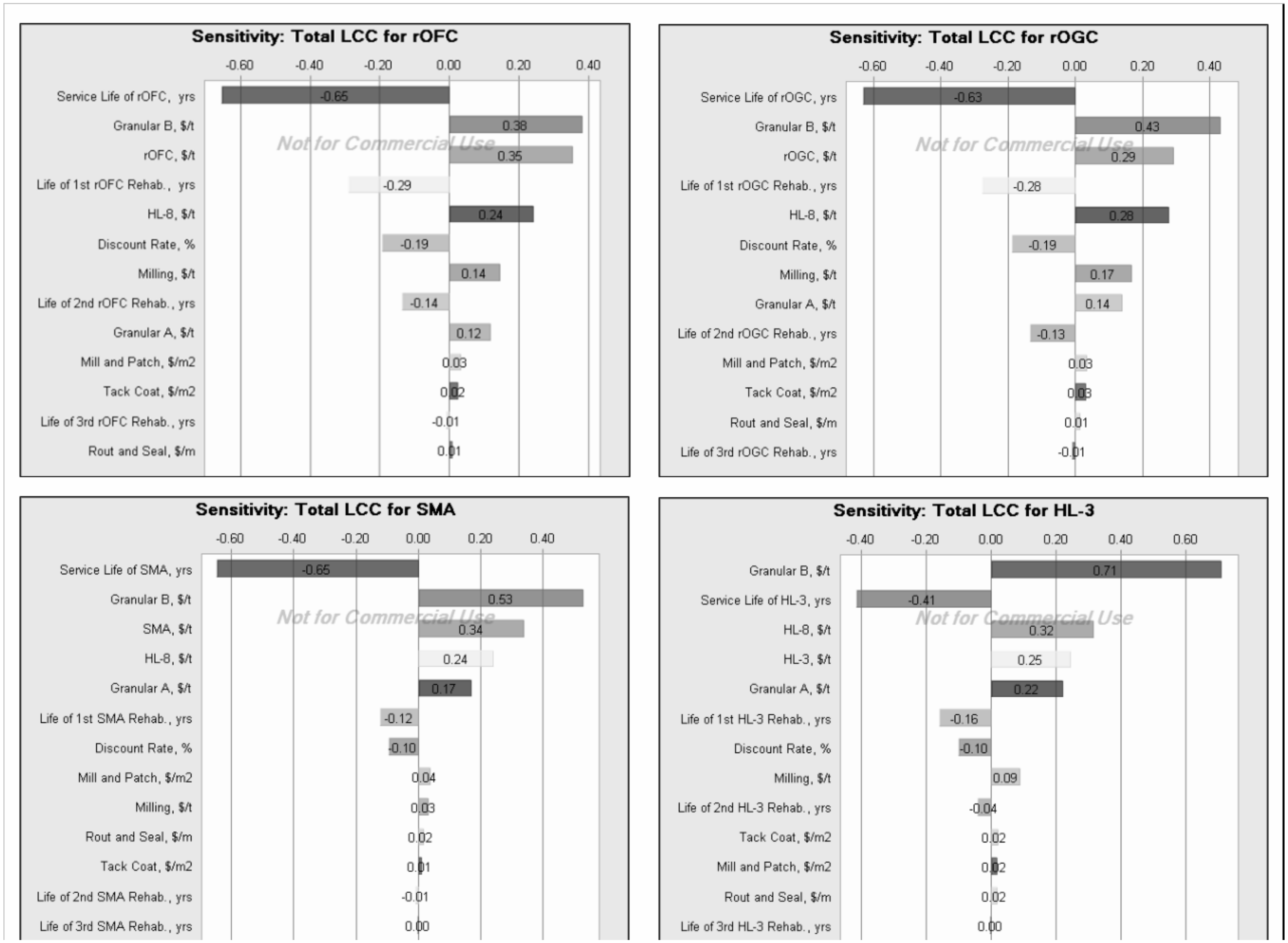
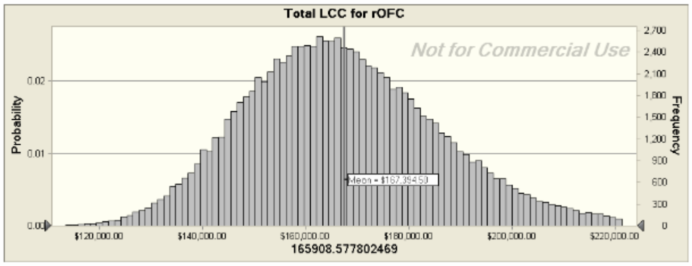


Figure F.2 – Sensitivity Probabilistic Analysis Using Normal Distribution Cost Input Parameters

Forecast: Total LCC for rOFC

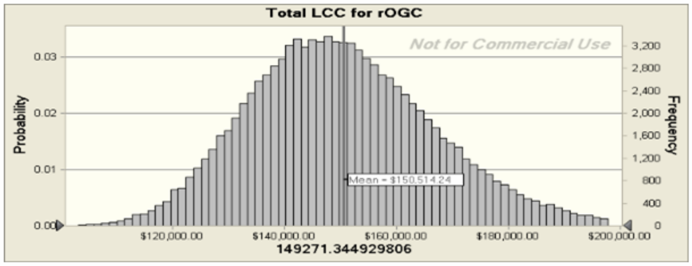
Summary:
Entire range is from $104,796.80 to $283,871.00
Base case is $165,908.58
After 100,000 trials, the std. error of the mean is $60.93



Statistics:	Forecast values
Trials	100,000
Mean	$167,394.50
Median	$165,893.26
Mode	—
Standard Deviation	$19,266.73
Variance	$371,207,039.53
Skewness	0.4808
Kurtosis	3.43
Coeff. of Variability	0.1151
Minimum	$104,796.80
Maximum	$283,871.00
Range Width	$179,074.20
Mean Std. Error	$60.93

Forecast: Total LCC for rOGC

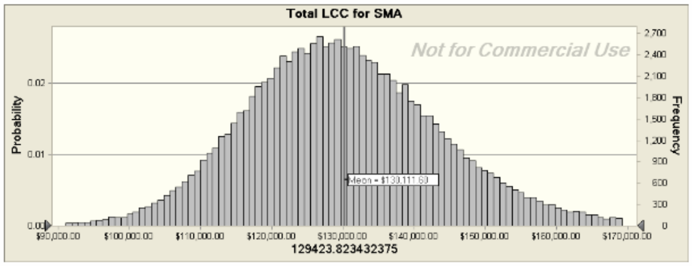
Summary:
Entire range is from $92,603.87 to $244,276.15
Base case is $149,271.34
After 100,000 trials, the std. error of the mean is $53.38



Statistics:	Forecast values
Trials	100,000
Mean	$150,514.24
Median	$149,253.80
Mode	—
Standard Deviation	$16,880.93
Variance	$284,965,699.32
Skewness	0.4581
Kurtosis	3.40
Coeff. of Variability	0.1122
Minimum	$92,603.87
Maximum	$244,276.15
Range Width	$151,672.28
Mean Std. Error	$53.38

Forecast: Total LCC for SMA

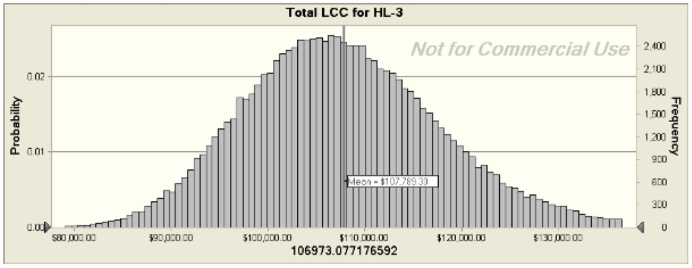
Summary:
Entire range is from $81,057.11 to $216,094.93
Base case is $129,423.82
After 100,000 trials, the std. error of the mean is $44.11



Statistics:	Forecast values
Trials	100,000
Mean	$130,111.60
Median	$129,276.62
Mode	—
Standard Deviation	$13,948.67
Variance	$194,565,261.08
Skewness	0.4025
Kurtosis	3.60
Coeff. of Variability	0.1072
Minimum	$81,057.11
Maximum	$216,094.93
Range Width	$135,037.83
Mean Std. Error	$44.11

Forecast: Total LCC for HL-3

Summary:
Entire range is from $75,310.53 to $176,437.36
Base case is $106,973.08
After 100,000 trials, the std. error of the mean is $32.42



Statistics:	Forecast values
Trials	100,000
Mean	$107,789.30
Median	$107,138.52
Mode	—
Standard Deviation	$10,253.44
Variance	$105,133,062.26
Skewness	0.4114
Kurtosis	3.37
Coeff. of Variability	0.0951
Minimum	$75,310.53
Maximum	$176,437.36
Range Width	$101,126.83
Mean Std. Error	$32.42

Figure F.3 – Probabilistic LCCA Using Log-Normal Distribution Cost Input Parameters

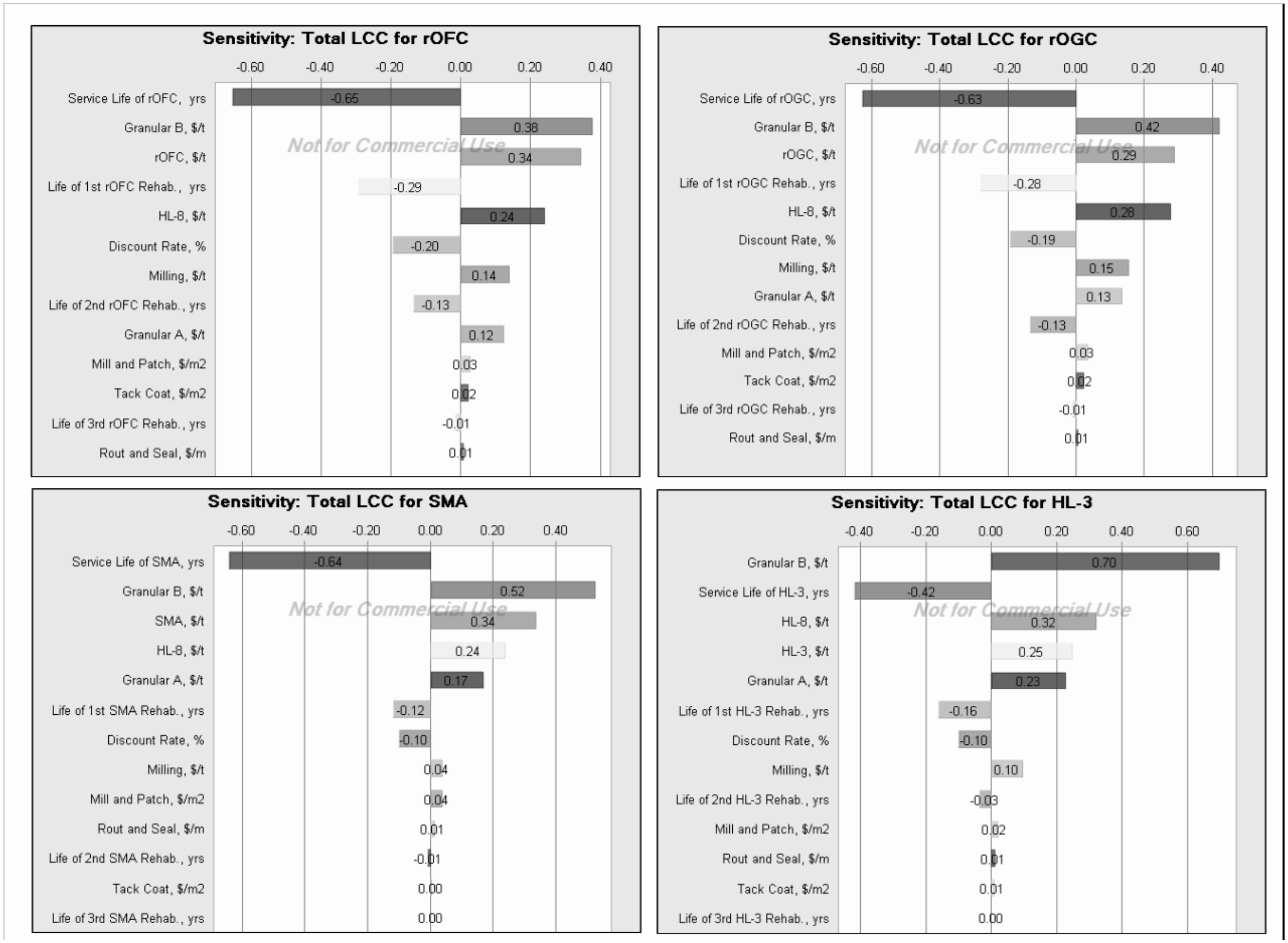


Figure F.4 – Sensitivity Probabilistic Analysis Using Log-Normal Distribution Cost Input Parameters