Safe, Quiet and Durable Pavement Surfaces

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Skidding contributes to up to 35% of wet pavement accidents. Pavement surface friction therefore is an important component of highway safety. The skid resistance also varies seasonally and reduces over time due to surface polishing. These leave the pavement in a state of increased risk of skidding accidents. An adequate surface friction that accommodates the seasonal and long term variations is essential for safety over the pavement surface service life. The resistance to skidding, however, depends on surface microtexture and macrotexture. Alternatively, increased texture aimed at increased and durable surface friction may affect the noise generated on the road. In fact, traffic noise is a growing problem throughout the world. Noise barriers, traditionally used for noise reduction, are expensive and inefficient in some cases. As the pavement surface characteristics play a key role in noise generation and propagation, it provides a window for noise reduction by altering the pavement surface. The challenge, however, is to provide a smooth, quiet, long-lasting, and economic pavement with adequate and durable surface friction. This research has been directed to address this challenge and to provide a realistic guideline.

The tire-pavement noise, sound absorption, and skid resistance performances of various flexible and rigid pavement surfaces have been examined using the field and laboratory test data. Models for the prediction of pavement skid resistance including the seasonal and long term variations have also been developed correlating the influencing factors. A value engineering approach has been proposed to accommodate the construction and maintenance costs, longevity, smoothness, safety and noise in the selection of pavement surfaces.

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Dedication

This thesis is dedicated to my lovely mother, Asia Khatun, and in tribute to my late father, Md. Joynal Abedin, whom I lost when I was a high school student.

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Chapter 1 Introduction

1.1 BACKGROUND

The main purpose of a transportation system is to facilitate safe and efficient movement of people and goods. However, over one million people die and fifty million are injured annually from highway crashes around the world (Snyder 2006). According to Transport Canada (2004), 2,766 people have died and another 222,455 have been injured (17,730 seriously) on Canadian roads in 2003 from 156,904 police reported crashes. Highway crashes cost Canadians about $25 billion annually, an enormous economic loss to our society. In the US, 42,643 fatalities and about 2.9 million injuries have occurred from about 6.3 million reported traffic crashes in 2000. Such traffic related incidents significantly affect the US economy with an estimated $230.6 billion loss as of year 2000 in addition to the pain and suffering of the society (Noyce et al. 2005).

Driver skill and behaviour, roadway geometry, pavement condition, vehicle and tire conditions/loadings, vehicle speed and brake performance are primary factors that contribute to highway crashes. However, uncontrolled skidding due to inadequate surface friction and poor visibility due to splash and spray have been found to be the two primary causes of highway crashes during wet weather. As indicated by Anon (2005), skidding on wet pavements contributes to 13.5% of fatal and up to 25% of all accidents. Hoerner and Smith (2002) mentioned that skidding contributes to 15 to 35% of wet weather accidents.

A number studies have indicated that skid related accidents can be reduced by an improvement in pavement surface friction (MTO 2003). For example, Kennedy et al. (1990) and Hosking (1987) mentioned that an improvement of surface friction coefficient of 0.1 could reduce the wet-accident rate by 13 percent. The wet to dry pavement accident ratio has been shown to increase sharply from 0.23 to about 0.7 as the skid number (SN) measured at 64 km/h (SN_{64}) dropped below 41, the critical skid number (Rizenbergs et al. 1976). The wet-weather accidents have been shown to reduce by 35% with a net return of 540% after laying anti-skid surfacing at more than 2,000 sites in London, UK (Kennedy et al. 1990). Inadequate surface friction may also play a role in many crashes on dry pavement surface, especially at intersections and work zones (frequent stop-slow-go operations) as well as curved sections (Snyder 2006). Pavement surface friction, an important component of highway safety, therefore represents one of the major functional performances of the pavement that include smoothness, safety, and comfort in ride.

The surface friction or resistance to skidding is available from different shapes of texture on pavement surfaces. According to Goodman et al. (2006), a combination of microtexture and macrotexture primarily contributes to available friction of road surfaces. According to Dahir and Gramling (1990), textures provide a retarding force at the tire-pavement interface that resist sliding when a braking force is applied. This facilitates controlled driving manoeuvres, especially on wet surfaces. In fact, 70% of the wet weather crashes are preventable with improved texture/friction on pavement surfaces (Larson et al. 2004).

Increased temperature and moisture can significantly reduce the available surface friction. These leave pavements at increased risk of skid related accidents. A study has shown that pavement surface friction reduces at about 1.2 *SN* for an increase in temperature of 10°C (Hill and Henry 1981). Average difference of surface friction measured in winter and summer has shown to be six *SN* (Jayawickrama et al. 1981). Pavement friction also changes over time due to environmental and traffic related polishing/wear. A study in Maryland has shown that pavement surface friction decreases at 0.22 *SN* per year on rural roads and 0.26 *SN* per year on urban roads (Song et al. 2006). Therefore, according to TAC (1997), variation of surface friction with time is an important measure of pavement deterioration.

Durable surface texture/friction is also important for the economy of highway construction and operation (no or minimal surface treatment to restore the skid resistance). According to Voigt and Wu (1995), for a skid resistant surface, the resistance to wear (i.e., durability of surface) is an important factor as both microtexture and macrotexture wear under traffic resulting in a decrease in available skid resistance. The splash and spray that contributes to 10 percent of the wet weather accidents due to poor visibility can also be minimized with deeper texture on the pavement surfaces (Hoerner and Smith 2002). The available surface friction also decreases as the speed of the vehicle increases. Pavement surfaces should therefore be designed not only for sufficient initial friction at the speed of the roadway but also for a sufficient friction over the service life that accommodates the short-term seasonal fluctuation and long term polish/wear due to traffic action, material degradation and environmental effect.

Improved and durable surface friction can be achieved through increased texture and/or changing the surface materials or mix. Increased surface texture, however, may influence the tire-pavement noise resulting in an increase in overall traffic noise. Deeper textures are also associated with surface roughness that causes travelers discomfort due to increased vibration of the vehicle. It is also associated with vehicle wear and extra fuel consumption.

Noise is an environmental pollutant that affects both public health and economy. A study has indicated that 30% of European Union (EU) citizens are exposed to traffic noise exceeding the World Health Organization (WHO) recommended acceptable level with 10% complaining of sleep disturbance at night. About 800 to 2,200 people in Denmark are admitted to hospitals annually with high blood pressure or heart disease and 200 to 500 die prematurely which are considered associated with high levels of traffic noise (FEHRL 2006). In addition, a 1dB increase in noise results in 1% decrease in house prices near busy roads in Denmark. Overall, noise costs the Danish society about €780 to €1150 million annually. Preliminary estimates suggest that the UK residents would save €800 million annually per 1dB reduction in noise measured at dwellings. A significant part of the economy of the EU countries is affected by noise impact and noise reduction policies where health related costs alone account to be 0.2 % to 2.0 % of the annual Gross National Product (FEHRL 2006).

In fact, traffic noise has been identified as a growing problem throughout the world. According to Herman (1998), traffic noise impacts on communities are escalating worldwide due to increasing traffic volume and development near highway facilities. Major problems are encountered in dense urban areas near busy roads carrying a high volume of traffic (Sandberg and Ejsmont 2002). A survey has shown that half of Canadians are bothered, disturbed, or annoyed by noise originated outside their home where the most bothersome type is the road traffic noise (PWC 2002). A French study has shown that 75% of the residents in West European countries are bothered by noise, particularly from roadway traffic (Ballie 2000). Noise on roads also causes driver fatigue and impaired performance, and therefore may affect traveler safety, in addition to driver and bystander(s) discomfort (Descornet 1989). Provincial transportation agencies, cities, and municipalities are therefore under increased pressure to reduce the traffic noise pollution. According to Mcnerney (2000), for many urban communities throughout the world, traffic noise is a serious concern.

Noise Abatement Criteria (NAC) and guidelines developed by public agencies recommend physical noise mitigation measure if the traffic noise exceeds some acceptable maximum limits. Current standard noise mitigation measures are noise barriers to control sound level at the outdoor living area. These kinds of noise mitigation methods are very expensive to construct and maintain. For example, noise barriers that break the line of sight between the source and the receiver can reduce the outdoor noise level by five dBA (Rochat 2005). Their construction costs vary from over \$0.6 million per km (\$1 million per mile) to as high as \$3 million per km (\$5 million per mile) (Bernhard and McDaniel 2005). The future maintenance expenses are extra. Barriers are also impractical and/or inefficient for bridges and mountainous areas as well as some urban highways, where noise is a major concern, because of access points and/or intersections that provide sound escape paths. Furthermore, barriers can only prevent the noise propagation but not actually reduce the traffic noise from the source, and therefore cannot reduce noise exposure for the travelers and passers-by.

The three main sources of roadway traffic noise are vehicle engine (power train), aerodynamics and tire-pavement interaction. With current vehicle/tire technologies, the tire-pavement interaction was found to be the major contributor to traffic noise for passenger vehicles traveling at a constant speed of 35 km/h or greater (McDaniel and Thornton 2005). As mentioned by Herman (1998), tire-pavement noise is the critical component of traffic noise at the cruise speed, especially on freeway. The pavement surface can influence both generation and propagation of tire-pavement interaction noise (Phillips and Kinsey 2000). As the pavement surface characteristics play an important role in noise generation and propagation, it provides some opportunities of noise reduction by altering the pavement surface. For example, a reduction in maximum aggregate size in Superpave™ mix from 19 mm to 12.5 mm can reduce the noise by 1 to 3 dBA (FHWA Team 2005). In France, a 5 dBA and 7.4 dBA noise reduction (at 90 km/h) have been obtained with crumb rubber modified 0/10 mm and 0/6 mm surfacing, respectively (Ballie 2000).

The quality of a roadway is judged also by the comfort level it renders to the users. From the standpoint of the traveling public, surface smoothness is probably the single most important indicator of pavement performance because the difference between a smooth and rough roadway is easily understood and felt by travelers (Wolters 2002). Pavement construction and maintenance costs as well as structural capacity and durability are also prime consideration in the selection of surface type, particularly in the current context of tremendous budget shortfall for most of the public agencies. All these factors combined result in many challenges to transportation engineers and highway agencies, as they must balance the surface characteristics for comfort (smooth and quiet) and durability/economy without compromising the safety.

1.2 PROBLEM STATEMENT AND RESEARCH NEED

It has now been noted that a smooth or low texture surface is desired for a quiet and comfortable ride as well as a quiet neighbourhood, while travelers' safety, pavement durability, and economy in construction and maintenance are of paramount importance. Pavement surfaces must also provide adequate skid resistance over the service life withstanding the wear due to traffic movement and seasonal weather related variation. A systematic understanding of the effect of each aspect of pavement surface texture and friction is required to optimize the surface performance with respect to safety and noise. Highway agencies and researchers must come with a solution that produces the quietest surface possible with proven economy and durability, and preserves superior safety of the travelers.

However, according to Larson et al. (2005), no specific guidance is provided in current state specifications on improving the surface texture or friction to reduce the number of crashes. Furthermore, little emphasis is given on specifying the desirable noise levels, which has resulted in a large variation in noise levels of the pavement already constructed, even for the same pavement type. It has been recommended that an end-result specification should be developed to ensure the desired texture and friction levels during the construction and Road Safety Audits should include criteria for desirable surface characteristics. As mentioned by

Flintsch et al. (2003a), the functional characteristics that include ride quality, safety, and noise must be optimized for pavement surface mixes to ensure a safe and smooth riding.

Review of available published literature has shown some advancement in quiet pavement research around the world. However, very limited studies have been carried out from Canadian perspective, which are mainly to quantify overall traffic noise rather than the tire-pavement noise. Some other international research studies have been directed to pavement surface friction issue with limited focus on seasonal and long term variations. Inappropriate interpretation and/or conflicting or unrealistic conclusions are apparent in many of these studies. Published work on pavement surface friction is scarce in Canada. Alternatively, the relationship between pavement surface characteristics and performance, namely surface texture, friction and noise including performance variation over time has not yet adequately examined. A comprehensive study on pavement surface characteristics incorporating all these aspects is therefore most needed, particularly for Canadian jurisdictions, to aid the pavement engineers in the selection of appropriate surface texture or surface mix.

1.3 RESEARCH OBJECTIVES

The discussion presented above indicates that there is a demand for a comprehensive guideline incorporating different aspects of pavement surface performance to aid highway agencies in the selection of a quiet and durable surface with adequate skid resistance over the service life. This research study is an initiative towards such efforts. Accordingly, the main objectives of the research have been set as:

i) Quantifying the tire-pavement noise, sound absorption, and skid resistance of various portland cement concrete (PCC) and asphalt concrete (AC) surfaces and benchmarking based on the performances.

ii) Developing relationships of surface texture, skid resistance, and tire-pavement interaction noise. Correlating the as-built AC density as well as thickness with sound absorption.

iii) Quantifying the long term variation of PCC (rigid) and AC (flexible) pavements surface friction as well as tire-pavement noise, and developing performance models correlating with the factors that cause the variation.

iv) Evaluating the seasonal variation of both AC and PCC pavements surface friction in the Canadian environment, quantifying the variation, and developing model correlating the influencing factors.

v) Prepare guideline for highway agencies to aid in the selection of pavement surfaces accommodating construction and maintenance costs, pavement durability, smoothness and safety, and noise performances over service life.

1.4 RESEARCH SCOPE

The scope of the research work has been identified as:

i) Provide an overview of the pavement surface characteristics. Review the available relevant published literature and summarize the findings including the data and methodologies used, and their implications.

ii) Measure the tire-pavement Close Proximity (CPX), In-Vehicle, and Controlled Pass-By (CPB) noise of nine PCC and nineteen AC surfaces on Ontario provincial/private highways for benchmarking typical pavements that are currently in use and examining tire-pavement noise variation over time. The 0 to 12-year old PCC pavements include a longitudinal and eight transversely tined surfaces. The 0 to 8-year old AC surfaces include five regular and five fine graded 12.5 mm Superpave (SP), a fine graded 9.5 mm SP, three 12.5 mm Stone Mastic Asphalt (SMA), two fine and two coarse Microsurfacings, and a conventional dense asphalt.

iii) Measure the CPX, In-Vehicle and CPB noise, surface texture (sand patch method) and skid resistance (with skid trailer) for four AC pavement surfaces at CPATT Quiet Pavement (QP) site on Waterloo Regional Road 11 to evaluate performance variations and develop models. The surface mixes, each with 16 mm nominal maximum size aggregate, include 3-year old Rubberized Open Friction Course (ROFC), Rubberized Open Graded Course (ROGC), SMA, and traditional dense hot laid HL3.

iv) Measure the skid resistance using the skid trailer as well as the British Pendulum tester and surface macrotexture using the sand patch method as well as Automated Road Analyzer (ARAN) for five AC pavement surfaces at CPATT test track located at the Waterloo landfill (LF) station. These surfaces include 3-year old HL3, Polymer Modified HL3 Asphalt (PMA), SMA, and SP, each with 16 mm nominal maximum size aggregate. Use the data to evaluate performance variations and develop models, correlate static and dynamic skid resistance values, and correlate macrotexture values with two different methods.

v) Measure the sound absorption capabilities, using the CPATT impedance tube, of thirteen as-built (new) AC pavement surfaces of Ontario provincial highways. These surfaces include 12.5 mm SMA, regular 12.5 mm SP and fine graded 12.5 mm SP mixes.

vi) Prepare laboratory samples of PCC and surface finish in various texture configurations. Test these samples for surface macrotexture using the sand patch method, skid resistance using the British Pendulum tester and sound absorption using the impedance tube. The surface texturization of PCC include screed finish, burlap, broom and turf drags, exposed aggregate surfaces, and tining in different configurations. Prepare PCC panels in varying thickness of 76 mm, 200 mm and 260 mm with the same surface finish to examine the true effect of PCC pavement thickness on sound absorption.

vii) Test PCC samples with six different surface textures and five AC pavement surfaces at LF for seasonal variation of skid resistance over nine months (February to October). The PCC surfaces include screed finish, burlap drag, astroturf drag, broom drag, exposed aggregate and longitudinal tine.

viii) Use the Long Term Pavement Performance (LTPP) program data, available online at DataPav*e* of the US Federal Highway Administration (FHWA), to examine the long term variation of both AC and PCC pavements surface friction and develop performance models.

ix) Test the skid resistance and macrotexture of PCC pavements constructed with seven different surface textures at the Waterloo landfill station (CPATT test track). Reclaimed concrete aggregate (RCA) has been used in the PCC mixes with 0% (plain concrete), 15%, 30%, and 50% replacement of virgin aggregates, respectively.

1.5 Thesis Organization

An introduction has been provided in this Chapter accommodating the background, statement of the problem and research need as well as the objectives and scope of the research. Chapter 2 provides an overview of the key elements of pavement surface characteristics including the fundamentals of texture, friction and noise, related issues and policies, and measurement techniques. A summary of the relevant past research studies together with analysis of the methodologies, results and their significance is presented in Chapter 3. Chapter 4 describes the research approach as well as data collection and preparation processes while Chapter 5 presents the data analysis and results/findings including their significance. The models developed for both AC and PCC surfaces skid resistance, macrotexture, and acoustic performances, together with their interpretation, are presented in Chapter 6. Chapter 6 also includes the suggested strategy for incorporating pavement surface characteristics namely the smoothness, skid resistance, and noise into the Pavement Management System (PMS). Finally, Chapter 7 presents the overall conclusions drawn from this research including recommendations for future work in this area. The thesis ends with providing a list of references in Chapter 8.

Chapter 2 Overview of Pavement Surface Characteristics

This chapter provides an overview of the key elements of pavement surface characteristics namely the texture, skid resistance, noise, and safety including associated issues, policies, and measurement techniques.

2.1 PAVEMENT SURFACE TEXTURE

The irregularities of pavement surface from the smooth horizontal plane surface are known as surface texture. Texture influences several aspects of tire-pavement interaction depending on its sizes as defined by texture amplitude and wavelength. These include resistance to skidding (especially on wet-weather), tire-pavement noise, splash and spray, rolling resistance, and tire wear (Henry 2000). The available surface texture depends on aggregate mineralogy, aggregate size and gradation, surface voids, pavement finishing techniques and profiles, and surface wear.

Pavement surface texture is classified into microtexture, macrotexture, megatexture and unevenness (roughness) based on texture amplitude (depth) and wavelength. Figure 2-1 shows the classification suggested by the Permanent International Association of Road Congresses (PIARC) with an indication of the possible tire-pavement interaction effects (CTRE 2006, PIARC 1987). Microtexture refers to surface irregularities having a wavelength of less than 0.5 mm and a vertical amplitude of less than 0.2 mm. Alternatively, macrotexture wavelength ranges from 0.5 mm to 50 mm and vertical amplitude ranges from 0.1 mm to 20 mm. Megatexture has wavelengths in the order of 50 mm to 500 mm and vertical amplitudes of 0.1 mm to 50 mm. Surface irregularities having wavelengths exceeding the megatexture size, i.e., greater than 500 mm, are called roughness or unevenness (Henry 2000).

As shown in Figure 2-1, microtexture and macrotexture are needed for resistance to skidding i.e., the surface friction, developed at the tire-pavement contact for a given tire, largely depends on the pavement surface microtexture and macrotexture. According to Hutchinson et al. (1975), friction prediction may lack any correlation if surface texture is not taken into account. Holt and Musgrove (1982) mentioned that driver's ability to stop on wet pavement surface depends on the vehicle tire and the pavement surface texture.

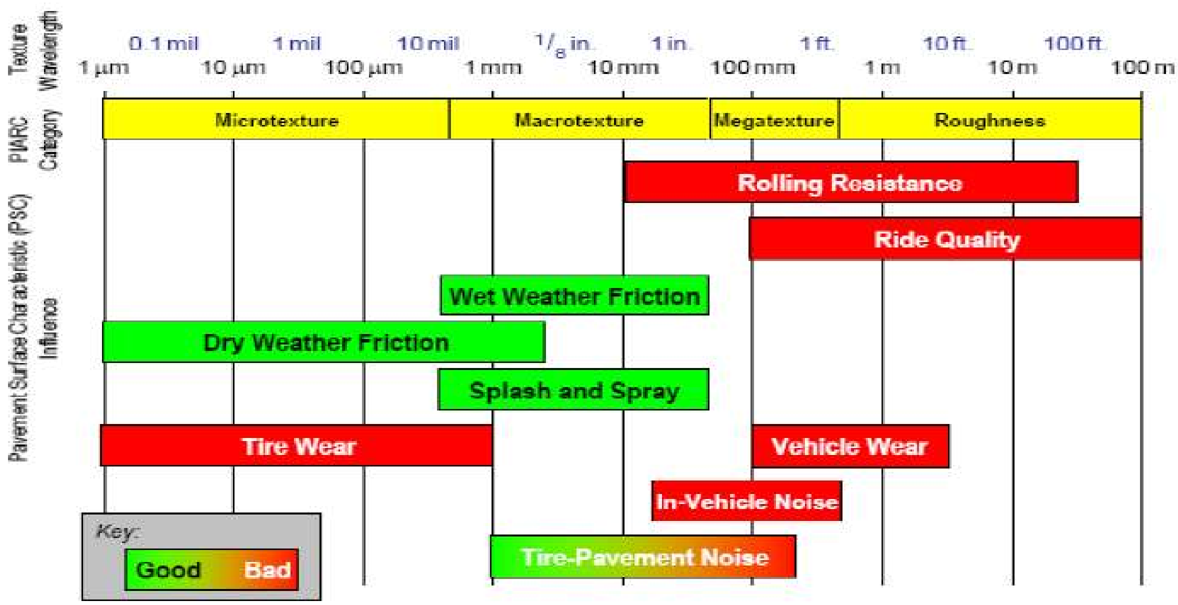

Figure 2-1 Ranges of Texture and Anticipated Effects (CTRE 2006, PIARC 1987).

Microtexture penetrates the thin film of water on wet pavement surface to maintain intimate tire-pavement contact whereas macrotexture prevents the build up of water i.e., prevents hydroplaning (Forster 1989). According to Browne (1975), macrotexture is of particular importance for wet weather friction as it facilitates surface water drainage to maintain intimate tire-pavement contact. It should be noted that hydroplaning, a dangerous phenomenon, occurs when a tire is completely separated from the pavement surface in the presence of water or other fluid film. In a hydroplaning condition, the driver loses braking traction and has no directional control or stability (Browne 1975).

According to Fulop et al. (2000), macrotexture is large-scale roughness that facilitates better drainage of surface water and absorbs some kinetic energy. It therefore has a direct impact on skid resistance and safety. Goodman et al. (2006) defined these terms in a slightly different way. Microtexture provides adhesive force as the asperities on the aggregate surface contact the tire. As described in Goodman et al. (2006), macrotexture causes an energy loss (hysteresis), when the tire deforms around the coarse aggregate particles, and produces a retarding force. If the available surface friction produced by the microtexture and macrotexture is greater than the friction demand in a particular driving condition that includes vehicle type, speed and loading, pavement temperature, surface condition (either wet, dry or contaminated), roadway geometry, etc., the vehicles can safely accelerate, brake or conduct other manoeuvres. Macrotexture also reduces the splash and spray on wet pavements, which is also an important component of highway safety.

Macrotexture and megatexture, on the other hand, are responsible for tire-pavement noise, in-vehicle noise, and rolling resistance where the higher order macrotexture has greater contribution in noise generation. A low order macrotexture, however, is beneficial in terms of tire-pavement noise reduction (Figure 2-1).

Overall, it is clear that pavement surface characteristics are foremost features of highway safety in terms of skid resistance, and splash and spray. It also has an effect on the quality and economy of ride in terms of smoothness, rolling resistance and vehicle wear. Furthermore, texture plays an important role in noise generation and propagation from the tire-pavement interface to the adjacent area/community and within the moving vehicle.

No specific guideline has been provided by highway agencies in North America with respect to desired macrotexture level. Some European countries, however, specified a minimum desired macrotexture depending on the measurement techniques (volumetric or automated laser based), road class (speed) and location (rural or urban), longitudinal grade and pavement width. For example, France has set specification for desired macrotexture measured using glass beads. The specifications are aimed to achieve the macrotexture, as microtexture cannot be measured at site in a simple/practical manner. However, a guide has been provided based on experience of aggregate performance as a surface course. The specified mean texture depth (*MTD*) is ≥0.40 mm to ≥0.70 mm on urban and suburban roads depending on speed (<50 km/h to >90 km/h), longitudinal slope of ≤ 5% and number of lanes per direction with special consideration for slope greater than 5%. For rural (interurban) roads, the desired *MTD* is ≥ 0.60 mm to ≥0.80 mm depending on speed (90 km/h to 130 km/h), longitudinal slope (≤ 5% or > 5%), curve radius (≥ 1000 m or ≥ 600 m) and number of lanes per direction (Dupont and Bauduin 2005).

Current British specification requires a minimum 0.65 mm sand patch *MTD* for transversely textured new PCC surfaces (Phillips and Kinsey 2000). For new AC surfaces the *MTD* should be a minimum of 1.5 mm. Studies, however, have indicated that a laser based *MTD* of 1.0 mm are expected to meet the skid resistance requirement. There is no requirement for texture depth on in-service pavement but the pavement should have a specified minimum surface friction before rehabilitation is needed (Roe and Lagarde-Forest 2005). In fact, a desirable surface must be the one that has good microtexture and a good lower order macrotexture for adequate surface friction and drainage with minimum tire wear, rolling resistance and noise. Furthermore, both microtexture and macrotexture wear under traffic and result in reduced skid resistance over time (Wu and Nagi 1995). Therefore, durable texture is essential to ensure sufficient friction over the service life.

2.2 SKID RESISTANCE

Skid resistance is the force developed at the tire-pavement interface of a running vehicle i.e., it is the force that resists the sliding of a vehicle tire on the pavement surface. The terms skid resistance and surface friction are used interchangeably. The friction characteristic of a pavement surface is expressed in terms of friction coefficient or friction number (*FN*) or skid number (*SN*). The *FN* or *SN* is obtained by multiplying the friction factor by 100. The friction force provides necessary grip and facilitates controlled manoeuvres during running, turning and stopping of a vehicle. As mentioned by Noyce et al. (2005), friction force is critical in preventing excessive skidding and reducing the stopping distance during emergency braking situations. It therefore is an essential component of safety on the roadway.

Pavement surface friction can be measured as part of the initial, as-built construction quality. This is a very common practice with airport pavement construction but less common with roads. However, during the in-service performance evaluation and as part of pavement management, it is necessary to monitor surface friction and ensure that the road is safe for the travelers and for planning of maintenance/rehabilitation (Ahammed and Tighe 2008a). This is especially true in high priority areas, if an accident has occurred or if the area is prone to poor conditions during winter (i.e., icing).

Pavement surface friction can vary seasonally or in short term due to several factors including changes in temperature, moisture, surface contamination, and microtexture. Skid resistance can also be reduced over long term due to inadequate construction or polishing/wear of the surface by traffic and/or environmental effects (Ahammed and Tighe 2008b). According to TAC (1997), rapid changes in surface friction can occur in a short term due to rainfall (Figure 2-2). Furthermore, nearly all pavement surface friction changes with time (season) and decreases continuously with age or traffic exposure (Figure 2-3). According to TAC (1997), the possible contributors to these changes may include porosity, surface wear, polishing of surface aggregates, pavement rutting, bleeding or flushing of the binder, and surface contamination (oil, dust, torn tire rubber).

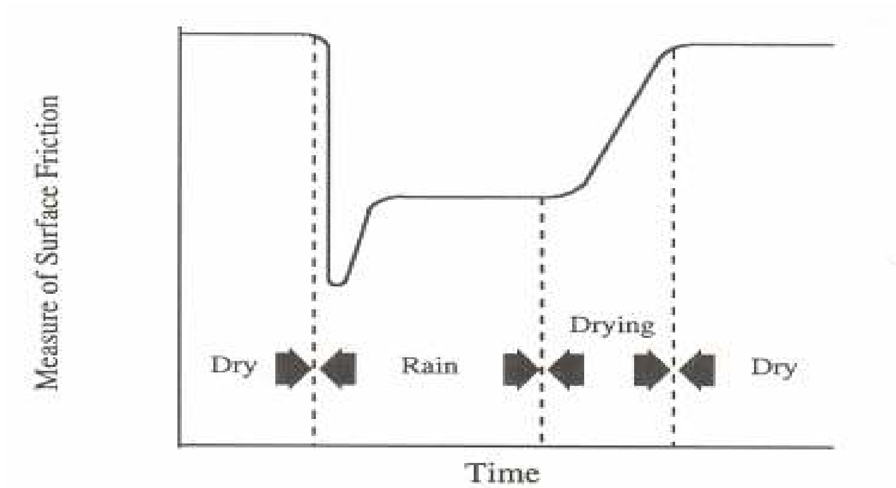

Figure 2-2 Short Term Variation in Surface Friction Due to Rain (TAC 1997).

According to Jayawickrama and Thomas (1981), the fundamental process that governs the variation of skid resistance seasonally has not been clearly defined. The general hypothesis is that fine particles accumulate on the pavement surface during prolonged dry period in summer making the surface smooth. This causes microtexture and macrotexture loss, and thereby a reduction in surface friction. Contamination due to oil or grease drip/spillage causes further reduction of available surface friction. Alternatively, de-icing salts, applied during winter, causes wear of pavement surface or aggregate. The surface texture is thus rejuvenated with exposure of new particles or regeneration of microtexture. Heavy rainfall flushes out fine grit and clears drainage channels between aggregate particles during the early spring. This results in an increased macrotexture from the coarser aggregate that produces increased skid resistance in spring (Roe 1977, Jayawickrama and Thomas 1981).

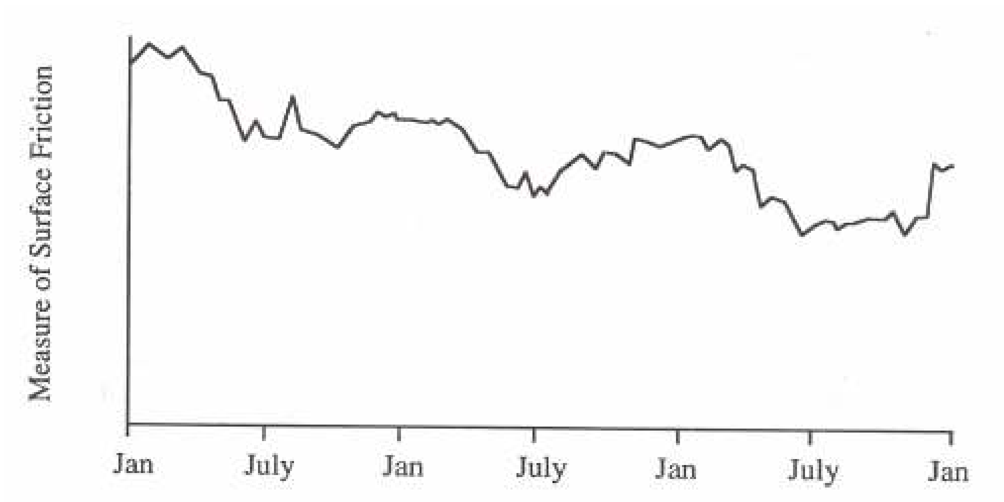

Figure 2-3 Seasonal and Long Term Changes in Surface Friction (TAC 1997).

2.3 SAFETY

Safety of a pavement may be defined in terms of available surface friction (i.e., skid resistance) provided by the surface (depends on surface texture and condition) as compared to friction demand (needed) by a vehicle for safe driving, braking and turning. If the skid resistance provided by the road surface is higher than the friction demand on a particular situation (time of the year, surface condition and speed), no pavement associated safety hazard exists. The most critical situation exists when the pavement is wet because nearly all pavements have sufficient skid resistance in the dry condition. As mentioned by Rice (1977), wet pavement skid resistance is substantially lower than the dry pavements due to lubrication of tire and pavement surfaces. It was also mentioned that most drivers are unaware of the danger and do not reduce the speed on wet road unless the visibility is limited.

Figure 2-4 shows a relationship of the coefficient of friction with locked-wheel-stopping distance. As shown in the figure, the required stopping distance increases as the available surface friction decreases. Therefore, an adequate friction level is desired for safe stopping and reducing collision potentials on wet pavements.

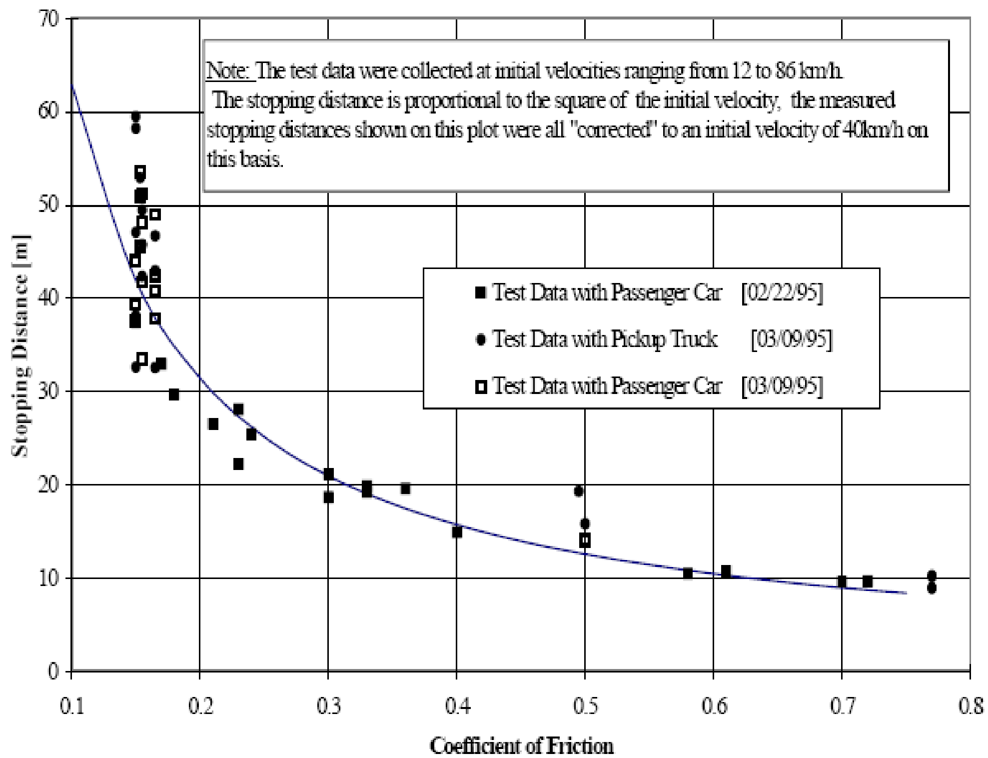

Figure 2-4 Stopping Distance for 40 km/h Initial Speed Vs Friction Coefficient on Ice and Snow Covered Pavements (Rogers et al. 2004).

A study in Japan has indicated that the accident rate could be reduced by 30% if there was no snow on the road (Hagiwara et al. 1990). Alternatively, for a particular environment or road condition, the available surface friction decreases as the vehicle speed increases. Road and runway pavements should therefore have adequate surface friction for safe manoeuvres at different operating speeds and over various surface condition states.

As mentioned earlier in Chapter 1, wet pavement skidding contributes to a substantial portion of highway crashes and surface friction plays a major role. However, according to the literature, no transportation agencies in Canada or the US set standards for minimum surface friction, because of the litigation risk that may arise from skidding accidents. Different agencies have developed some criteria for identifying low friction surface and initiating possible countermeasures (TAC 1997). An example of such a guideline, developed in Pennsylvania, is shown in Table 2-1 (Halstead 1983, TAC 1997).

Table 2-1 Criteria for Identifying Low Friction Pavement Surface (TAC 1997)

Category	Skid Number (SN_{40})	Accident Problem	Action by Engineering District
A	< 31	Yes	Improvements or general maintenance programs considered for betterment
B	31 – 34	Yes	Maintain surveillance and take corrective action as required
C	34 or less	No	Maintain surveillance and take corrective action as required
D	35 – 40	-	Maintain surveillance and take corrective action as required
E	> 40		No further action is required

Ontario highways accident reduction program starts with posting "Slippery When Wet" and wet pavement advisory speed limit signs at black spots locations. Black spot is a 0.1 km section of highway having three or more wet accidents and wet to total (wet plus dry) accident ratio of 30% or more. Pavement sections with low friction levels and consistently high wet accident rate are rehabilitated (Kamel and Gartshore 1982). A tentative guideline, as shown in Table 2-2, had been used to assess the surface friction level.

2.4 FUNDAMENTALS OF SOUND (NOISE)

2.4.1 Sound and Noise

Sound is what we hear. It is a fluctuation in the density and pressure of air due to vibration in the air medium. Alternatively, noise is unwanted or unpleasant or objectionable sound. The classification of a sound as acceptable (not bothering) or pleasant versus noise or undesirable sound is somewhat subjective. Although, because of the subjective nature, it is difficult to determine and quantify which sound is unpleasant, sound from traffic is annoying to most people, and therefore it is considered as noise (Sandberg 2002). In general, noise causes annoyance, sleep disturbance, fatigue, high blood pressure, loss of concentration, disturbance in personal recreation, interference with conversation and hearing loss.

Table 2-2 Ontario Surface Friction Classification System (Kamel and Gartshore 1982)

Facility Type	Speed Limit, km/h	SN at Speed Limit		
		Good	**Borderline**	**Low**
Freeways and Main Highways	100	≥ 31	25 - 30	< 25
Two-lane and Four-lane	80	≥ 32	27 - 31	< 27
Intersections	80	≥ 40	31 - 39	< 31
	60	≥ 45	36 - 44	< 36

2.4.2 Sound Power, Pressure and Intensity

A sound source emits acoustic energy that propagates through the air and results in a pressure to a receiving medium. The power (energy/time) radiated into the surrounding air by the sound source is called the sound power, expressed as watts (W). The variation in air pressure above and below the normal atmospheric pressure is termed as the sound pressure, which is expressed in Pascal, Pa (N/m^2). A young person with normal hearing can detect air pressure variation of as low as 20 μPa, a fractional variation in the order of 2×10^{-10} as compared to the normal atmospheric pressure of 101.3×10^3 Pa (Beranek 1992). The sound intensity is defined as the continuous flow of sound power at a point on the sound wave propagation path per unit area. It is expressed as watts per square metre (W/m^2).

The sound pressure level (*SPL*) is a measure of sound pressure with respect to the threshold of hearing (i.e., pressure detectable to the human ear). It is given as the ratio of the mean amplitude of the measured sound pressure (p) to the mean amplitude at threshold of hearing (p_0). Since a healthy ear can detect sound pressure fluctuations from as low as 2×10^{-5} N/m^2 to about 63 N/m^2 at which the threshold of pain begins, it is difficult to work with or manipulate such a large range (Wayson 1998). To make sound level measurement practically distinguishable or meaningful, an internationally accepted standard has been developed in the logarithm scale for the *SPL*, known as the decibel (dB) taking the threshold of hearing at 1,000 Hz (1 kHz) i.e., 2×10^{-5} N/m^2 (20 μPa) as a reference quantity. In this scale, 0 dB *SPL* (a reference sound level for comparing other sound levels) represents an uncomfortably quiet environment and 140 dB is the loudest sound that generally occurs near a space rocket launching pad. Sandberg and Ejsmont (2002) suggest that a good environment should have noise levels below approximately 40 dBA. The *SPL* is expressed as:

$$SPL = 10\log_{10}\left(\frac{p}{p_0}\right)^2 \qquad (2\text{-}1)$$

Where,

SPL = Sound Pressure Level (dB)

p = Mean amplitude of the measured sound pressure, N/m^2 and

p_0 = Mean amplitude of the sound pressure at the threshold of hearing, N/m^2

It should be noted that although sound intensity and sound pressure are two different qualities, the sound pressure level is analogous to sound intensity level and both of them are expressed in dB or dBA.

Sound wave frequencies in the range of 20 Hz to 20,000 Hz can be detected by a healthy human ear. However, the most sensitive frequencies that can easily be detected range from 250 Hz to 10,000 Hz (Karamihas and Cable 2004). The tonal quality of a sound is dependent on the frequency spectrum of that sound. In fact, the different frequency spectrums of sound from various sources enable the human ear to detect the differences among the sounds. A low frequency sound is less attenuated with distance and more objectionable or annoying to humans. Such noise is therefore a primary concern for traffic and tire-pavement related noise.

The loudness of a sound depends on both frequency and pressure, which is expressed as the phons. At a frequency of 1,000 Hz (1 kHz), the loudness level in phons is numerically equal to the sound pressure level in dB (FEHRL 2006). As the human ear response to different sound frequencies are not linear, the same *SPL* but at different pure tones (discrete frequencies) will have different loudness levels. Figure 2-5 shows the equal loudness contours which was developed by the International Organization for Standardization (ISO 226-2003) based on research of human ear perception of sound (AIST 2007). As shown in the figure, a 60 dB *SPL* will be perceived as 70 dB (indicated as 70 phons) at 250 Hz which is 10 dB louder than the perceived dB at 1,000 Hz (60 phons).

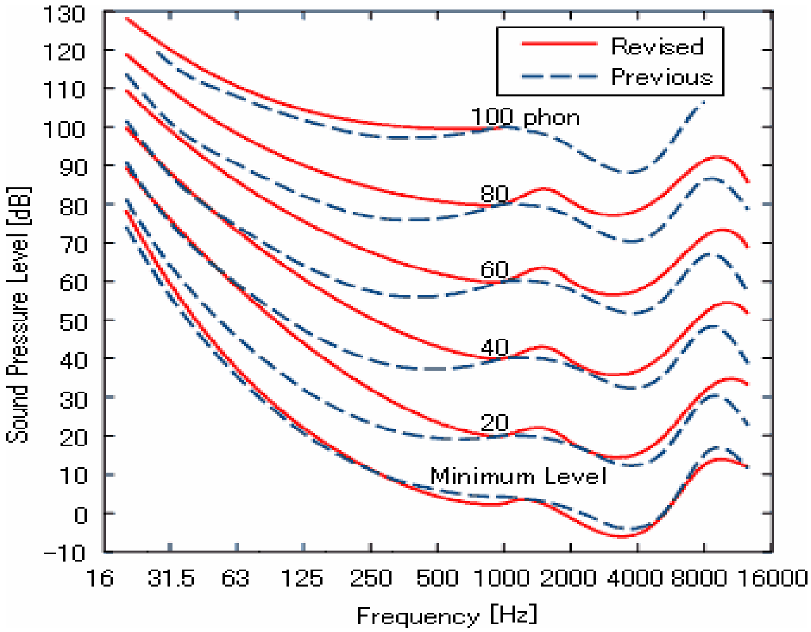

Figure 2-5 Equal Loudness Contour for Pure Tones (ISO 226-2003, AIST 2007).

An increase or decrease in *SPL* by 1-3 dB is just a perceptible change in loudness for the human ear, while an increase or decrease of 5 dB is a noticeable change. An increase or decrease in *SPL* by 10 dB is perceived as twice or half loud while an increase or decrease in *SPL* by 20 dB is perceived as four times or one quarter loud (Bruel and Kjær 2007b). Two independent sound sources with equal *SPL* result in an equivalent *SPL* that is 3 dB greater than the *SPL* of individual source (Figure 2-6). Accordingly, doubling the traffic volume with same composition will result in an increase in sound level of 3 dB, the perceptible difference.

2.4.3 A-Weighting Filter, Maximum and Equivalent Noise Levels

To measure the sound (noise) level simulating the human hearing sensitivity, a system of frequency filtering and weighting is used. The filtering system that best corresponds to human perception is known as “A” weighting filter and the measured *SPL* is known as the A-weighted *SPL*. Tire-pavement or traffic noise, rated as moderate sounds, is always measured with such a filtering system. This A-weighted *SPL* is designated as dB (A) or dBA (Sandberg and Ejsmont 2002, Bruel and Kjaer 2007a).

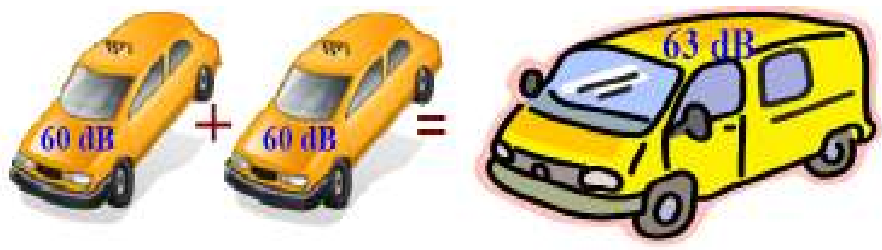

Figure 2-6 Sounds from Two Independent Sources (Ahammed and Tighe 2008c).

Noise emitted from traffic is continuous but varies in strength over time depending on the time of the day, traffic volume, vehicle types and speeds, weather and surface conditions, etc. To convert the non-uniform sounds to a meaningful single number, several descriptors are used. The most common descriptors of traffic and tire-pavement noise are L_{max}, L_{eq} and L_{xx}. L_{max} denotes the maximum while L_{eq} denotes the equivalent (obtained by time averaging the sound energy) sound levels over a measurement duration. For example, L_{eq} *(24h)* of 84 dB means that sound energy is averaged over 24 hours and the average *SPL* is 84 dB. L_{xx} is a statistical descriptor of sound that represents the level that is exceeded for only XX% of time during measurement duration. For example, L_{10} *(24h)* of 88 dB indicates that a sound level of 88 dB is exceeded 10 % of the time during the 24-hour period.

2.5 TRAFFIC NOISE

2.5.1 Traffic Noise Contributors

As mentioned earlier, the sound generated by roadway traffic is generally treated as traffic noise and is found to be annoying to the public. It is therefore a growing public concern, especially in urban areas, and is a leading cause of public complaints as the urban communities trying to be more environmentally friendly and green (Lee and Fleming 2002, Bernhard and McDaniel 2005). However, the responsiveness to traffic noise pollution is also extending to suburban areas.

The noise from a traffic stream is the combination of all sounds produced by the vehicles traveling across a roadway and received by abutters (community noise) or the travelers (on road or in-vehicle noise). Highway and environmental agencies are mainly concerned about the roadside noise for quiet neighbourhoods while auto and tire makers are more interested in in-vehicle noise for comfortable ride. Consequently, both roadside and in-vehicle noises are of concern to the community.

The noise generated by an individual vehicle is composed of sounds from three main sources. They are aerodynamic noise, power unit (propulsion) noise, and tire-pavement noise. Aerodynamic noise is produced by wind turbulence around the vehicle as it travels compressing the surrounding air. Power unit noise includes sound generated by fan, engine, exhaust and transmission systems. The tire-pavement noise is the sound generated by the interaction of rolling, slipping or dragging tires and the road surface.

For a given tire, the noise generated by different sources of a running vehicle traveling on a particular road surface depends on the vehicle type and speed. Figure 2-7 demonstrates the variation of overall vehicle noise level as well as the contribution of propulsion and tire-pavement noises at varying car speeds. As shown in the figure, propulsion noise dominates the overall noise levels at very low speeds and is independent of vehicle speed. As the speed increases and crosses a certain limit, called the cross over speed, the tire-pavement noise becomes the dominant source in overall noise generated by a vehicle. The tire-pavement noise increases linearly with an increase in speed. The contribution of aerodynamic noise to the overall exterior noise is not significant at vehicle speeds up to 120 km/h but may be significant for in-vehicle noise (Sandberg and Ejsmont 2002).

The crossover speeds depend on vehicle types (car and truck) as well as their driving manoeuvres such as driving at constant speed (cruising) or accelerating. For vehicles produced after 1985 and traveling on typical dense graded asphalt or a 10 mm-14 mm SMA surface, the crossover speeds are shown in Table 2-3 (Sandberg and Ejsmont 2002).

McDaniel and Bernhard (2005) also mentioned that noise generated by the interaction between tire and pavement becomes a dominant source when the vehicle travels (cruise) at 35 km/h or greater. Bernhard and Wayson (2005), and Donavan (2007) indicated that the tire-road dominates the overall noise when car speed exceeds about 50 km/h. It probably reflects the accelerating condition, if compared with the crossover speed in Table 2-3.

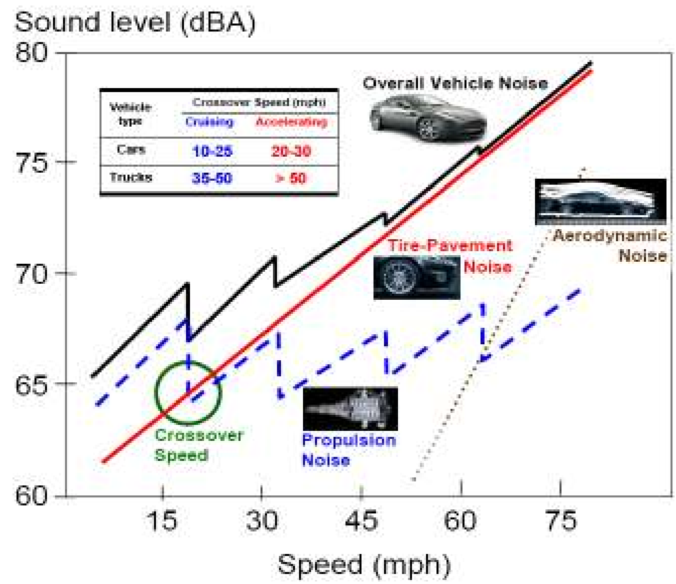

Figure 2-7 Speed Effects on Vehicle Noise Sources and Crossover Speed (Rasmussen et al. 2007).

Table 2-3 Crossover Speed for Cars and Trucks (Sandberg and Ejsmont 2002, with Permission)

Vehicle Type	Cruising	Accelerating
Cars	15-35 km/h (9-22 mph)	30-50 km/h (19-31 mph)
Trucks	30-50 km/h (19-31 mph)	45-55 km/h (28-34 mph)

According to Rasmussen et al. (2007), the cross over speed may be taken as a practical threshold to judge the benefit of quiet pavements, and therefore it is an important concept for the selection of pavement surfaces. In other words, at any speed exceeding the limits shown in Table 2-3, the tire-pavement noise is the dominant source and construction of quiet pavement is considered beneficial.

Vehicle type is a significant factor in noise generation. Heavy vehicles are the noisiest vehicles on the road because of their large engine/power system, larger tires, and the fact that they have more tires that causes more tire-pavement interaction. A typical heavy truck is about 10 dBA louder than a typical passenger car traveling at highway speed i.e., a truck can generate sound energy equivalent to ten cars. Accordingly, if a traffic stream contains 10% or more trucks, sound created by the trucks will dominate the overall noise level on the road (Rasmussen et al. 2007).

The overall noise level will increase by about 2-3 dBA for an increase in vehicle speed of 16 km/h (10 mph). However, traffic volume does not have a significant impact in overall noise level because doubling the traffic volume will result in an increase in overall noise level of approximately 3 dBA (Rasmussen et al. 2007). Alternatively, doubling or halving the distance of receiver from a line (e.g. bumper to bumper traffic) and a point (e.g. single vehicle) sources will result in a decrease or an increase of noise level of 3 and 6 dBA, respectively (Snyder 2006). Traffic noise will therefore vary (decrease or increase) between 3 to 6 dBA for doubled or halved distance of the receiver from the roadway.

2.5.2 Traffic Noise Control Guidelines and Modeling

In 1999, the World Health Organization (WHO) published guidelines for community noise to develop public awareness, and provide a guide to environmental health authorities and professionals regarding the impacts of noise on human health. According to the guidelines, L_{eq} of 55 dBA is the threshold of serious annoyance and 50 dBA is the threshold of moderate annoyance based on day criterion. Based on night time criterion, the threshold of annoyance is L_{eq} of 45 dBA (Berglund et al. 1999).

The US FHWA Policy 23 CFR 772 (FHWA 2001) has provided procedures for abatement of highway traffic and construction noises. Exterior areas are given primary consideration when determining traffic noise impacts and needs for noise abatement measure. Noise abatement is considered only where frequent human uses occur and a lowered noise level would be beneficial. For example, noise abatement measure should be considered when traffic noise exceeds 67 dBA (L_{eq}) at places of public activities including residences outdoor, schools, parks, playgrounds, hospitals, etc. The threshold of interior noise is 55 dBA (L_{eq}).

In Washington State, the feasibility of noise abatement is determined based on the cost and desired noise reduction of 7 dBA at one impacted residence and 5 dBA reduction at a majority of other impacted residences. A noise barrier cannot be installed if the condition is not met (Bernhard and Rasmussen 2006). Noise is considered as the primary environmental nuisance in France and a law was passed in 1992 to limit the traffic and road related noise. The regulation requires the noise at nearby communities not to exceed 60 dBA L_{eq} from 6 a.m. to 10 p.m. and 55 dBA L_{eq} from 10 p.m. to 6 a.m. (Bérengier and Anfosso-Lédée 1998).

The Ontario Ministry of the Environment (MOE) has set guidelines for road noise control measures based on sound level to be determined through the Ontario Road Noise Analysis Method for Environment and Transportation (ORNAMENT) (MOE 1997). If the daytime (07:00-23:00) L_{eq} is greater than 60 dBA, control measures are required to reduce the level to 55 dBA provided that physical noise control measures are proven to be technically, economically, and administratively feasible.

A noise policy is enforced in the Region of Waterloo (Ontario) to predict future noise levels using STAMSON (a computer program developed by the MOE). The developer must construct noise walls if the expected backyard noise after 10 years exceeds 60 dBA L_{eq} (16 h). When improving an existing road, the Region constructs noise barriers if the projected noise after 10 years exceeds the current level by more than 5 dBA or exceeds the threshold of 65 dBA (RMW 2004, MacDonald 2005).

MTO policy (MTO 2006) for environmental noise control requires that the noise impact to be quantified based on change in sound level due to proposed construction. The future sound level in the Noise Sensitive Areas (NAS) without the proposed improvements is compared to the future sound level with the proposed improvements. ORNAMENT and STMINA 2.0 softwares are used for noise prediction. Noise abatement is considered when the projected noise, due to construction, increases by at least 5 dBA or exceeds 65 dBA. The proposed measure, however, should be technically, economically, and administratively feasible as outlined below:

Technical Feasibility: Review the constructability of the noise mitigation measure (i.e., design of wall, roadside safety, shadow effect, topography, possibility of achieving a 5 dBA reduction, ability to provide a continuous barrier, etc.).

Economic Feasibility: Carry out a cost/benefit assessment of the noise mitigation measure (i.e., determine cost per benefited receiver).

Administrative Feasibility: Determine the ability to locate the noise mitigation measure on lands within public ownership (i.e., provincial or municipal right-of-way).

All these indicate that noise reduction policies by highway agencies do not always warrant noise abatement measures even though the noise level is high because of many practical limitations. Quiet pavement may be a practical solution in such cases.

A number of noise modeling computer software programs are available in North America and else where around the world to predict roadway traffic noise. Ontario and many other Canadian provinces and municipalities use the STAMSON program (an updated version of ORNAMENT), developed by MOE during the 1980's. STAMSON input parameters include total traffic volume, medium and heavy truck percentages, road grade, distance to the road, and the elevations of the traffic noise source and the noise receiver. The "receiver" position is located at 1.5 m above the ground surface i.e., at ear height level and 3 m off the back wall of a residence (backyard or outdoor living area). For indoor noise, the second floor window is considered the receiver (Schroterm and Chiu 1989, MacDonald and Tighe 2005).

To aid in compliance with policies and procedures under FHWA noise control regulations and measures, the FHWA developed the Traffic Noise Model (TNM) software. The TNM is an advanced computer program used for predicting noise impacts near highways that enables accurate and easy modeling of highway noise, including the design of effective, cost-efficient highway noise barriers. It uses a mix of cars, medium trucks, heavy trucks, buses, and motorcycles (Lau et al. 2004).

2.5.3 Noise Control Measures

To control the road traffic noise impact, the MOE has provided guidelines for the control measures. The guidelines recommend that physical noise mitigation measures are required if the predicted traffic noise level exceed the acceptable limits. The current standard types of physical mitigation measures are construction of noise barriers to reduce noise level measured at the outdoor living area to or below the acceptable limit. Indoor noise reduction measures include upgrading building components, and installing central air conditioning units in the buildings.

The noise barriers block the sound transmission from roadway to the neighbouring community. Noise barriers breaking the line of sight between the source and receiver can reduce the noise level by five dBA and each additional one meter height reduces noise by 1.5 dBA (Rochat 2005). However, according to Meij (1989), the noise radiation at low frequencies makes barriers less effective.

Noise barriers are usually built of brick, concrete, plastic, plexiglass, metal, recycled materials, or wood. Barriers with hard, dense, and smooth surfaces reflect back the sound and are known as reflective sound barriers. Part of the sound energy is transmitted through the barrier wall but most of the sound energy is reflected back toward the noise source when the sound strikes a reflective barrier surface. Two reflective sound barrier walls on two sides of a road form a sound canyon between two walls. Alternatively, absorptive sound barriers that have acoustic absorption properties can reduce noise reflection. Sound absorptive materials include HDPE, wood, sheet metal, masonry, fibreglass, and mineral wool (Stacy 2008).

Barriers are generally very costly and may result in poor road aesthetics (Neithalath et al. 2005). Typical costs vary from $0.6 million to $3 million per km ($1 million to $5 million per mile) (Bernhard and McDaniel 2005) excluding future maintenance expenses. They are also impractical and/or inefficient for bridges, mountainous areas, and some urban highways (main noise problem zone) because of access points and intersections that provide escape paths for the sound. Furthermore, in some instances noise barriers may not alleviate but rather may actually aggravate the noise exposure by the travelers and passers-by depending on the roadway/barrier geometrics and barrier materials. The redistribution and amplification of the reflected noise is particularly noticeable where noise barriers exist on both sides of a road. The mentioned noise mitigation measures therefore are neither economical nor practical because they can only prevent the noise propagation, but can actually not reduce the traffic noise at the source. Noise reducing pavements could be beneficial in these respects.

2.6 MECHANISM OF TIRE-PAVEMENT NOISE GENERATION

The tire-pavement noise depends on the properties of both tire and road surface, and the complex interaction between these two factors. The contribution of the tire depends on the hardness of the tire material, type of filler used, tire age, tire size, tire profile, and tread pattern/depth. The contribution of pavement depends on the surface texture characteristics that include texture amplitude (depth), wavelength, orientation, acoustic absorption, and relative stiffness of the surface. In general, the stiffer the tire material and the pavement surface are, the greater the level of noise generated due to their interaction. The important mechanisms of tire-pavement interaction and noise generation are briefly described below:

2.6.1 Tire-Pavement Noise Due to Impact

The impact mechanism generates noise through radial (mostly) and tangential vibrations of the tire. Vibration is induced by continuous impacts between the tire tread block and pavement surface due to sudden displacements of the rotating tire. It is similar to a rubber hammer striking the pavement surface hundreds or thousands of times per second, depending on the vehicle speed, and each generating sound over a wide range of frequencies (Figure 2-8). The repetitiveness of the impacts can be reduced by randomization of the tread pattern and pavement surface texture. This will change the character of the sound generated and reduce the annoyance that results from pure tone (Bernhard and Wayson 2005).

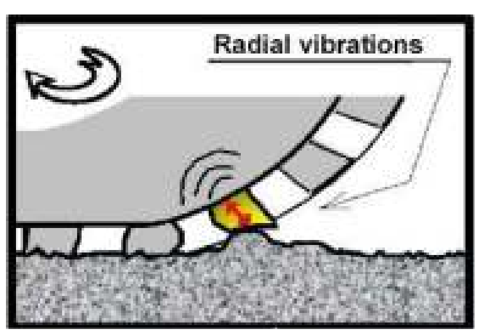

Figure 2-8 Noise Generation by Impact (Sandberg and Ejsmont 2002, with Permission).

2.6.2 Tire-Pavement Noise Due to Stick-Slip and Stick-Snap

Sticking occurs as the tire rubber deforms on the pavement surface and periodically slips as the horizontal force exerted by moving tire exceeds the horizontal surface friction. This results in tangential vibration and high frequency noises (Figure 2-9a). Stick and snap is the mechanism of adhesion and release of tire tread block as it rolls on the pavement surface. As a tread block exits from its contact patch, the adhesive force tends to hold the tread block. As the tread block is released due to rolling force, tangential or radial vibration of tire tread block and carcass is produced (Figure 2-9b). The magnitude of such adhesion force, and the resulting vibration and noise depends on the properties of rubber for tire tread.

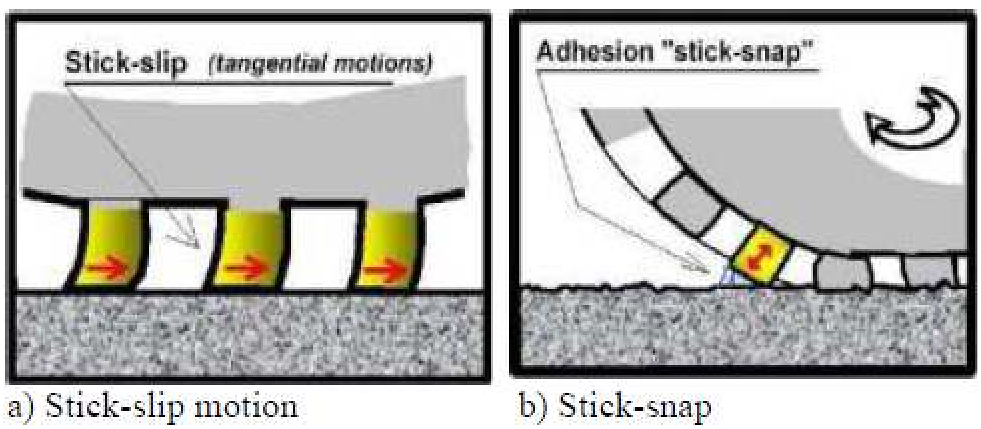

Figure 2-9 Noise Generation by Stick-Slip Motion and Stick-Snap (Sandberg and Ejsmont 2002, with Permission).

2.6.3 Air Pumping

As a tire tread block enters the contact patch, the entrapped air between pavement and tire tread is compressed and pumped out (Figure 2-10a). The air is pumped in as the tire tread block leaves the contact patch (Figure 2-10b). This aerodynamic process can generate high frequency sound and the magnitude depends on the tire tread and pavement surface texture patterns as well as the porosity of the pavement.

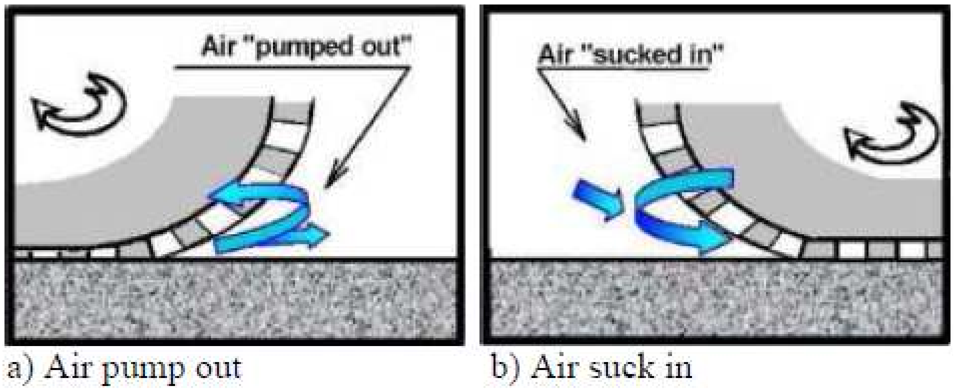

Figure 2-10 Air Pumping at Contact Patch (Sandberg and Ejsmont 2002, with Permission).

2.6.4 Tire-Pavement Interaction Noise Amplification

The tire-pavement interaction noise described in last Section may be amplified (or reduced) because of several other mechanisms such as inefficient radiation of sound energy, smaller tread blocks and other aerodynamic effects. The tire-pavement noise amplification mechanisms are described below:

Horn Effect

The wedge shaped geometry at both leading and tailing edges of tires act as horns or megaphones when a tire rolls on the pavement surface (Figure 2-11) and significantly amplifies the noise generated at tire-pavement interface. The order of amplification depends on tire width, and the acoustic properties of the pavement (Snyder 2006). Rough surfaces tend to disperse the sound while porous surfaces absorb the sound from the tire-pavement interface (Sandberg and Ejsmont 2002).

Helmholtz and Pipe Resonances

Helmholtz (air) resonance is a sound amplification mechanism through air displacement into or out of connected air voids between tire tread and pavement surface at leading and tailing edges of a rolling tire (Figure 2-12a). It can be compared with a pop bottle that blows when opened. It has the most significant amplifying effect for high frequency sounds.

The sound is amplified when air is blown across an organ pipe depending on the length of the pipe and number of openings in the pipe. Various grooves and sips on tire can be pinched off and opened out at different locations beneath the tire-pavement contact patch and form geometry similar to an organ pipe (Rasmussen et al. 2007). Noise generated elsewhere at the tire-pavement contact thus can be amplified and radiated through this channel (Figure 2-12b).

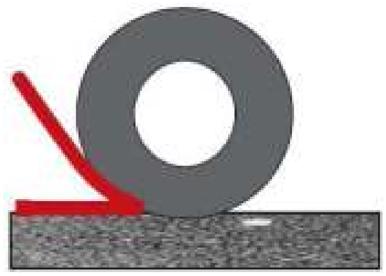

Figure 2-11 Sound Amplification by Horn Effect (Snyder 2006, McDaniel and Thornton 2005).

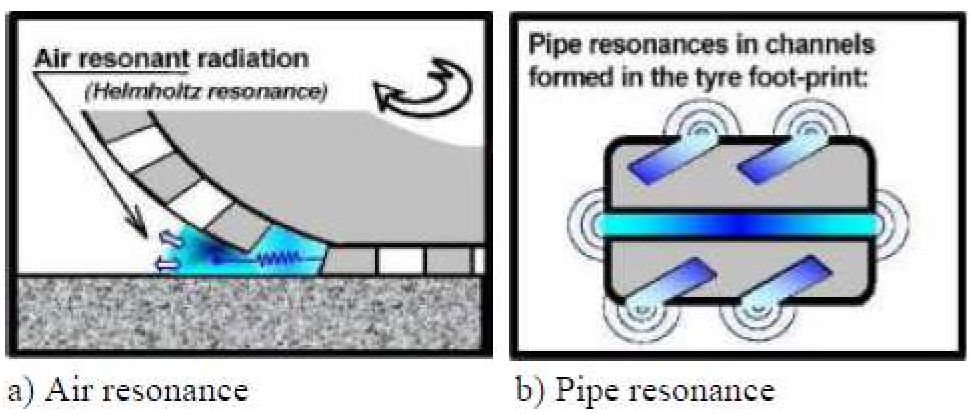

Figure 2-12 Sound Amplification by Air and Pipe Resonances (Sandberg and Ejsmont 2002, with Permission).

Tire Belt/Carcass and Sidewall Vibrations

The vibration produced due to tire-pavement interaction may be amplified due to the response of the tire carcass (Figure 2-13a) and may result in sound radiation from the tire carcass. The tire carcass sidewalls also vibrate due to tire-pavement interaction and radiate sound (Figure 2-13b).

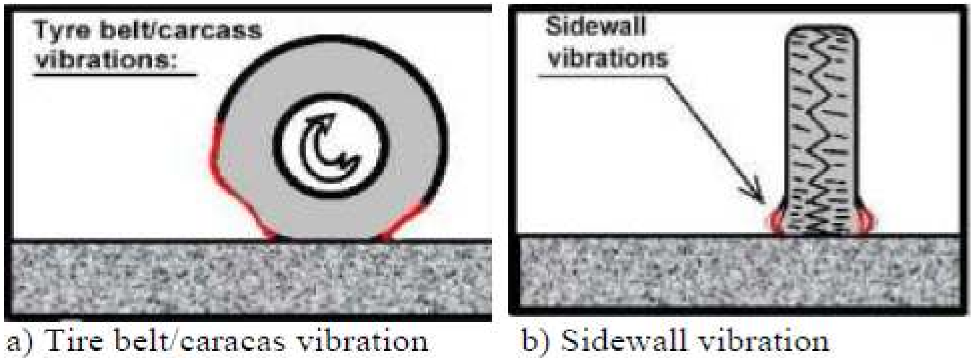

Figure 2-13 Sound Amplification by Tire Belt/Caracas and Sidewall Vibrations (Sandberg and Ejsmont 2002, with Permission).

Acoustic Impedance

The inflating air inside the tire itself is also energized by the excitation of the tire due to the interaction with the pavement or other possible mechanism such as tire rotation. This, consequently, causes a distinctive ringing (Figure 2-14). This sound is better heard inside the vehicle, as the vehicle itself tends to amplify its frequency (Rasmussen et al. 2007). This mechanism is less important for propagation of noise outside the vehicle.

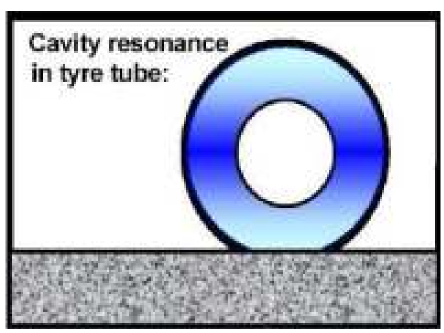

Figure 2-14 Acoustic Impedance Effect (Sandberg and Ejsmont 2002, with Permission).

2.6.5 Effect of Tire Design

Tires are designed to meet several performance requirements that include rolling noise, grip, and friction, durability and stiffness, and size. As mentioned earlier, many parameters of tire design and geometry influence the tire-pavement interaction noise. The combined effect of all these design parameters in noise generation varies widely among the tire types because of wide variations in tread geometry, construction, materials, and mould shape. In general, more aggressive tire tread blocks (clearly defined blocks and gaps) generate louder noise. The objectionable tonal frequencies can be minimized with randomization of tread block sizes and/or skewing i.e., angled blocks (Rasmussen et al. 2007). Larger tires with deeper and larger tread blocks produce greater tire-pavement interaction noise. Wear and tear of the tires also influences the tire-pavement interaction noise.

Studies in Europe prior to 1990's have shown a 9 dB variation in tire-pavement noise among different tires tested at 80 km/h on the same surface under identical conditions (Sandberg and Ejsmont 2002). However, competitiveness among tire companies and research has helped significantly reduce the noise related to tire design as compared to that prior to 1990's.

2.6.6 Role of Pavement in Noise Mitigation

Many factors play a role in the generation of sound due to tire-pavement interaction. These include tire size, design and condition (new versus worn), vehicle type, size, condition (new versus old), loading and speed, traffic volumes, and pavement surface texture. Assuming all other factors are constant, the traffic noise levels will vary with the variation in pavement surface characteristics (Snyder 2006). According to Mcnerney (2000), a reduction of 3 dB at source will result in reduced noise exposure at the receiver of equal value (3 dB).

The noise reduction mechanisms by the pavement itself include acoustic and mechanical impedance (Neithalath et al. 2005). The acoustic impedance largely depends on the system of interconnected voids on the surface i.e., pavement surface type (porous or non-porous) and the pavement surface texture. The mechanical impedance is related to the relative stiffness of the tire and the pavement. Wayson (1998) mentioned that an absorptive surface prevents effective reflection of sound energy and helps to reduce the roadside noise. An elastic surface can reduce the noise generation through mechanical impedance.

Many transportation agencies throughout the globe are now investigating the type of pavements that can reduce the tire-pavement interaction noise while past focus was on measuring overall traffic-generated noise for external noise abatement measures. Experiences reported from the US, Europe, and Japan show that noise-reducing pavements can significantly reduce the overall road traffic noise. These pavements include rubberized asphalt, open-graded asphalt, and SMA. Significant improvement has also been achieved in reducing the tire-pavement noise on PCC surfaces through research on surface texturization methods. Longitudinal tining, diamond grinding, innovative transverse tining, exposed aggregate, and plastic bristle brushing are indicated to be promising. Other innovative approaches under investigation in Europe are two-layer porous AC or PCC pavements.

The SMA was introduced in the US during 1990 after an American Association of State Highway and Transportation Officials (AASHTO) team's European Asphalt Study Tour (Powell 2005). It is currently being used in several projects in Canada. It is a gap-graded asphalt mixture with intermediate size aggregate missing i.e., the mixture contains larger stones and mastic, which is a blend of asphaltic binder and fine aggregates/fillers. The stone rich blend provides close contact with each other and prevents segregation during placement and compaction. The durability has also been found to be good. However, early life skid resistance is a concern because of rich bitumen film on surface aggregates. A study in the UK has found that there is 30% chance that SMA will not attain desired (investigatory level) surface friction in 12 months after laying and full skid resistance is attained after two to three years depending on the traffic level (Bastow et al. 2008).

The blending concept of open-graded asphalt such as open-graded friction course (OGFC), designed for high skid resistance, is similar to porous pavement but it contains lower air voids, which is achieved through use of a greater amount of fine aggregates. It also provides for noise reduction potential because part of the sound energy is absorbed through the voids in the mix. It has greater durability than the traditional porous pavement but potential durability problems are higher when compared to SMA and dense hot mix asphalt (HMA).

2.7 SURFACE TEXTURIZATION

2.7.1 Surface Texturization Methods

AC pavements surface texture and friction generally are controlled by the choice of surface mix aggregate gradation, type (wear and polish resistant) and size. According to Noyce et al.

(2005), microtexture is the surface irregularities of the stone particles that make it feel smooth or rough (Figure 2-15). The initial roughness of the aggregate surface and the ability to preserve and/or regenerate the roughness when exposed to traffic determines the magnitude of available microtexture (Rogers et al. 2004, Noyce et al. 2005). According to Balmer and Hegmon (1980), coarse aggregate with hard and angular fine particles and/or harsh fine aggregates bonded on AC surface provide beneficial microtexture. The microtexture therefore is a property of aggregates that can be controlled through the selection of aggregate with desired polish resistant characteristics. Good polish resistance is characterized by high Polish Stone Value (PSV) (Rogers et al. 2004).

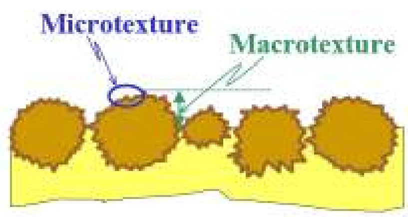

Figure 2-15 Surface Microtexture and Macrotexture (Flintsch et al. 2003b).

Alternatively, macrotexture, called coarse-scale texture, are larger irregularities associated with voids between the stone particles (Figure 2-15). It depends on size, shape, and gradation of coarse aggregate in the paving mixture and the construction practices for the surface layer (Noyce et al. 2005). According to Rogers at al. (2004), macrotexture depends on the wear resistance of the aggregate (hardness of the mineral grains) and properties of the asphalt mix design (stone content and resistance to embedment under traffic).

Different practices are in use for providing macrotexture friction surfaces during the initial construction and/or restoring the surface friction. In general, sprinkle treatments (application of polish-resistant aggregate on the surface of hot-mix asphalt mat) are used on low traffic roads while seal coats with a good polish-resistant aggregate or slurry seals are used on secondary as well as low volume roads. OGFC with polish-resistant aggregates are used on interstate and primary highways (high traffic volume and high speed) while dense-graded overlays are common treatments to achieve friction surfaces (Halstead 1983). Surface friction of airport pavements is sometimes restored or improved by abrading the surface with shot blasting. Such practice is not common for highway pavements.

The mechanism of microtexture development for PCC pavements surfaces is the same as for AC pavements. Microtexture on PCC pavement surfaces is mainly contributed by the fine aggregate in the mortar (ACI 1988). Hard and angular sands on the surface can provide excellent microtexture for PCC pavements (Balmer and Hegmon 1980). According to Fleischer et al. (2005), concrete pavement surface texture develops in three phases. Phase 1 is characterized by the texture of the surface mortar (developed during concrete placement) which is decisive for initial skid resistance. In Phase II, contribution of sand is predominant, and finally in phase III, the exposed coarse grain sizes contribute to skid resistance along with sand. German standard requires above 8 mm maximum size coarse aggregate with minimum PSV value of 53 and high polish resistant sand with minimum PSV of 0.55 (German polish resistance test) for exposed surface.

Alternatively, macrotexture on concrete surfaces, which is measurable and of deeper striation, are deliberately formed through texturization that include small surface channel, indentations, or grooves on fresh concrete (cost-effective option) or cut on hardened concrete (ACI 1988*,* Hoerner et al. 2003). ACI (ACI 1988), ACPA SR 902P (ACPA 2000) and many other publications have listed the common surface texturization methods of fresh and hardened concrete on PCC pavements.

Fresh Concrete

- Burlap Drag: Coarse burlap drag that produces 1.5 mm - 3 mm (1/16 in. - 1/8 in.) deep striations
- Artificial Turf Drag: Moulded polyethylene with turf blades (1.5 mm - 3 mm deep striations)
- Transverse Broom: Hand or mechanical broom lightly dragged in transverse direction. They also produce 1.5 mm - 3 mm deep striations.
- Longitudinal Broom: Same as transverse broom but broom is dragged in longitudinal direction.

- Transverse Tine: Achieved by mechanical devices equipped with tining head (rake). The spacing (10 - 75 mm), depth (3 - 6 mm) and width (generally 3 mm) vary among agencies.
- Longitudinal Tine: Same as transverse tine but tine rake is dragged in longitudinal direction.
- Exposed Aggregate: It is formed by washing out the surface mortar with application of retarder on fresh PCC surface (not common in North America).

Hardened Concrete

- Diamond Ground: Longitudinal grinding using diamond cutting head. Produces 164 - 197 grooves/m (50 - 60 grooves/ft) removing 3 - 20 mm from the pavement surface.
- Diamond Grooving: Longitudinal (on highways) or transverse (on airports) sawed grooves. Typical highway pavement groove depth, width, and spacing are 6 mm (1/4 in.), 3 mm (1/8 in.) and 20 mm (3/4 in.), respectively. However, they vary among agencies.
- Abraded (Shot-blasted): Removal of thin layer of mortar and aggregate using abrasive media shot-blasted on the pavement surface.

Fresh concrete tining is usually preceded with a burlap or turf drag for better surface friction. Other methods include chip sprinkling that strews polish-resistant stones (14 mm - 20 mm size) onto the compacted and profiled fresh concrete, and the use of porous concrete with high voids content (e.g. 20 % by volume) for quick drainage of water (Hoerner et al. 2003).

2.7.2 Role of Texturization

Historically pavement design and construction has focused on the load carrying capacity. Surface finishing or surface mix selection has been aimed at achieving a surface that is free of defects. No consideration was given to the skid resistance properties as the stopping distance was determined based on the vehicle braking system. With the increase of traffic volume and crashes/fatalities, related to hydroplaning/skidding, increased attention has been given to improve the skid resistance of the pavement surface (Wu and Nagi 1995). As mentioned in ACI (1988), the importance of providing a uniform surface texture to improve skid resistance of both highways and airport pavements has been recognized for many decades while serious concern was raised about the pavement safety in the US during the late 1940s and early 1950s.

As mentioned earlier, both microtexture and macrotexture contribute to pavement's skid resistance performance. According to Dames (1990), large-scale texture draws and drains off the surface water and maintains the effectiveness of the fine-scale texture to activate the friction forces. This facilitates better contact between tire and road surfaces, and reduces accidents (Zipkes 1976). According to Hoerner et al. (2003), good microtexture can provide adequate friction for stopping when speed is less than 72 km/h (45 mph) while good macrotexture is desired on PCC pavements constructed for 72 km/h or greater speed. The paper also mentioned that shallow drag-type textures on PCC might not produce long lasting surface friction due to surface wear. Macrotexture is required for this and economy over the long term. According to Augustin (1994), not only the characteristics of new surfaces are important, the performance over time and under traffic must also be taken into account.

Hibbs and Larson (1996) mentioned that good macrotexture is needed for adequate drainage and skid resistance on PCC pavements when the speed is ≥ 80 km/h (50 mph). Additional benefits with deeper textures are reduced splash and spray, and reduction of headlight glare due to rougher surface (ACI 1988). These in turn reduce accidents by providing improved visibility, especially on PCC pavements. On AC pavement surfaces, microtexture can provide adequate surface friction when the vehicle speed is 48 km/h (30 mph) or below. Macrotexture, together with microtexture, provides the surface drainage properties and skid resistance on AC pavements at speed over 48 km/h (30 mph) (Noyce et al. 2005).

The above discussion indicates that raised texture and increased surface friction can provide an economic benefit in terms of wet accident reduction and reduced resurfacing cost. However, raised texture is associated with increased noise, tire-wear, fuel consumption, and travelers discomfort due to increased vibration (Ivey and McFarland 1981, Flintsch et al.

2003a). Ardani (1996) also mentioned that the quality of ride, skid resistance, and noise characteristics of pavement could be affected by the PCC pavement surface texture depth, spacing, and texture direction. Therefore, Fleischer et al. (2005) stated that pavement surfaces should have a roughness suitable for high skid resistance and be designed to have low noise.

Transverse texture provides higher skid resistance and better drainage but there is a concern for adequacy of cornering friction. Longitudinal texture increases cornering friction, whereas transverse texture increases longitudinal braking friction (ACI 1988). PCC pavements constructed with high quality materials and tined transversely can provide high surface friction with noise similar to the dense-graded asphalt (DGA) pavements (Hibbs and Larson 1996). Random transverse, skewed random transverse and longitudinal tine textures exhibit higher surface friction and lower tire-pavement noise as compared to other tining configurations (Kuemmel et al. 2000a).

On AC pavement side, DGA surface mixes have shown to maintain SN_{40} of 40 to 50 at 64 km/h (40 mph). Open graded asphalt pavement surface produces better skid number with lower noise. However, the surfaces need to be cleaned twice a year to maintain satisfactory performance (Hibbs and Larson 1996).

A review of quiet pavement trials in different countries has shown that techniques are available to reduce the noise without sacrificing the safety and durability. However, careful selection (of materials) and construction (surface texturization, finishing, etc.) are the keys to achieve beneficial noise reduction by the pavement itself (Ahammed and Tighe 2008d).

2.7.3 Acoustic (Sound) Absorption and Porous Pavements

Sound absorption is different from sound generation. As mentioned earlier, the sound is generated through complex interactions between the pavement surface and the tire. It is dependent on the tire characteristics and pavement surface texture. In contrast, sound absorption depends on a system of interconnected voids in the pavement mix. As mentioned by García and Mérida (2005), sound absorption depends on void content, thickness, resistance to airflow (measure of noise dissipation through the pavement) and shape factor (ratio of square of sound speed through air to the square of sound speed within the pavement mixture). Higher void ratio, greater thickness, lower resistance to airflow and lower shape factor mean increased sound absorption.

Figure 2-16 shows the mechanism of sound propagation (dissipation of acoustic energy) through the pavement layer that reduces the sound amplification (Bernhard and McDaniel 2005). Therefore, for identical surface textures and a given tire, the noise propagation will decrease as the sound absorption increases. In addition, the reduced air compression due to air escaping through the pavement voids may be helpful in terms of reduced noise generation. Paving mixes with air void contents of 15% - 20% provide sound absorption coefficients of 0.10 to 0.20. Field measurements of tire-pavement noise for these pavements have shown a noise reduction of one to two dBA (Sandberg and Ejsmont 2002).

One of the major problems with porous pavements is clogging of voids and reduction of permeability, and therefore noise-reduction benefits. Clogging of voids is manifested within six months to a year from construction with 1 to 2 dBA increase in noise. Different agencies recommended quarterly to bi-annual vacuum swiping to protect voids from clogging. Thorough cleaning (high pressure water blasting followed by vacuum cleaning) every two years is recommended to flush out winter maintenance deposits from voids.

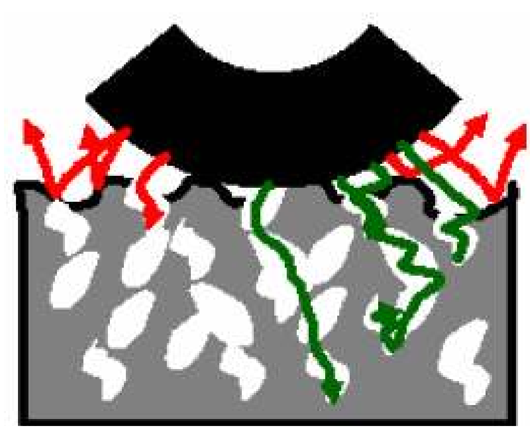

Figure 2-16 Possible Noise Reduction Mechanism for Porous Surfaces (Bernhard and McDaniel 2005).

2.8 MEASUREMENT TECHNIQUES

2.8.1 Surface Texture Measurement Techniques

A number of techniques are used to measure the macrotexture on the pavement surface. The sand patch test is the traditional volumetric method (ASTM E 965). A known volume of sand or glass beads is spread on the pavement surface (in a circle) and the area of the sand circle is used to calculate the *MTD*. The outflow meter is another manual method that indirectly estimates the surface texture of pavement. It uses a known volume of water and the time needed for the water to escape from a cylinder is used to compare various surfaces. Laser based techniques are available that permit texture measurement in the laboratory and in the field. Examples of laser based techniques are Automatic Road Analyzer (ARAN), Circular Track Meter (CTM), Road Surface Analyzer (ROSAN), RoboTex, etc.

In CTM, a laser sensor is mounted on an arm that rotates on a circular path of 142 mm radius and measures the texture with a sampling interval of approximately 0.9 mm (ASTM E 2157). ARAN can measure the surface texture and roughness along with pavement distress survey at the speed of the roadway. It measures the texture Mean Profile Depth (*MPD*) according to ASTM E 1845 and ISO13473-1 Standards.

The ROSAN was developed by the Turner Fairbanks Research Center in Virginia a couple of years ago and then its use was stopped within a short period due to unknown reasons. RoboTex, developed in the US, is a six-wheeled remote controlled robot that runs over a road surface at walking speed and captures 3-D texture information. It has a lateral resolution of 0.5 mm to 1.0 mm and a vertical resolution of 0.01 mm (CTRE 2006).

2.8.2 Skid Resistance Measurement Techniques

A large number of skid resistance testers are available worldwide with 84 different devices being used in the US and Canada alone. However, the most common types are the ASTM locked wheel skid trailer (ASTM E 274), Runway Friction Tester (RFT), Saab Friction Tester (SFT), Mu-Meter, GripTester, and Sideways Force Coefficient Routine Investigation

Machine (SCRIM) (NCHRP 1994, TAC 1997). Other portable friction measurement devices include the BPT (ASTM E 303) and Dynamic Friction Tester (DFT) (ASTM E 1911).

The ASTM skid trailer can measure the locked wheel (100% slip) *SN* at different speeds and is the most widely used device in North America for highway pavement skid resistance measurements. The common practice is to measure the *SN* at 64 km/h (40 mph) either using a standard ribbed (ASTM E 501) or smooth tire (ASTM E 524). RFT uses a retractable fifth wheel for runway friction measurement. It is widely used in the US (Federal Aviation Administration standard equipment). SAAB is used for airport runway surface friction measurement in Canada (Transport Canada Standard equipment). It measures the *SN* at constant 15% slip (TAC 1997). It should be noted that zero slip corresponds to free rolling of tire while 100% slip occurs when the tire is fully locked (no rotation).

Mu-Meter (ASTM E 670) measures the sideway force coefficient (SFC) at some yaw angles i.e., test wheels are turned at some angles for measurement of cornering friction. Typical yaw angle is 7.5° with respect to the direction of travel. The SCRIM is similar to the Mu-Meter in principle but uses a 20° yaw angle. The SCRIM was developed by WDM Limited (WDM 2008) under license to Transport Research Laboratory (TRL), UK. It can continuously measure the SFC at a speed from 25 km/h to 85 km/h. A smooth pneumatic tire is used in SFC measurement. BPT uses a rubber slider that is attached to the end of a pendulum arm. The arm is released from a certain height and the measured surface friction is called the British Pendulum Number (*BPN*). In DFT, three rubber sliders are attached to a rotating disc. The equipment measures the wet surface friction at a typical speed of 90 km/h (55 mph).

2.8.3 Noise Measurement Techniques

Several techniques are being used for measuring the overall traffic noise and tire-pavement interaction noise. However, all these techniques are mainly a variation of two basic methods, namely the pass-by and close proximity methods. The pass-by approach is also known as far field, wayside or roadside while the close proximity is known as near-field measurements. The pass-by measurement is taken by placing the sound level meter (SLM) or other suitable equipment at a specified distance from the traffic lane centerline or at different locations in roadside development. The variations of pass-by technique for traffic or tire-pavement noise measurement include Statistical Pass-By (SPB) and Controlled Pass-By (CPB) methods. Several laboratory methods have been developed for measurement of either tire-pavement noise or acoustic absorption.

SPB Method

As mentioned earlier, the overall noise from a traffic stream on a particular road depends on several variables including vehicle types, sizes, conditions, loading and speeds, tire sizes and patterns, traffic volume and composition, and environmental conditions. It is not possible to determine the overall noise that a roadside community will experience based on measurement from a single vehicle. In SPB method, noise from random samples of typical vehicles is measured and overall noise level is estimated using suitable software. The estimated value is called the Statistical Pass-By Index (SPBI).

For classification of highway corridors, the microphones are placed usually at 7.5 m (25 ft) (European standard) and occasionally at 15 m (50 ft) (US practice) from the centre line of the travel lane and at 1.2 m height with respect to pavement surface. Noise measurements are taken for three classes of vehicles: passenger cars, dual-axle heavy vehicles with more than four wheels (bus, coach, and truck) and multiple-axle heavy vehicles (trucks with three or more axles and trailers). The composition includes at least 100 passenger cars and 80 heavy vehicles with a minimum of thirty vehicles for each of two heavy vehicle categories.

The ISO describes the measurement of SPB noise in ISO 11819-1 (1997) manual. This method relies on normal traffic stream on a particular road, and therefore it may not be used to compare various pavement surfaces at a network level as the vehicle combinations, types and conditions may not be comparable for different roads. It is mainly used for determining or predicting overall traffic noise to aid in the decision making process of possible noise abatement measure at a specific location.

CPB Method

The CPB method is used worldwide to compare various pavement surfaces and textures. This method is similar to the SPB method in terms of the measurement setup whereby a microphone or microphones are placed at a specified distance and height with respect to centre line of the nearest travel lane. However, in this case, a single test vehicle or a set of test vehicles are driven on test surfaces at specified speed(s) and pass-by noise levels are measured. A selected or standard tire(s) such as Standard Reference Test Tire (SRTT) specified in ASTM F 2493 can be used. As the test tire(s) on each vehicle remain the same, this method can be used to compare the roadside noise produced by different road surfaces.

CPX Method

The CPX method is widely used to compare tires, vehicles, and road surfaces for noise. For tire and road surface testing, the microphones can be mounted near the tire-road interface of a specified vehicle or mounted near the tire-road interface of a special trailer that is pulled by another vehicle. An enclosure for the microphones is usually provided to curb the noise from other surrounding sources. A normal tire or standard tire (e.g. ASTM F 2493) may be used. The CPX noise testing method is described in the ISO manual ISO 11819-2 (2000). Figure 2-17 shows the schematic view of microphone positions for ISO CPX method.

On-Board Sound Intensity (OBSI) Test

The OBSI method is a variation of CPX method developed by General Motors (Donavan 2006). In this method, the intensity of sound power due to tire-pavement interaction is measured as opposed to measuring the *SPL* according to the ISO CPX method. The microphones are mounted in close proximity to the tire, and therefore it is called Close Proximity Sound Intensity (CPSI). Alternatively, the ISO CPX method measures the Close Proximity Sound Pressure (CPSP). This method is currently under development in the US As no standardization has been done yet, the physical setup varies among the tire and vehicle manufacturing companies as well as the highway agencies.

It should be noted again that although the units/magnitudes of sound pressure and sound intensity are different in raw scale, both of them have identical values in standardized dB scale. This means that under an ideal condition of enclosure, road surface, vehicle/tire and microphone position, the value of sound intensity in dB should match the value of sound pressure in dB. A NCAT study found that the OBSI values are 1-2 dB greater than the SPL (Smit and Waller 2007). However, for OBSI measurement, the microphones were mounted closer to the tire as compared to microphones in ISO CPX method. It should be noted here that the noise perceived by the human ear is the sound pressure (changes in atmospheric pressure) not the sound power or intensity.

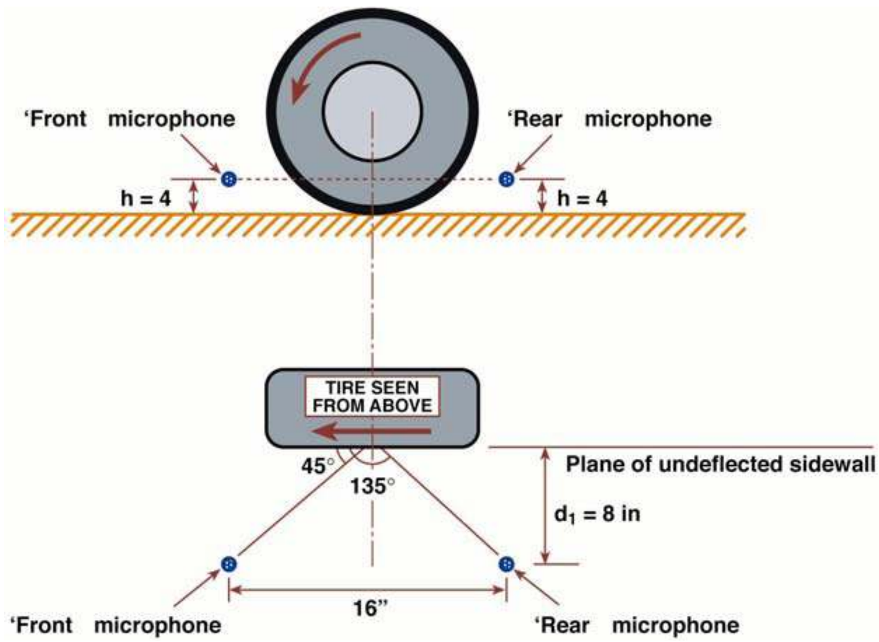

Figure 2-17 Microphone Locations in CPX Noise Test (Hanson et al. 2004a).

Laboratory Measurements of Pavement Acoustic Performance

The method used in the laboratory for measurement of tire-pavement noise is known as the drum method. Specially moulded pavement specimen blocks are mounted around a circular drum and standard tire(s) are rolled on it. As the selected tire(s) roll around the replica of pavements, the tire-pavement noise is measured with microphones mounted similarly as done in the CPX method. This method allows for comparison of many alternative surfaces. However, the test speed is usually very low (50 km/h) as compared to actual roads. The small blocks result in many joints that may influence the measured noise levels. In addition, the background noise, especially that generated by the drum power unit, is a big problem.

The common method used to measure the acoustic absorption properties of the pavement layer is the impedance tube method as outlined in ISO 10534-2:1998 or ASTM E-1050. This method differs from other methods discussed above in that the sound is generated by something other than tire-pavement interaction and sound absorption is measured as opposed to direct measurement of sound pressure level or sound intensity. The test specimens may be prepared in the laboratory or obtained by coring from the field.

2.9 OPTIMIZATION OF SURFACE TEXTURE, FRICTION AND NOISE

According to Descornet (1989), several aspects should be considered for optimizing the pavement surface characteristics. These include: a) safety as related to skid resistance, splash and spray, visibility of the road and markings, and road-holding (tire grip) qualities; b) economy as related to fuel consumption, tire and vehicle wear, and extra dynamic loads (vertical oscillation); c) user and residents comfort as related to noise, vibration inside and outside the vehicles.

It has been seen that, in general, pavement surface friction and tire-pavement noise are inversely related. This means, as the surface friction is increased through increased texture, tire-pavement noise is adversely affected (noise increase). Figure 2-1, however, shows that some texture is needed for lower noise. Ahammed and Tighe (2008e) also found that pavement surfaces with lower texture are louder than moderately textured surfaces. Alternatively, a high level of texture does not necessarily mean increased surface friction because beyond a certain texture level the actual tire-pavement contact does not increase (Ahammed and Tighe 2008f).

Davis et al. (2005) indicated that skid resistance and texture are two features that can be readily controlled by resurfacing to reduce the crash risk. However, emphasis should be on increasing the surface friction rather than the texture. Ahammed and Tighe (2008f) also found that aggregate quality is of prime importance for surface friction than the texture depth. Therefore, high quality materials with good frictional properties used in a surface mix that produce a lower level macrotexture may be a good trade-off between safety and noise.

Splash and spray is another major concern for safety on wet pavements. As mentioned by Descornet (1989), splash and spray can be minimized with more effective drainage for which macrotexture has a favourable effect. The paper also indicated that texture wavelengths in the range of 8 mm to 16 mm provide the most effective drainage at tire-pavement contact.

In Belgium, the permitted surface treatments of PCC pavements are transverse brushing, deep (5 mm deep with 15 mm to 30 mm variable spacing) transverse grooving, chip-sprinkling and aggregate exposure. The desired minimum SFC at 80 km/h is 0.45. With the increased concern of noise, 7 mm or 8 mm maximum size aggregate has been recommended for exposed aggregate surface course. Grinding has shown to be efficient technique for noise reduction in European countries. A significant noise reduction, 3.2 to 4.5 dBA for heavy vehicles and 5.3 to 5.8 dBA for private cars, was achieved after diamond grinding of deep transversely tined motorway sections in Belgium. The paper thus concluded that PCC pavement could be constructed to meet safety, comfort, and economy of road users and a friendly acoustic environment (Descornet and Fuchs 1992). Rasmussen et al. (2007) mentioned that texture should be small (<10 mm) and negative (Figure 2-18) to minimize stab (strike) at and poke (push) into the tire, and thereby minimize the generation of undesirable noise.

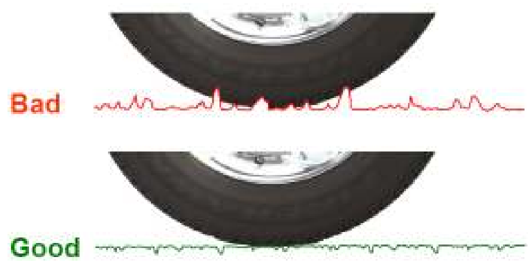

Figure 2-18 Conceptual Schematic of Good and Bad Textures (Rasmussen et al. 2007).

The wear and polish of surfaces over time due to traffic use and environmental effects are also major concerns. As mentioned by Leyder and Reichert (1974), highway agencies are also facing the challenge of restoring skid resistance of both asphalt and concrete pavements due to inadequate construction or polishing of surface aggregate by traffic action. Ahammed and Tighe (2008g) found that AC and PCC pavements surface friction decreases at 1.2 *SN* and 0.7 *SN* per year, respectively. Ong and Fwa (2008) mentioned that as the pavement groove deteriorates the risk of hydroplaning increases. This may affect the safety over long term because of inadequate surface friction (Ahammed and Tighe 2007).

Skid resistance can be imparted to polished/slippery PCC pavements by grooving or grinding, such processes, however, are costly and feasible only if surface aggregates are high polish resistant. Skid resistance can also be restored using synthetic resin, mixed with hard and polish resistant aggregate, surfacing on both AC and PCC pavements with good foundation condition (no other defects). Such surfacing is also associated with a very high cost (Leyder and Reichert 1974). These points out the importance of providing a durable surface texture and skid resistance during the design and construction of surface layer. A negative texture may reduce the rate of wear as well as minimize the tire-pavement noise. However, in all cases, the specifying agencies must ensure adequate resistance to skidding over the life of surface course as the safety is the first priority.

The trade-off between pavement surface friction (safety) and tire-pavement noise has not yet been established in terms of cost and benefit because of the lack of tools to express them monetarily. This is because not only that research to establish the relationship between surface friction and safety is still ongoing, but also that the health effects of noise are hard to place value. So the compromise has to be based on a subjective evaluation of needs of each individual site, rather than using a benefit/cost methodology.

There has also been debate on the advantages/disadvantages of AC and PCC pavements. According to Kuemmel and Jaeckel (1996), AC and other porous surfaces have acoustic advantages over PCC in terms of reduced tire-pavement noise and higher acoustic absorption. However, such benefits exist only for the first 5 to 6 years of their construction. Alternatively, PCC pavements are known to provide durable surface (defect free) with longer service life and higher stability. Higher noise and texture durability, however, are major concerns. As mentioned by Christory (2005), although PCC pavements may not be best from standpoint of noise, it is likely to be the best when noise, safety, and durability are accounted for. According to Karamihas and Cable (2004), appropriate surface texturization can minimize the tire-pavement noise and provide durable skid resistance. Each aspect of texture such as shape (pattern), direction, and depth that affect noise as well as safety is therefore needed to be understood in order to build the highway pavements with desirable surface characteristics.

No Canadian agencies specify the desirable surface texture for adequate and durable friction. Furthermore, no specification or guideline is provided for acceptable noise levels in pavement perspective, although the environmental agencies/departments provide some guidance on traffic noise levels for noise barrier consideration. This resulted in a large variation in noise levels among the pavements already constructed or under construction (Ahammed and Tighe 2008a). A specific guideline in regard to desired minimum surface friction and acceptable maximum noise may be helpful in the selection of pavement surfaces. However, the main objective of PCC surface texturization or selection of AC surface mix should be reducing the number and severity of accidents. Safety and durability should not be compromised for slight reduction in noise. According to Wayson (1998), a balance between noise and safety is the best option in practicing highway design.

2.10 SUMMARY OF SURFACE CHARACTERISTICS

i) Both microtexture and macrotexture contribute to available surface friction. Microtexture maintains intimate tire-pavement contact by penetrating into the water film whereas macrotexture allows for drainage of water and energy loss that creates a retarding force.

ii) The available surface friction varies with vehicle speed, changes seasonally and continuously decreases with time/traffic exposure. Durable texture is essential to ensure sufficient wet weather friction and safety against skidding at the speed of the roadway over all seasons and the life of pavement surfaces.

iii) Noise is an environmental pollutant. Traffic noise is the most bothersome and growing problem throughout the world.

iv) Standard noise mitigation measures, namely the noise barriers, are costly and ineffective in many cases where noise is of most concern.

v) At speeds exceeding 50 km/h, tire-pavement interaction is the primary source of highway noise. It provides an opportunity for designing pavement surfaces that produce low tire-pavement noise, and thereby contribute to lower overall traffic noise.

vi) The mechanism of tire-pavement interaction noise generation and propagation are complex functions of many characteristics of the pavement, vehicle, and tire. A low textured surface may not provide a quiet pavement i.e., some texture is essential for noise reduction.

vii) Reduced texture for reduced noise may be a concern for adequacy of skid resistance. Appropriate surface texturization or selection of surface mix can minimize the tire-pavement noise and provide a durable skid resistance.

viii) AC pavements and other porous surfaces have acoustic advantages over PCC in terms of reduced tire-pavement noise and higher acoustic absorption. However, these advantages may not last long.

Chapter 3 Literature Review

This chapter provides a summary of the available relevant past research, associated data, and methodologies used in those studies. The findings and their practical significance are also discussed, as applicable.

3.1 SURFACE TEXTURE AND SKID RESISTANCE

Hayes and Ivey (1975) measured the texture and skid resistance of five surfaces. Lightweight aggregate chip seal was shown to produce the highest texture and highest *SN* while Jennite flush seal was shown to produce the lowest texture and the lowest skid resistance. Despite similar texture depths, rounded gravel hot mix was shown to produce lower skid resistance than lightweight aggregate hot mix due to microtexture and asperity shape. These indicated that both texture depth and aggregate quality are important for surface friction. The variation of *SN* and *BPN*, however, was not shown to be identical.

Henderson (2006) also found that a mix with a higher percentage of crushed chips exhibits higher skid resistance. The paper mentioned that crushing increases the skid resistance in two ways: greater microtexture and more angularity or irregularity as compared to rounded uncrushed aggregates. It also indicated that an increase in friction up to 25% is achievable for a mix containing 100% crushed chips as compared to that with 0% crushed chips.

Agrawal and Daiutolo (1981) investigated the effect of PCC groove spacing on available surface friction on an airport runway. The available surface friction was calculated from aircraft speed and stopping distance on pavements having 6.35 mm (0.25") wide and 6.35 mm deep grooves spaced at 31.3 mm (1.25") to 101.6 mm (4"). The study found that a groove spacing of 76.2 mm (3") or less would probably provide acceptable breaking performance for aircraft on a wet surface with the desired friction coefficient of 0.15.

Franklin (1978) inserted various PCC mix specimens onto UK's motorway through core insert and tested the skid resistance using the BPT. The study found that the low speed skid resistance of PCC surfaces is mainly dependent on fine aggregate properties and to a lesser degree on fine aggregate content. Coarse aggregate quality as determined by PSV was found to be significant in the case of heavy traffic roads but to a very limited extent. The model for skid resistance was given as:

$$SRV = 15 + 0.60PMV + 0.25FAC \qquad (3\text{-}1)$$

Where,

SRV = Skid Resistance Value

PMV = Polish Mortar Value for fine aggregate, and

FAC = Fine Aggregate Content (% passing 5 mm sieve).

Yager and Buhlmann (1982) measured the surface texture on fifteen pavement sections using three different methods, which included sand patch, silicone putty, and the grease method. Good correlations were found between the sand patch and other two methods. However, the study found no correlation between the *BPN* and texture depths. Based on skid resistance measurement on textured mortar surfaces, Liu et al. (2004), however, confirmed that *BPN* depends on both surface microtexture and macrotexture.

Corley-Lay (1998) measured the texture and surface friction of fourteen AC pavement sections in North Carolina and found that the variation in *BPN* from section to section resembles the variation in *SN*. The highest surface friction was exhibited by large-stone mix (95% passing 19.1 mm) and Heavy Duty Surface (HDS) course (95% passing 9.5 mm). The skid numbers were 52.2 (*BPN* = 62.9) and 53.1 (*BPN* = 64.3) with *MTD* of 0.78 mm and 0.822 mm, respectively. The lowest surface friction was observed for rubber or fibre modified SMA (95% passing 12.5 mm). The *SN* ranged from 47.1 (*BPN* = 60.5) with a *MTD* of 0.89 mm to 50.9 (*BPN* = 67.8) with a *MTD* of 1.07 mm.

Henry and Saito (1983) presented a large number of regression models for prediction of *SN*, *MTD*, and *BPN* using data obtained from 22 sites in Pennsylvania. The tested pavements include different AC and PCC pavements with varying traffic conditions. The important models developed are as follows:

$$SN_{64}^{R} = -9.7 + 4.72MTD + 0.766BPN \qquad R^2 = 0.850 \qquad (3\text{-}2)$$

$$SN_{64}^{B} = -19.5 + 17.3MTD + 0.628BPN \qquad R^2 = 0.841 \qquad (3\text{-}3)$$

$$BPN = 20.0 + 0.405SN_{64}^{R} + 0.039SN_{64}^{B} \qquad R^2 = 0.819 \qquad (3\text{-}4)$$

$$MTD = 0.490 - 0.0289SN_{64}^{R} + 0.0426SN_{64}^{B} \qquad R^2 = 0.728 \qquad (3\text{-}5)$$

Where,

SN_{64}^{B} = *SN* at 64 km/h with blank tire (ASTM E 524)

SN_{64}^{R} = *SN* at 64 km/h with ribbed tire (ASTM E 501)

MTD = Mean Texture Depth, mm

BPN = British Pendulum Number, and

R^2 = Coefficient of determination for the model

The models presented above had shown good R^2 values. It should be noted, however, that skid resistance, regardless of method used (e.g. SN_{64}^{B}, SN_{64}^{R}, or *BPN*), is highly dependent on pavement surface texture, e.g. *MTD* or tire-contact area. Therefore, they are correlated with each other. Correlating any two is meaningful given that the correlation is statistically significant. However, inclusion of several highly inter-dependent predictors in a single model is considered statistically inappropriate because of multicollinearity problem (Ahammed and Tighe 2008h). The correlation of *MTD* with the *SN* (Equation 3-5) is not also logical because of opposite signs associated with ribbed and bald tires *SN*. Similar (Equation 3-5) *MTD* prediction models have been presented in NCHRP 1-43 (2007) and Larson et al. (2008). It should also be noted that *MTD* is not a response (dependent), but causal variable with respect to the skid resistance (*MTD* causes change in skid resistance).

Wambold (1988a) refined some of the above models (Equation 3-2 to 3-5) including some additional data but without altering the model forms. The acceptable skid numbers were indicated as 20 and 35 for smooth and ribbed tires, respectively. Alternatively, the acceptable *BPN* was considered 55.

Wambold (1988b) developed two models using data from pavements in New York, Florida and Texas for the prediction of low speed skid resistance. The study also included both ribbed and bald tires *SN* as independent variables in the same model that is considered statistically erroneous. Forster (1989) attempted to develop some models correlating the texture shape factor and percentage contact area (*CA*) with the *BPN* or *SN*. The examination of outliers, however, indicated possible problems with both texture and skid data. The developed models therefore were not useful.

Fulop et al. (2000) presented Markov models for skid resistance and macrotexture to harmonize the Hungarian device specific values with the International Friction Index (*IFI*) and texture parameter known as speed number (S_p). The *IFI* was developed by the PIARC Technical Committee on Surface Characteristics to harmonize different friction measuring methods/devices that are being used in different countries throughout the world. An international experiment (PIARC 1995) was carried out in 1992 to accomplish this. The S_p is a function of macrotexture and indicated to be constant for all devices.

Wambold et al. (2004) presented the correlations of *MTD* with the international texture parameter (S_p) as well as *BPN* and DFT with the *IFI* developed in international PIARC experiment. The correlations are:

$$S_P = 113.6MTD - 11.59 \tag{3-6}$$

$$F_{60} = 0.0079BPN + 0.0778 \tag{3-7}$$

$$F_{60} = 0.081 + 0.732DFT20\exp(\frac{-40}{S_P}) \tag{3-8}$$

Where,

S_p = Texture Parameter of PIARC experiment

MTD = Mean Texture Depth with sand patch method, mm

F_{60} = *IFI* at 60 km/h

BPN = British Pendulum Number, and

DFT_{20} = Friction at 20 km/h with Dynamic Friction Tester

Bol and Bennis (2000) attempted to validate the PIARC model based on measurements taken with six devices on fourteen test surfaces (porous and non-porous asphalts) in Netherlands. It was found that the correlation between *S*p and macrotexture is better if estimated for each device separately i.e., *S*p is device specific (not constant).

Do et al. (2000) introduced an algorithm for the angular parameter of surface microtexture (called theta) from laser based texture profile. A fair correlation ($r = 0.84$) between the theta parameter and SRT (Skid Resistance Tester which is also called the BPT) friction was found. However, no model was presented.

Using the DFT, Himeno et al. (2000) measured the skid resistance of seventeen laboratory prepared AC samples with varying aggregate gradations. The surface friction was shown to decrease with an increase in the *MPD* contrasting the general concept that skid resistance increases with an increase in texture. It was therefore concluded that *MPD* is not an effective factor for evaluating the skid resistance. The skid resistance was shown to be highly dependent on the fine sands passing the 0.15 mm sieve.

Viner et al. (2000a) correlated the macrotexture values measured using various devices on 56 sections (each 10 m long) of PCC and AC pavements in the UK. The texture measuring devices were the sand patch method, Mini Texture Meter (MTM), High Speed Texture Meter (HSTM), profile beam and Highway Agency Road Research Information System (HARRIS). The MTM with 0.2 mm vertical resolution and 1.1 to 2.8 mm sampling interval provides 10 m average *MPD* value. The HSTM with 0.2 mm vertical resolution and 2.3 mm to 7 mm sampling intervals also provides 10 m average value. The profile beam is a stationary device that provides 1 m texture profile with vertical resolution of 0.01 mm and sampling interval of 0.2 mm. The HARRIS has 0.02 mm vertical resolution and 0.23 mm to 0.44 mm sampling intervals. Good correlations were found among the device specific macrotexture values with R^2 values of 0.82 to 0.98.

Abe et al. (2001) developed a good relationship between the texture *MPD* measured with CTM and *MTD* using data collected at NASA Wallops Flight Facility in Virginia (US) and Sperenberg test track in Berlin (Germany) as:

$$MTD = 1.03MPD + 0.15 \qquad R^2 = 0.98 \qquad (3\text{-}9)$$

Where,

MTD = Mean Texture Depth in mm by sand patch method, and

MPD = Mean Profile Depth with Circular Texture Meter, mm

Flintsch et al. (2003a) also developed good correlations, as given by Equations 3-10 and 3-11, among macrotextures measured with three different devices on a SMA, an OGFC, and five Superpave surfaces in Virginia. Equation 3-11, however, did not agree with the correlation given in ASTM E 1845 ($ETD = 0.8MPD + 0.2$, where ETD is the estimated texture depth in mm), indicating possible bias in the laser profiler used or difference in computation algorithm. It should be noted that when MTD is estimated from the MPD, it is called the ETD.

$$MTD = 0.982MPD_{CTM} + 0.0364 \qquad R^2 = 0.943 \qquad (3\text{-}10)$$

$$MTD = 0.7796MPD_{LP} - 0.379 \qquad R^2 = 0.884 \qquad (3\text{-}11)$$

Where,

MTD = Mean Texture Depth with sand patch test, mm

MPD_{CTM} = Mean Profile Depth with Circular Texture Meter (CTM), mm and

MPD_{LP} = Mean Profile Depth with Laser Profiler (ASTM E 1845), mm

Gothie et al. (2004) developed good correlation among macrotextures measured with three methods (sand patch and two lasers) and confirmed that MPD values are device specific. Values obtained from one method may not be directly compared with those obtained from another method. McGhee and Flintsch (2004), however, found that MTD and CTM's MPD are equivalent contrasting the findings by others.

Viner et al. (2000b) measured surface friction and texture of 144 surfaces of PCC and AC pavements in the UK. Surface friction was shown to decrease with an increase in speed for both smooth and ribbed tires. The texture depth was shown to be less sensitive for low speed ($\leq$ 50 km/h) skid resistance. Ribbed tires were shown to be equivalent to 1.25 mm surface texture (MPD) and this compensates for low texture on pavement surface by allowing dissipation of thin water film.

Wambold (2000) compared Norsemeter's ROAR (Road Analyzer and Recorder) and SALTER friction testers with several friction testers used in North America such as the ASTM skid trailer, Saab friction tester, K. J. Law runway friction tester, Swedish BV 11 and Swedish USFT (US version airport Surface Friction Tester). Up to 50% difference was noted among the device specific friction values. The study found good correlation of ROAR (less durable) and SALTER (at low speed of 30 km/h) friction values with the skid trailer values. At higher speeds, SALTER showed higher friction values than the skid trailer because of constant water flow rate in SALTER while other devices have variable flow rate to maintain same water film thickness regardless of speed.

Wennink and Gerritsen (2000) used the ARAN for texture measurement in Netherlands and then to predict type of road surface, maximum size of grain (aggregate) and aggregate shape through profile spectrum analysis. The prediction was indicated to be reasonable, the methodology, however, was not clearly described.

Davis et al. (2002) developed a model, using data of seven asphalt surfaces on the Virginia Smart Road, for an estimation of laser based texture *MPD* from mix properties. The developed model, as given by Equation 3-12, indicates that macrotexture will increase with an increase in aggregate size and percentage voids in mineral aggregates (*VMA*). A study by Ahammed and Tighe (2008f), however, found no statistically significant relationship of *VMA* (an internal property) with the texture *MTD*.

$$MPD = -2.896 + 0.2993NMS + 0.0698VMA \qquad R^2 = 0.965 \qquad (3\text{-}12)$$

Where,

MPD = Mean Profile Depth, mm

NMS = Nominal Maximum Aggregate Size, mm and

VMA = Voids in Mineral Aggregates, %

Kokkalis et al. (2002) attempted to develop a model for skid resistance through fractals interpolation assuming some typical *SN* for different surfaces (rough, polished, etc.). However, the analysis ended with the conclusion that further investigation is needed to develop a meaningful relationship. Fwa et al. (2003) studied the effect of aggregate spacing on tire-pavement contact and skid resistance. Results indicated that the skid resistance is negatively correlated with aggregate gap width and positively correlated with the magnitude of rubber (tire) contact area. However, the paper indicated that these correlations are not simple and further research is needed for better understanding the texture-skid resistance relationship.

Stroup-Gardiner and Brown (2003) presented a model (Equation 3-13) for estimation of macrotexture measured with ROSAN from AC mix properties. Flintsch et al. (2003b) found that the proposed model could not correctly predict the macrotexture of AC surfaces.

$$ETD = 0.01980MS - 0.004984P_{4.75} + 0.1038C_c - 0.004861C_u \qquad (3\text{-}13)$$

Where,

ETD = Estimated Texture Depth (mm)

MS = Maximum size of the aggregate in the AC mix, mm

$P_{4.75}$ = Percentage of aggregate passing the 4.75mm sieve

Cc = Coefficient of curvature of the aggregates in AC mix

C_u = Coefficient of uniformity the aggregates in AC mix

Zimmer (2003) assessed the appropriateness of ASTM E-274 in measuring the surface friction of open-grated steel bridge decks in Florida. Data obtained over ten years (1990-2001) showed that skid numbers on open-grated steel deck and approach asphalt pavement surfaces are comparable. This led to a conclusion that skid trailer could be used to address the safety and maintenance consideration of steel bridge decks.

Maurer (2004) evaluated the influence of different tires on surface friction. Friction data were obtained from fourteen pavements in Australia using RoadSTAR equipped with a laser sensor for texture and friction measurement simultaneously. The data showed that the PIARC standard ribbed tire skid resistance represents the worst case of the available surface friction. Conventional car tires produce higher surface friction. Therefore, skid resistance measurement with standard tire represents safer condition for the actual tires in use. Among the conventional tires, all season tires produce the worst friction followed by winter tires.

Stroup-Gardiner et al. (2004) compared the surface texture (ROSAN *ETD*) and skid resistance (*BPN*) of Superpave and Marshal mixes on different projects in Alabama. No statistically significant difference was found in macrotextures due to mix design methods. Wet pavement surface friction was shown to be dependent on the coarseness of aggregate fraction above 1.18 mm sieve (for 9.5 mm to 19 mm nominal maximum aggregate size).

Ergun et al. (2005) developed a complex model for the prediction of surface friction from macrotexture and microtexture data of eighteen PCC and AC pavement sections in Belgium. The surface friction was measured using the Odoliograph. Alternatively, the surface texture was measured using an image analysis system. However, the authors doubted themselves about the acceptance of the method because of its imprecision in addition to the complexity.

Roe and Lagarde-Forest (2005) tested the surface friction of new to 18 months old 25 SMA surfaces in the UK. Dry SMA pavements were shown to exhibit significantly lower surface friction as compared to the hot rolled asphalt dry surfaces over the first six months. The study found that at lower speed (20 km/h), the dry surface friction could be up to 20% lower while at intermediate (50 km/h) and high (80 km/h) speeds, the dry surface friction could be 30 to 40% lower. On wet SMA surfaces, the early life surface friction was shown to be higher than the SMA dry surfaces. The reason was not explained. The study found no correlation between sand patch *MTD* and sensor based texture for both thin surfacing and SMA.

Choubane et al. (2006) assessed the desired precision level for skid resistance measured with locked-wheel skid testers. It was suggested that skid resistance at 64 km/h (40 mph) should not differ by more than 3.7 *SN* and 4.5 *SN* for ribbed and smooth tires, respectively, in repeated tests with the same equipment. The difference in *SN* with two different skid testers should not exceed 4.0 and 5.1 for ribbed and smooth tires, respectively. This indicates better precision of ribbed tire *SN* at 95% confidence level. Larson et al. (2008) also found a better correlation of wet/total crash ratio and the ribbed tire *SN* as compared to the smooth tire *SN*. It therefore recommended the ribbed tire skid measurement if one tire is to be used.

Goodman et al. (2006) compared the surface textures of field, obtained by coring from eight sites in Ottawa (Canada), and Superpave gyratory samples. Good correlation was found between the *MTD* of field and gyratory samples (Equation 3-14). However, the correlation between the *BPN* of field and gyratory samples was shown to be poor. This indicated that aggregates are oriented in a different manner by field compaction equipment as compared to the gyratory compactor.

$$MTD_{Field} = 1.14(MTD_{TopSurfae})^2 - 0.81(MTD_{TopSurface}) + 0.40 \qquad R^2 = 0.99 \quad (3\text{-}14)$$

Where,

MTD_{Field} = Mean Texture Depth of field sample, mm and

$MTD_{\text{TopSurface}}$= Mean Texture Depth of gyratory sample top surface, mm

Fwa and Ong (2006a) evaluated the hydroplaning of tires on transversely tined PCC using a simulation model. The hydroplaning speed and skid resistance at the onset of hydroplaning were shown to increase significantly (compared to that on smooth surface with no groove) with an increase in tine width and a reduction in tine spacing with marginal effect from tine depth. Another simulation model found that typical longitudinal tining (3 mm wide, 3 mm deep and 19 mm interval) has marginal effect in increasing the hydroplaning speed and skid resistance at the onset of hydroplaning (Fwa and Ong 2006b). Using a simulation model, Li et al. (2006) also found that increased tine width is more effective than increased tine depth for increased surface friction.

Further simulation model by Ong and Fwa (2007) indicated that a longitudinal grooved PCC pavement exhibits significantly higher skid resistance than a smooth surface if the skidding direction deviates from the true longitudinal direction. The skid resistance increases as the angle of deviation increase and reaches to the maximum when deviation is ninety degrees (represents transverse groove). This angular friction provides the wheel traction to keep the sliding vehicle within the roadway and reduces the wet-pavement accidents. It therefore gave an indication that a longitudinal tined surface is not unsafe.

Luce et al. (2007) evaluated the aggregate texture and its relationship to skid resistance on several pavements in Texas. The aggregate type (gravel, sandstone, and quartzite) was shown to be statistically significant for skid resistance. The aggregate gradation, however, was shown not to explain the difference in skid resistance among the AC mixes.

Trifirò et al. (2008) compared surface friction values measured with three locked-wheel skid trailers mounting the smooth as well as ribbed tires and a DFT. No correlation was found between the locked-wheel smooth and ribbed tires friction values. Correlations between DFT and locked wheel friction values were shown also to be poor.

3.2 SURFACE TEXTURE AND VEHICLE OPERATION

Through laboratory simulation and testing in the field, Martinez (1976) found that longitudinal grooves have no detrimental effect on motor cycle at speeds ≤ 89 km/h (55 mph). When speed approaches 113 km/h (70 mph), the riders experience noticeable wobble (side-to-side front-wheel movement) when they do not follow the groove. No undesirable effect on riders was shown on transversely grooved pavement.

A French study with medium-sized cars showed that evenness rating from excellent (short wavelengths) to poor (large wavelengths) results in 0% to 6 % extra fuel consumption due to rolling resistance. Changes in *MTD* from fine (0.1 mm) to extremely coarse (3 mm) can also result in 0% to 6% extra fuel consumption. The effects of unevenness and macrotexture were shown to be independent and additive indicating that both unevenness and macrotexture factors must be considered in pavement management (Laganier and Lucas 1990).

In a Swedish study on twenty pavements, Sandberg (1990) found that passenger cars fuel consumption can increase by up to 11% if texture wavelengths are in the range of 0.6 mm to 3.5 m, and by approximately 7% if texture wavelengths are in the range of 2 to 50 mm. Alternatively, unevenness can result in 10% extra fuel consumption for commercial vehicles (Gyenes and Mitchell 1994). Plessis et al. (1994), however, indicated that pavement surface characteristics could cost 20% extra in fuel consumption for buses and trucks.

Descornet (1990) found that the worst paved surfaces could produce 47% extra rolling resistance as compared to the best surfaces (texture wavelengths of ≤ 2.5 mm). Observation showed that megatexture (wavelengths of 50 mm to 500 mm) is the main factor for excess rolling resistance, and is responsible for tire-pavement noise. Based on study on five trial strips in France, Delanne (1994) found that macrotexture is responsible for extra fuel consumption, in-vehicle and outside low frequency noise and inside vibration (discomfort).

3.3 SEASONAL AND SHORT TERM VARIATIONS OF SKID RESISTANCE

Rice (1977) summarized the experience of different States and Countries in regards to seasonal variation of pavement skid resistance. In the UK, the seasonal variation of AC pavements surface friction was shown to be 0.10 to 0.15. In Arizona, the PCC surface friction tested with the Mu-meter was shown to be 33 in September, 52 in January and then down to 32 in May. Rainfall and temperature data did not explain the variation. The paper, however, did not indicate the possible causes.

In Connecticut, AC surface friction was shown to vary by 15 *SN* between July-August and late fall/early spring which was explained to be associated with surface contamination. Illinois experienced 5 *SN* to 10 *SN* variations between fall and spring for AC pavements. Kansas reported seasonal variations of 30 *SN* for AC and 14 *SN* for PCC. Kentucky observed a variation of 10 *SN* for sand-asphalts. Louisiana did not find any seasonal variation between cold, mild and hot weather. Missouri found a variation between fall and spring of 0.10 for PCC and 0.17 for AC surfaces. Texas reported a variation of 10 *SN* between summer and winter and explained this to be associated with polishing and rainfall. West Virginia observed a reduction of 14 *SN* from March to October and an increase of 10 *SN* from December to May. Although some of the estimates presented above seem to be high, they, however, indicate that some variations do occur that needs to be considered in the design of surfaces.

Hegmon (1978) evaluated the repeatability of the ASTM E 274 standard skid tester to validate the report presented by Rice (1977). The study found that 98% of the test results are within ± 5 *SN* with respect to the mean indicating a variation of 10 *SN* between low and high numbers. A location variation of 15 *SN* was observed on a uniform 4.8 km (3 mile) long section. This emphasizes the importance of testing the same section every time for better estimation of the seasonal or long term variations.

Elkin et al. (1980) examined fifteen AC pavements in Indiana to identify the surface that offers and preserves satisfactory skid resistance independent of speed and seasonal variation due to rainfall and temperature. Hot emulsified asphalt containing natural sand or slag (4.75 mm maximum size) and hot mix AC with slag (12.5 mm maximum size) were shown to exhibit a $SN_{64} \geq 50$ whereas OGFC and limestone AC mixes (12.5 mm maximum size) were shown to exhibit SN_{64} of about 40 or less. However, mixes containing slag had shown a greater potential for polishing as compared to limestone or dolomite. Skid resistance was shown to be less vulnerable to short term temperature changes during the summer as compared to that during the spring or fall, although skid resistance was recorded to be the lowest in summer and highest in the spring, regardless of the type of AC mix.

Shakely et al. (1980) measured the *SN* of a dense-graded asphalt surface and collected the dust sample to examine the effect of contamination on skid resistance variation. Several models were developed for the prediction of low speed *SN* from the dust mass of different sizes. The best correlation (Equation 3-15) was found for dust mass up to 0.007 gm/m^2 in 7.0 µm - 50.0 µm size ranges. Sizes over 50.0 µm and mass over 0.007 gm/m^2 had shown no significant effect on the skid resistance variation.

$$SN_0 = 64.21 - 1862.0M_1 \qquad R^2 = 0.82 \qquad (3\text{-}15)$$

Where,

SN_0 = Low speed Skid Number (intercept of Pennsylvania model), and

M_1 = Mass of dust particles, 7.0 µm - 50.0 µm size and not exceeding 0.007 gm/m^2.

The developed model predicts SN_0 of 64.21 for no dust (clean/washed surface) and SN_0 of 51.18 for 0.007 gm/m^2 of dust i.e., a reduction in 13 *SN*. Skid testing at 27 km/h (low speed) on the test site before and after scrubbing (three times, with stiff broom), washing out of the test surface and a heavy rainfall showed an increase in *SN* of 2.8. The validity of the developed model may therefore be questioned. More specifically, it is not clear how the dust mass could be separated and weighed so precisely with a vacuum, filter and weighing system attached to a running vehicle.

Hill and Henry (1981) examined the short term, weather related, variation of skid resistance and developed models (e.g. Equations 3-16 to 3-18) using data collected from 21 sites (16 AC and five PCC pavements) in Pennsylvania and 10 sites (eight AC and two PCC pavements) in North Carolina and Tennessee. The year round skid data showed a reduction of 1.7 *SN* for a seven-day period without rain (dry-spell) and 1.2 *SN* for an increase in temperature of 10°C.

Based on 21 sites in Pennsylvania:

$$SN_{OR} = 3.79 - 1.17DSF - 0.014T_P \qquad R^2 = 0.12\ (r = 0.35) \qquad (3\text{-}16)$$

Based on one site in Pennsylvania:

$$SN_{OR} = 5.09 - 0.232T_P \qquad R^2 = 0.25\ (r = 0.50) \qquad (3\text{-}17)$$

Based on ten sites in North Carolina and Tennessee:

$$SN_{OR} = 1.88 - 0.77DSF - 0.15T_P \qquad R^2 = 0.32\ (r = 0.57) \qquad (3\text{-}18)$$

Where,

SN_{OR} = Short-term variation of skid resistance

DSF = Dry-Spell Factor = $\ln(t_R + 1)$

T_p = Pavements temperature (°C)

R_i = Rainfall on the i^{th} day prior to the test (i = 1 to 5), and

t_R = Number of days (maximum seven) since last rainfall of 2.5 mm (0.1 in.) or more.

Equations 3-16 to 3-18 show 0.014 *SN*, 0.232 *SN* and 0.15 *SN* reductions, respectively, for each 1°C increase in pavement temperature. Furthermore, for the same *DSF* of 2.08 (at t_R = 7 days) and T_p of 30°C, the Pennsylvania Model (Equation 3-16) estimates a SN_{OR} of 0.94 i.e., 0.94 *SN* increase whereas the North Carolina/Tennessee model (Equation 3-18) estimates SN_{OR} of - 4.22 i.e., a 4.22 *SN* reduction.

Jayawickrama and Thomas (1998) collected skid data at two weeks to month intervals from six different asphalt pavements in Texas to examine seasonal variation. The data showed a variation of 10 *SN* to 12 *SN* in a biweekly period. Average difference between winter and summer was 6 *SN*. The developed model for seasonal skid resistance variation is:

$$SN_{64} = 32.28 - 0.14(TEMP_5) + 0.031(RF_5) - 0.66\sin[(\frac{2\pi}{365})JD]$$
$$+13.53I_1 - 3.12I_2 - 2.78I_3 - 9.52I_4 + 7.43I_5 \qquad R^2 = 0.917 \qquad (3-19)$$

Where,

SN_{64} = Skid Number at 64 km/h

$TEMP_5$ = Average of daily temperature for five days prior to skid measurement

RF_5 = Cumulative rainfall over the 5-day period preceding the skid measurement

JD = Julian calendar day corresponding to the day of skid measurement, and

I_1 through I_5 = Indicator variables that account for the differences in the mean *SN* from one test pavement to other pavements.

The number of dry days prior to skid measurement was not statistically significant. No justification or clarification of the variables [sin (2π/365)] and I_1 through I_5 was presented. It is completely illogical that surface friction of a pavement type will vary with the difference in surface friction with other pavement types. Furthermore, pavement surface friction on a particular day of the year can only be estimated if the surface condition (e.g. texture, temperature, contamination) on that day is known in advance.

Data from 31 surfaces in Pennsylvania, Tennessee, and North Carolina showed that seasonal skid resistance variations are similar for all AC pavement mixes (Saito and Henry 1983). A declining trend from a maximum skid resistance in early spring to a minimum in late fall was observed. The skid resistance was then shown to rejuvenate approximately to the initial level in winter. Several equations were also developed for use in the general Penn State Model (Equation 3-20).

$$SN_V = SN_0 \exp[-(\frac{PNG}{100})V] \qquad (3\text{-}20)$$

Where,

SN_v = Skid number at velocity of V, km/h

SN_o = Intercept of skid number and speed correlation, and

PNG = Percentage Normalized Gradient, h/km

Equation 3-20 predicts the expected fall (low) SN from skid resistance measurements at any other time during the year. It was indicated that SN_o is related to pavement surface microtexture and it is a complex function of time and polish susceptibility. The PNG was indicated to be related to surface macrotexture that can be obtained from Equation 3-21.

$$PNG = (\frac{100}{SN}) * [\frac{d(SN)}{dV}] \qquad (3\text{-}21)$$

A regression model for the prediction of SN_0 of PCC pavement was given as:

$$SN_0 = -32.83 + 1.445BPN \qquad R^2 = 0.88\ (r = 0.938) \qquad (3\text{-}22)$$

Where,

SN_o = Intercept of skid number and speed correlation, and

BPN = British Pendulum Number

The SN_o represents the low speed skid resistance for use in Equation 3-20 together with PNG from Equation 3-21. Using Equation 3-22, the SN_o will be 68 for a measured BPN of 70 while the SN_o will be 25 for a BPN of 40. The difference in predicted SN_o will be 43 for a difference in BPN of 30. Further investigation is needed to examine the validity of the developed models that produce such unreasonable variation.

Oliver et al. (1988) monitored the seasonal variation of skid resistance on thirty asphalt and spray sealed pavements in Australia. Skid resistance was measured bi-weekly over two years. In general, rainfall pattern did not show any effect on long term average of skid resistance. The seasonal skid resistance variation was shown to take the shape of a sinusoidal curve with different amplitudes in different years. The authors could not identify the reason. In fact, the seasonal variation of skid resistance may not be adequately explained by the month or day of the year as it depends on pavement condition on the particular day/time of skid resistance measurement (Ahammed and Tighe 2009).

Kulakowski and Harwood (1990) examined the effect of water accumulation on pavement surface and found that a 0.05 mm (0.002 in.) thick water film can reduce the skid resistance of dry rough surface (good texture) by 20% to 30%. Alternatively, a 0.025 mm (0.001 in.) thick water film can reduce the skid resistance by up to 75% in the case of smooth (no texture) surface. An hourly rain of 0.25 mm (0.1 in.) is expected to produce pavement wetness exceeding the stated level.

Flintsch (2004) et al. studied the effect of temperature on skid resistance variation of seven asphalt pavements surfaces in Virginia. The skid numbers measured at different speeds using the skid trailer mounted with ribbed and smooth tires showed no to poor (R^2 value of 0.02 to 0.22), yet controversial (positive as well as negative) correlations with variation in pavement temperature. Such variation was sought to be due to the difference in actual surface condition of the pavements. The models for a mix containing 9.5 mm maximum size aggregate and PG 70-22 binder were given as:

$$SN_S(T) = (159 - 1.14T) * e^{\frac{-(2.27-0.02T)*V}{100}} \tag{3-23}$$

$$SN_R(T) = (118 - 0.73T) * e^{\frac{-(1.00-0.01T)*V}{100}} \tag{3-24}$$

Where,

$SN_S\ (T)$ = Smooth tire skid number at temperature T

$SN_R\ (T)$ = Ribbed tire skid number at temperature T

V = Vehicle speed in km/h, and

T = Temperature, °C

For a particular speed, Equation 3-23 (smooth tire) predicts an increase in skid resistance with an increase in temperature while Equation 3-24 (ribbed tire) predicts the reverse i.e., *SN* decreases with an increase in temperature. This calls for further evaluation of the models.

Bazlamit and Reza (2005) also studied the effect of temperature on ten AC surfaces skid resistance variation. The mix proportion, binder content, and aggregate type were found to be statistically significant for variation in the *BPN*. The sample to sample (briquette preparation) variation for the same mix was also shown to be statistically significant indicating that construction variation may significantly affect the available surface friction. Temperature was shown not to be statistically significant for unpolished surface skid resistance variation, but was shown to be significant (5% level) after some degree of polishing (Equation 3-25) and the reason was not clear.

$$BPN_T = 125.2508 - 0.232T \qquad R^2 = 0.99358 \qquad (3\text{-}25)$$

Where,

T = Temperature in Kelvin, and

BPN_T = *BPN* at temperature T

The developed model, however, did not accommodate the variations in mix type and surface texture although they were statistically significant. Equation 3-25 indicates that surface friction will decrease at 0.232 *BPN* for 1°K increase in temperature.

Song et al. (2006) examined the effect of surface age, highway location (urban or rural), traffic volume, temperature and rainfall on the variation of skid resistance of HMA surfaces in Maryland State. The surface friction was shown to decrease at 0.22 *FN* and 0.26 *FN* per year on rural and urban roads, respectively. Alternatively, the friction was shown to increase at 1.26 *FN* for every 2.54 mm (0.1 in.) increase in rainfall and decrease at 1.0 *FN* for every 0.56°C (1°F) increase in average daily temperature. With this trend, surface friction will drop from 50 *FN* to 0 *FN* (no friction) for temperature increase from 5°*C* to 33°*C* (28°C or 50°F change). As compared to the findings in other similar studies, such trend seems to be an overestimate of skid resistance variation due to temperature change.

3.4 Long Term Variation of Skid Resistance

Maynard and Weller (1970) as well as Franklin and Calder (1974) examined the effect of materials and traffic on brushed PCC pavements skid resistance change. The fine aggregate quality (abrasion and polishing) was found to be the major influencing factor. The resistance to abrasion and polishing was assumed the same as that of coarse aggregate from the same sources but this may not be true in most cases. The study found a difference of 20 *BPN* between the surfaces that contain the softest - most easily polished and the hardest - most polish resistant fine aggregates. In contrast, harder coarse aggregate and stronger concrete were shown to be associated with lower skid resistance. An increase in commercial traffic from 1,500 to 3,500 veh/lane/day was shown to reduce the skid resistance of 6 *BPN*.

Franklin (1988), however, found no correlation of fine aggregate abrasion resistance with skid resistance. Yearly measurements of SFC in the UK over ten years (1975-76 to1985-86) on brushed PCC surface had shown that most influential factor affecting skid resistance is the acid-soluble materials in fine aggregates. Fine aggregate containing 25% acid soluble materials has been shown to reduce the SFC of 0.11. It took 4 to 5 years to attain full skid resistance due to carbonate content in fine aggregates used for PCC mixes. The PSV of coarse aggregates was also shown to be significant where a difference in PSV of 25 had resulted in a difference in SFC of 0.05 after 10-year traffic exposure.

Leyder and Reichert (1974) monitored the performance of five PCC pavements in Belgium over ten years. Surfaces with chips embedded on fresh concrete and with a deep transverse groove had exhibited excellent SCRIM friction of 0.53-0.64 and 0.55-0.75, respectively, after ten years of traffic use.

Using 110 data points from eleven different PCC pavements in New York, Grady and Chamberlin (1981) estimated the decay of grooved texture. At 65 km/h (40 mph), the maximum *SN* was recorded to be 62.0 for a sand patch *MTD* of 1.70 mm (0.067 in.) whereas the lowest *SN* was recorded to be 34.8 for a *MTD* of 0.41 mm (0.016 in.). The passing lanes were shown to exhibit 9 to 22 *SN* higher skid resistance as compared to the driving lanes with a higher *MTD* of 0.10 mm (0.004 in.) to 0.23 mm (0.009 in.) indicating significant traffic related wear on the driving lanes. Pavement grooves of 4.76 mm (3/16 in.) width spaced at 19 mm (¾ in.) were found to wear at a mean rate of 0.33 mm (0.013 in.) per million vehicle passes. A *MGD* of 1.27 mm (0.05 in.) was found to be necessary to ensure a minimum acceptable level of skid resistance of 32 (*SN*). Models were also developed for skid resistance and macrotexture variation over time:

$$SN_{40} = 44.49 - 4.88(\log MGD) \tag{3-26}$$

$$SN_{40} = 18.33 + 17.15(\log MGD) \qquad (3\text{-}27)$$

$$\log SN_{40} = 1.64 - 0.13(\log CVP) \qquad R^2 = 0.79\ (r = 0.887) \qquad (3\text{-}28)$$

$$MTD = 0.037 - 0.0044mvp \qquad R^2 = 0.17\ (r = -0.410) \qquad (3\text{-}29)$$

$$MGD = 0.128 - 0.013mvp \qquad R^2 = 0.16\ (r = -0.406) \qquad (3\text{-}30)$$

Where,

SN_{40} = Skid Number at 40 mph

CVP = Cumulative Vehicle Passes, million

MTD = Sand patch Mean Texture Depth, in.

mvp = Million Vehicle Passes, and

MGD = Mean Groove Depth with depth gauge, in.

Equation 3-26 shows a consistent decrease in the predicted *SN* with an increase in *MGD* whereas Equation 3-27 shows the reverse trend (similar models also for *SN* at 55 mph). Such trends indicate that either pavement should be constructed without any surface texture or smooth tires should be used on textured surfaces for better skid resistance and safe driving.

Doty (1975) found a good positive correlation (Equation 3-31) between the ribbed tire and smooth tire skid numbers measured at 32 km/h (20 mph) to 97 km/h (60 mph) on deep textured, smooth and grooved PCC pavements. This further indicates that the negative correlations found by Grady and Chamberlin (1981) are not justified.

$$SN_R = 17 + 0.79SN_S \qquad r = 0.95 \qquad (3\text{-}31)$$

Where,

SN_R = Ribbed tire *SN*, and

SN_S = Smooth tire *SN*

Emery et al. (1982) developed models for long term skid resistance using three-year data from Highway 401 and Highway 7 in Toronto (Canada). The Marshall parameters (stability, flow and air voids) and equivalent traffic were shown to be statistically significant for the prediction of skid resistance of AC pavements. A model for dense graded surface course (HL-1) and dense friction course on Highway 401 was developed as:

$$SN_{100} = 0.714(MS) + 0.356(FLOW) + 1.048(VOIDS) + 40.904[EQT(F)^{0.081} - 17.323$$

$$r = 0.926 \qquad (3\text{-}32)$$

Where,

SN_{100} = Skid Number at 100 km/h (ASTM E-274)

MS = Marshall Stability

$FLOW$ = Marshall flow (0.25 mm)

$VOIDS$ = Air voids in mix, and

$EQT(F)$ = Equivalent Traffic (F = commercial vehicle equivalence factor)

Equation 3-32 shows that an AC mix with higher stability would exhibit higher skid resistance because of higher capability of the mix in resisting the coarse aggregate immersion in the matrix. The positive sign associated with *FLOW*, however, indicates that higher flow yield higher skid resistance which is in contrast to stability. The reason was not explained.

Dames (1990) tested the polishing resistance of various sands and evaluated its relation to skid resistance. Natural and five crushed sands (from basalt, granite, blast-furnace-slag, limestone, and alpine moraine) were subjected to polishing at the Technical University in Berlin. All sands, except limestone, were shown to maintain high polishing values from 0.79 to 0.59 whereas the limestone (marl) was shown to exhibit a poor polishing resistance value of 0.28. Six AC surfaces with 0/11 mm chipping and different sands were also constructed. After one year of construction, the pavement surfaces shown a similar variation in skid resistance with high skid numbers for five mixes and a very low value for the mix containing limestone sand (marl) resembling the laboratory polishing resistance. It was then concluded that the mortar component of the AC surface mix strongly influences the skid resistance while the degree of sharpness of the mortar surface is governed by the polishing resistance of fine sand (0.2/0.4 mm fraction). Accordingly, the Berlin Road Administration specified the minimum polishing resistance value of 0.45 for chipping and 0.60 for sand that will be used in surface layer on high-volume and high-speed motorway.

Diringer and Barros (1990) correlated the aggregate polish value with the skid resistance of five bituminous pavements in New Jersey. The model was given as:

$$SN_{terminal} = 12.4(1 - e^{-0.023PV}) + 1.15PV \tag{3-33}$$

Where,

$SN_{terminal}$ = Terminal Skid Number (ASTM E-274, Ribbed Tire), and

PV = Polish Value (using British Polishing Wheel)

The terminal skid value was defined as the *SN* of the pavements after two million vehicle passes. The paper mentioned that the skid resistance of the pavements varies predominantly due to day-to-day and seasonal weather changes after such level of traffic use. The authors recommended an 8 *SN* higher terminal skid resistance, to be conservative with respect to the prediction error and seasonal variability of skid resistance, to determine the desired PV of aggregates. For example, a *SN* of 43 will be used in Equation 3-33 for a desired terminal *SN* of 35. Accordingly, the minimum PV should be 32 for the aggregate to be acceptable.

Augustin (1994) carried out laboratory polishing of AC pavement surfaces containing dolomite and diabase chippings. Dolomite and diabase surfaces skid resistance were shown to decrease from 58 *BPN* to 46 *BPN* and from 67 *BPN* to 60 *BPN*, respectively, showing that diabase exhibits higher initial skid resistance and performs better under traffic as well.

Drakopoulos et al. (1998) presented a model, used by the Wisconsin Department of Transportation, for the prediction of transversely tined PCC pavement surface friction deterioration over time. The model was given as:

$$\ln(FN) = 3.99 - 0.0419\ln(LAVP) - 0.00129DOL + 0.00474HV\ln(FN) \tag{3-34}$$

Where,

FN = Friction (skid) Number at 60 km/h

LAVP = Summation of all vehicles expected to pass over design life of the pavements, million

DOL = Limestone, dolomite or ankerite content, % by weight of coarse aggregate Materials, and

HV = Percent of heavy vehicles in design lane, % of lane average daily traffic

The use of Equation 3-34 is limited to a single tine texture. Furthermore, the positive sign associated with *HV* indicates that skid resistance will increase with an increase in heavy vehicle on the design lane. Such variation seems to be unreasonable because heavy vehicles, with their higher weights and higher number of large tires, are expected to produce greater wear of the surface. Pavement surfaces therefore are expected to exhibit increased deterioration of available skid resistance. Ahammed and Tighe (2008b) also found that heavy vehicles cause loss of PCC pavement skid resistance over time and the rate of loss is greater than that caused by the passenger vehicles.

Rao et al. (1999) studied the performance of 193 rehabilitated PCC pavements in different US States. On five diamond ground sections, the smooth tire *SN* was shown to increase from 42 to 80 (90% increase), a significant improvement of safety. Another safety comparison between 30 diamond ground and 21 tined pavement surfaces showed that diamond ground surfaces exhibit 58% of the accident rate of tined surfaces under both dry and wet conditions. However, the paper did not mention what types of tines were used and whether all sections are located on the same highway. The service life of the ground surfaces was shown to be about ten years after which regrinding or other measures are required. Using the data from 35 sections, a regression model (Equation 3-35) for the longevity of diamond ground PCC pavements surface texture was also developed.

$$MTD = 0.887 - 0.152\,(1 + 0.233\,FREEZE)\ln(AGE) \qquad R^2 = 0.83 \qquad (3\text{-}35)$$

Where,

MTD = Mean Texture Depth, mm

FREEZE = A dummy variable (wet non-freeze or dry non-freeze = 0 and wet-freeze or dry-freeze = 1), and

AGE = Age since grinding, year

Gerritsen et al. (2004) presented the long term performance trend (Figure 3-1) over several years under traffic for different AC mixes in Netherlands. Exposed aggregate concrete and surface dressing were shown to exhibit high early skid resistance and experience continuous decrease with increased wheel passes. SMA, porous asphalt, and dense asphalt concrete exhibited low surface friction during the early age. The skid resistance of these surfaces were shown to increase until asphalt binder film is completely removed due to traffic movement. The skid resistance then decreases as the pavement surfaces begin to polish/wear. Overall, SMA was shown to exhibit better performance over the long term, although initial early life skid resistance may be an issue. In a Virginia study, Voigt and Wu (1995) found that concrete pavement textures wore by 25% to 35 % in first two to three years and stabilize after about two million of vehicle passes.

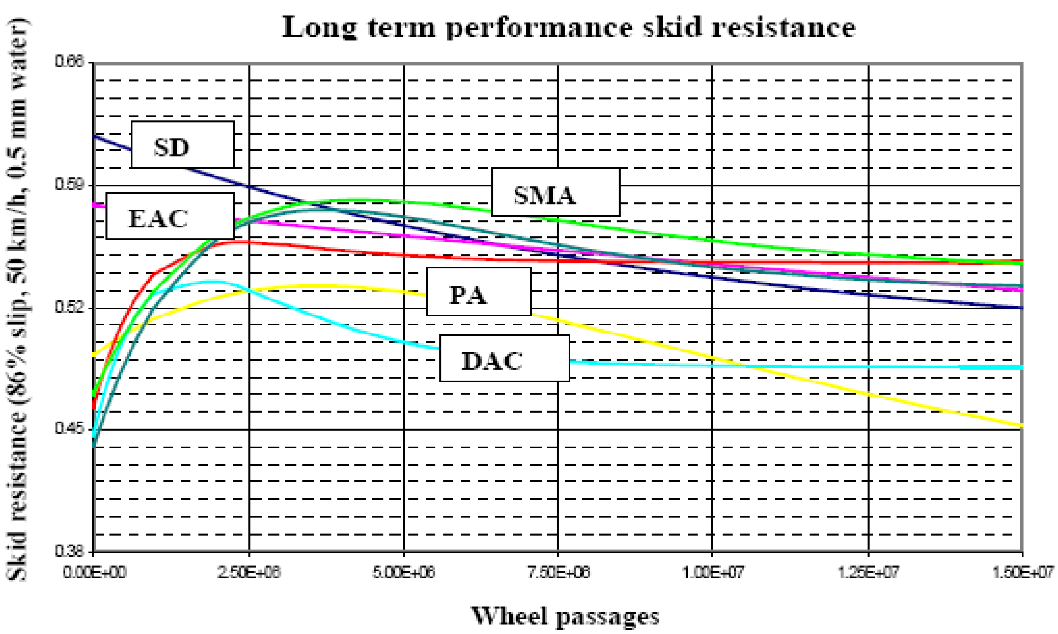

Figure 3-1 Long Term Skid Resistance Performance for Several Asphalt Surfaces in Netherlands (Gerritsen et al. 2004).

Awoke and Goulias (2008) developed a model (Equation 3-36) for AC pavements long term surface friction using 2000-2006 data of Maryland PMS.

$$FN = -1.576(X1) - 0.00022(X2) + 0.41014(X3) + 105.38 \quad (3\text{-}36)$$

Where,

FN = Friction Number (ribbed tire)

$X1$= Speed, mph

$X2$ = Annual Average Daily Traffic (AADT), and

$X3$ = Years since last maintenance of the pavement.

Equation 3-36 shows that surface friction decreases with an increase in vehicle's speed as well as AADT but increases with an increase in age of the pavement surface. Such increase in surface friction is counter intuitive to the general findings in other similar studies.

3.5 SURFACE TEXTURE, SAFETY (SKID RESISTANCE) AND NOISE

Rizenbergs (1976) found a good correlation of wet/dry pavement accident ratio (based on 3-year accident data) and skid resistance measured on 230 (217 AC and 13 PCC) pavements in Kentucky. The wet/dry pavement accident ratio showed a declining trend as skid resistance equalled or exceeded 41 SN_{64}. The wet/dry pavement accident ratio was shown to increase sharply from 0.23 to about 0.7 as the SN_{64} dropped below 41. The critical (desired minimum) ribbed tire SN_{64} therefore was considered 41 for reduced wet pavement accidents.

Mahone et al. (1977) examined the skid resistance and tire-pavement noise performances of eleven different surfaces of PCC pavements to select the optimum and durable surface texture considering the increased traffic and speed on the interstate highways in Virginia. The skid testing results indicated that tined surfaces experienced slight wear after four years of traffic exposure at 14,000 veh/day (AADT) and are expected to last for many more years. The study indicated that burlap drag alone does not produce the desired initial harshness for interstate highways and was shown to wear substantially with age (bald tire SN_{64} of 35 and 20 on passing and traffic lanes, respectively). The 19 mm spaced transversely tined surface was also shown to exhibit excellent skid resistance (bald tire SN_{64} of 47). Similar longitudinal tining was shown to exhibit bald tire SN_{64} of 33 to 36. The exposed aggregate surface was shown to provide good skid resistance (bald tire SN_{64} of 33) but with rapid wear potential. Sprinkled and exposed aggregate textures were also associated with considerable extra cost.

Alternatively, exposed aggregate, sprinkled and dimpled textures were shown to produce higher roadside (7.6 m off the road) noise (85.8 to 86.9 dBA at 77 km/h) compared to that of tined (79.6 to 82.5 dBA) and AC (78.8 to 79.2 dBA) pavements. Finally, considering skid resistance and noise, two textures were recommended for PCC pavements. They are: (1) transverse tining spaced at 19 mm (bald tire S*N* = 47 and interior noise = 60.8 dBA at 89 km/h) and (2) cross texturing of longitudinal (spaced at 19 mm) and transverse (spaced at 76 mm) tining (bald tire S*N* = 43, roadside noise = 79.6 dBA and interior noise = 62.3 dBA).

Franklin et al. (1979) measured the pass-by noise, surface texture and skid resistance of 34 surfaces in the UK. Pavement noise was shown to be a function of both texture depth and road surface type (brushed and grooved PCC, rolled AC and surface dressing). Noise was shown to correlate well with the percentage change in surface friction from 50 km/h to 130 km/h (skidding resistance index). The justification of such correlation was not provided. Furthermore, the friction index was shown to have both positive and negative values indicating that skid resistance increased for some surfaces but decreased for others with an increase in vehicle speed that is in contrast to established fact.

In another study in the UK by Nelson and Ross (1981), the pass-by noise at 70 km/h on open textured bituminous surfaces was shown to be 4 dBA lower for light vehicles and 3 dBA lower for heavy vehicles as compared to conventional bituminous surfaces. Based on measurements at sixteen sites, the study concluded that the noise reduction benefit is independent of pavement age, cumulative traffic passes or friction index.

O’Connor (1980), based on a study of thirteen PCC pavement surfaces in Minnesota, found that 38 mm (1.5”) and 76 mm (3”) tine spacing act differently than other spacing with a sharp drop in noise for 38 mm spacing. Therefore, Minnesota adopted 38 mm spaced transverse tining as a standard for PCC pavements. Voigt and Wu (1995), however, found that between 13 mm and 38 mm spaced transverse tines, 38 mm spacing produces audibly more intense and objectionable noise.

Burchett and Rizenbergs (1982) developed a correlation between the *SN* and two-year wet accidents (1976-1977) on two-lane roads in Kentucky (Equation 3-37). A minimum *SN* of 32 was recommended taking into account the service life and traffic volume because of deterioration over time/use. The benefit-cost analysis had shown that the benefit from accident reduction exceeds the cost of an overlay when an existing surface with AADT of greater than 5,000 exhibits *SN* of 35 or less. Overlay on an existing surface with *SN* of less than 30 was shown to be beneficial if the AADT is greater than 2,500. The OGFC was shown to provide the highest benefit/cost ratio.

$$Y = 16.0 + 10(1.92 - 0.027SN) \quad (3\text{-}37)$$

Where,

Y = Wet-pavement accidents as a percentage of total wet plus dry accidents (adjusted for 12 % wet time)

SN = Skid Number (ASTM E-274, Ribbed Tire)

Baran and Henry (1983) measured the tire-pavement noise for 22 sections in Pennsylvania and developed a large number of regression models for the prediction of skid resistance from near-field noise frequencies (2.915 to 6.785 kHz). The paper, however, did not justify the developed models. Another set of models were developed for far field noise correlating with the ribbed tire *SN*, blank tire *SN* and *BPN* (e.g. Equation 3-38). As all these three skid resistance values are function of surface characteristics (e.g. surface material and texture), they are highly correlated. Such models lack appropriate statistical model criteria because of the multicollinearity problem. Furthermore, the signs (+ or -) associated with the independent variables indicate that noise level will increase with an increase in bald tire *SN* but will decrease with an increase in both ribbed tire *SN* and *BPN*. The developed models therefore are considered logically incorrect and statistically inappropriate.

$$dBA_{48} = 2.03SN_{64}^{B} - 0.007SN_{64}^{R} - 0.039BPN - 14.27 \quad R^2\text{=0.14 } (r = 0.38) \quad (3\text{-}38)$$

Where,

dBA_{48} = Far field noise level at 48 km/h

SN_{64}^{B} = Blank tire *SN* at 64 km/h

SN_{64}^{R} = Ribbed tire *SN* at 64 km/h

BPN = British Pendulum Number.

Wielen (1989) tested the tire-pavement noise on 25 PCC pavement surfaces in South Africa. An increase in tine spacing from 27 mm to 40 mm had shown an increase in car pass-by noise of 4.5 dBA but increased spacing from 40 mm to 54 mm had resulted in a drop of 1.5

dBA. In case of cars, noise was shown to increase with an increase in skid resistance. However, no trend was observed for truck noise with skid resistance variation. The study also found that noise generated by a car on transversely grooved PCC surface with *MTD* of 0.2 mm is similar to noise generated on non-transversely grooved surface with *MTD* of 1.3 mm.

Two models (Equations 3-39 and 3-40) were developed in the US for wet weather accidents on high (89 km/h) and low (less than 89 km/h) speed roads, respectively (Griffin 1984, Wallman and Astrom 2001). Both models indicate that pavement surface friction is a significant factor for wet accident. Equations 3-39 (R^2 = 0.58) and 3-40 (R^2 = 0.46) indicate that wet accident will reduce by 4 accidents/mile/year on high and 0.25 accidents/mile/year on low speed roads, respectively, for each 10 *SN* increase of skid resistance.

$$WAR = -2.17 + 0.0009ADT + 2.34ACC - 0.40SN + 286TW + 1.32LN \quad (3\text{-}39)$$

$$WAR = -0.75 + 0.0001ADT - 0.053VM + 0.54V + 0.69ACC - 0.025SN \quad (3\text{-}40)$$

Where,

WAR = Wet pavement accidents per mile per year
ADT = Average Daily Traffic, veh/day
ACC = Access, a measure of traffic congestion
SN = Skid Number at 40 mph
TW = Proportion of Time Wet
LN = Number of traffic lanes
VM = Mean traffic speed (mph)
V = Standard deviation of speed distribution (mph)

Wagner (1994) found that different brands of car tires can result in up to four dBA variation in coast-by noise for cars driven in second gear. The study also found that under similar conditions of temperature, tire, road age, and vehicle, the drive-by noise in repeated measurements on the same pavement could differ by three dBA. It also indicated that for every 5°C drop in temperature from the standard 20°C, the measured noise should be corrected (increased) at a 0.5 dBA rate. Smit and Waller (2008), however, found no influence of temperature on noise. The effect of air temperature on near field noise was studied for 46

HMA at the National Center for Asphalt Technology (NCAT) in Alabama. The air temperature during the tests ranged from 50 °F to 86 °F (10 °C to 30 °C). Statistical ANOVA showed that the measured SPL are insensitive to changes in air temperature and it was concluded that no temperature correction is needed for all practical applications.

In studies in Denver, Colorado Ardani (1996) as well as Ardani and Outcalt (2005) found that semi-truck (18-wheelers) produce 7 dBA greater road side (7.5 m off the road, at 105 km/h) noise than cars on burlap drag plus uniform 25 mm spaced transversely tined PCC surface (control section, state standard). The surface with randomly spaced transverse tining over astroturf drag exhibited the highest road side noise (1 dBA louder than the control section) with ribbed tire SN_{64} of 69 among nine test sections. The surface with longitudinal astroturf drag was shown to be 6 dBA quieter than the control section with the lowest SN_{64} of 52. The surface with 19 mm longitudinal tining over astroturf drag was shown to be 4 to 5.5 dBA quieter than the control section. Considering surface friction and noise, longitudinal tine texture was recommended for PCC pavements. Further study by Ardani (2007) had shown that PCC surfaces skid resistance drop significantly between the first and second year and remain unchanged after the second year.

In Arizona, Henderson and Kalevela (1996) found that roadside noise from tined and grooved PCC surfaces are 3.3 to 5.7 dBA and 0.2 to 2.1 dBA, respectively, greater than that from Asphalt Rubber Asphalt Concrete Friction Course (ARACFC) overlay on PCC. Four-year old ARACFC surfaces were shown to produce 0.6 to 1.5 dBA greater roadside noise than the new ones. Six to 8-year old ground surfaces were shown to produce 1.5 to 1.8 dBA greater road noise as compared to newly ground surfaces. Traffic noise measurements at nearby residential locations adjacent to the Ontario Provincial Highway 401 also showed that the differences in sound levels between AC and PCC surfaces are about 2 to 3 dBA *L*eq (24 hr) (Hajek et al. 2008).

Kuemmel (1997) studied the skid resistance and noise performances of twelve PCC and four AC pavements in Wisconsin and Minnesota. Exterior noise was measured at 7.6 m (25 ft) off the pavement centerline (1.5 m above pavement surface) for a car traveling at 96 km/h (60 mph). The 13 mm tine was shown to produce the lowest exterior noise (L_{max}) of 78.0 dBA among the tined (uniform 13 mm, 18 mm, 25 mm and 38 mm transverse, random 10 mm to 40 mm straight and skewed transverse, and 25 mm longitudinal over 150 mm transverse) PCC surfaces with a ribbed tire SN_{64} of 53. Superpave AC was shown to produce the lowest noise among tested PCC and AC (including 9.5 mm SMA, 16 mm SMA, and dense asphalt) surfaces with exterior L_{max} of 76.5 dBA and SN_{64} of 45. Plastic broom textured PCC surface was shown to produce exterior L_{max} of 77.2 dBA with SN_{64} of 39. The PCC surface with uniformly spaced tining was shown to produce low frequency interior noise whine whereas the surfaces with 10 mm to 40 mm randomly spaced tining was shown to produce the lowest whine among the tested surfaces.

Drakopoulos et al. (1998) compared the 6-year (1988-1993) crash rates on 30 continuously ground (290 km) and 21 transversely tined (115 km) PCC pavements in Wisconsin. Overall, 86 and 135 crashes per 100 million vehicle-km of travel were recorded on ground and tined sites, respectively i.e., ground PCC surfaces were shown to experience only 60% of the crashes when compared to the tined surfaces.

Mcnerney et al. (1998) measured the CPX and roadside noise for 15 sections of new as well as aged AC and PCC pavements in Texas. The roadside noise ranged from 79.5 dBA for aged Novachip to 86.0 for grooved AC. The CPX L_{max} ranged from 101.7 dBA for aged Novachip to 109.7 dBA for aged AC. Ungrooved or untined PCC pavements were shown to produce 81.9 to 82.4 dBA at roadside and 104.2 to 105.4 dBA CPX L_{max}. Aged and new PCC pavements with tine/groove were shown to exhibit roadside and CPX noise of 83.8 to 84.4 dBA and 106.3 to 107.8 dBA, respectively.

Wayson (1998) prepared a comprehensive report on tire-pavement noise and concluded that in general PCC pavements have advantages with respect to durability and surface friction over dense AC pavements. However, PCC pavements produce higher roadside noise where the uniform 26 mm (1 in.) transverse tining generates the most annoying noise. Longitudinal tined PCC surfaces produce lower noise as compared to transversely tined surfaces but at a cost of reduced surface friction. In Europe, an exposed aggregate top layer (8 mm maximum size) was shown to produce 5 dBA less noise when compared to a transversely tined PCC surface. However, US studies did not found noise reduction with exposed aggregate (about 1 dBA reduction only). The reason was not quite clear (likely a variation in construction).

Wayson (1998) also found that porous AC and PCC pavements provide noise reduction but cause great concern over plugging of voids, deterioration with freezing/thawing and effectiveness of de-icing. Dense graded AC surfaces were 2 to 3 dBA quieter than the quietest conventional PCC surfaces but with lower skid resistance and durability. The report indicated that open-graded AC pavements can reduce the pass-by noise from 1 to 9 dBA when compared to dense-graded AC pavements, but such noise reduction benefit diminishes in 5 to 7 years. Finally, the report indicated that construction quality plays an important role in noise and skid resistance performance regardless of pavement type.

Herman et al. (2000) measured the Statistical Pass-By Index (SPBI) for 1 to 7-year old ten AC and two PCC pavements in Ohio. One-year old open graded AC (82.2 dBA) and random transversely grooved PCC (88.9 dBA) surfaces were shown to be quietest and loudest pavements, respectively. Dense AC surfaces (1 to 7-year old) produced SPBI of 84.5 to 86.4 dBA whereas a 3-year old SMA (louder than dense AC) exhibited SPBI of 86.8 dBA.

Lancieri et al. (2000) measured the sound absorption and tire-pavement noise for three porous pavements. Double layer (25 mm 0/10 over 40 mm 0/18) porous pavement (PA) was shown to be 3.3 dBA (sound absorption coefficient of 0.39) quieter than the single layer (40 mm 0/18). The 4-year old (0/18) PA was shown to be 1.7 dBA louder than a similar new one.

In a Wisconsin study, Kuemmel et al. (2000b) summarized the tire-pavement noise of Fifty seven 3 to 17-year old AC and PCC pavements in six US States. The Wisconsin standard AC pavement (Std. ACP) was shown to be the quietest in terms of both road-side and in-vehicle noise. Transversely tined PCC pavement (PCCP) was shown to be the loudest with respect to exterior noise while abraded and milled PCCP were shown to be loudest with respect to in-vehicle noise i.e., the variations of in-vehicle and pass-by noise were not identical. Longitudinal tined surfaces were shown to be quieter among the PCC pavements with pass-by noise levels just 0.7 to 1.8 dBA (at 97 km/h or 60 mph) on average, greater than the SMA. The skid resistance of longitudinal tined PCC surfaces (bald tire SN = 54) was, however, shown to be substantially higher than that of SMA (bald tire SN = 32). Jaeckel et al (2000) also mentioned that longitudinal tined PCC is similar to or quieter than some AC pavements. However, no conclusive relationship was found among the noise level, skid resistance, texture depth, tine width, and tine depth.

Schlaefer and LaForce (2001) measured the pavement noise and skid resistance of four pavements in Colorado that include longitudinal and transversely tined PCC, 6.35 mm (1/4") deep ground PCC and 9.5 mm (3/8") SMA. The pass-by noise (at 7.6 m) were shown to be 75 dBA, 82 dBA, 76 dBA and 74 dBA, respectively with ribbed tire *SN* of 43.3, 43.5, 47.6 and 51.5, respectively. It shows that the SMA surface exhibited the highest skid resistance with the lowest pass-by noise contrasting the Wisconsin result mentioned above. After diamond grinding of transversely tined PCC, the pass-by noise was shown to reduce by 6 dBA while the skid resistance was shown to increase by 4.1 *SN*.

In-vehicle noise from regular Hot Laid (HL), Open Friction Course (OFC) and Microsurfaced (MS) asphalt pavements on Ontario Provincial Highway 416 near Ottawa was measured in 2002. The results showed that OFC is 1.1 dBA and MS is 3.9 dBA louder than the HL pavement (Leq = 68.8 dBA) (Blaney 2003). In 2004 i.e., after two years, all three pavements were shown to exhibit similar in-vehicle noise (Leq = 68.3 to 68.4 dBA) (Blaney 2004). The possible reasons were mentioned to be a difference in truck/tire combination, air temperature and aging of the surface. It seems that no attempt was made to isolate the noise testing vehicle from the surrounding traffic stream.

Burgé et al. (2002) compared noise and skid resistance performance of longitudinal diamond ground (LDG) and random transversely tined (TT) PCC pavements on I-190 in Buffalo, New York. The LDG surface was shown to produce 2 to 5 dBA, depending on the traffic mix, lower noise than the TT surface. The result, however, shows that traffic mix influences the measured or predicted noise levels, and therefore the SPBI may not be an appropriate measure for comparison of noise performance to different pavements.

The LDG was shown to exhibit higher initial skid resistance than the TT surface with a smooth tire *SN* of 42 and 33, respectively. After one year of traffic use, they were 35 *SN* and 32 *SN*, respectively, showing that the ground surface has lost 7 *SN* whereas the tined surface has lost 1 *SN* in one year. This seems to be unrealistic. The ribbed tire initial skid numbers were shown to be identical with average *SN* of 45 on LDG and 44 on TT surfaces both having identical *MTD* of 0.58 mm. The ribbed tire skid numbers were shown to remain identical after one year with *SN* of 42 and 44 on LDG and TT surfaces, respectively. Despite such results, the authors mentioned that the ribbed tire *SN* represents the microtexture while smooth tire *SN* is related to macrotexture.

Chandler et al. (2003) measured the noise, texture and surface friction of exposed aggregate concrete (EAC) on UK motorways for five years and compared the measured noise with hot rolled asphalt (HRA). The SCRIM (at 20 km//h) coefficient (SC) on EAC surfaces ranged from 0.43 to 0.51 (as compared to 0.54 to 0.56 on HRA) with no significant changes in texture or skid resistance over the 5-year period. Statistical pass-by (SPB) noise on 10-6 mm EAC was 1.7 dBA lower for light vehicles (at 110 km/h) and 1.3 dBA lower for heavy vehicles (at 90 km/h) as compared to similar HRA. The 14-8 mm EAC was shown to exhibit similar noise as the HRA. The SMA, Superpave (SP) 10 mm and SP14 mm were shown to be 4.9, 1.3 and 0.9 dBA, respectively, quieter for light vehicles while 3.7, 2.5 and 1.4 dBA, respectively, quieter for heavy vehicles as compared to the HRA. The EAC and HRA were shown to experience 1.5 dBA and 2.6 dBA, respectively, increase after 82 months. The SMA had shown an increase of 2.0 dBA in 34 months. The SP10mm and SP14 mm had shown an increase of 1.5 dBA in 38 months and 2.1 dBA in 42 months, respectively. The results indicated that SMA is the quietest pavement and expected to remain quieter for a long period despite slightly higher noise deterioration over time.

The State of Arizona has adopted a new diamond grinding concept, known as whisper grinding, which produces low texture surfaces for PCC pavements. These surfaces were shown to be the quietest and smoothest PCC pavement in Arizona’s history (possibly quietest in the whole US). Overall, the CPX noise was shown to be three dBA lower on newly ground surfaces, with expectation of further noise reduction after some traffic use, as compared to the 19 mm (3/4”) longitudinal tined surface. The roughness was shown to reduce by 58% while the surface friction was shown to increase by 27% (Scofield 2003).

Boscaino et al. (2004) found that macrotexture positively influences the sound absorption i.e., sound absorption increases with an increase in texture and negatively influences the skid resistance i.e., skid resistance decreases with an increase in texture. The *BPN* and sound absorption coefficient of 0/10 SMA were shown to vary from 60 to 72 and 0.06 to 0.10, respectively. For 0/15 SMA, they ranged from 58 to 68 and 0.06 to 0.12, respectively. The paper, however, concluded that more research is needed to find the actual correlation.

Crocker et al. (2004) measured the sound absorption and tire-pavement CPX noise of six dense AC (Superpave and SMA) and two OGFC mixes. The SMA showed a peak sound absorption coefficient of 0.12 with a CPX noise of 94.6 dBA and Superpave mixes showed peak sound absorptions of 0.06 to 0.07 with the CPX noise from 90.9 to 94.6 dBA. The 50.8 mm and 25.4 mm thick OGFC showed peak sound absorptions of 0.8 and 0.92, respectively, which seems to be unreasonable.

Gerritsen et al. (2004) compared the noise and skid resistance of Porous Asphalt (PA) with that of traditional Dense Asphalt Course (DAC) with 0-16 mm aggregates. Noise reduction of up to 7 dBA (at 80 km/h) with 2-6 mm PA and 5.5 dBA with 4-8 mm PA on top of 11-16 mm PA layer were possible as compared to the DAC. However, the initial low skid resistance on dry as well as wet pavements and ravelling were concerns for such PA. Experimental post treatment included 1-3 mm chipping and 0-3 mm crushed slug applied on hot (40°C to 80°C) PA surfaces. The chipping improved the wet surface friction from 0.43 (untreated PA) to 0.49. The crushed slug improved the wet surface friction to 0.53-0.55 (at 50 km/h). However, shorter service life of the PA, 6-10 years as compared to 12-20 years for DAC and 15-20 years for SMA, and the durability of texture remained the concerns.

Hanson and James (2004) measured the tire-pavement noise of eighteen PCC and AC pavements in Colorado. The OGFC surface was shown to be the quietest AC pavement with CPX noise of 95.3 dBA. An 11-year old transversely tined PCC pavement was shown to produce the highest CPX noise 102.6 dBA. A longitudinal tined surface was shown to produce the lowest CPX noise of 97.5 dBA among PCC pavements. No texture information, however, was provided.

Olek et al. (2004) studied the influence of PCC textures on tire-pavement noise using the drum method. No significant difference in noise levels were observed for variations in the tine edge geometry (rectangular, curved and bevel). The surfaces with astroturf, transverse broom and longitudinal broom finishes were shown to produce similar noise. Good correlations were found between noise and tine width (Equation 3-41), skid resistance and texture depth (Equation 3-42) as well as noise and skid resistance (Equation 3-43). Noise was shown to increase with an increase in both the tine width and skid resistance. The *DFT* was shown to be insensitive to texture direction with poor correlation with the texture depth.

$$S = -0.0299w^2 + 1.577w + 96.945 \qquad R^2 = 0.9935 \qquad (3\text{-}41)$$

$$BPN = 54.083d + 51.808 \qquad R^2 = 0.9975 \qquad (3\text{-}42)$$

$$S = -0.0049(BPN)^2 + 0.8671BPN + 67.883 \qquad R^2 = 0.9999 \qquad (3\text{-}43)$$

Where,

S = Overall noise levels at 48 km/h, dBA

w = Transverse tine widths, mm

BPN = British Pendulum Number

d = Texture depths (with laser profilometer) for astroturf, magnesium trowel, transverse broom and longitudinal broom finishes, mm

Bennert et al. (2005) measured the CPX noise on 42 sections of AC (DGA, OGFC with and without rubber crumb, SMA, NovaChip and Microsurfacing) and PCC (diamond ground, transversely grooved, transversely tined and broomed) surfaces in New Jersey. The average noise on AC was shown to be 98.5 dBA (at 96.5 km/h) as compared to 102.6 dBA on PCC surfaces. AC mixes with smaller maximum size aggregate (9.5 mm) was shown to produce lower noise than mixes with larger aggregates (12.5 or 19 mm). The OGFC modified with crumb rubber and 12.5 mm SMA mixes were shown to generate the lowest and the greatest noise of 96.5 dBA and 100.5 dBA, respectively, among the AC pavements. Alternatively, the diamond ground and transversely tined surfaces were shown to produce the lowest and the greatest noise of 98.7 dBA and 106.2 dBA, respectively, among the PCC pavements. Tire-pavement noise was shown to increase at 1.8 dBA for every 16 km/h (10 mph) increase in vehicle speed.

Donavan (2005) presented the summaries of tire-pavement noise levels on various pavements in California/Arizona and typical European pavements. Noise level was shown to vary widely even within the same pavement type. In general, rubberized and open graded asphalts had shown to be quieter than other surfaces.

García and Mérida (2005) developed a model (Equation 3-44) for 15-minute equivalent noise based on noise measurement for twelve pavements in Valencia City (Spain). The paper did not provide any information of the constant for various pavements. In addition, the sign associated with speed indicates that noise level will decrease with an increase in vehicle speed that is counterintuitive to reality. The study also indicated that increased asphalt thickness of 2 cm or 3 cm has no significant effect in sound absorption. A thickness of 6-10 cm is needed for acoustic advantage but it is not economical.

$$L_{eq15} = 62.116 + 3.41777\log(V_{15}) - 1.52647\log(S_{15}) - C_{PAV} \qquad R^2 = 0.8154 \quad (3\text{-}44)$$

Where,

L_{eq15} = Equivalent noise level for fifteen minutes
V_{15} = Traffic volume for fifteen minutes
S_{15} = Average speed for fifteen minutes, and
C_{PAV} = Constant corresponding to each type of pavement

MacDonald and Tighe (2005), and Leung and Tighe (2007) measured the noise for four different AC surfaces in Waterloo (Ontario) that include Rubber-modified Open Friction Course (ROFC), Rubber-modified Open Graded Course (ROGC), SMA, HL3 (regional standard). The pass-by and CPX noise were measured using thirteen different vehicles at 60 to 90 km/h after closing the road for traffic. In the CPX test, the SMA was shown to produce 1.1 dBA lower for medium size and 1.6 dBA higher for light vehicles as compared HL3. ROFC and ROGC had shown the greatest noise reduction of 2.5 dBA and 2.8 dBA, respectively, for medium size vehicles with only 0.8 dBA and 1.1 dBA, respectively, reduction for light vehicles. In pass-by measurements, the L_{eq} of both ROFC and ROGC surfaces was shown to be 2.5 dBA lower than that of the HL3 surface. Leung et al. (2006) measured the sound absorption of these mixes. The ROFC and ROGC were shown to absorb 9% to 10% while HL3 and SMA were shown to absorb 8% and 6% of sound, respectively.

A 2005 study of SPB traffic noise for different pavement surfaces in MTO's Eastern Region had shown that the average noise levels are similar (72 dBA) for Microsurfaced (MS), HL-4, HL-1, Double Seal Coat (DSC) Class 6, and HL-1 Ultrathin asphalt pavements for cars travelling between 80 and 90 km/h. The DSC Class 1 was shown to be 3 dBA louder than other surfaces (Golder 2006). Measured noise levels in 2006 for the same pavements did not agree with that in 2005. These led to a conclusion that there is no clear association of SPB noise levels and surface ages or number of traffic passes. However, the in-vehicle noise was shown to decrease with age or number of traffic passes. A 1-year old HL-1 ultrathin (Leq = 58.3 dBA) was shown to be 2.7 dBA quieter than a 1-year old HL-1 (Leq = 61.0 dBA) while a 1-year old MS (Leq = 67.2 dBA) was shown to be 6.2. dBA louder than HL-1. A 3-year old MS was shown to be 5 dBA quieter than a 1-year old MS. A 4-year old DSC (Leq = 63.0 dBA) was shown to be 7.8 dBA quieter than a new DSC (Leq = 70.8 dBA) (Golder 2007).

It should be noted that the SPB method uses existing traffic stream and different ranges of speed (speed bins) for traffic noise determination at different sites. It may not accurately compare the noise contribution of different pavements rather it provides an input for a noise abatement decision for a individual site. The in-vehicle noise level may also be influenced by passing or opposing vehicles as no attempt was made for isolating the test vehicle from the traffic stream.

McDaniel and Thornton (2005) compared the skid resistance and tire-pavement noise of Porous Friction Course (PFC) with that of SMA and Superpave on I-74 near Indianapolis. The PFC had 23.1% air voids while both SMA and Superpave had 4% air voids with the same aggregate and binder. On average, Superpave and SMA surfaces were shown to produce 3.5 dB and 4.7 dB, respectively, higher CPX noise (at 72 km/h and 97 km/h) as compared to the PFC surface. The pass-by noise (at 80 km/h) from Superpave and SMA were 4.2 dB and 5.9 dB, respectively, higher than the PFC. The *MPD* (with CTM) was 1.37 mm, 1.17 mm and 0.30 mm while the *IFI* (at 60 km/h) was 0.36, 0.28, and 0.19 for PFC, SMA, and Superpave, respectively. The results showed a good correlation of skid resistance and surface texture. The Superpave was shown to be 1.7 dB quieter than the SMA but with substantially lower surface texture and skid resistance.

Neithalath et al. (2005) examined the effectiveness of Enhanced Porosity Concrete (EPC) in sound absorption. EPC was produced using gap-graded coarse aggregate and eliminating or reducing the sand volume in the fresh mix that leaves a network of interconnected pores in the hardened concrete. Three coarse aggregate sizes that include #8 (minus 4.75 mm to plus 2.36 mm), #4 (minus 9.5 mm to plus 4.75 mm) and ⅜ in. (minus 12.5 mm to plus 9.5 mm) as well as some blends of two aggregate sizes were used to produce the EPC. The porosity of concrete varied from 15% to about 33%. Blends of 75% #4 with 25% #8 and 50% #4 with 50% #8 aggregates were shown to be the most effective in absorbing the sound with an absorption coefficient of approximately 0.80 as compared to normal concrete absorption coefficient of 0.03 to 0.05. For the same porosity, smaller pores were shown to be more effective in sound absorption than large pores (large size aggregates).

Scofield and Donavan (2005) presented preliminary results of the quiet pavement project in Phoenix (Arizona). The study found that pavement type is a matter for noise generation. The differences in CPX noise, measured at 97 km/h (60 mph), among pavements was up to 13 dBA. This is equivalent to a noise reduction with 6.1 m to 7.6 m (20 to 25 ft) high walls, assuming a 4 dBA reduction per 1.8 m (6 ft) to 2.4 m (8 ft) wall. Asphalt rubber friction course (ARFC) had shown average noise reductions of five dBA at nearby residences and 7 to 9 dBA at 15 m (50 ft) away from the road as compared to standard (uniform 25 mm spaced) transversely tined PCC surface.

Carter and Gardiner (2006) measured the CPX noise on nineteen AC and PCC pavements in Quebec that included three bituminous surface treatments on HMA, six dense graded HMA, one SMA and nine PCC pavements with longitudinal tined, transversely tined, chemical sprayed and dragged textures. Tire-pavement noise was shown to increase on surface treated HMA and decrease on some dense HMA with a decrease in *MTD*. However, no correlation was found between the *MTD* and noise for some other HMA sections. The noise levels were shown to vary from 93 to 103 dBA for similar surfaces with a *MTD* from 0.4 mm to 0.6 mm. All these indicate that tire-pavement noise generation and the propagation mechanism are not something simple. More close study is needed to understand these aspects.

In a study in New Zealand, Dravitzki (2006) found that different pavements have noticeable difference in noise levels even at 50 km/h speed. The difference in noise levels between the quietest bituminous seal and the loudest chip seal were shown to be seven dBA for light vehicles and four dBA for heavy vehicles.

Herman et al. (2006) found that the reconstruction of an existing AC pavement on I-76 in Ohio with random space transversely tined PCC pavement has created objectionable noise at a distance up to 800 m (2600 ft) from the roadway. The PCC surface was then retextured through diamond grinding and the traffic noise before and after ground was compared. The ground surface had shown average noise reduction of 3.5 dB at 7.5 m (25 ft) and 3.1 dB at 15 m (50 ft) with no conclusive evidence of noise variation at 800 m from the travel lane.

Pouliot et al. (2006) examined the variation of tire-pavement on-road noise with pavement age. Two-year old and less HMA surfaces in Quebec (Canada) were shown to produce 105.1 to 108.2 dBA. Alternatively, for 7 to10-year old HMA's, the noise levels were shown to vary from 109.3 to 109.9 dBA. Five-year old and less PCC pavements were shown to produce 108.8 dBA (abraded) to 111.4 dBA (10 mm deep transverse tine). A correlation between the PCC pavement surface texture and standard CPX noise was developed (Equation 3-45) that shows an increase in noise level with an increase in texture depth.

$$SPL = 95.75 + 6.82MTD \qquad R^2 = 0.73 \qquad (3\text{-}45)$$

Where,

SPL = Sound Pressure Level in dBA with standard CPX method, and

MTD = Mean Texture Depth (mm).

Treleaven et al. (2006) examined the noise performance of Asphalt Rubber Concrete (ARC) pavement in Alberta (Canada). The ARC was produced with gap-graded aggregates, less than 2.5% fines and 7.5% to 8.5% rubber modified asphalt binder as compared to 5% to 6% in conventional AC pavement (ACP) mixes. The special aggregates and rubber blending resulted in a 50% higher cost as compared to the ACP. However, the average cost per km of an ARC overlay was half the cost of a conventional 4 feet high noise barrier. Reduction in *L*eq (26h) noise with ARC was shown to be -0.2 to 2.4 dBA as compared to the ACP. The study concluded that concerns over durability of the surface, uncertainty in noise reduction benefit over time and higher cost might make ARC an unfavourable choice.

Mark et al. (2007) presented the noise test results for a thin (less than 1 in.) Asphalt Rubber – Asphaltic Concrete Friction Course (ARACFC) placed over an existing PCC pavement in Arizona. The overlaid pavement was shown to be 4 to 6 dB quieter than the existing PCC surface for noise measured in the neighbourhood. Sachakamol and Dai (2007) measured tire-pavement noise of twelve AC and Asphalt Rubber Concrete (ARC) pavements in Saskatchewan with a custom built CPX trailer. New ARC and old AC with a recent flush coat were shown to be the quietest (90.6 dBA) and loudest (97.2 dBA) pavements, respectively. New and newer AC pavements were shown to exhibit 91.0 and 91.4 dBA respectively. Alternatively, a very old rough AC was shown to exhibit 91.7 dBA.

Ongel et al. (2007) presented the results of noise and skid resistance measurements on 23 AC pavements in California. Rubberized mixes were shown to exhibit a 6-7 *BPN* lower skid resistance as compared to the non-rubberized mixes. Dense-graded asphalt was shown to exhibit the highest *BPN* of 63 while the gap-graded rubberized asphalt was shown to exhibit the lowest *BPN* of 52. Rubberized open-graded asphalt (OGA) was shown to be the quietest pavement among the tested surfaces. The non-rubberized OGA showed a high variability in measured sound (OBSI) levels. The noise levels were shown to decrease consistently with an increase in texture *MPD*, which is somewhat counterintuitive to general findings.

A study in Washington had shown that 1-year old Asphalt Rubber modified Open-Graded Friction Course (OGFC-AR) and Styrene-Butadiene-Styrene polymer modified Open-Graded Friction Course (OGFC-SBS) with 9.5 mm (3/8 in.) aggregate are 1.5 and 3.3 dBA, respectively, quieter than the conventional HMA with 12.5 mm (½ in.) aggregate. The OBSI levels of OGFC-AR, OGFC-SBS, and HMA pavements were shown to increase, on average, by 4.9 dBA, 2.8 dBA and 2.5 dBA, respectively, in a 1-year period (Anderson et al. 2008).

Munden et al. (2008) reported a variation in OBSI of up to 8.3 dBA within the same section of OGFC-AR. The average SN_{64} were shown to be 55.5, 53.9, and 55.4 on OGFC-AR, OGFC-SBS, and HMA, respectively. The durability of these modified OGFC mixes became an issue for Washington's climate conditions and studded tire use. Ahammed and Tighe

(2008i) also found that although open graded mixes were quieter during the first year of construction, the noise reduction properties diminished in just three years. Tests after three years showed that SMA is the quietest pavement with excellent skid resistance properties.

Lyon and Persaud (2008) studied the impact of pavement surface friction improvement on highway safety. The surface friction was measured as part of the New York State skid related accident reduction program. Sections with a high proportion (35-40%) of wet-road accident and/or low surface friction (*SN* <32) were treated with hot mix asphalt resurfacing or microsurfacing. Analysis had shown a high cost-effectiveness for safety treatment of both intersections and road segments that warranted skid resistance improvement.

Nelson et al. (2008) measured the acoustical absorption coefficient for over 140 pavement cores using the impedance tube. The sound intensity levels for the corresponding sections were also measured in the field. The sound intensities on open graded asphalt concrete (OGAC) were shown to increase with an increase in sound absorption at 500 Hz, 630Hz, and 800 Hz. Alternatively, the sound intensities on OGAC pavements were shown to decline with an increase in sound absorption at 1,250 Hz and 1,600 Hz. At 1,000 Hz, the correlation was nil. The dense graded and gap graded asphalts had shown a decline in sound intensities with an increase in sound absorption over all frequency bands. The presented results therefore would mean that the OGAC is not beneficial for low frequency noise reduction.

Pardillo-Mayora and Jurado-Pina (2008) examined the effect of SCRIM skid resistance levels in wet accident reduction based on data collected from 1,750 km of two-lane rural roads in Spain. A significant difference was found in mean wet pavement crash rates between segments with an average SCRIM coefficient above and below a threshold value of 55. Both tangents and curves with a radius equal to or less than 500 m had shown similar performance. Improved pavement surface friction from a mean SCRIM value of less than 50 to a value above 60 had resulted in an average 68% reduction of wet pavement crash rates.

Rasmussen (2008) and Rasmussen et al. (2008a) presented the results of OBSI and CPX noise tests on 31 pavements and SPB noise tests on seven pavements in Colorado. In general, a wide variation in measured noise levels was observed for both AC and PCC pavements. No discussion was presented for such variation but it was indicated that additional measurements in future would be required to evaluate noise variation over time. Good correlation was found between the CPX noise and OBSI levels (OSBI 2.0 dB greater than the CPX). The trends for SPB versus the OBSI or CPX levels were, however, scattered indicating that low near-field noise does not necessarily mean a low pass-by noise.

3.6 PCC CONSTRUCTION AND FINISHING ISSUES

Kuemmel et al. (2000b) found a substantial variation in as-built textures from specifications across the US and emphasized that a good quality control of tine spacing, depth, and width is essential if a national guideline is to be developed. Rasmussen et al. (2008b) summarized the best construction practices for achieving low noise PCC surfaces. It mentioned that better practices for improving the surface performance are dependent on the control of conventional texturing techniques practices and materials. It is not about designing or building “innovative” surfaces. According to Scofield and Smith (2006), understanding of the construction variability and performance of the existing textures for implementation of textures that produce lower noise without reducing surface friction and safety is essential to develop quieter PCC pavements.

The variables that influence the PCC surface texture performance are materials, climate, and construction (Figure 3-2). The overlapping area of these three major variables represents the optimum conditions and it depicts the required control of influencing factors for optimization of PCC surface texture. As no control on climate may be possible, control measures should focus the materials and construction practices (Rasmussen et al. 2008b).

Taylor et al. (2006) mentioned that it is important to apply the texture as uniformly as possible to produce uniform surface friction and noise levels regardless of the technique used. The paper also listed the factors that influence the variability in texture. These include: consistency of concrete properties (workability), time of texturing (related to concrete placement), presence of bleed water on the fresh concrete surface, total pressure and variability of pressure on the texturing tools, evenness of the tools on the surface, tining angle and cleanliness of the burlap, turf or tines. It further indicated that the texture depth primarily depends on both the time at which the texturing tool is applied (relative to when the concrete was placed and finished) and the amount of pressure applied to the texturing tool. It is therefore important to determine the optimum time to begin texturing and the amount of pressure required to achieve the desired depth and then consistently apply the texture at that time and pressure.

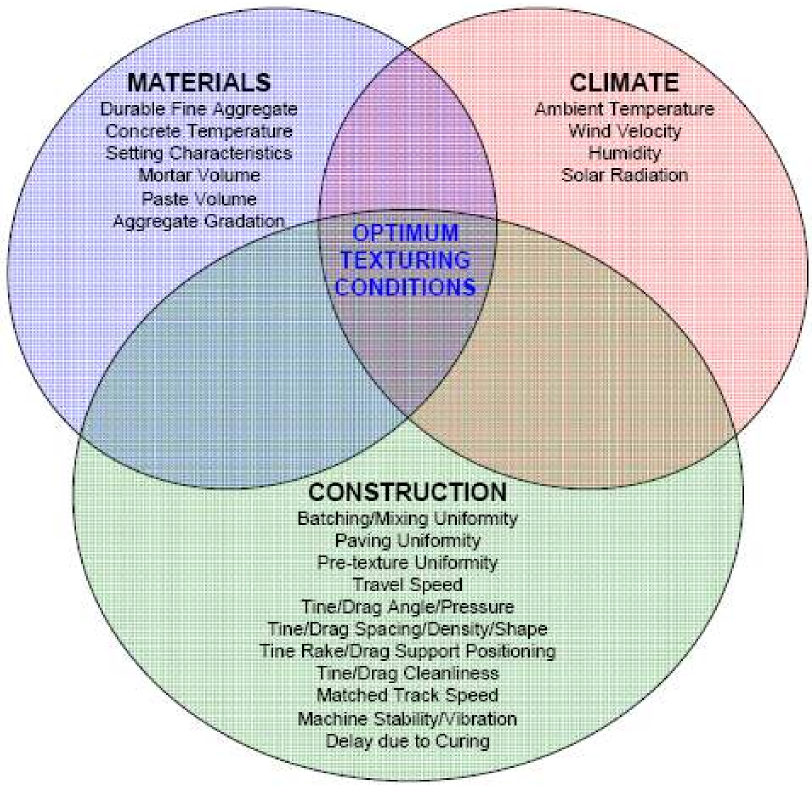

Figure 3-2 Variables Affecting Texture and the Concept of an Optimum Texture Window (Rasmussen 2008b).

3.7 LITERATURE SUMMARY

A critical review of the available relevant research papers/reports together with analysis/comments on methodologies, usefulness and drawbacks, as applicable, are presented in this chapter. In general, a good number of past studies have been devoted globally to pavement surface texture, surface friction, tire-pavement or traffic noise and sound absorption in separate jurisdictions. A very limited number of studies dealt with skid resistance and noise in the same context. A few of the researchers have studied the durability of the surface texture or friction while a few others attempted to examine the seasonal/short term variations. A good number of statistical models have also been developed for the prediction of skid resistance, texture depth, and noise. These studies have resulted in some significant contributions/advancements in the area of pavement surface characteristics, but yet left many gaps for further investigation and/or verification. The following general conclusions may be drawn from the reviewed papers/reports:

i) A large variation in measured skid resistance of different pavements has been found in research conducted in different places globally. The variation in texture and materials were not adequately captured, as required.

ii) Overall, aggregate quality has shown to be of prime importance in achieving adequate and durable surface friction.

iii) A high texture level does not necessarily mean a high skid resistance.

iv) Research studies also have shown a large variation in noise among the pavements, within a pavement or a section of the same pavement. Variations in construction and measurement techniques probably are major factors.

v) In general, open graded mixes have been shown to produce quieter AC pavements. The durability of those pavements and the loss of noise reducing properties within a short time, however, are major concerns. The SMA and Superpave mixes have shown to be promising with respect to noise reduction. The skid resistance of SMA, however, could be an issue, especially during the early life.

vi) Among the PCC pavements, 13 mm to 19 mm longitudinal tined and diamond ground surfaces have shown to be quieter with adequate surface friction. However, it is important to achieve the desired texture in the field.

vii) Rubber/polymer modified asphalt surfaces have shown noise reduction potentials with some concerns over durability and noise increase over time.

viii) Many of the developed models lack appropriate interpretation with respect to practical significance and statistical adequacy.

ix) The short-term, seasonal, and long term variations of skid resistance have not yet been studied adequately. The findings in past studies are controversial in some cases while poorly or inadequately interpreted in some other cases.

x) A comprehensive and cognisant study incorporating the pavement surface texture, safety, and noise in one envelop is still missing.

xi) Studies on pavement surface characteristics in Canadian, especially Ontario, jurisdictions are scarce and inadequate for evaluating the skid resistance and noise performance of different pavements.

xii) The prospect of incorporating safety and noise performances into the PMS together with other factors such as construction/maintenance costs, smoothness and durability as well as seasonal and long term variations has not been explored well yet.

Chapter 4 Research Approach, Data Collection and Preparation

A comprehensive review of the pavement surface characteristics, related issues, and relevant past research studies has been provided in Chapters 2 and 3. The review/analysis presented in these two chapters indicates that there are significant deficiencies in pavement surface characteristics research. This research study emphasizes the importance of understanding the effect of both surface materials and texture geometry on their performance including performance variation over time. Therefore, a comprehensive study has been carried out encompassing all these aspects. This Chapter presents the research approach including data collection, preparation, and descriptive statistics.

4.1 RESEARCH APPROACH

As mentioned earlier, this research involves a comprehensive and systematic study of both AC and PCC pavements surface characteristics that include surface texture, surface friction, acoustic absorption, and tire-pavement noise levels for different surfaces. As the highway agencies are also facing challenges due to variation of skid resistance over time, it is one of the key factors in the selection of surface material/mix and/or texture. This research therefore incorporated a controlled and thorough study of seasonal and long term variations of pavement surface friction. Attempt has also been made to evaluate the variation of tire-pavement noise with the variation of pavement surface age.

The process of establishing the desired minimum surface friction and maximum acceptable noise level is included to assist the highway engineers in the selection of the pavement surface layer. As the criteria for the selection of the pavement surface layer should not be limited to skid resistance and noise performances alone, the process of incorporating the surface characteristics into the PMS together with construction and maintenance costs, and pavement stability/durability has also been incorporated. Because of such extensive coverage, the empirical analysis included in this research has been divided into four major parts. The framework of the research studies is shown schematically in Figure 4-1.

The review of the available relevant published literature has been done until finalizing this thesis to summarize the up to date research information carried out throughout the globe. Part I of the experimental studies involves preparing PCC specimens and obtaining AC cores from test sections for surface texture and friction measurements in the laboratory. It also involves the surface texture and skid resistance testing in the field as part of integrating the field and laboratory testing capabilities with respect to pavement surface characteristics research. The effect of mix properties on surface texture and friction development and the effect of surface texture on available friction have been evaluated independent of the large variability in aggregate mineralogy, construction, and environment. In addition, the effect of Reclaimed Concrete Aggregate (RCA) on surface friction was examined based on measurements on new PCC sections constructed at the CPATT landfill test site.

Part II involves examining the true effect of the environment on the seasonal variation of skid resistance. Selected PCC and AC surfaces were tested periodically to examine the effect of rainfall, surface and ambient temperatures, prior temperature, and dry spells on surface friction variation.

Part III covers the analysis of the early life and long term variations of surface friction using field data available in the LTPP program database. The test sites are spatially located in all geographic and climatic regions of Canada and the US. The age, traffic exposure and mix properties also vary among the test sites. This allowed examining the effect of environmental conditions, materials, and traffic use on long term skid resistance of both PCC and AC pavements.

In Part IV, the tire-pavement interaction noise was measured in the field on 28 PCC and AC pavements surfaces of Ontario provincial highways as well as four AC pavement surfaces at the CPATT quiet pavement test site using the CPATT instrumented van. The sound absorption of PCC and AC samples was measured in the laboratory using an impedance tube. The correlation of surface texture, skid resistance, and noise was also examined. The performance of PCC and AC surfaces was compared and performance models were developed in each Part correlating the statistically significant variables.

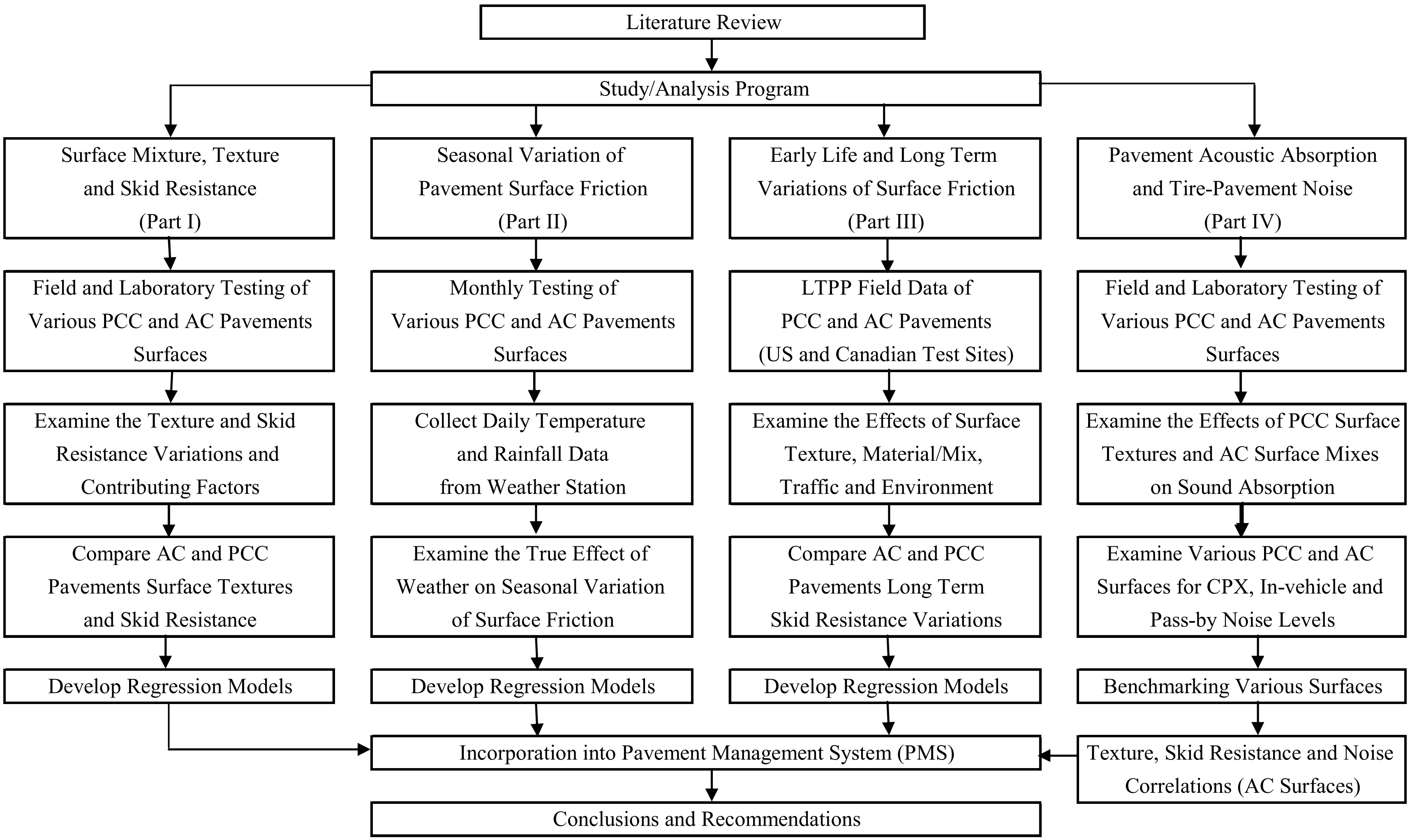

Figure 4-1 Framework of the Research Studies

4.2 DATA COLLECTION

4.2.1 Surface Mixture, Texture and Skid Resistance (Part I)

Preparation of PCC Specimens

A standard 30 MPa ready mix concrete with 20 mm nominal maximum size aggregate was used to prepare the PCC specimens in the laboratory. It is a standard PCC mix used for various structural applications in Ontario. The mix was supplied by *Dufferin Concrete* on September 05, 2006. The quality of the fresh concrete was tested at delivery point and specimens were prepared for compressive and flexural strength testing. Table 4-1 shows the description of the mix. The compressive strength of the supplied mix was 37 MPa, well above the design strength of 30 MPa.

Moulds for the PCC specimens were prepared by cutting the 152 mm diameter standard cylindrical mould (used for compressive strength testing). Seventy-Two cylinder specimens, all 152 mm (6 in.) diameter, and 76 mm (3 in.) thick, were prepared at the same time, in the concrete laboratory of the Civil and Environmental Engineering Department at the University of Waterloo (UW), Ontario. Specimen size was chosen to fit into the Impedance Tube for sound absorption testing and skid resistance testing with the British Pendulum. Specimen preparation in such a manner has enabled to evaluate the true effect of various surface textures on skid resistance properties, by controlling the effect of varying materials/mixes, temperature, aggregate gradation and age/uses. Figure 4-2 shows the pictures of concrete delivery, sample preparation, finishing and surface texturization of cylindrical PCC specimens.

Texturization of PCC Specimens

The PCC specimens were surface textured in 24 different configurations with three replicate specimens in each configuration. These include screed finish, burlap, corn broom and plastic turf drag, exposed aggregate, and 3.2 mm wide and 4 mm deep various tining using steel tines having rectangular and triangular (45°) tips. Two exposed aggregate surface textures were produced by spraying different rates of surface retarder.

Table 4-1 Properties PCC Mixture Used for Laboratory Specimens

Criteria	Design or Plant Test	Test at Laboratory
Nominal Maximum Size	20 mm	-
Concrete Temperature	-	22.8º C
Slump	120 mm	100 mm
Air Content	5-8 %	5.4 %
Compressive Strength, 7-day	-	33.55 MPa
Compressive Strength, 28-day	30 MPa	37.31 MPa
Flexural Strength, 28-day	-	5.00 MPa

a) Ready Mix Supply

b) Sample Preparation

c) Finished Surfaces

d) Surface Texturization

Figure 4-2 PCC Specimen Preparation at Concrete Laboratory, University of Waterloo.

The tines were spaced uniformly at 16 mm c/c or randomly at 10 to 22 mm c/c. Although two different tips were used, the resulting grooves after concrete hardening showed no noticeable difference probably due to texturization timing. Furthermore, during the tining some coarse aggregates were pulled up to the surface, and therefore a number of specimens lost their individual texture characteristics. Although attempt was made to grind the protruding aggregates, the identity of individual texture was a concern because of extensive surface voids. These surfaces therefore were excluded from testing and this limited the number of available texture configurations. Figure 4-3 shows sample pictures of textured PCC surfaces.

Figure 4-3 Sample Pictures of the Textured PCC Surfaces.

Table 4-2 shows the list of surface texture configurations that were finally tested. As the specimens could be rotated, turning them by 90° provided transverse textures with same texture dimension. This enabled a direct comparison of skid resistance of longitudinal and transversely textured surfaces. Therefore, fifteen PCC texture configurations were available for skid resistance testing in the laboratory.

Table 4-2 List of PCC Textures Available for Testing

Group	Tools	Texture Configuration
Reference	Screed Finish	Smooth Surface
Drag	Coarse Burlap	Longitudinal Burlap Drag
		Transverse Burlap Drag
	Broom (Corn)	Longitudinal Broom Drag
		Transverse Broom Drag
	Plastic Turf	Longitudinal Turf Drag
		Transverse Plastic Turf
Exposed Aggregate	Retarder: 250 sq-ft/gallon	Low Exposed Aggregate (1)
	Retarder: 150 sq-ft/gallon	High Exposed Aggregate (2)
Tining (3.2 mm wide, 4 mm deep for all specimens)	Steel Tine	Longitudinal 10-22 mm Random
		Transverse 10-22 mm Random
	Coarse Burlap/ Steel Tine	Burlap Drag and Longitudinal 10-22 mm Random
		Burlap Drag and Transverse 10-22 mm Random
		Burlap Drag and Longitudinal 16 mm c/c Uniform
		Burlap Drag and Transverse 16 mm c/c Uniform

PCC Test Sections at CPATT Landfill Test Site

The PCC pavement surface texturization at the CPATT test track, located at the Waterloo landfill (LF) site, was coordinated with an ongoing research program examining the feasibility of RCA in new concrete mix. Four sections, each about 50 m long, containing different percentages of RCA were constructed in June 2007 with surface texturization of various configurations. The reclaimed concrete was crushed and used as coarse aggregate in the ready mix concrete with 0% (i.e., conventional mix with 100% virgin aggregate), 15%, 30%, and 50% replacement of virgin coarse aggregate. The concrete mixes were designed to meet the MTO Standard 30 MPa compressive strength requirement. Figures 4-4 and 4-5 show the pictures of various surface texturizations and a schematic view of five different as-built textures, respectively. The longitudinal tining was accomplished with a 3.2 mm wide steel tine spaced at 16 mm c/c. The tine rakes were assembled with a tining bridge to produce 4 mm ± 1 mm deep groove according to MTO practice as specified in OPSS 350 (1998). The geometry of the transverse tine was same as that of the longitudinal tine but was performed manually with a tining rake. Table 4-3 provides the description of textures.

a) Burlap Drag
b) Longitudinal Tining
c) Longitudinal Tining (Close View)
d) Transverse Tining

Figure 4-4 PCC Surface Texturization at CPATT Test Site.

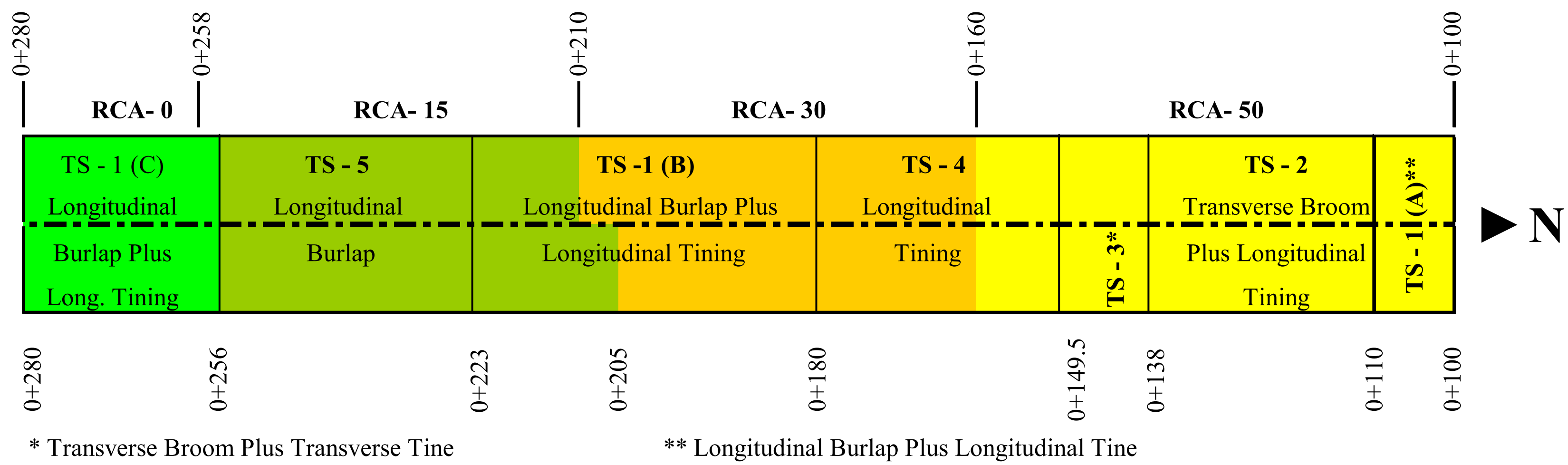

Figure 4-5 As-Built Textures at CPATT Test Track, Waterloo Landfill Site

Table 4-3 Description of PCC Texture Configurations at Landfill Site

Texture ID		**TS - 1 (A)**	**TS – 2**	**TS – 3**	**TS - 4**	**TS - 1 (B)**	**TS - 5**	**TS - 1 (C)**
Station	*From*	*0 + 100*	*0 + 110*	*0 + 138*	*0 + 149.5*	*0 + 180*	*0 + 223*	*0 + 256*
	To	*0 + 110*	*0 + 138*	*0 + 149.5*	*0 + 180*	*0 + 223*	*0 + 256*	*0 + 280*
Texture		Longitudinal Burlap Drag Followed by 16 mm c/c Longitudinal Tining	Transverse Broom Drag Followed by 16 mm c/c Longitudinal Tining	Transverse Broom Drag Followed by 16 mm c/c Transverse Tining	16 mm c/c Longitudinal Tining	Longitudinal Burlap Drag Followed by 16 mm c/c Longitudinal Tining	Longitudinal Burlap Drag	Longitudinal Burlap Drag Followed by 16 mm c/c Longitudinal Tining

Description of AC Pavement Sections

The tested AC pavements are located at two sites in the Region of Waterloo (ROW). The first test site, called the CPATT test track, is located at the Waterloo landfill (LF) and consists of five sections each about 140 m long (Figure 4-6). The surface mixes are: HL3 (two control sections), Polymer Modified HL3 (PMA), SMA and Superpave (SP). The other site, named as ROW-CPATT quiet pavement (QP) site, is located on regional Road 11 (William Hasting Line) between Manser Road and Chalmers Forrest Road at Crosshill (CH) in the Township of Wellesley (Figure 4-7). Four AC sections, each 600 m long, at this site include: 1) ROFC, 2) ROGC, 3) SMA, and 4) HL3. The ROFC and ROGC are similar in mix design but the ROFC contains premium quality aggregates (100% crushed coarse and fine) for high skid resistance properties. For ROFC and ROGC mixes, ground tire rubber was added (10% by weight of asphalt binder) in the wet process (at asphalt refinery). Table 4-4 shows the summary of the asphalt mixes used at the LF and QP test sites.

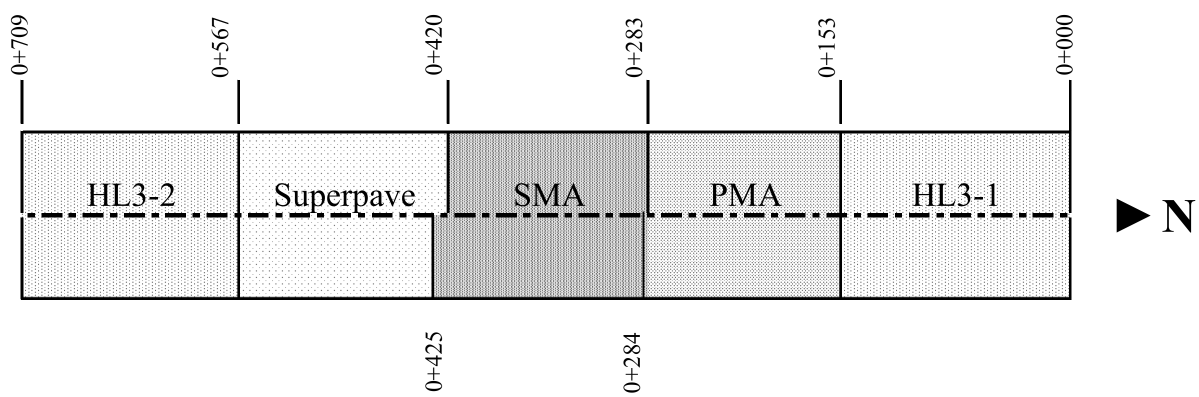

Figure 4-6 AC Pavement Sections at Waterloo Landfill Site.

Each of the surface courses contain 16 mm maximum size aggregates from the same source with similar Micro-Deval abrasion (17% to 18%) that enabled direct evaluation of the effect of aggregate gradation independent of a variation in aggregate size and mineralogy. However, the SP and SMA (on both sites) contain premium aggregates (in addition to ROFC) while all other sections contain conventional aggregates. All test sections were constructed in 2004 utilizing the same contractor, which has probably eliminated or reduced the variability in construction practices.

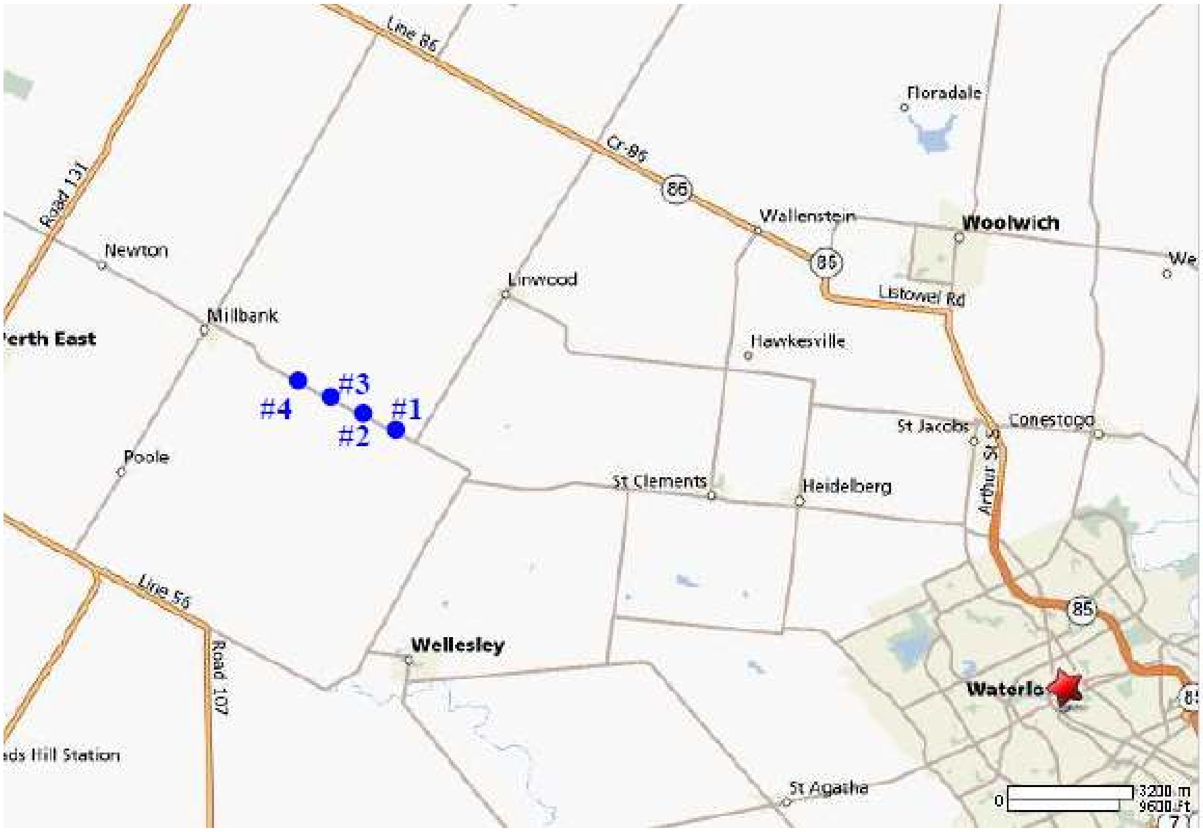

Figure 4-7 CPATT-ROW Quiet Pavement Test Site at Crosshill (Adopted from Mapquest www.mapquest.com)

Table 4-4 Summary of AC Mixes at CPATT Test Sites

Mix	Percentage of Constituent Material or Property				
	% Coarse	% Fine	% Filler	% AC	% Voids
HL3 (LF)	45.8	54.2	3.1	5.0	4.62
PMA	45.8	54.2	3.1	5.0	4.62
SMA	75.8	24.2	8.6	5.7	4.00
Superpave (SP)	49.0	51	3.0	4.9	4.25
ROFC	72.9	24.6	2.5	5.6	6.9
ROGC	72.1	23.8	4.1	5.8	8.6
SMA-QP	77.6	14.3	8.1	5.7	3.9
HL3-QP	41.3	53.8	4.9	5	3.7

Note: HL3-LF: HL3 at Landfill Site and HL3-QP: HL3 at Quiet Pavement Test Site

Skid Resistance and Texture Measurements

The macrotexture of PCC surfaces was measured using the sand patch method (ASTM E965). For laboratory measurements, a sufficient volume of glass beads was poured on the circular specimens (diameter known) and the volume of the spread sand was measured (Figure 4-8a). For texture measurement in the field (PCC test sections), a known volume of sand was spread on each marked spot and the average diameter of the sand circle was measured. Three replicate measurements were taken on each test spot or specimen. The mean texture depth (*MTD*) was determined by dividing the sand volume by the specimen diameter or the average diameter of the sand circle.

a) Texture Measurement in Laboratory　　b) Skid Testing in Laboratory

Figure 4-8 Sand Patch *MTD* and *BPN* Measurement Set-ups

The surface friction was measured using a portable skid resistance tester known as the British Pendulum (ASTM E-303). The measured skid resistance is called the British Pendulum Number (*BPN*). A wooden frame was prepared to secure the specimen on its position during the skid testing in the laboratory (Figure 4-8b). As the degree of saturation has shown a remarkable variation in measured skid resistance of PCC surfaces, all of the laboratory specimens were soaked in water for 24 hours prior to testing to be consistent in moisture content and minimize the test variability. The test points in the field were also watered until the skid resistance values are consistent. Five replicate friction measurements were taken and the average reading was taken as the *BPN* of each test point or specimen.

It should be noted that three PCC specimens were prepared for each texture configuration. Measurements were taken on all three specimens to account for the sample-to-sample variation and obtain average *BPN* and *MTD* of each texture configuration. Similarly, measurements were taken at three randomized spots for each texture configuration at the landfill test track. The surface and ambient temperatures were also recorded immediately after the skid measurement for each test specimen or field test spot. The wet surface temperature during the skid testing varied from 17°C to 19°C in the laboratory and 19°C to 27°C in the field.

For laboratory testing of AC pavements, fifteen 152 mm diameter specimens were obtained by coring from five sections (three cores from each section) at the landfill site. All of these cores were tested for the *BPN* and sand patch *MTD* following the procedure mentioned for the PCC specimens. A full-scale dynamic pavement friction tester from Dynatest (Figure 4-9) that meets the ASTM E 274 standard (ASTM skid trailer), mounted with a standard ribbed tire (ASTM E501), was then used for skid resistance measurements on these sections. The measured skid resistance is called the skid number (*SN*). The *SN* of each section was measured at 64, 80, 90, and 100 km/h at 25 m intervals through multiple passes of the skid tester on a single day in October 2007. In addition, the surface macrotexture of these sections were measured with the Automated Road Analyzer (ARAN) laser profiler (Figure 4-10). The measured macrotexture is called the mean profile depth (*MPD*).

Figure 4-9 Skid Resistance Measurement with Dynatest Friction Tester.

Figure 4-10 Automatic Road Analyzer (ARAN) (Courtesy: Roadware, Paris, Ontario).

Alternatively, twelve cores were obtained from four sections at the quiet pavement Crosshill test site in another CPATT research program. These cores were tested only for sand patch *MTD* because of the smaller diameter than that required for *BPN* measurement. However, the *SN* of each section was measured at 64 km/h, 80 km/h, 90 km/h, and 100 km/h on the same day (in October 2007) of skid testing at the landfill site. All the skid testing was carried out on wet surfaces.

4.2.2 Seasonal Variation of Surface Friction (Part II)

The seasonal variation of surface friction was measured from February to October 2007 for six PCC and five AC pavement surfaces. The PCC surfaces included smooth surface (screed finish), burlap, broom and astroturf dragged, exposed aggregate, and longitudinal tined textures with three specimens in each texture configuration (total 18 specimens). The description of the mix and specimen preparation with different surface texturizations is already presented in Subsection 4.2.1. Fifteen AC surface course specimens, obtained by coring from the midlane (away from wheel paths) of five test sections at Waterloo landfill site, were also included in the test scheme to evaluate the seasonal skid resistance variation and to compare with that of the PCC surfaces. The surfaces includes HL3 (two sections), Superpave, SMA and PMA. As mentioned earlier, these five mixes contain aggregates from the same source. They were constructed by single contractor in one season (same age pavements).

All the test specimens were left exposed to the outside environment and surface friction was measured monthly using the British Pendulum. For few months, *BPN* was measured directly on the AC road surfaces at midlane from where the cores were taken. The road is located at a landfill (not exposed to general traffic) for movement of garbage dump trucks but it was mostly close during the testing period. Friction measurements were taken on the wet surface after thoroughly cleaning the dust or other debris. The surface texture was measured time-to-time using the sand patch method to determine possible changes in surface texture. Daily low and high temperatures and rainfall data were obtained from the University of Waterloo weather station in addition to pavement and ambient temperatures during the testing. It allowed for determining the true effect of rainfall, prior temperature, dry spell, and temperature during the testing on surface friction variation.

4.2.3 Long Term Variation of Surface Friction (Part III)

For long term surface friction, field data from the Long Term Pavement Performance (LTPP) program Release 21 was obtained for both PCC and AC pavements incorporating all geographic/climatic regions of Canada and US (LTPP 2006). It should be noted that the LTPP program is managed by the FHWA. It maintains the world's largest pavement performance database, known as DataPave Online. The program was begun in 1987 for a comprehensive 20-year study of in-service pavements. The test sections comprise more than 2,400 AC and PCC pavement sections in the US and Canada.

The LTPP data obtained for this study covers all the PCC pavements sections under GPS-3, GPS-4, GPS-5, and GPS-9 consisting of 1,692 *SN* measurements. The GPS-3, GPS-4, GPS-5, and GPS-9 represent Jointed Plain Concrete Pavement (JPCP), Jointed Reinforced Concrete Pavement (JRCP), Continuously Reinforced Concrete Pavement (CRCP), and Unbounded PCC Overlays on PCC Pavements, respectively. The obtained AC pavements data includes all sections under GPS-1 (AC on granular base), GPS-2 (AC on bound base), GPS-6 (AC overlay on AC), and GPS-7 (AC overlay on PCC) consisting of 2,742 *SN* measurements.

The obtained data covers all four geographic regions, namely North Atlantic, North Central, Southern and Western Regions. The climatic regions include Wet Freeze, Wet No Freeze, Dry Freeze, and Dry No Freeze. For each section the information/data obtained include friction (skid) number, traffic use, age, annual wet days, annual average temperature, climatic region, speed and temperature during testing, asphalt mix gradation, air void, voids in mineral aggregates (VMA) and stability, and PCC texture type and compressive strength.

4.2.4 Tire-Pavement Noise and Sound Absorption (Part IV)

Site Selection and Pavement Description

This part of the research program was directed at examining and benchmarking different rigid and flexible pavements in terms of tire-pavement noise. Accordingly, typical AC and PCC pavement surfaces that are currently being used in different regions were selected for tire-pavement noise measurement. Another major objective of this study was to determine the variation of tire-pavement noise over time (age). Therefore, both AC and PCC pavement surfaces of varying age were selected, as available. Overall, 32 sites (23 PCC and nine AC pavements) were finally chosen of which 26 are located on Ontario provincial highways, two on a private toll route, and the remaining four on a Waterloo regional road.

The 28 sites on provincial (MTO) and private (toll) highways are located in three regions of Ontario, namely the Central Region (CR), East Region (ER) and West Region (WR). Figures 4-11 and 4-12 show the spatial distribution of 28 test sites (site #4 through site #32) on provincial and toll highways. The AC pavements included 12.5 mm regular Superpave, 12.5 mm fine graded Superpave, 9.5 mm fine graded Superpave, 12.5 mm SMA, coarse Microsurfacing (Type III Modified), fine Microsurfacing (Type II), and conventional dense AC. The PCC pavements include MTO standard transversely and longitudinal tined surfaces.

The four AC pavement surfaces on the regional road are located at the CPATT-ROW quiet pavement test site. As mentioned earlier, the surface mixes at the quiet pavement site include ROFC with high friction aggregates, ROGC with local aggregates, SMA (SMA-QP) and HL3. The location of the quiet pavement sections is shown in Figure 4-7. Table 4-5 shows the list of sites by pavement types that were selected for testing.

Figure 4-11 Test Sites in South and Central Regions (Adopted from Mapquest www.mapquest.com).

Figure 4-12 Test Sites in East Region (Adopted from Mapquest www.mapquest.com).

Table 4-5 List of Selected Sites/Pavements in CPATT- MTO Noise Testing Program

Site #	Contract	Region	Highway	Surf. Year	Age	Pavement	Test Site Location
1	CPATT-UW	Waterloo	Reg. 11	2004	3	ROFC	Between Manser Road and Chalmers Forrest Road at Crosshill
2	CPATT-UW	Waterloo	Reg. 11	2004	3	ROGC	Between Manser Road and Chalmers Forrest Road at Crosshill
3	CPATT-UW	Waterloo	Reg. 11	2004	3	SMA	Between Manser Road and Chalmers Forrest Road at Crosshill
4	CPATT-UW	Waterloo	Reg. 11	2004	3	HL 3	Between Manser Road and Chalmers Forrest Road at Crosshill
28	N/A	MTO-ER	416NB	2006	1	Microsurfacing (Coarse)	Rogers Stevens Dr. to Century Road
27	N/A	MTO-ER	416SB	2005	2	Microsurfacing (Coarse)	Rogers Stevens Dr. to Century Road
18	N/A	MTO-WR	10	2006	1	Microsurfacing (Fine)	Camilla to Primrose
19	N/A	MTO-WR	10	2005	2	Microsurfacing (Fine)	1.8 km north of Hockley Valley Rd. to Camilla
15	2005-3046	MTO-WR	401WB	2007	0	PCC-Long.	Rochester Township, 13+000 to 14+000 (Between IC 34 and IC 48)
6	2006-2018	MTO-CR	410	2007	0	PCC-Transverse	Hwy 410 Extn, Bovaird Dr. to Mayfield Rd.
14	2005-3046	MTO-WR	401	2007	0	PCC-Transverse	1.1 km E of Essex Rd 27 (IC 34) Easterly to 3.1 km E of Hwy 77 (IC 48)
29	2006-3029	MTO-WR	402EB	2007	0	PCC-Transverse	Lambton Rd 26 to Lambton Rd 30
16	2005-3001	MTO-WR	401	2006	1	PCC-Transverse	2.9 km W of Essex Rd 19 (IC 21) Easterly to 2.6 km E of Essex Rd 25 (IC 28)
17	2004-3002	MTO-WR	401	2005	2	PCC-Transverse	1.2 km W of Hwy 77 (IC 48) Easterly to 1.0 km E of Essex Rd 42 (IC 56)
25	2003-4029	MTO-ER	417WB	2004	3	PCC-Transverse	IC 9 (Hwy 17) to Dunvegan Road
26	2000-0025	MTO-ER	417EB	2002	5	PCC-Transverse	IC 9 (Hwy 17) to Dunvegan Road
30	N/A	Private-CR	407EB	1996	12	PCC-Transverse	KP 92.5 - KP 95
11	2006-3037	MTO-WR	401	2006	1	SMA	Highbury Ave. to Dorchester Road (IC 189 to IC 199)
12	2004-3021	MTO-WR	401WB	2005	2	SMA	Dorchester Road to Putnam Road (IC 199 and IC 208)
13	2004-3021	MTO-WR	401EB	2004	3	SMA	Dorchester Road to Putnam Road (IC 199 and IC 208)
21	2007-4002	MTO-ER	TIP	2007	0	SP12.5Fine	2.5 km W of Reynolds Road to 2.8 km E of Rockport
22	2005-4013	MTO-ER	15	2006	1	SP12.5FC1Fine	Joyceville Northerly
23	2006-4061	MTO-ER	401EB	2005	2	SP12.5FC2Fine	I/C # 778, E'ly for 18 km, Cornwall
24	2003-4019	MTO-ER	15	2004	3	SP12.5FC1Fine	Hwy 401 –Northerly
32	2002-4031	MTO-ER	417	2003	5	SP12.5FC1Fine	KP 6 to KP 8
7	2005-3031	MTO-WR	401	2007	0	SP12.5FC2	1.7 km W of Oxford 3 Easterly to 1.9 km W of Waterloo RR 97
8	2005-3049	MTO-WR	6	2006	1	SP12.5FC2	Maddaugh Rd Northerly to South of Calfass Rd/Wellington Rd 36
9	2003-3019	MTO-WR	402WB	2005	2	SP12.5FC2	1.9 km E of Lambton Rd 30 (IC 25) easterly to 2.7 km E of Hwy 21 (IC 34)
10	2003-3019	MTO-WR	402EB	2004	3	SP12.5FC2	1.9 km E of Lambton Rd 30 (IC 25) easterly to 2.7 km E of Hwy 21 (IC 34)
5	2003-2011	MTO-CR	6	2003	4	SP12.5	Existing (Old) Hwy 6 to Garner Road (Near Hwy 403)
20	N/A	MTO-ER	132	2007	0	SP9.5Fine	5 km W of Renfrew for 10.5 km
31	N/A	Private-CR	407EB	2000	8	AC	KP 94

As shown in Table 4-5, Microsurfacings (both fine and coarse) were 1-year and 2-year old. PCC and AC surface ages varied from less than a year (referred to as new) to 5 years, except for a 12-year old PCC and an 8-year old dense AC on Highway 407ETR, a privatized toll route. The longitudinal tined PCC pavement (PCC-Long.) section is the first trial section of longitudinal tining in the province of Ontario. PCC-Transverse sections are MTO standard PCC pavement surfaces with transverse tining. The MTO tining specification (4 mm ±1 mm deep, 3 mm ± 1 mm wide and 16 mm ± 3 mm c/c uniform spacing) is the same for both transverse and longitudinal directions.

All the AC surface mixes (Superpave and SMA) on provincial highways contain blended aggregates of 12.5 mm nominal maximum size, except the SP9.5Fine. However, Superpave mixes in the ER are blended to finer gradation and designated as SP12.5Fine. The SP9.5Fine is a Superpave (SP) fine mix with 9.5 mm nominal maximum size aggregate. The symbol FC1 with SP12.5 denotes that Superpave mixes contain premium coarse aggregate while FC2 denotes that mixes contain both coarse and fine premium aggregates. The SP12.5 represents a Superpave mix with 12.5 mm nominal maximum size conventional aggregates.

The tested pavements were free of cracks or other surface distresses except for the SP9.5Fine (on Highway 132) and 5-year old SP12.5FC1Fine (on Highway 417) surfaces in the ER. Despite SP9.5Fine being a new surface, the whole section contains visible micro-cracks and harsh spots, which are probably related to a fine mix stability (holding) problem during the compaction and/or reflection cracking. The 5-year old SP12.5FC1Fine surface on Highway 417 was shown to contain severe transverse and longitudinal cracks. Figures 4-13 and 4-15 show pictures of typical surfaces that were tested in this part of the research. From the pictures, variations in surface texture among the same pavements are apparent.

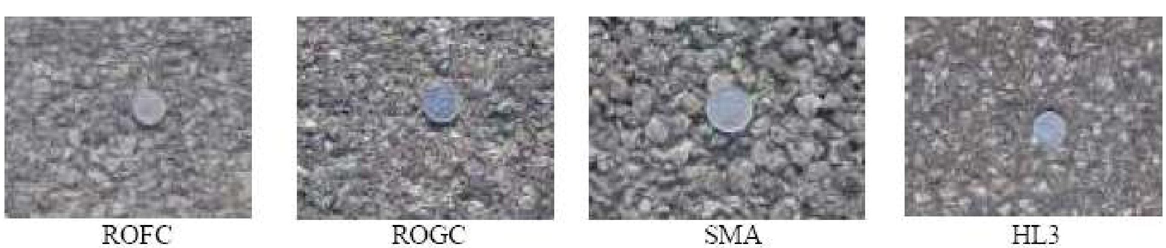

Figure 4-13 AC Pavement Surfaces at CAPTT-ROW Quiet Pavement Test Site.

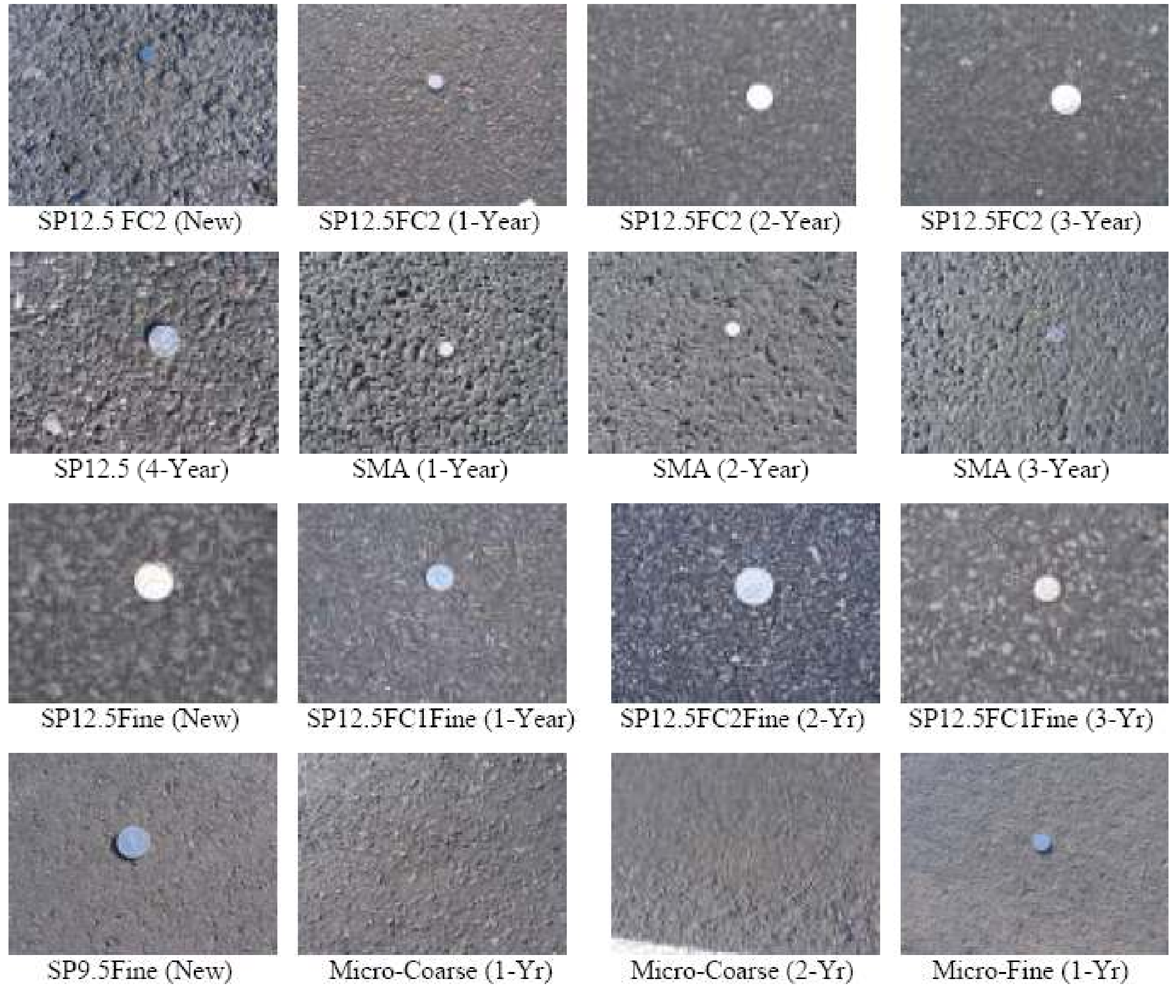

Figure 4-14 Typical AC Pavement Surfaces on Ontario Provincial Highways.

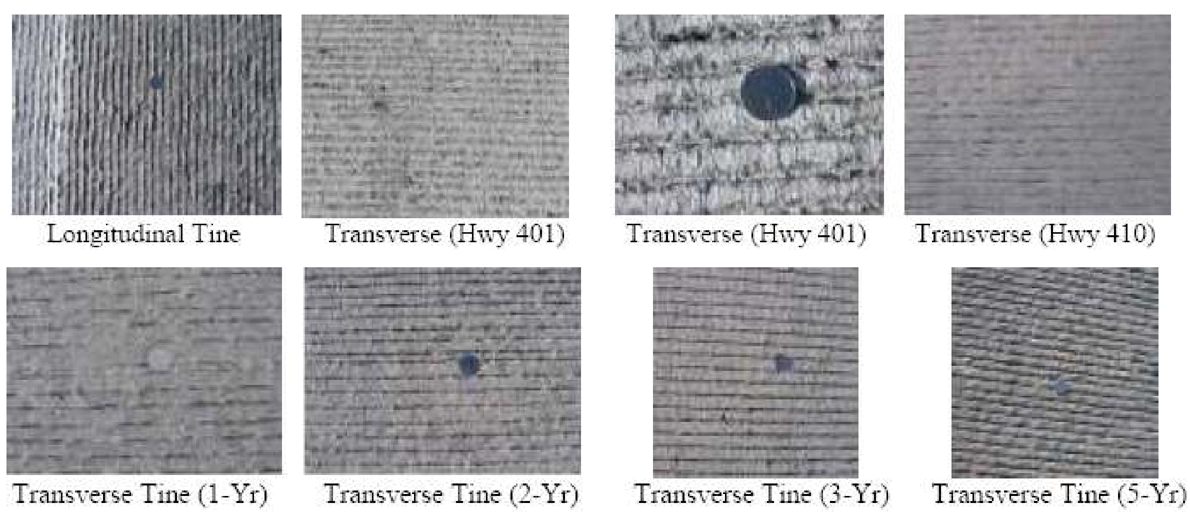

Figure 4-15 Typical PCC Pavement Surfaces on Ontario Provincial Highways.

CPX and In-Vehicle Noise Measurement

The CPATT at the University of Waterloo currently owns and operates a Bruel & Kjaer sound testing system. It is composed of a five-channel computerized acoustic data acquisition, query, and display facility. The system can capture noise data with high level of accuracy using a world leading acoustic technology. It has been configured for simultaneous measurement of CPX and in-vehicle noise. For noise measurement in this research, two microphones were mounted near the rear-passenger tire while two other microphones were mounted near the driver's ear to capture the near-field and in-vehicle noise, respectively.

The CPX noise measurement physical set-up meets ISO standards with the exception of not having an acoustic enclosure. Following the ISO standards, the front (leading edge) and rear (tailing edge) microphones were positioned with a separation distance of 406 mm (16"). The distances of the microphones from the tire side wall and road surface were 203 mm (8") and 102 mm (4"), respectively. Figure 4-16 shows the CPX noise measurement physical set-up with CPATT van. The schematic view of microphones positions is shown in Figure 2-18 (Chapter 2). The physical set-up of in-vehicle noise measurement is shown in Figure 4-17.

Figure 4-16 Physical Set-up for CPX Noise Measurement.

Figure 4-17 Physical Set-up for In-Vehicle Noise Measurement.

The test vehicle was mounted with continental all season tubeless radial tires (Vanco four season) LT 245/75 R16. As the main objective was to characterize different pavement surfaces in terms of tire-pavement interaction noise, only a single vehicle and a single type of tire were used for entire noise measurement in this study. In short, the noise measurement was a benchmarking exercise rather than determining the absolute noise level for each pavement. It allowed for direct comparison of noise performance of different surfaces.

The CPX and in-vehicle noise measurements were taken simultaneously on each of the 28 sites as the test van traveled freely on each test section at 80 km/h, 90 km/h, and 100 km/h speeds with no passing or opposing vehicle near the test van. All the measurements on these 28 sections were taken during the months of October to December in 2007. For some sites, the CPX and/or in-vehicle noise were measured in both travel directions that were resurfaced in the same year i.e., the tire-pavement noise of same age pavements were also compared for some sites. These extra sections are numbered with a letter “A” attached to site number (e.g. 7A, 11A). An additional four sections were tested for CPX noise at 100 km/h during April and May of 2008. All the measurements were taken on dry pavements and in calm weather (wind speed below 15 km/h and relative humidity of less than 80%). Pavement (-18°C to 16° C) and air (-7°C to 14° C) temperatures during the noise measurements were also recorded.

The vehicle was set at cruise control for uniformly maintaining the desired testing speed. The duration of measurement was typically ten seconds. The manual option was employed to enable the operator to stop the analyzer in case another vehicle was approaching the test van, as this would affect the measured noise level. Three to five repeated measurements were taken on each section to obtain average noise level. Any interrupted reading was deleted from the database during the actual testing. As the tire-pavement noise was measured using a single test vehicle (CPATT van) with onboard equipment, the duration of measurement has shown no effect on the measured CPX and in-vehicle noise levels.

The CPX noise measurements were repeated for selected sections tested in October to December in 2007 with OBSI measurements taken by CAC in April and May (2008). All these measurements were taken only at 100 km/h. However, the wind speed was recorded to be as high as 23 km/h in some cases of these repeated measurements. A comparison of noise measurements in October to December (2007) and April to May (2008) are also presented.

Pass-By Noise Measurement

The CPATT also owns a Larson Davis Analyzer (Model 3000+) which is a two-channel acoustic data acquisition system. It can be used for measuring the CPX or in-vehicle or pass-by noise (sound pressure) separately because of the limited number of channels. It captures and records the sound pressure data in the analyzer itself. The data is then downloaded into the computer, is transformed into workable format, and is viewed using the RTAUtility software provided with the analyzer. The Larson Davis analyzer set-up was used for measuring the controlled pass-by (CPB) noise. Figure 4-18 shows the set-up of the microphone for pass-by (wayside or far field) noise measurement.

The microphone was mounted at 1.2 m above the road surface and at 15 m off the right lane centre line. The pass-by sound was measured for 27 sections at 80 km/h, 90 km/h and 100 km/h as the CPATT van passed the instrument station while measuring the CPX and in-vehicle noise. Every attempt was made to isolate the test vehicle from passing or opposing vehicles on the road. All interrupted readings were deleted and measurement repeated as much as possible to obtain reading avoiding the passing, leading or tailing vehicles.

However, it was extremely difficult to clearly isolating test vehicle from opposing vehicle in few cases, especially for Highway 6 in the WR (Contract 2005-3049).

Figure 4-18 Physical Set-up for CPB Noise Measurement.

Measurement of AC Pavement's Sound Absorption

In addition to noise testing in the field for benchmarking different pavement surfaces based on tire-pavement interaction noise levels, the study also aimed at integrating field and laboratory testing capabilities for measuring the pavement acoustic performance. It was proposed that pavement cores would be obtained from sections where noise measurement would be carried out in the field. However, due to some practical limitations, it was not feasible. Therefore, laboratory testing of sound absorption was limited to available spare cores obtained from MTO that were extracted as part of construction quality control/ assurance. The asphalt mixes of available cores include six regular Superpave, six fine graded Superpave and a SMA (total thirteen contracts) as listed in Table 4-6. Five to ten cores were available for each contract, except SMA for which only two cores were available.

Table 4-6 Sound Absorption of Various AC Surfaces

Contract No.	Surface Mix Type	Average Height, mm	Frequency at Peak Noise , Hz	Sound Absorption Coefficient
2006.3035	SP12.5FC2	41.72	933	0.062
2005-2008	SP12.5FC2	36.03	833	0.079
2005-2026	SP12.5FC2	39.15	700	0.067
2005-3024	SP12.5FC1	51.10	600	0.057
2005-2026	SP12.5FC1	42.30	567	0.048
2006-3100	SP12.5	33.49	733	0.067
Average	***Superpave***	***40.63***	***728***	***0.063***
2005-2008	***SMA***	***48.83***	***450***	***0.075***
2006-4081	SP12.5FC2Fine	44.25	1033	0.092
2006-4016	SP12.5FC2Fine	43.78	1100	0.086
2006-4070	SP12.5FC2Fine	39.56	967	0.085
2007-4001	SP12.5FC1Fine	48.05	1033	0.092
2006-4082	SP12.5FC1Fine	36.96	833	0.068
2007-4022	SP12.5FC1Fine	45.26	1100	0.089
Average	***Fine Superpave***	***42.98***	***1011***	***0.085***

Three cores of approximately equal thickness were selected from each contract, except the SMA and Superpave on Highway 10 (contract 2005-3023). For the SMA, both of the available cores were selected. For the Superpave on Highway 10 (contract 2005-3023), five cores of varying thickness were selected to examine the effect of varying asphalt layer thickness. The bottom surface of each core was ground or saw cut to provide a similar smooth bottom surface to be consistent in sample preparation. The thickness of each core was then measured. Air dry (for a couple of months) samples were then tested for sound absorption using the impedance tube method (Figure 4-19).

In this method, the cylindrical specimen is mounted at one end and a speaker is mounted on other end (yellow box) of the tube. A pulse is generated by an analyzer and is amplified by an amplifier that sends a sound wave into the tube through the speaker. The generated sound is propagated to the specimen that absorbs part of the sound energy and remaining energy is reflected back. Two microphones capture the incident and reflected sound wave amplitudes, respectively, which are then used to calculate the sound absorption coefficient or percentage of sound absorption of the material under test. Five repeated measurements (transfer functions of incident and reflected wave amplitudes) were taken for each core and the sound absorption of each core was calculated using the ACUPRO software developed at Kentucky University. The specific gravity (bulk relative density) of each core was then measured.

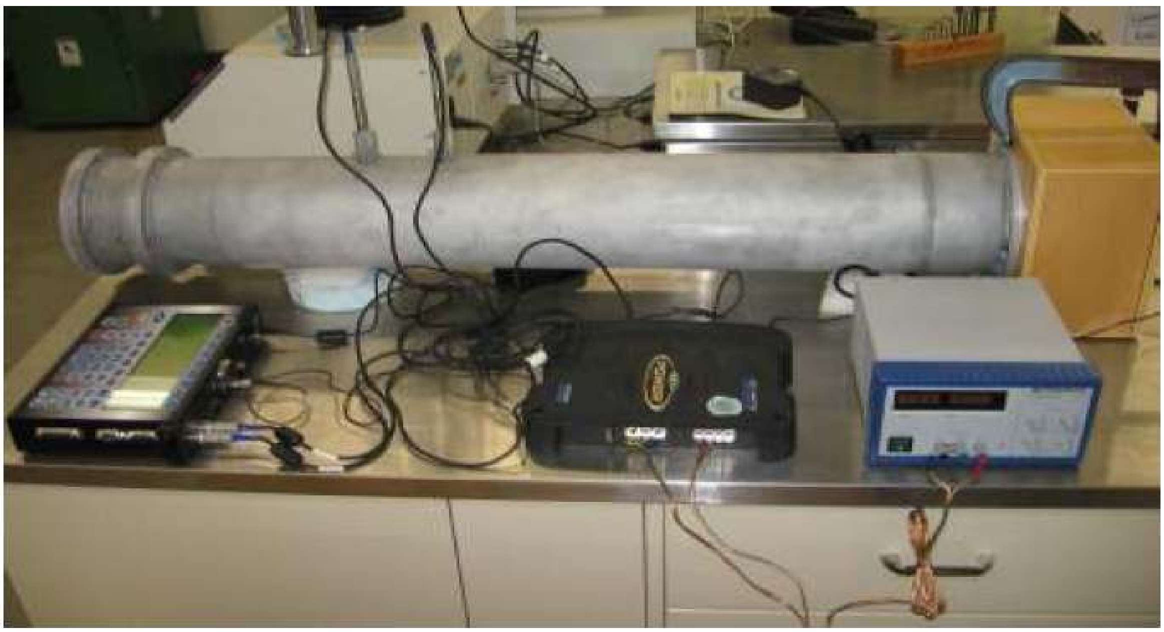

Figure 4-19 Impedance Tube for Sound Absorption Test at CPATT Laboratory.

Measurement of PCC Pavement's Sound Absorption

As mentioned in Subsection 4.2.1, cylindrical PCC specimens with various surface texturizations were prepared in the laboratory from a single 30 MPa ready mix concrete. The specimen size was chosen to facilitate both sound absorption and skid testing on the same specimens. The thickness of the samples was kept fixed to determine the true effect of surface texture variation on the variation of sound absorption. The sound absorption was measured using the CPATT impedance tube prior to skid testing.

To determine the effect of PCC thickness on sound absorption, three large slabs (1.20 m on both sides, large enough to place the CPATT reverberation chamber as shown in Figure 4-21) were prepared in the laboratory from the same PCC mix and on the same day of cylindrical PCC sample preparation. The thicknesses of the slabs were 76 mm, 200 mm and 260 mm (Figure 4-20). These panels were surface finished with wooden screed (similar surface finishing for all) that allowed for the determination of the difference in sound absorption purely due to variation in thickness.

a) Forms for PCC Slabs   b) Finished PCC Slabs

Figure 4-20 PCC Panels for Sound Absorption Testing.

Figure 4-21 Sound Absorption Testing using Reverberation Chamber.

The sound absorption of the PCC panels was measured using the portable reverberation chamber (Figure 4-21). The portable reverberation chamber is an innovative method for measuring the sound absorption of actual in-situ pavement and pavement slabs prepared in the laboratory or obtained from the field. The CPATT at the University of Waterloo has developed this method with the help of an acoustic consultant. The small chamber (1 m x 1 m) is placed on the pavement surface, a sound is generated in the chamber (using the noise signal generator, amplifier, and speaker as in the case of the impedance tube), and the sound decay time is measured using the microphone mounted on the top of the chamber. The decay time is then used to calculate the sound absorption coefficient of the test pavement.

4.3 Data Processing and Descriptive Statistics

4.3.1 Surface Mixture, Texture and Skid Resistance (Part I)

The skid resistance measured using the British Pendulum was corrected for surface temperature using the factor provided with the test equipment. The corrected *BPN* represents the skid resistance at 20°C. Table 4-7 shows the *BPN* exhibited by different PCC surface textures of the specimens prepared in the laboratory from conventional concrete mix and the corresponding field section with similar mix. The *BPN* represents the average values from three replicate specimens or test spots with five runs on each i.e., average of fifteen runs. The field section (identified by “F” in parenthesis) with conventional concrete mix (0% RCA) is similar to a laboratory texture that received a combination of longitudinal burlap drag and uniform 16 mm c/c longitudinal tining. The mix designs are also the same (30MPa). Therefore, this section has been included in the same context of the laboratory samples in all analysis.

As shown in Table 4-7, the *BPN* of the PCC surfaces containing conventional aggregates varied from 52 to 83 with a mean *BPN* of 70. The average *MTD* of these surfaces varied from 0.57 mm to 2.17 mm with a mean *MTD* of 1.43 mm. Table 4-8 shows the skid resistance exhibited by different PCC surfaces at the CPATT landfill test track. The *BPN* of the field sections were shown to vary from 54 to 82 (mean *BPN* of 68) with a *MTD* of 0.45 mm to 1.07 mm (mean *MTD* of 0.73 mm).

The summary of the skid resistance and texture of various AC pavements is shown in Table 4-9. The *MTD* of the tested surfaces varied from 0.56 mm to 1.75 mm with a mean *MTD* of 1.09 mm. The *BPN* of five AC surfaces at the LF site was shown to vary from 63 to 79 with a mean *BPN* of 69. Table 4-9 shows that the actual speed during the full-scale skid testing with skid trailer varied from the target speeds. Therefore, a correlation of *SN* with actual speed was developed and the measured *SN* values were normalized to target speeds. The skid number-speed correlation has shown that skid resistance decreases at 0.26 *SN* (on average) for each 1 km/h increase in vehicle speed. This value was then used as a correction factor. The corrected values allowed for better comparison of the *SN* of different AC surfaces and to examine the effect of surface texture as well as mix properties on skid resistance variation.

Table 4-7 Skid Resistance of PCC Surfaces (Conventional Mix)

Texture Type	***MTD* (mm)**	***BPN***
Screed	0.57	52
Longitudinal Burlap	0.87	64
Transverse Burlap	0.87	69
Longitudinal Broom	1.84	73
Transverse Broom	1.84	83
Longitudinal Astroturf	1.21	66
Transverse Astroturf	1.21	72
Exposed-1	1.86	65
Exposed-2	2.17	73
Longitudinal Random	1.70	73
Transverse Random Tine	1.70	76
Burlap+ Longitudinal Random Tine	1.57	73
Burlap+ Transverse Random Tine	1.57	79
Longitudinal Uniform Tine	1.65	73
Transverse Uniform Tine	1.65	81
Burlap+ Longitudinal Tine (F)	0.61	54
Minimum	***0.57***	***52***
Maximum	***2.17***	***83***
Average	***1.43***	***70***
Standard Deviation	***0.48***	***9***

Table 4-8 Skid Resistance of PCC Surfaces at Landfill Site

Section #	Surface Texture	RCA (%)	*MTD* (mm)	*BPN*
TS-1A	Burlap+Longitudinal Tine	50	0.79	58
TS-2	Broom+Longitudinal Tine	50	0.75	71
TS-3	Broom+Transverse Tine	50	0.79	82
TS-4	Longitudinal Tine	50	0.61	67
TS-4	Longitudinal Tine	30	1.07	78
TS-1B	Burlap+Longitudinal Tine	30	0.72	78
TS-1B	Burlap+Longitudinal Tine	15	0.74	73
TS-5	Longitudinal Burlap	15	0.45	55
TS-1C	Burlap+Longitudinal Tine	0	0.61	54
Minimum		***0***	***0.45***	***54***
Maximum		***50***	***1.07***	***82***
Average		***31***	***0.73***	***68***
Standard Deviation		***19***	***0.17***	***11***

4.3.2 Seasonal Variation of Surface Friction (Part II)

The monthly skid data were routinely checked during the testing for accuracy and consistency relative to preceding month(s). Measurements were repeated if any doubtful situation occurred. To determine the effect of prior weather, the measured surface friction was normalized to *BPN* at 20°C using correction factors for surface temperatures during the testing. Table 4-10 shows the summary of seasonal (monthly) skid testing data.

As shown in Table 4-10, the PCC and AC surfaces skid resistance (*BPN*) varied from 62 to 72 with a mean *BPN* of 68 and 63 to 76 with a mean *BPN* of 69, respectively. The PCC and AC surface temperature during the skid testing was shown to vary from 4°C to 30°C (mean = 18°C) and 4°C to 35°C (mean = 19°C), respectively. The 7-day, 5-day, 3-day, 1-day mean (low and high) temperatures, total precipitation, and the number of dry days prior to skid testing day were calculated from the weather record. The summary of the weather conditions prior to skid testing is shown in Table 4-11.

Table 4-9 Summary of Skid Resistance of Various AC Pavement Surfaces

Site	AC Pavement Surfaces	*MTD* (mm)	*BPN*	Target Speed (km/h)	Actual Speed (km/h)	*SN*	Corrected *SN*
CH	ROFC	1.19		64	62.6	57.9	57.5
CH	ROGC	1.15		64	64.5	43.6	43.7
CH	SMA (QP)	1.53		64	63.9	57.0	57.0
CH	HL3 (QP)	0.56		64	63.7	48.6	48.5
CH	ROFC	1.19		80	78.7	55.2	54.9
CH	ROGC	1.15		80	80.4	42.2	42.2
CH	SMA (QP)	1.53		80	79.1	56.3	56.1
CH	HL3 (QP)	0.56		80	79.5	43.4	43.2
CH	ROFC	1.19		90	87.0	51.0	50.2
CH	ROGC	1.15		90	88.0	40.1	39.5
CH	SMA (QP)	1.53		90	87.8	52.9	52.3
CH	HL3 (QP)	0.56		90	89.4	41.3	41.1
CH	ROFC	1.19		100	99.6	46.9	46.8
CH	ROGC	1.15		100	97.9	38.1	37.6
CH	SMA (QP)	1.53		100	98.5	51.2	50.8
CH	HL3 (QP)	0.56		100	98.8	36.7	36.4
LF	HL3-1	0.9	63	64	63.5	47.9	47.8
LF	HL3-2	0.8	64	64	63.7	44.2	44.1
LF	PMA	0.9	63	64	61.3	53.0	52.3
LF	SMA (LF)	1.8	79	64	60.0	59.5	58.4
LF	SP	0.9	75	64	61.6	61.4	60.8
LF	HL3-1	0.9	63	80	84.1	46.3	47.3
LF	HL3-2	0.8	64	80	71.6	42.7	40.5
LF	PMA	0.9	63	80	80.0	54.0	54.0
LF	SMA (LF)	1.8	79	80	75.5	57.3	56.2
LF	SP	0.9	75	80	79.7	54.6	54.5
Minimum		***0.56***	***63***	***64***	***60.0***	***36.7***	***36.4***
Maximum		***1.75***	***79***	***100***	***99.6***	***61.4***	***60.8***
Average		***1.08***	***69***	***79***	***77.7***	***49.3***	***49.0***
Std. Deviation		***0.36***	***7***	***13.1***	***13.2***	***7.1***	***7.0***

Table 4-10 Summary of the Seasonal (Monthly) Skid Data

Month	***PCC Pavements***					***AC Pavements***				
	***MTD* (mm)**	**Ambient Temp. (°C)**	**Surface Temp. (°C)**	***BPN***	**Corrected *BPN***	***MTD* (mm)**	**Amb. Temp. (°C)**	**Surf. Temp. (°C)**	***BPN***	**Corrected *BPN***
February	1.38	4.7	5.1	71.1	66.1	1.04	4.2	4.9	71.3	66.3
March-9	1.38	5.8	8.6	72.0	69.0	1.04	3.0	9.7	75.8	72.8
March-23	1.38	5.7	3.8	71.2	66.2	1.04	9.3	3.6	73.4	68.4
April	1.38	31.6	27.6	62.9	63.9	1.04	32.4	35.1	65.5	68.5
May	1.38	27.8	29.0	63.0	65.0	1.02	23.6	24.2	71.0	72.0
June	1.38	25.3	21.8	65.3	65.3	1.02	34.8	34.6	62.5	65.5
July	1.38	27.7	21.5	65.3	65.3	1.02	20.0	22.4	66.7	66.7
August	1.37	33.4	30.2	62.4	64.4	1.11	28.9	25.2	63.7	64.7
September	1.37	18.3	17.2	72.4	71.4	1.11	21.9	21.0	67.6	67.6
October	1.37	15.6	12.7	71.9	69.9	1.11	10.5	10.9	73.9	70.9
Minimum	***1.37***	***4.7***	***3.8***	***62.4***	***63.9***	***1.02***	***3.0***	***3.6***	***62.5***	***64.7***
Maximum	***1.38***	***33.4***	***30.2***	***72.4***	***71.4***	***1.11***	***34.8***	***35.1***	***75.8***	***72.8***
Average	***1.38***	***19.6***	***17.7***	***67.8***	***66.7***	***1.05***	***18.8***	***19.2***	***69.2***	***68.4***
Std. Dev.	***0.01***	***11.2***	***9.9***	***4.3***	***2.5***	***0.04***	***11.5***	***11.4***	***4.6***	***2.8***

Table 4-11 Summary of Prior Weather Data (University of Waterloo)

Date of Testing	Mean Prior Temperature (°C)								Prior Rainfall Total (mm)				No. of Dry Days
	7-Day		5-Day		3-Day		1-Day						
	Low	High	Low	High	Low	High	Low	High	7-Day	5-Day	3-Day	1-Day	
20-Feb	-26.8	-8.1	-20.8	-6.4	-21.1	-4.5	-26.7	2.9	11.8	2.3	0.0	0.0	3.0
09-Mar	-12.1	-4.7	-15.6	-6.3	-18.6	-8.5	-12.8	-4.1	16.3	3.8	0.9	0.0	1.0
23-Mar	-6.8	2.3	-6.8	4.1	-6.4	6.0	-1.6	11.5	5.2	8.7	6.1	5.2	0.0
20-Apr	0.0	7.1	0.9	8.7	1.4	10.7	-0.1	16.3	1.7	1.2	0.6	0.0	1.0
18-May	6.5	18.4	6.2	17.7	8.7	18.0	5.5	12.9	38.4	38.4	38.4	2.4	0.0
18-Jun	14.3	28.3	14.3	27.4	14.7	28.6	14.3	31.1	0.0	0.0	0.0	0.0	9.0
27-Jul	12.5	24.9	13.0	25.7	14.8	25.0	13.6	26.1	1.8	1.8	1.8	0.0	2.0
10-Aug	16.3	27.7	15.8	25.0	16.8	23.7	16.5	21.6	35.0	32.4	32.4	0.2	0.0
20-Sep	6.0	21.1	5.0	20.4	6.5	24.0	9.3	27.9	4.0	0.2	0.0	0.0	4.0
24-Oct	11.0	19.9	11.1	20.1	10.0	21.1	4.7	16.6	12.8	11.6	11.4	11.4	0.0
Min.	*-26.8*	*-8.1*	*-20.8*	*-6.4*	*-21.1*	*-8.5*	*-26.7*	*-4.1*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Max.	*16.3*	*28.3*	*15.8*	*27.4*	*16.8*	*28.6*	*16.5*	*31.1*	*38.4*	*38.4*	*38.4*	*11.4*	*9.0*
Mean	*2.1*	*13.7*	*2.3*	*13.6*	*2.7*	*14.4*	*2.3*	*16.3*	*12.7*	*10.0*	*9.2*	*1.9*	*2.0*
Std. Dev.	*13.7*	*13.5*	*12.8*	*12.8*	*13.7*	*13.0*	*13.4*	*11.1*	*13.8*	*13.9*	*14.4*	*3.7*	*2.8*

4.3.3 Long Term Variation of Surface Friction (Part III)

The skid resistance data in the LTPP database consists of measurement taken by several types of friction testers. Therefore, measurements taken by a single equipment type that has the maximum number of measurement points were selected to be consistent in the analysis and findings. The selected equipment is the ASTM locked wheel skid trailer (ASTM E 274). Among the locked wheel friction tests, the smooth tire was used for a couple of sections. These sections were also filtered out to be consistent with respect to the method of friction measurement and equipment used. Thereby only the locked wheel skid data obtained using the ribbed tire were used in the analysis of PCC pavement surface friction variation the over long term. For AC pavements, friction data were further sorted to select the measurements that were taken with a single manufacturer's skid trailer. This allowed for a further reduction of data volumes and being more consistent in all analysis. For PCC pavements, it was not possible to limit the data to equipment from one manufacturer, as it would not have permitted including all of the available surface textures and variation in environmental conditions.

The surface friction data of selected sections were then individually checked for accuracy/ practicality and consistency such as unusual increase or decrease. All of the suspect data were filtered out to obtain meaningful and useful results/models. As the main objective was to examine the skid resistance performance over long term, sections with at least two surface friction measurements in succession of time were used in the analysis, except for the ranking of the PCC pavements various surface textures in terms of average skid resistance. Finally, data from 238 PCC pavement sections in 38 states/provinces of United Sates and Canada were used in the analysis. For AC pavements, data from 256 sections in 33 states/provinces were used in the analysis.

The average skid number of multiple measurements on each section was calculated and used as the available surface friction of that section at each age level. The time (age) between successive skid resistance measurements and cumulative age of each section was then calculated. As all the LTPP data are recorded in imperial (U.S.) units, the temperature during the skid testing, vehicle speed, and all other data were converted to metric units. Mean Annual Average Daily Traffic (AADT) and percentage of trucks on LTPP lanes were calculated from the traffic data during the years of surface friction measurements. Cumulative traffic on LTPP lanes was then calculated. Mean percentage of annual wet days (number of wet days as a percentage of total days in each year) and average annual mean temperatures were calculated from weather data from years 1986 to 2005 (twenty years). For PCC surfaces, average 28-day compressive strength was calculated for each section with appropriate correction for tests conducted at different ages. The 7-day strength was taken as 75% of the 28-day strength while 56-day and 90-day strengths were taken to be 10% and 15%, respectively, greater than the 28-day strength (CAC 2007). For AC surfaces, mean Marshall Stability, flow, air voids, and VMA were calculated. The percentage of coarse aggregate and maximum aggregate size was also retrieved for each surface mix.

Table 4-12 shows the summary statistics of the data used in the analysis for long term skid resistance. The PCC pavements *SN* was shown to range from 22 to 66 *SN* with a mean *SN* of 47. The AC pavements *SN* ranged from 23 to 69 with a mean *SN* of 45. The PCC and AC surfaces were exposed to a maximum 42 million traffic passes in sixteen years and 37 million traffic passes in twelve years, respectively. The percentages of trucks on the LTPP lane were shown to vary from 3% to 69%. The speed and temperature during the skid testing ranged from 42 km/h to 89 km/h and 0°C to 42°C, respectively. The 20-year average annual wet days were shown to be in the range of 7% to 57% while the 20-year average annual temperature ranged from 3°C to 25°C.

Table 4-12 also shows that the PCC mixes 28-day compressive strengths varied from 21 MPa to 57 MPa with a mean compressive strength of 37 MPa while the AC mixes Marshall Stability ranged from 3.5 kN to 19.9 kN with a mean stability of 8.3 kN. In AC mixes, the air voids and voids in mineral aggregates (VMA) were shown to range from 1.7% to 17% (mean air voids of 5.8%) and 11.8% to 29.2% (mean VMA of 17.5%), respectively. The maximum aggregate sizes and percentages of coarse aggregate in the AC mixes were shown to vary from 9.5 mm to 37.5 mm and 2% to 69%, respectively. The data covers four climatic regions, namely dry freeze, wet freeze, dry no freeze, and wet no freeze. These variations in mix properties, environmental exposures, and traffic uses are expected to produce useful results and pervasive models.

Table 4-12 Descriptive Statistics of the Processed LTPP Data

Statistics	Count	Min.	Max.	Mean	Stand. Dev.
Rigid Pavements					
SN	743	22.0	65.5	46.6	6.86
Age, years	743	0	15.95	2.85	3.22
AADT	277	462	13,637	4,757	3,153
Cumulative Traffic, million	277	0	42.02	5.85	7.82
Truck %	277	2.9	68.5	18.1	12.6
Speed, mph	743	41.8	88.5	65.3	4.64
Air Temperature, °C	655	0	41.7	22.3	8.25
Compressive Strength, MPa	677	20.64	56.67	37.2	7.60
Avg. Annual Temperature, °C	743	2.8	22.9	13.4	4.25
Avg. Annual Wet Days, %	743	9.2	51.8	34.6	8.16
Flexible Pavements					
SN	1,229	23.0	68.5	44.8	8.01
Age, years	1,229	0	12.05	2.12	2.26
AADT	474	407	16,700	3,723	3,387
Cumulative Traffic, million	474	0	37.3	3.6	4.98
Truck %	474	3.8	44.9	15.5	9.85
Speed, mph	1,229	57.9	88.5	67.5	7.86
Air Temperature, °C	1,164	0	42.8	22.5	8.22
Marshall Stability, N	218	3,526	19,907	8,336	2,927
Annual Avg. Temperature, °C	1,079	2.7	25.1	12.7	4.23
Annual Avg. Wet Days, %	1,079	6.5	56.6	35.0	9.59
Max. Aggregate Size, mm	484	9.5	38	16.9	4.1
Coarse Aggregate, %	515	2	69	39.4	11.33
VMA, %	266	11.8	29.2	17.5	3.11
Air Voids, %	432	1.7	17	5.8	2.57

4.3.4 Tire-Pavement Noise and Acoustic Absorption (Part IV)

As mentioned earlier, the tire-pavement noise measurements were taken with a single vehicle, mounted with a single brand of tire, maintaining the desired speeds uniformly. Every attempt was made to isolate the test vehicle from the surrounding traffic stream to avoid interference in the measured noise levels. The cases with possible interference (as perceived) were removed from the database during the measurements. However, it was not possible to isolate the test vehicle to create ideal condition, as would be the case of roads closed for traffic. As a result, some sort of outside influence could not be eliminated because of high traffic volumes on the highways included in the testing scheme. Therefore, all the data were further checked for consistency and practicality. All the doubtful data were excluded from the analysis program. Although the temperature during tire-pavement noise measurements varied from section to section, no correction for temperature was applied as the effect of temperature on measured tire-pavement noise levels was yet to be established.

The maximum and equivalent noise levels and the corresponding frequencies were retrieved for each test section. The average noise levels of multiple measurements were calculated and used in the analysis. The summary of the measured noise levels is presented in next chapter (Chapter 5). The data from the sound absorption testing in the laboratory were also checked for accuracy and the average sound absorption from multiple (five) measurements were calculated for use in the analysis.

Chapter 5 Data Analysis and Results

This chapter presents the surface texture and skid resistance levels of various AC and PCC pavements and determines the effect of AC mix properties and PCC pavement various texturizations on surface macrotexture and skid resistance development. The trend of month-to-month skid resistance variation and effects of pavement as well as mix types and weather on seasonal variation are examined. The effects of mix properties, environment, age, and traffic on long term skid resistance variation are also assessed. Finally, the tire-pavement noise and sound absorption of various AC and PCC pavements together with benchmarking of various surfaces with respect to tire-pavement noise level are presented. The correlation of surface texture, skid resistance, and noise is also examined for selected pavements.

5.1 PAVEMENT SURFACE TEXTURE AND FRICTION (PART I)

5.1.1 Macrotexture and Skid Resistance of PCC Surfaces

Figure 5-1 compares the *MTD* and skid resistance (*BPN*) of sixteen different surface texture configurations (fifteen in the laboratory and one in the test track) for standard PCC (100% virgin aggregate). Among the studied surfaces, the greatest skid resistance (*BPN* of 83) is provided by the deep transverse broom drag, attained by dragging a corn broom. This surface has a *MTD* of 1.84 mm. It is followed by surface that received a 16 mm uniformly spaced transverse tining over a burlap dragged texture. The *BPN* has shown to be 81 with a *MTD* of 1.65 mm for this surface. The smooth surface (trowel finish) has exhibited the lowest friction (*BPN* of 52) with the lowest *MTD* of 0.52 mm.

The longitudinal randomly spaced tining with a *MTD* of 1.70 mm has shown to provide a *BPN* of 73 whereas similar longitudinal randomly spaced tining with an additional burlap drag in advance has exhibited a similar skid resistance (*BPN* of 73) but with a lower texture (*MTD* of 1.57 mm) due to the added benefit of microtexture. For the same texture configuration and *MTD*, the transversely textured surfaces have shown to exhibit 7% to 14% higher skid resistance as compared to longitudinal textured surfaces.

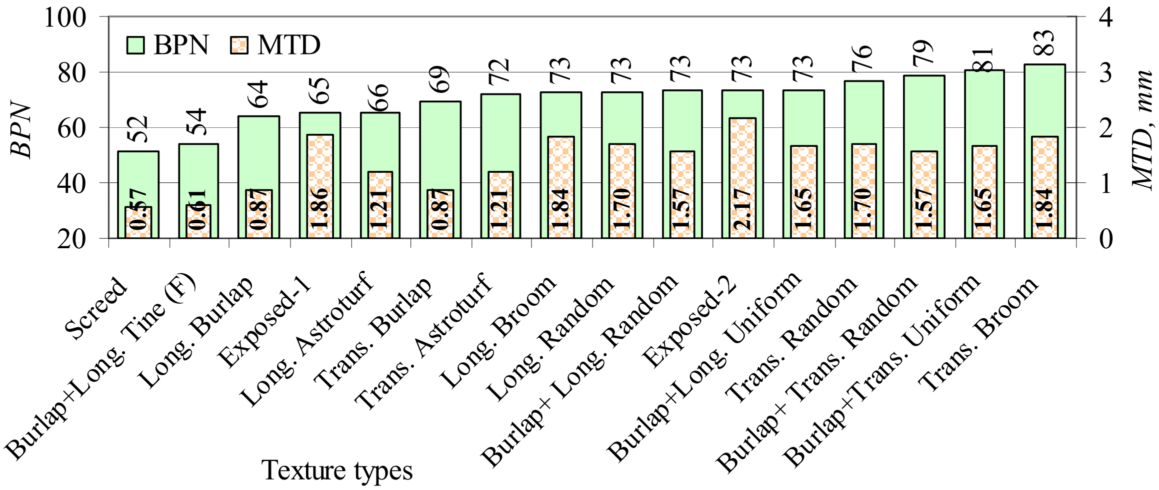

Figure 5-1 Comparison of Texture and Friction for Various PCC Surface Textures.

Figure 5-1 also shows that the highest *MTD* (1.86 mm and 2.17 mm) were available for two exposed aggregate surfaces, but the skid resistance provided by them are lower than other surfaces with lower *MTD*. This is probably the result of microtexture loss due to washing out of sand with the surface mortar. Therefore, exposed aggregate surface may not be a preferred texturing method considering lower skid resistance, construction difficulty and associated extra cost. Two exposed aggregate surfaces with a different macrotexture and friction showed that a variation in *MTD* of 0.31 mm result in a variation in skid resistance of 8 *BPN*. All these indicate that when specifying a texture configuration, it is important to indicate the actual texture depth in addition to the texturization method, direction, and pattern.

The field test section, although the tining specification (spacing/depth/width) is the same as the laboratory textured surface with uniformly spaced longitudinal tining over burlap drag (*MTD* of 1.65 mm and *BPN* of 73), produced a *MTD* of 0.61 mm that has resulted in a skid resistance of 54 *BPN* only. It further proves that construction variation is a big factor in achieving the desired surface texture and skid resistance. Therefore, the available surface friction is not just a subject of specification, but is dependent on what has actually been done in the field. This is particularly important for PCC pavement surfaces because of several factors that are involved in attaining the desired surfaces including weather, concrete placement time, texturing time (these three factors probably are responsible in this study), texturing tool and load, texture patterns, and concrete mix constituents and properties.

5.1.2 PCC Surface Texture and Friction Relationship

Figure 5-2 shows the variation of *BPN* with variation in *MTD* on surfaces of conventional PCC mix. As shown in the figure, the skid resistance increases to the maximum value for *MTD* value of about 1.8 mm and decreases thereafter as the *MTD* further increases. This can be justified from the fact that for higher *MTD* with deeper/wider textures the net tire and pavement surface contact will not increase but rather will decrease. This is because of constant tire deformation beyond a certain depth and reduction of tire-pavement contact area with an increase in texture wavelength beyond a certain limit. The available data therefore suggests that PCC texturing should be specified not to exceed a *MTD* of 1.8 mm, as the surface friction does not increase beyond such macrotexture level whereas driver's discomfort and tire-pavement noise are likely to increase.

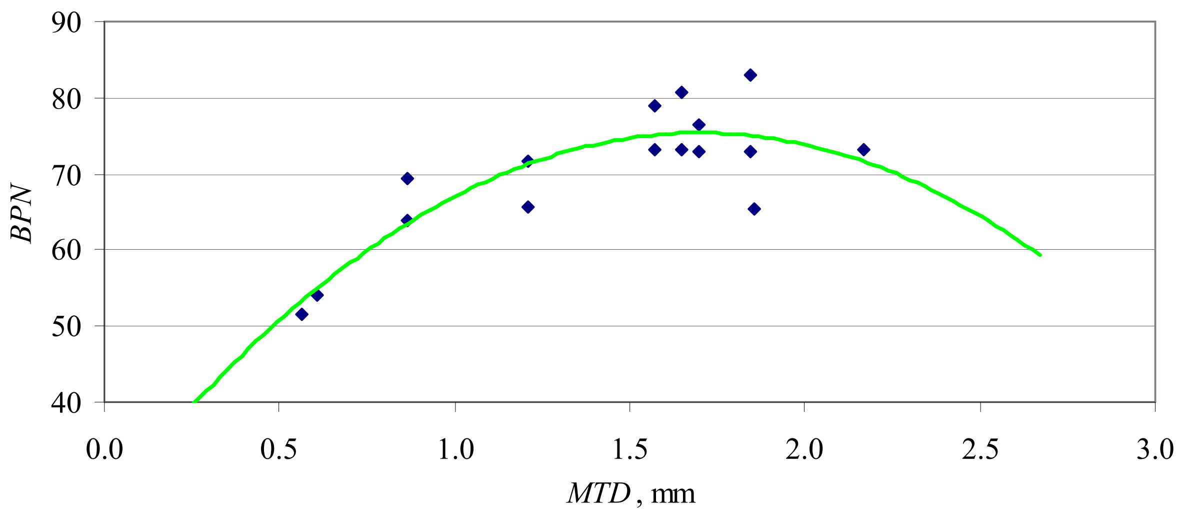

Figure 5-2 Variation of *BPN* with *MTD* on PCC Pavement.

Study results published elsewhere have indicated that a minimum *BPN* of 55 or a ribbed tire *SN* of 41 (at 64 km/h or 40 mph) is desired to reduce the wet pavement accidents. For example, Wambold (1988) has recommended a *BPN* of 55 as the desired minimum surface friction for adequate resistance to skidding on a wet surface. Rizenbergs et al. (1976) has indicated a SN_{40} of 41 is the critical value in recommending the desired surface friction. TAC (1997) also has provided similar guideline for monitoring the pavement surface friction and rehabilitation to improve the skid resistance. The trend in Figure 5-2 indicates that a *MTD* of 0.7 mm can exhibit such a level of skid resistance. However, considering the variability in skid as well as texture measurements and surface wear over time, the desired minimum *MTD* should be substantially higher depending on traffic volume and pattern, concrete mix materials and local environment as well as contaminant.

The specified (in Europe) minimum *MTD* ranges from 0.7 mm to 1.0 mm (Phillips and Kinsey 2000, Dupont and Bauduin 2005, Larson et al 2008). A *MTD* of maximum 1.8 mm would probably be adequate for every circumstance. However, it is recommended that the optimum or desired maximum macrotexture level should be verified through full scale skid testing such as the ASTM skid trailer, although this study found a justified variation of *BPN* with the *MTD*. The correlation has shown also to be statistically significant at a 5% level of significance (95% confidence level) with good correlation coefficient (r = 0.86).

5.1.3 Surface Texture and Friction of PCC with RCA

The comparison of macrotexture and surface friction of five different textures on PCC containing RCA is shown in Figure 5-3. The number at the base represents the percentages (0 to 50) of RCA in the PCC mixes. As shown in the figure, the texture with transverse tining over broom dragged surface (i.e., broom plus trans. tine) has exhibited the greatest skid resistance (*BPN* of 82) with a *MTD* of 0.79 mm. For the same 50% RCA mix, the surface with a burlap drag plus longitudinal tining textures has shown to exhibit only a *BPN* of 58 with identical *MTD* (0.79 mm). Alternatively, a surface with broom drag plus longitudinal tining has exhibited a *BPN* of 75 with similar *MTD* of 0.75 mm for the same 50% RCA mix. These further indicate that transversely tined surfaces provide better skid resistance and broom drag is a more effective texturization method than burlap drag. It should be noted here that the broom used in the field is different from that was used in the laboratory.

Figure 5-3 also shows that the same burlap drag plus longitudinal tining texture on four concrete mixes with 0%, 15%, 30% and 50% RCA has exhibited a *BPN* of 54, 73, 78 and 58 with a *MTD* of 0.61 mm, 0.74 mm, 0.72 mm and 0.79 mm, respectively. It indicates that both texture and RCA content have influence on skid resistance variation.

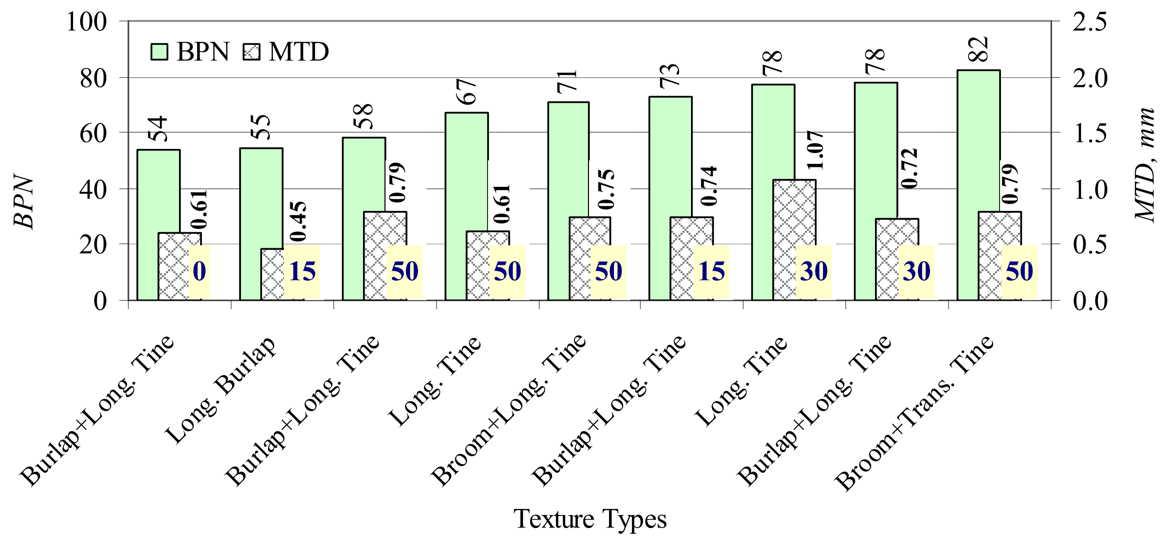

Figure 5-3 Surface Texture and Friction of PCC Sections with RCA.

Figures 5-4 and 5-5 show the variation of skid resistance with variations of *MTD* and RCA content, respectively. The quadratic trend in Figure 5-4 indicates that skid resistance increases with an increase in texture for the available *MTD* range (substantially lower than laboratory samples) and likely decrease beyond a certain *MTD* value. It seems to be logical and agrees with the trend of laboratory samples although the optimum point may not coincide because of the contribution of RCA. The correlation has been shown to be statistically significant (at 5% level) with a correlation coefficient (r) of 0.68. Alternatively, the trend in Figure 5-5 suggests that skid resistance increases linearly with an increase in RCA content for the available range. This is probably associated with additional microtexture of the crushed reclaimed concrete. However, the correlation (r = 0.42) was not statistically significant at the 5% level of significance.

5.1.4 Surface Texture and Skid Resistance of Various AC Pavement Surfaces

The comparison of *MTD* and *SN* at 64 km/h (SN_{64}) for nine asphalt pavement surfaces at two test sites is shown in Figure 5-6. As shown in the figure, two HL3 (HL3-1 and HL3-2) surfaces (control sections at landfill site having same aggregate gradation) have exhibited SN_{64} of 48 and 44 with *MTD* of 0.87 mm and 0.76 mm, respectively. It shows a difference in skid resistance of just four *SN* for a difference in *MTD* of 0.11 mm in the case of dense AC mix. The PMA mix that contains the same aggregate gradation as of HL3 at landfill (HL3-1 and HL3-2) has exhibited a SN_{64} of 52 with a *MTD* of 0.92 mm. This shows a good agreement of the ribbed tire *SN* and macrotexture variations based on measurements in the same context (site). Alternatively, the HL3 at Crosshill (QP) site was shown to exhibit a SN_{64} of 48 with a lower *MTD* of 0.56 mm than HL3 at LF. This is probably related to variation in surface contaminants (more contamination at LF site) at the two sites.

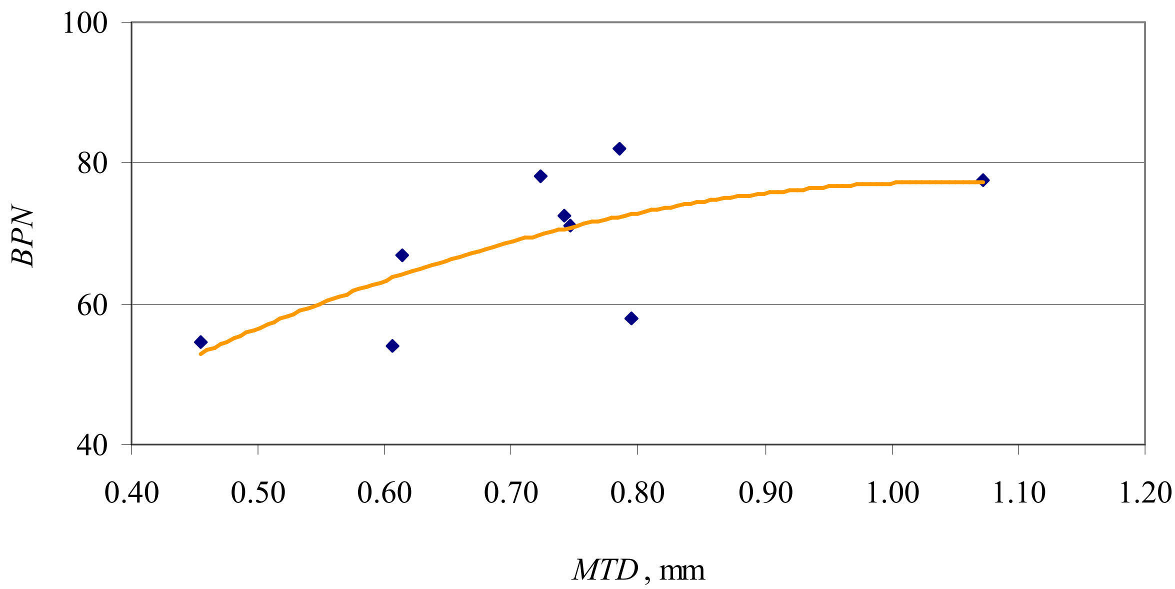

Figure 5-4 Variation of *BPN* with *MTD* of PCC Surfaces Containing RCA.

Figure 5-6 also shows that two SMA mixes have exhibited SN_{64} of 58 and 57 with the greatest *MTD* of 1.75 mm and 1.53 mm, respectively. It shows just one *SN* difference in skid resistance for a difference in *MTD* of 0.22 mm for the stone rich mix. Higher surface contaminant at the LF site probably has also contributed to such variation (higher *MTD* for the SMA at LF site and similar *SN* for both SMA). The Superpave mix was shown to exhibit the greatest SN_{64} of 61 among the tested surfaces with a low *MTD* of 0.91 mm despite being located at LF site (higher contaminant). The ROFC exhibited a good SN_{64} of 57 with a *MTD* of 1.19 mm whereas the ROGC with similar gradation of ROFC exhibited the lowest SN_{64} of 44 with a similar *MTD* of 1.15 mm. These indicate that the AC surface skid resistance is a complex function of many factors including surface texture level, aggregate and mix properties and net contact at tire-pavement interface.

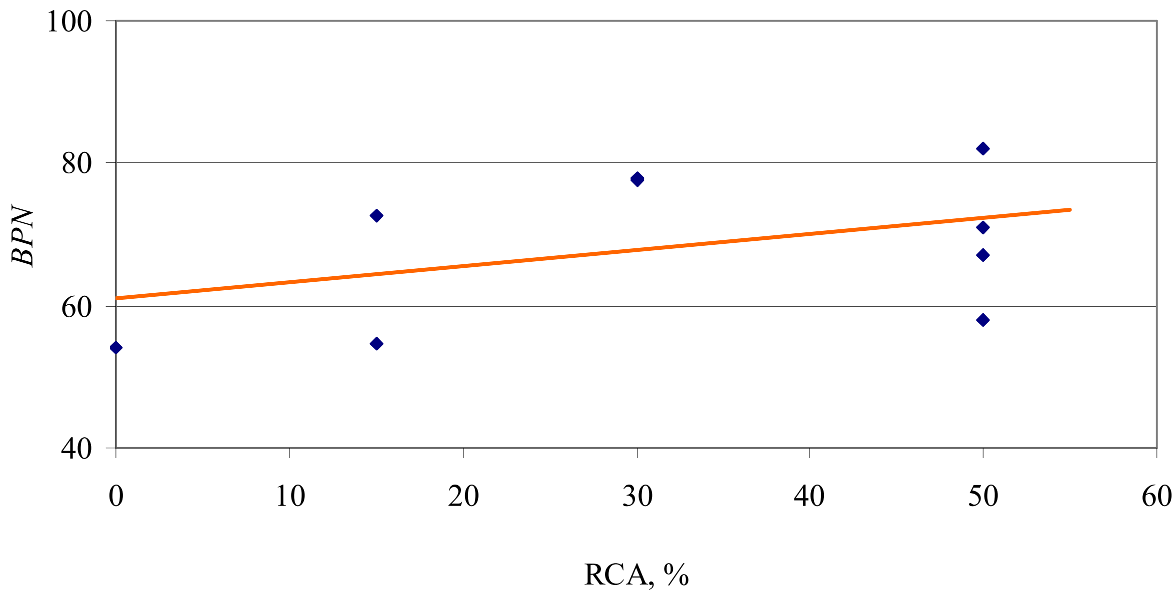

Figure 5-5 Variation of *BPN* with Variation of RCA Contents in PCC Mixes.

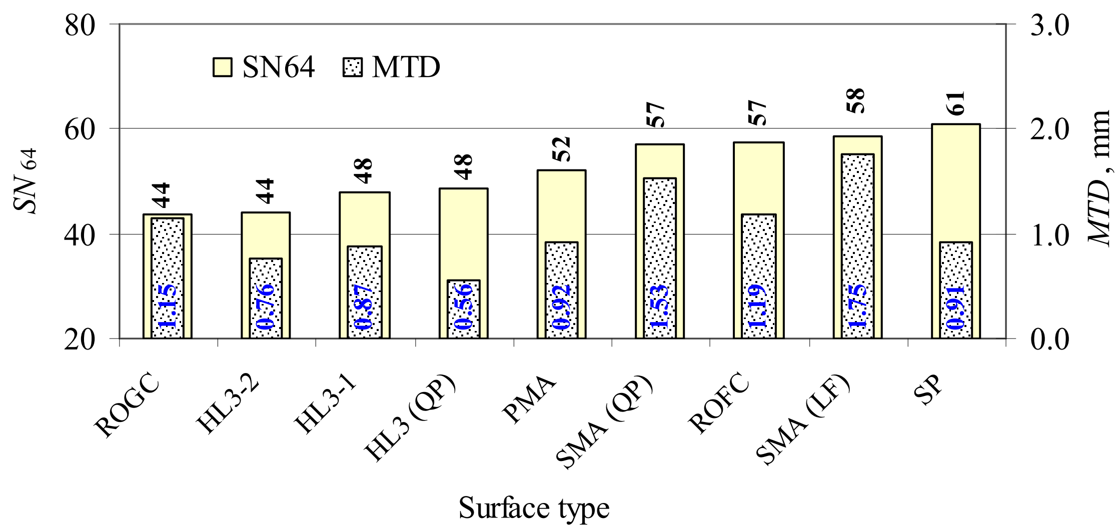

Figure 5-6 Comparison of Texture and Skid Resistance of Various AC Pavements.

5.1.5 Effect of Mix Properties on Texture and Skid Resistance of AC Pavements

The variation of SN_{64} and *MTD* with variation in the proportion of coarse and fine aggregates in the AC mix is shown in Figure 5-7. As shown in the figure, both *SN* and *MTD* increase linearly as the ratio of *C.A*. to *F.A*. percentage (by weight) increases. This suggests that coarser (% retained on 4.75 mm) AC mixes exhibit greater texture and skid resistance for the given range of C.A. /F.A. ratio. However, the correlation of *MTD* and C.A. /F.A. was shown to be much stronger ($r = 0.91$) than the correlation of *SN* and C.A. /F.A. ($r = 0.39$).

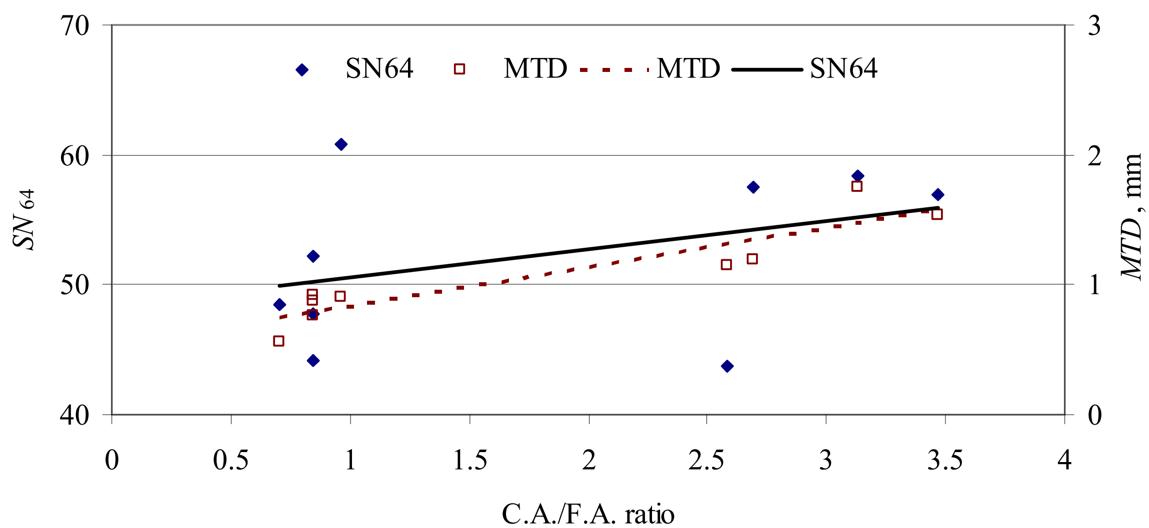

Figure 5-7 Effect of Aggregate Gradation on Texture and Friction of AC Pavements.

Figure 5-8 shows the relationships of AC pavement surface macrotexture (*MTD*) and SN_{64} with air void content (AV, %) in the compacted mixes. The trend for *SN* shows that skid resistance decreases with an increase in AV content while the trend for *MTD* is fairly constant. The variation of SN_{64} and *MTD* with the variation in VMA is shown in Figure 5-9. The SN_{64} is shown to be constant while the *MTD* is shown to increase slightly with an increase in VMA. Such trends have appeared to be counterintuitive to previous knowledge.

None of above relationships was shown to be statistically significant at 5% (even 10%) significance level indicating that AV and VMA, for the given ranges, have no significant effect on the *SN* or *MTD*. In fact, both the AV and VMA represent the voids within the compacted asphalt mix or aggregates. They therefore are the interior properties of asphalt mix. The surface microtexture as well as macrotexture and friction are the properties of uncoated aggregates texture and gap/depression between the exposed aggregates. This probably justifies why air voids and VMA are not significant factors in surface texture or skid resistance variation. Another suspect is the insitu voids of the tested pavements that may be lower than the mix design values due to over compaction during the construction or additional compaction due to traffic use. This may also affect the available skid resistance of the AC surfaces. Further study therefore is recommended to verify both aspects.

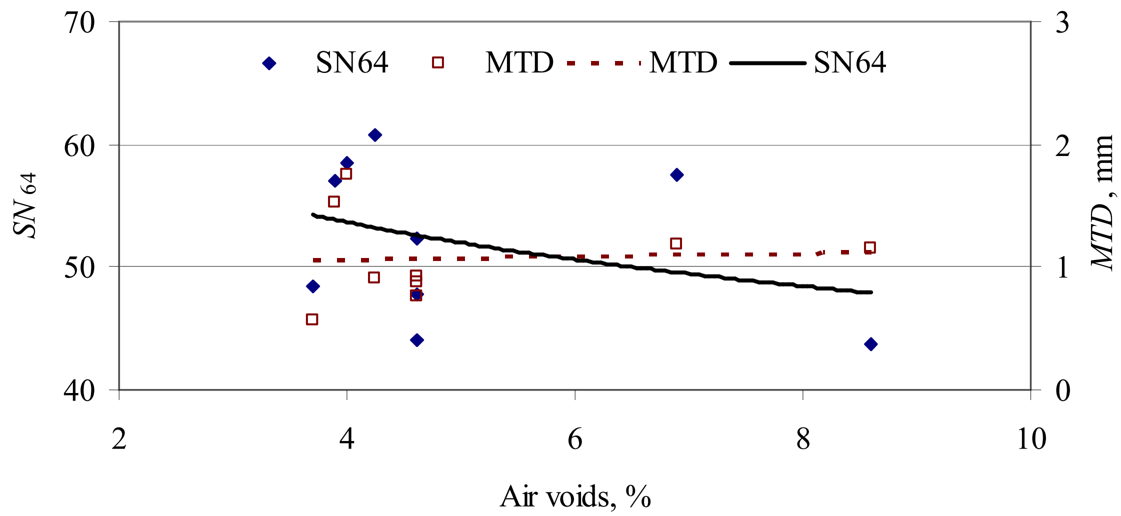

Figure 5-8 Effect of Air Voids on Texture and Friction of AC Pavements.

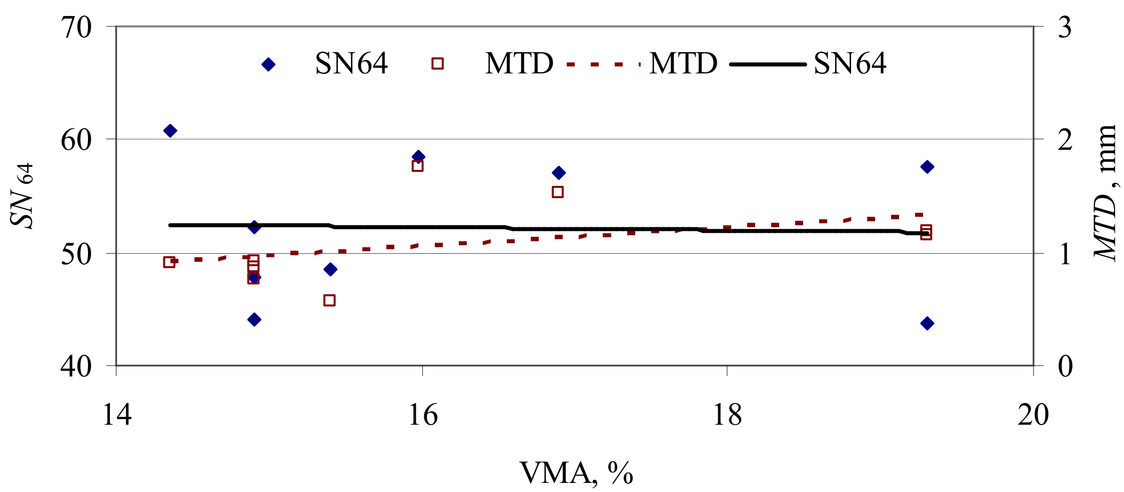

Figure 5-9 Effect of VMA on Texture and Friction of AC Pavements.

5.1.6 Variation of Skid Resistance with Surface Texture of AC Pavements

Figure 5-10 shows the variation of SN_{64} with the *MTD* of AC pavement surfaces. The trend for the variation of skid resistance with macrotexture (r = 0.53) has appeared to be different from that of PCC pavement surfaces. This is probably due to different scenarios of the surface macrotexture of the two pavement types where the asphalt pavements macrotexture generally is more complex with multi-directional variation as compared to the unidirectional macrotexture on PCC surfaces. Furthermore, the maximum *MTD* value is 1.75 mm for the AC mixes used in this analysis. However, the trend in Figure 5-10 shows that a *MTD* of 1.8 mm on AC surface can provide a SN_{64} of 60 that is similar to transverse texturing on PCC pavement surface with *BPN* of 78. A *MTD* of 1.8 mm therefore may also be taken as the desired maximum texture level for all pavement surfaces to reduce the rolling resistance, fuel consumption, and tire-pavement noise.

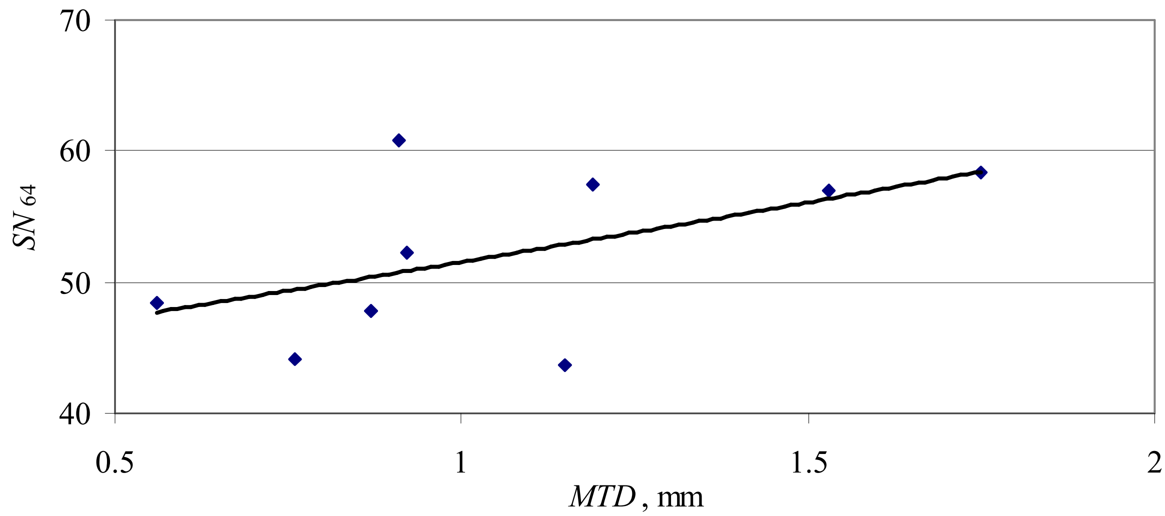

Figure 5-10 Variation of Skid Resistance with Surface Texture of AC Pavements.

5.1.7 Variation of Skid Resistance with Vehicle Speed on AC Pavements

The variation of skid number for nine different surfaces at the Crosshill and landfill sites with the variation in speed of the vehicle is shown in Figure 5-11. As shown in the figure, skid resistance decreases linearly with an increase in vehicle's speed. The correlation (trend) has indicated that skid resistance decreases at 2.6 *SN* (on average) for each 10 km/h increase in vehicle speed. The correlation was shown to be statistically significant at 5% significance level with a correlation coefficient (*r*) of 0.48.

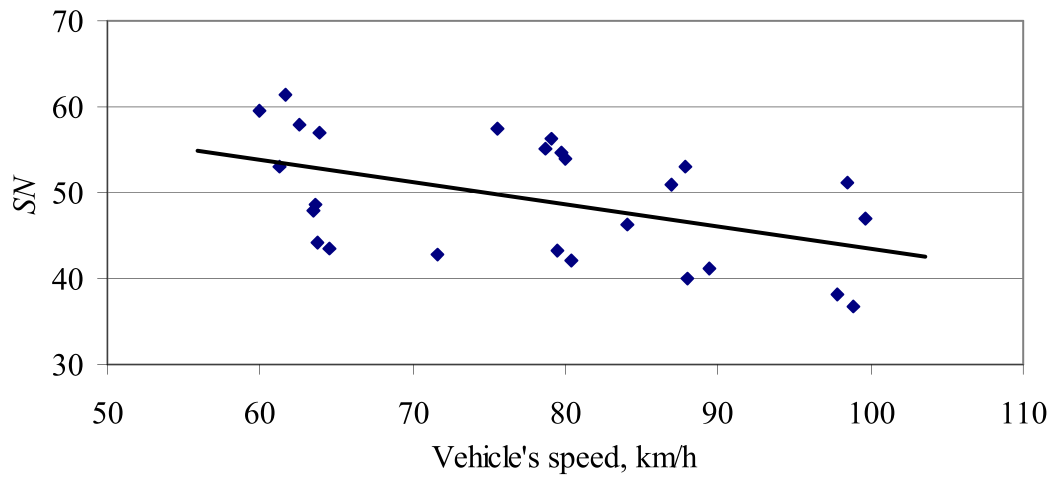

Figure 5-11 Variation of Skid Resistance with Vehicle Speed on AC Pavements.

The variations of skid resistance with the changes in speed of the vehicle for four different AC mixes at Crosshill site are shown in Figure 5-12. The correlation for individual mixes has shown to be very strong with a correlation coefficient (r) of 0.96 and higher but with different slopes and intercepts. After combing all mixes for a single trend line, the correlation coefficient is only 0.47. These indicated that the gradient is not something universal for all mixes and skid number-speed gradient should be developed for each mix separately for best utilization of the available friction from different surface mixes.

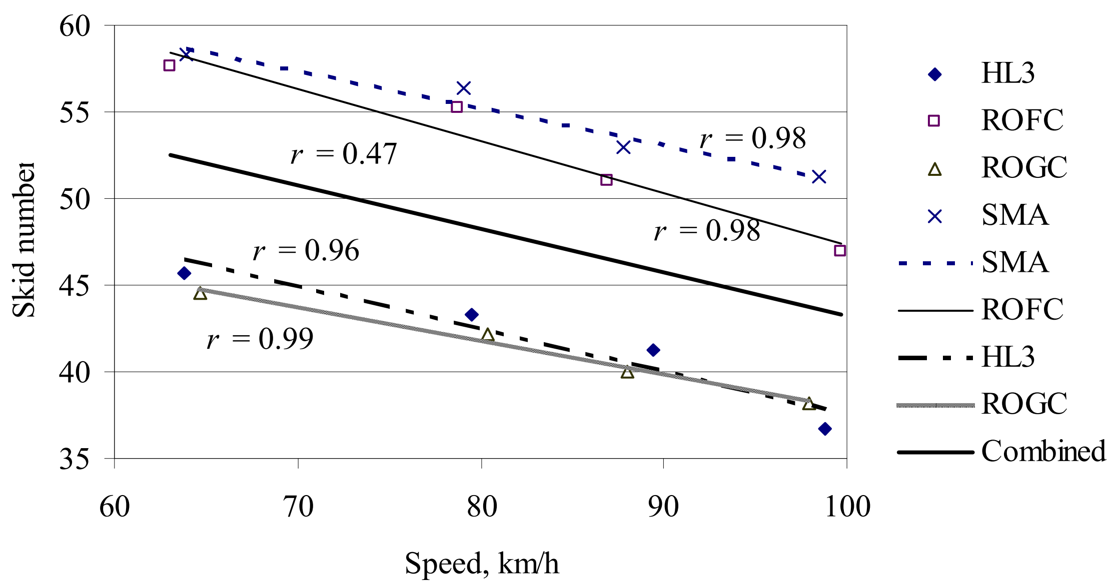

Figure 5-12 Skid Number-Speed Gradients for Various AC Mixes.

5.1.8 *BPN* and Skid Number Relationship

Figure 5-13 shows the comparison of *BPN* and SN_{64} for five surfaces at landfill site. As shown in the figure, variation of the *BPN* fairly resembles the variation of SN_{64}. This rejects the hypothesis that *BPN* is dependent on surface microtexture only and represents low speed friction. Alternatively, it further establishes the fact that *BPN* is dependent on both surface microtexture and macrotexture, and simulates well with other dynamic testing methods.

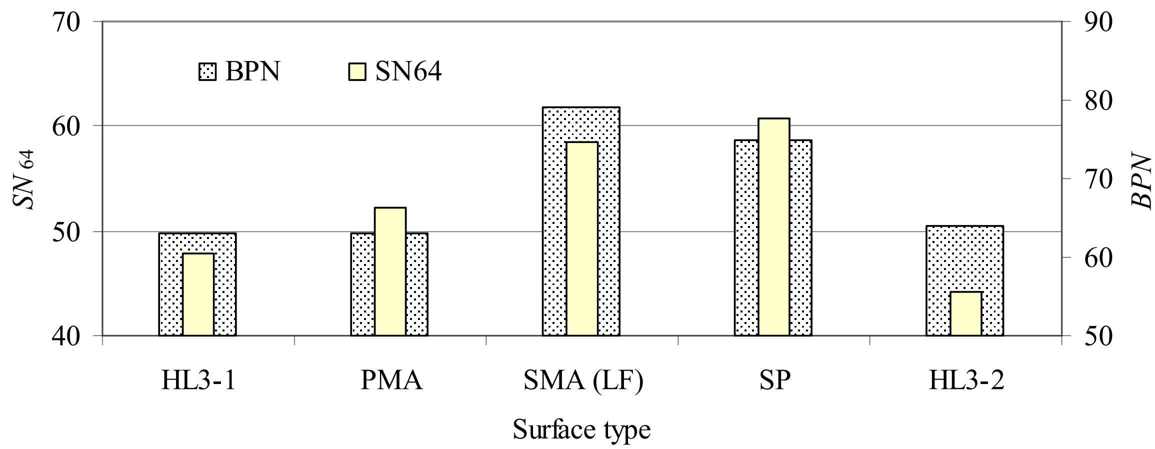

Figure 5-13 Comparison of *BPN* and Skid Number.

The correlation between *BPN* and SN_{64} (with the available data) as given by Equation 5-1 shows that SN_{64} is fairly 77% of the *BPN* value. With this correlation, a *BPN* of 55 would mean a SN_{64} of 42. This agrees well with some previous recommendations with respect to the desired minimum skid resistance despite the small number of data points used in this study. The developed correlation was shown to be statistically significant at 5% significance level with *t*-value of 30.65, *p*-value of 0.000 and good correlation coefficient (*r*) of 0.85.

$$SN_{64} = 0.7657BPN \tag{5-1}$$

Where,

SN_{64} = Skid Number at 64 km/h, and

BPN = British Pendulum Number.

Wambold (1988), however, has recommended a minimum *SN* of 35 and *BPN* of 55 indicating that *SN* is approximately 64% of the *BPN* value. While some degrees of variability are normal in all physical measurements, further investigation and correlation with a large number of data points may provide greater confidence.

5.1.9 Sand Patch and Laser Based Macrotextures

Figure 5-14 shows the variations of macrotexture Mean Profile Depth (*MPD*), Root Mean Square (*RMS*), and *MTD* for five AC pavements at the landfill site. Although the variation of *RMS* was shown to resemble the variation in *MPD* with excellent correlation (r = 0.994), they did not resemble the variation in *MTD* for the tested sections. It should be noted that *MPD* calculation excludes wavelengths below 2.5 mm or above 100 mm (Viner et al. 2000a). This may provide some variability in the measured *MPD* as compared to *MTD*. Furthermore, different texture patterns, e.g. negative versus positive textures, may not have similar correlations. Further close study is therefore recommended to a develop correlation between sand patch and laser macrotextures, and to validate the previously established correlations, specifically separating the negative and positive textures into two groups.

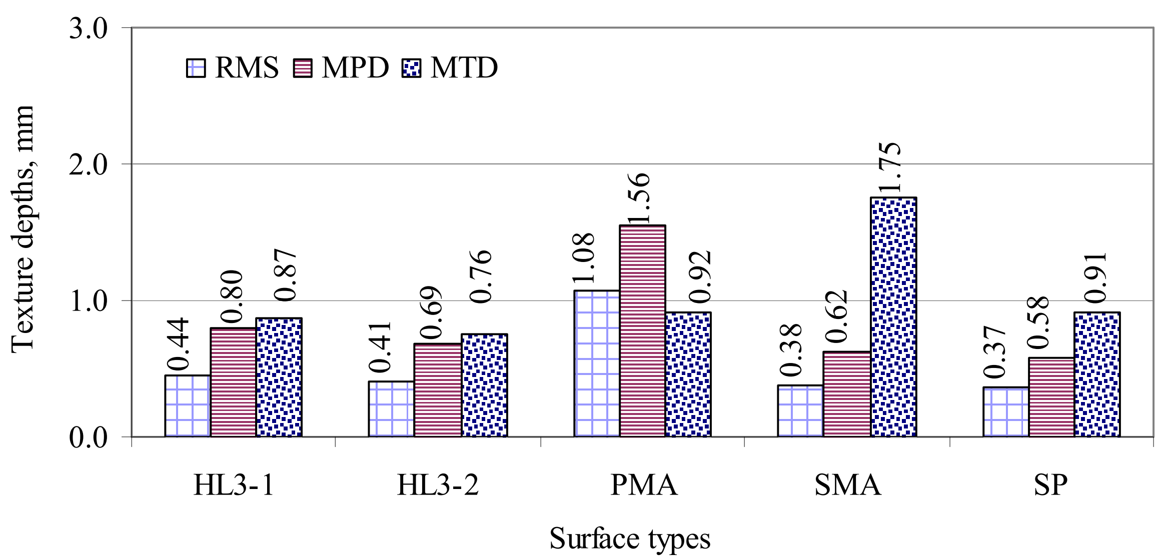

Figure 5-14 Comparison of Sand Patch and Laser Based Macrotextures.

5.2 SEASONAL VARIATION OF SURFACE FRICTION (PART II)

5.2.1 Effect of Pavement Types on Seasonal Surface Friction Variation

As mentioned earlier, four AC mixes (from five sections) and a PCC mix with six surface texture configurations were examined for seasonal variation of pavement surface friction. However, no separate trend was observed for different mixes or pavement types. In other words, seasonal variation of pavement surface friction was shown to be similar for PCC and various AC mixes. Statistical tests between the AC and PCC surfaces as well as among various AC mixes have also shown that neither pavement types nor pavement mix types are statistically significant at 5% significance level for monthly variation in wet surface friction.

5.2.2 Month to Month Variation of Pavement Surface Friction

The PCC and AC wet pavements uncorrected surface friction was shown to vary by up to 10 *BPN* and 13 *BPN*, respectively, depending on pavement or ambient temperatures during the testing (Table 4-10) and other factors that need to be established. Figure 5-15 shows the month to month fluctuation of corrected (normalized to 20°C) wet surface friction for both AC and PCC pavements that is likely to be related to seasonal variation of pavement surface characteristics. As shown in the figure, the variation of skid resistance for both AC and PCC surfaces are almost identical (slight deviations are probably related to repeatability of the tester). The difference between the lowest and highest wet surface friction was shown to be 8 *BPN* for both AC and PCC surfaces. This variation agrees well with that indicated by Jayawickrama and Thomas (1981) in regard to the seasonal variation of 6 *SN* between winter and summer taking the *SN* value as 77% of the *BPN* as found in this study.

5.2.3 Effect of Dry Spell on Surface Friction Variation

The effect of the dry period i.e., number of days without any precipitation (dry spell) prior to skid testing is shown in Figure 5-16. As shown in the figure, skid resistance decreases slightly at 0.22 *BPN* per dry day as the dry spell increase. The correlation (r = 0.22), however, was not shown to be statistically significant at 5% or 10% levels of significance.

Furthermore, the trend is constant if the 9 days data points are excluded from the analysis. These suggest that dry spell has no significant effect on surface friction variation.

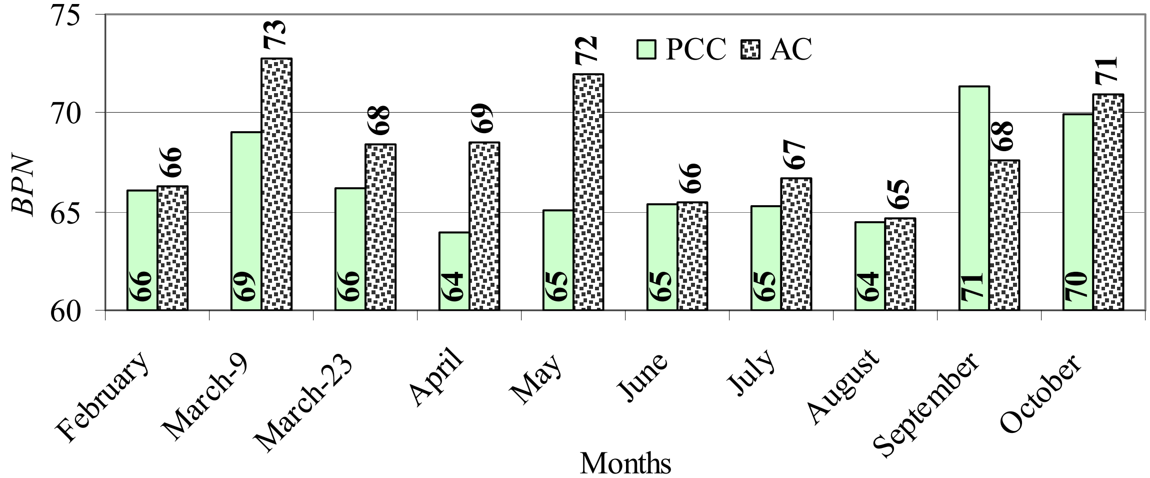

Figure 5-15 Seasonal Variation of Pavement Surface Friction.

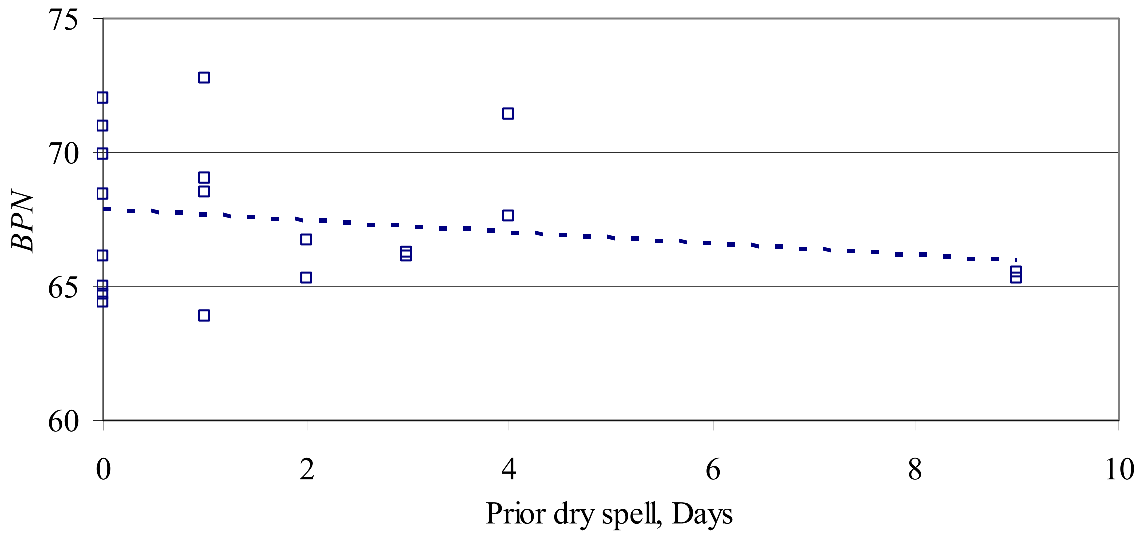

Figure 5-16 Effect of Dry Spell on Surface Friction Variation.

5.2.4 Effect of Prior Precipitation on Surface Friction Variation

Figure 5-17 shows the variation of pavement surface friction with the variation of precipitation prior to the skid testing. The 1-day trend (with r = 0.36) indicates that surface friction will increase at 0.27 *BPN* for each 1 mm precipitation in a one day period prior to the skid testing. This is probably related to washing out of the dust deposit and rejuvenation of surface microtexture. The trends for the total 3-day, 5-day, and 7-day prior precipitation have shown to be constant indicating that precipitation prior to the last 1-day has no effect on skid resistance variation. However, none of the correlations including the 1-day prior precipitation was shown to be statistically significant at the 5% or 10% levels of significance to explain the variation of surface friction over time.

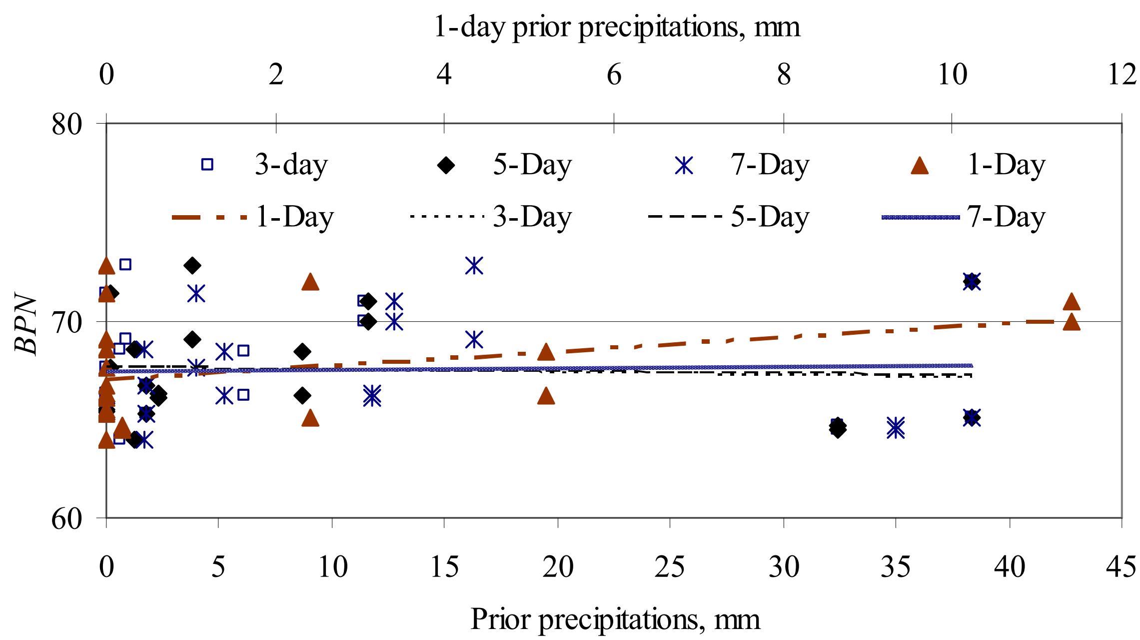

Figure 5-17 Effect of Prior Precipitations on Surface Friction.

5.2.5 Effect of Prior Temperatures on Surface Friction Variation

Figure 5-18 shows the effect of prior temperatures on the seasonal variation of pavement surface friction. As shown in the figure, the trends for 1-day, 3-day, 5-day, and 7-day mean high temperatures are almost identical with the slightly decreasing trend of surface friction with an increase in prior temperature. The trend for mean 1-day high temperature (sharpest among the trends with $r = 0.33$) has shown a negligible variation of surface friction of 0.08 *BPN* per 1°C increase in temperature. As for the cases of prior dry spell and precipitation, none of the prior temperatures has explained the variation of wet surface friction at the 5% or 10% significance levels.

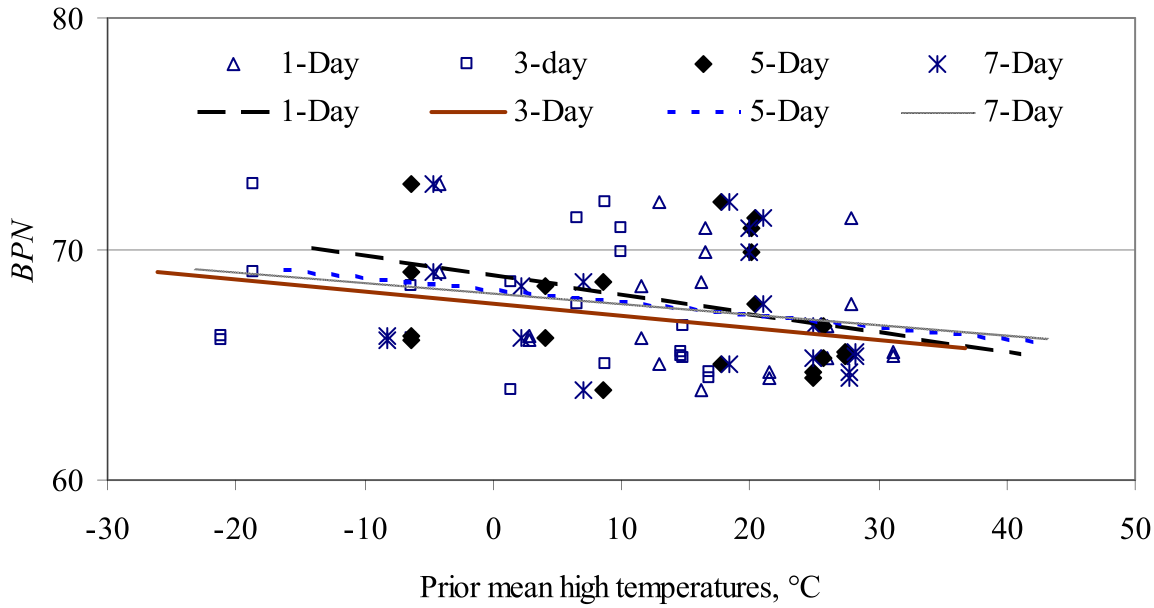

Figure 5-18 Effect of Prior Temperatures on Surface Friction Variation.

5.2.6 Effect of Prevailing Temperatures on Surface Friction Variation

As none of the prior temperatures, precipitation, and dry spells as well as their interactions (temperatures*precipitations, temperatures*dry spells, and precipitations*dry spells) was shown to be statistically significant, an attempt has been made to examine the trend of raw (uncorrected) surface friction with the variation of pavement surface and ambient temperatures. Figure 5-19 shows that trends for air and pavement surface temperatures are identical and overlapping each other with good correlation coefficient (r) of 0.84 to 0.88. The correlations are statistically significant at the 5% significance level. This indicates that the day to day variation in surface friction is mainly explained by the variation in pavement or ambient temperature during the testing (driving) which is mainly related to changes in tire rubber hardness. This indicates that the seasonal variation of available surface friction can roughly be estimated from either of the surface or ambient temperatures although ambient temperature has shown a slightly better correlation ($r = 0.88$).

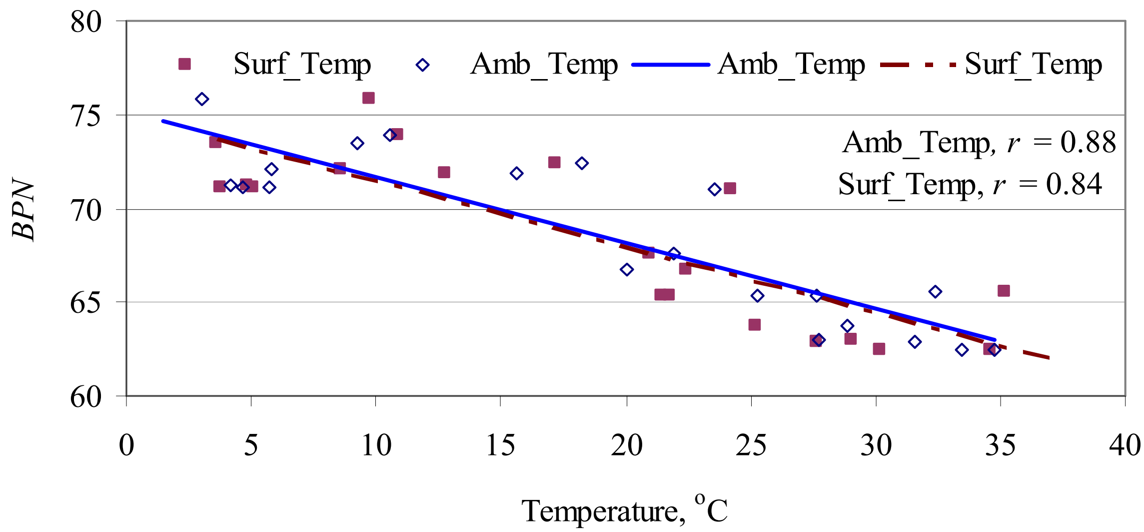

Figure 5-19 Effect of Prevailing Temperatures on Surface Friction Variation.

The correlation between the wet surface friction and temperature is given by Equation 5-2. It shows that for a 1°C increase in temperature the wet surface friction will decrease by 0.35 *BPN*. This translates to a SN_{64} of 0.27 using the correlation between *BPN* and *SN* developed in this study (Equation 5-1) i.e., for each 1°C increase in temperature the skid resistance will decrease at 0.27 SN_{64}. This estimate agrees closely with the finding by Hill and Henry (1981) in regards to the temperature effect.

$$BPN_T = 75.181 - 0.35T \qquad (5\text{-}2)$$

Where, BPN_T = *BPN* at temperature *T,* and

T = Ambient temperature (°C)

5.3 LONG TERM SKID RESISTANCE VARIATION (PART III)

Pavement surface friction usually increases at early age until the construction debris and loose materials on the surface are cleaned with traffic movement and/or environmental actions (e.g. rain). The full benefit of aggregate microtexture is available once the bitumen or cement coating from surface aggregate is completely removed. The surface friction then starts to decrease and continues to decrease until pavement surface distresses (e.g. ravelling, cracks, etc.) cause the friction to increase, if any. A data set comprising the two opposing trends are likely to compensate each other in all analysis and models aimed at determining the effect of contributing factors to surface friction variation. Therefore, the processed LTPP data was divided into two groups: the first group consists of an increase in surface friction during the early age while the second group consists of a decrease in surface friction after the early age increase. This allowed for analyzing, quantifying, and developing models for both early age and long term skid resistance of the pavement surfaces. Furthermore, to screen out the errant points, data with absolute z-score values >2.0 has been excluded in all analysis.

5.3.1 Early Life Increase of Pavement Surface Friction

To examine and quantify the early age increase in surface friction, the skid number at 64 km/h was separated. The trends of AC (r = 0.33) and PCC (r = 0.28) pavements early age surface friction are shown in Figures 5-20 and 5-21, respectively. The trends show that full surface friction is attained on an average after about 2½ years for PCC pavements and 18 months for AC pavements. Pavement surface friction has shown to start decreasing after this initial period of increase. The trends in the figures show that PCC surface friction will increase by about 4 SN_{64} on average from the initial SN whereas the expected increase is about 5 SN_{64} for AC pavements. This indicates that although AC pavements surface friction increases for a shorter period than the PCC surfaces, the overall increase is slightly higher for AC pavements. Both correlations were shown to be statistically significant at 5% significance level.

Roe and Lagarde-Forest (2005) mentioned that on an as-built new pavement, the aggregates are covered by a film of asphalt binder and new asphalt surfaces may exhibit lower skid resistance as compared to existing surfaces that have been under traffic for some time. A thick binder film may pose additional risk of pavement related accidents, especially during the first few months following the construction. The UK police also reported lower dry pavement friction on newly surfaced roads. The trends that have been presented above therefore represent what really happen in pavement’s life cycle. The early life low skid resistance is also a concern in North America, especially for some newly paved SMA surfaces (MTO 2008).

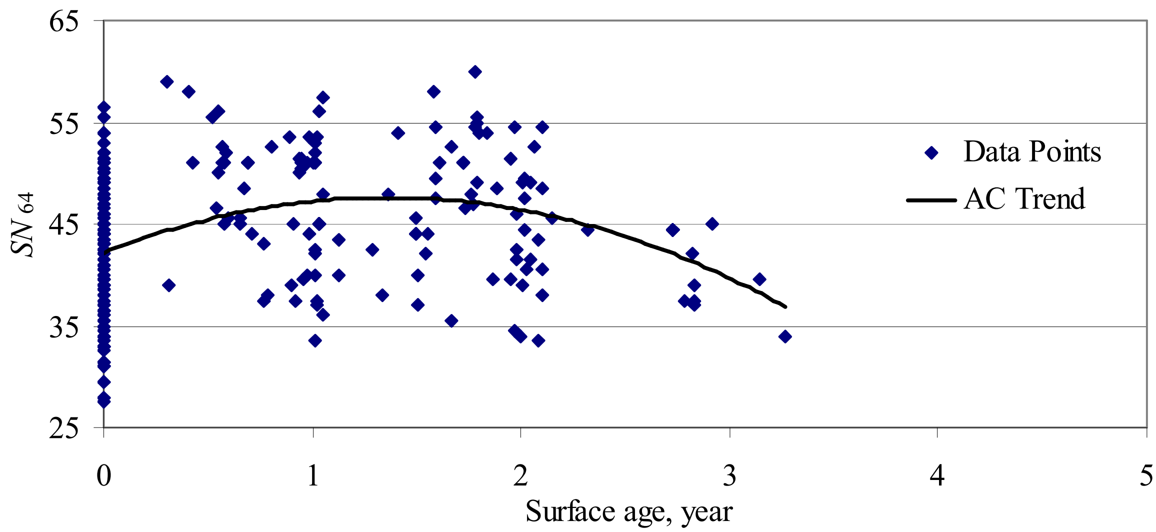

Figure 5-20 Early Age Changes in AC Pavements Surface Friction.

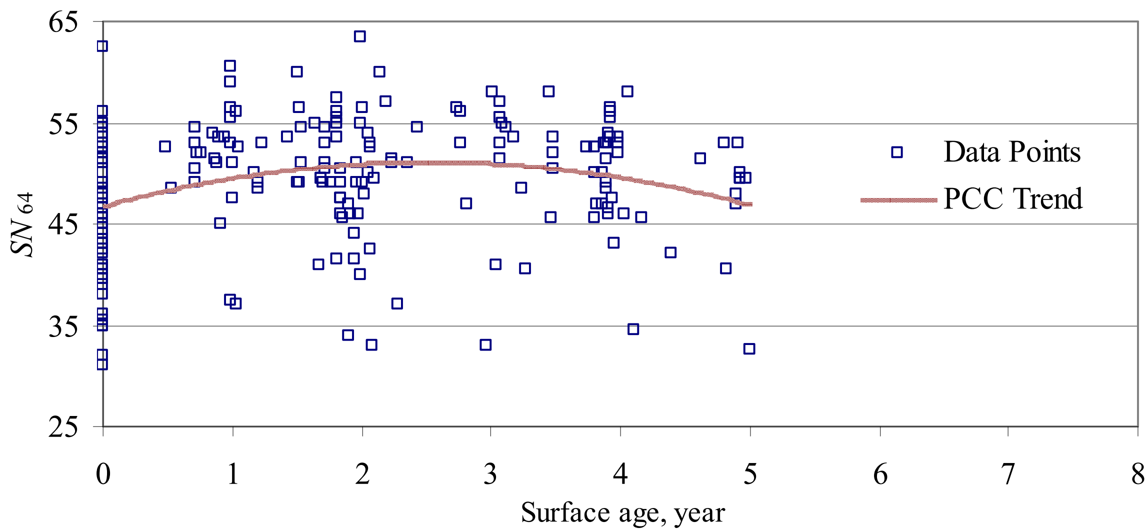

Figure 5-21 Early Age Changes in PCC Pavements Surface Friction.

5.3.2 Effect of PCC Texturization Methods on Surface Friction

For determining the contribution of different texturization methods of PCC on skid resistance, *SN* at the single speed of 64 km/h (40 mph) i.e., SN_{64} has been chosen. The variation of average SN_{64} and the ranks of different surface texture configurations are shown in Figure 5-22. The rank 1 represents the surface with the highest skid number with descending *SN* value as the rank decreases. Cross-textured surface with transverse groove after burlap drag was shown to exhibit the highest skid resistance (average SN_{64} of 50) while the astroturf dragged surface was shown to exhibit the lowest skid resistance (average SN_{64} of 41) among the PCC surfaces.

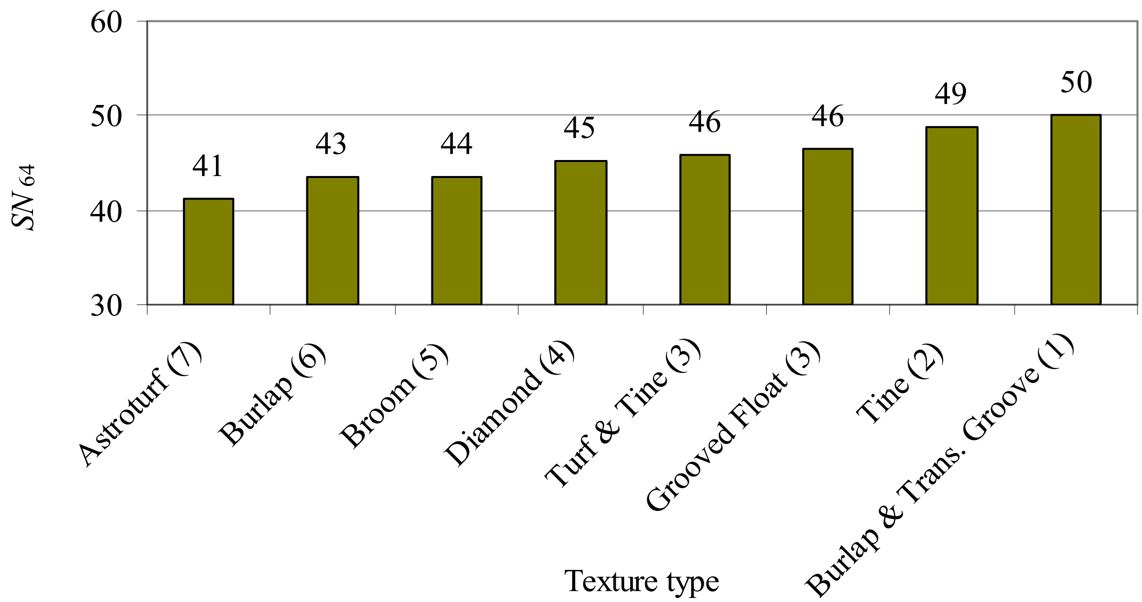

Figure 5-22 Average SN_{64} and Ranks for Different Texturization Methods of PCC.

5.3.3 Skid Resistance Variation with Age of Pavement Surfaces

The trend for change in AC pavement surface friction, measured at 64 km/h, after an early life increase is shown in Figure 5-23. The trend in the figure shows that AC surface friction is expected to reduce at an average 1.2 *SN* per year. Therefore, for a typical AC surface having fifteen years life, before any rehabilitation, the expected gross reduction in surface friction after the early life (1½ years) increase is (1.2 x 13.5 =) 16 *SN* (on average). The net expected reduction with respect to the skid resistance of new AC pavement surface is (16 - 5 =) 11 *SN* considering an early life increase of 5 *SN,* on an average. The correlation was shown to be statistically significant at the 5% level of significance (r = 0.31). The distribution of data points in Figure 5-23, however, suggests that AC pavements surface friction loss mainly occurs for about 8 years after the early life (1-½ years) friction increase.

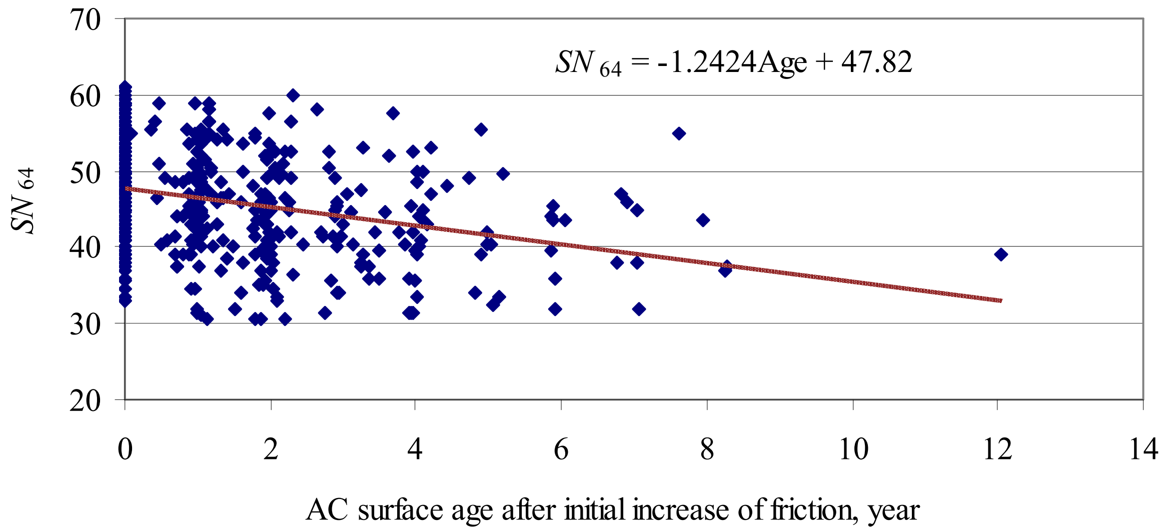

Figure 5-23 Changes in AC Skid Resistance with Age after an Early Life Increase.

Figure 5-24 shows the trend for change in surface friction of PCC pavements after an initial (early life) increase. The correlation was also shown to be statistically significant at the 5% significance level (r = 0.31). As shown in the figure, PCC surface friction, measured at 64 km/h, decreases at 0.7 *SN* per year, on an average. With this trend, a gross reduction of 19 *SN* is expected after the early life (2½ years) increase in surface friction for typical PCC pavements having a 30-year service life. The net reduction in surface friction with respect to new pavement surface friction is expected to be 15 *SN* considering 4 *SN* initial increase.

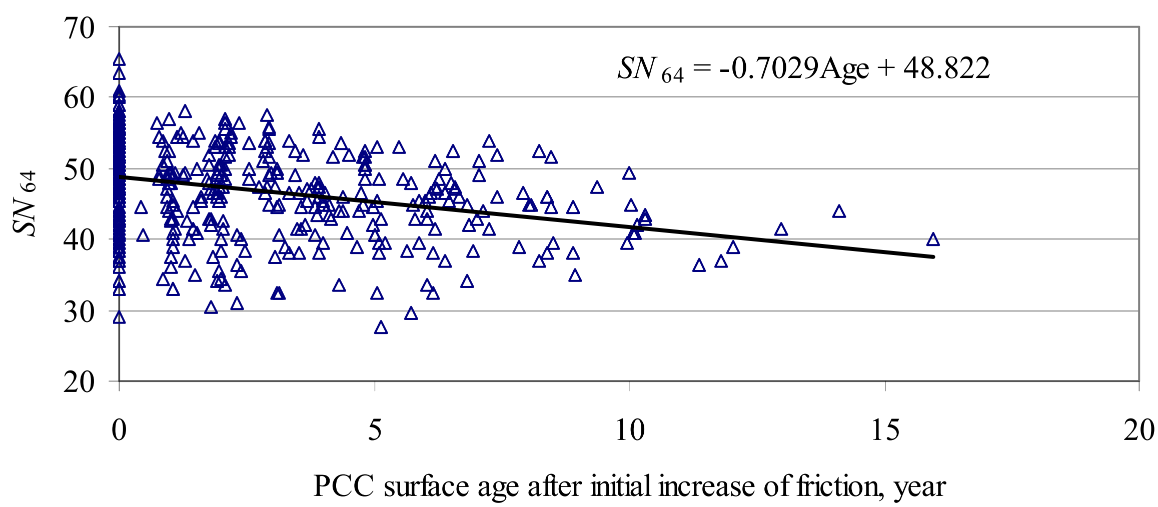

Figure 5-24 Changes in PCC Skid Resistance with Age after an Early Life Increase.

Kokkalis et al. (2002) indicated that the horizontal forces exerted by the vehicle tires causes the protruding aggregates on the pavement surface to be worn, polished, or removed and this reduces the surface microtexture and macrotexture over time. Furthermore, the protruding aggregates may be embedded into the pavement structure due to the compacting effect of traffic. The available skid resistance may be reduced by 40% due to the wear of surface textures. Therefore, the trends that have been found in this analysis are shown to be justified.

5.3.4 Effect of Traffic on Skid Resistance Variation

The skid resistance variation on AC pavement surfaces with the cumulative number of traffic passes, after the period of early life increase in surface friction, is shown in Figure 5-25. As shown in the figure, AC surface friction decreases with an increase in traffic exposure at 0.22 *SN* and 0.42 *SN* per million passes of passenger cars (PC) and heavy vehicles (HV), respectively. This indicates that heavy vehicles (trucks) cause substantially greater wear of the surface resulting in greater loss of skid resistance.

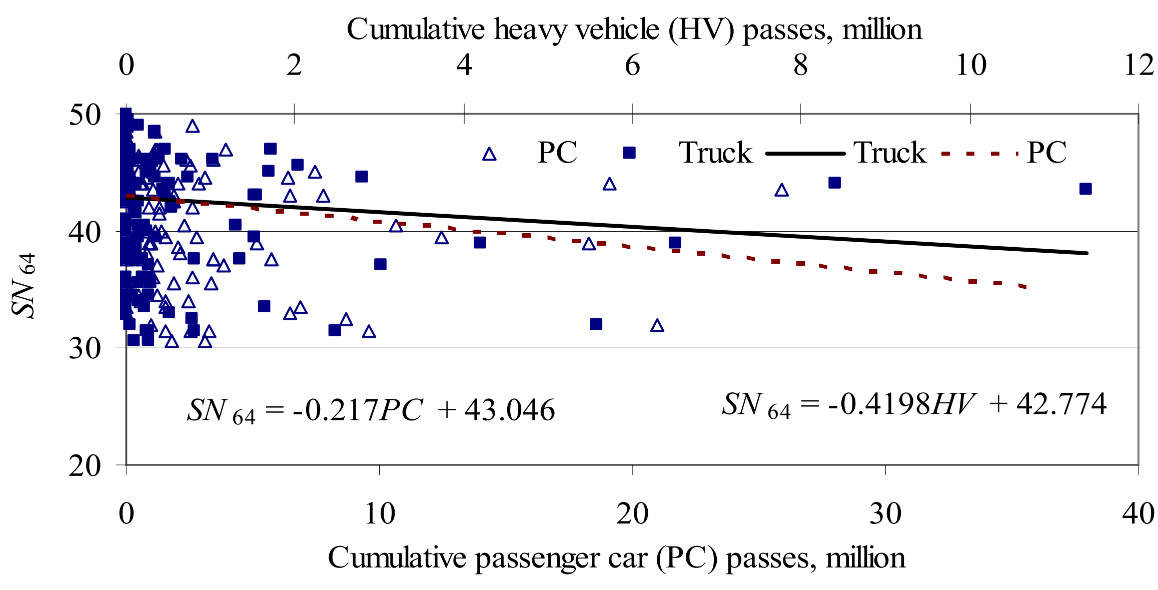

Figure 5-25 Effect of Traffic on AC Pavements Surface Friction.

Figure 5-26 shows the variation of skid resistance over time with cumulative traffic passes on PCC pavement surfaces. The individual rate of PCC surface friction loss due to passenger car and truck passes was not in good agreement with that for AC pavement surfaces when the rates were compared with surface friction variations with pavement age (Figures 5-23 and 5-24). However, the trends in Figure 5-26 indicate that heavy vehicles cause greater loss of surface friction also for PCC pavements.

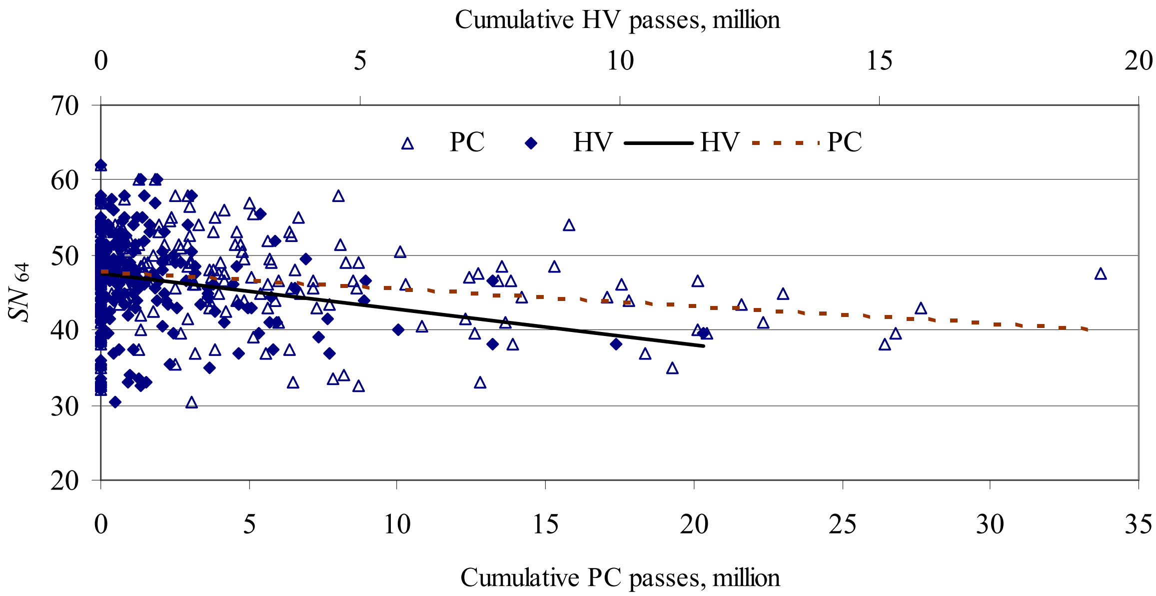

Figure 5-26 Effect of Traffic on PCC Pavements Surface Friction.

5.3.5 Effect of Mix Properties on Skid Resistance Variation

Figures 5-27 and 5-28 show the contribution of the AC mix aggregate gradation (percentage of coarse aggregate) and coarseness (maximum size), respectively, on long term skid resistance variation. As shown in the figures, both trends are constant with no changes in skid resistance value. This indicates that neither aggregate size nor mix proportion has significant effect on skid resistance variation over long term.

The trends for skid resistance variation with a variation of air voids content and stability are shown in Figures 5-29 and 5-30, respectively. These two trends indicate that AC pavements will exhibit slightly better skid resistance over the long term if the mix contains higher air voids and has better stiffness. However, none of these correlations was shown to be strong enough (not statistically significant at the 5% significance level) to draw any meaningful conclusion. The long term *SN* trend (Figure 5-29) with the variation of air void content in AC mixes also did not agree with that for AC surfaces at the CPATT test sites (Figure 5-8). Further investigation is recommended to determine the true effect of AC mixes air void content on surface friction variation.

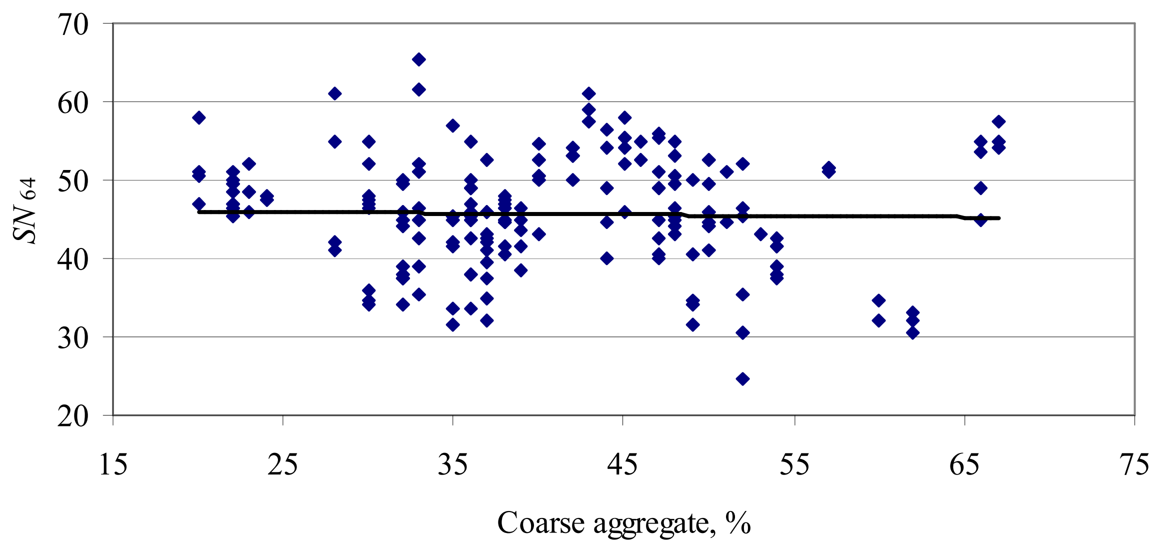

Figure 5-27 Effect of AC Mix Grading for Long Term Skid Resistance Variation.

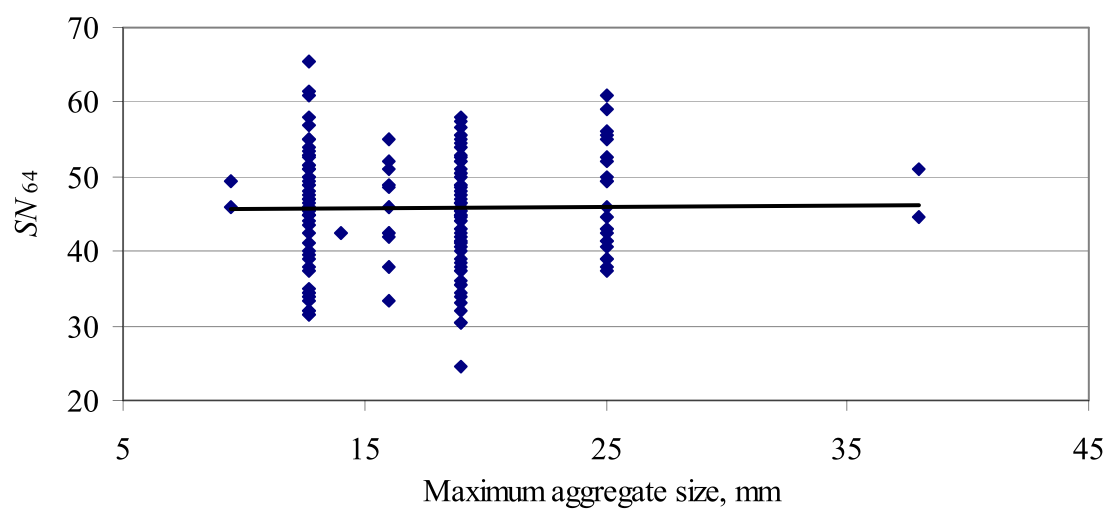

Figure 5-28 Effect of AC Mix Coarseness for Long Term Skid Resistance Variation.

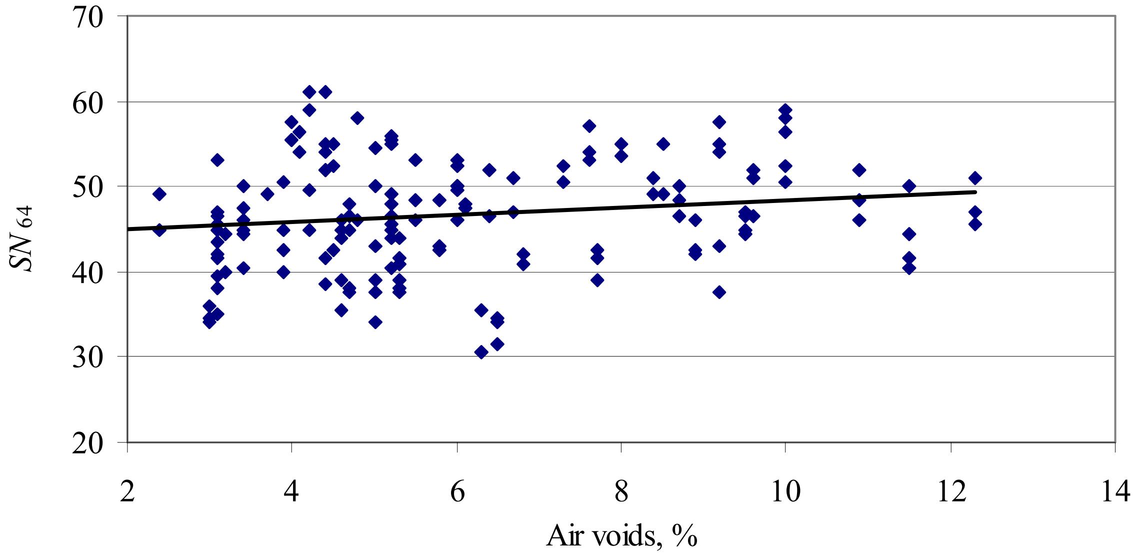

Figure 5-29 Effect of Air Voids for AC Long Term Skid Resistance Variation.

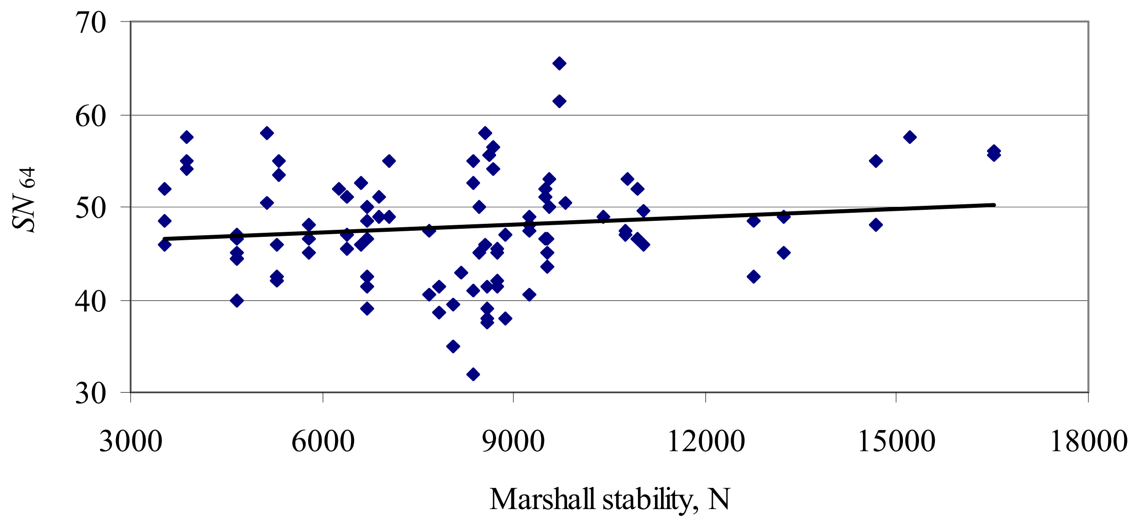

Figure 5-30 Effect of AC Mix Stability on Long Term Skid Resistance Variation.

The effect of concrete mix 28-day compressive strength on long term variation of PCC pavements skid resistance is shown in Figure 5-31. The trend in the figure is constant indicating that concrete strength has no noticeable effect on PCC surfaces skid resistance performance over long term.

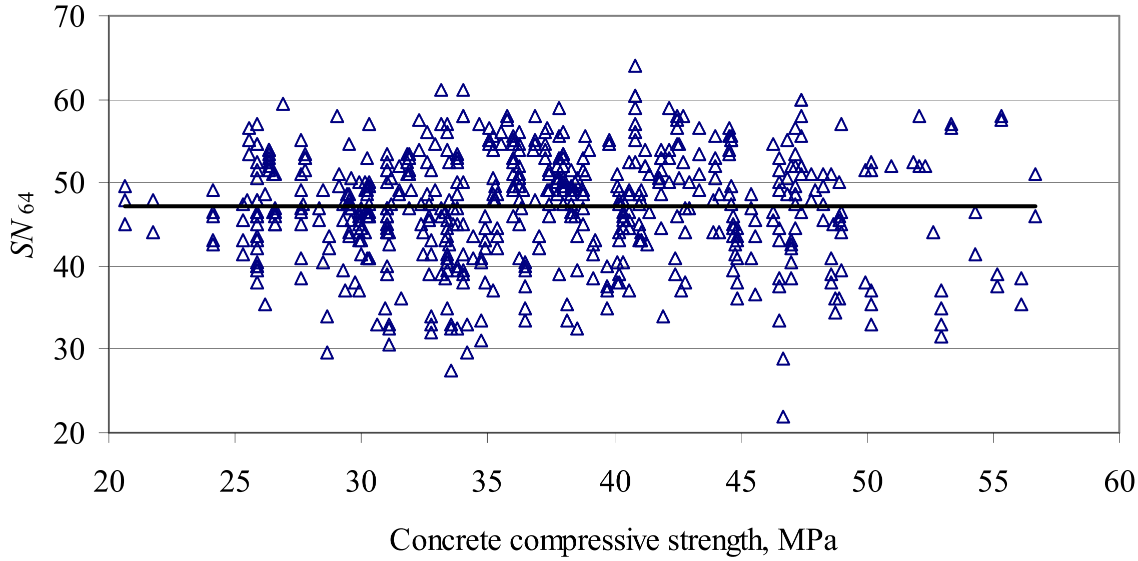

Figure 5-31 Effect of PCC Compressive Strength on Long Term Skid Resistance.

5.3.6 Effect of Long Term Weather on Skid Resistance Variation

Figures 5-32 and 5-33 show the effect of the long term weather on AC pavements skid resistance variation. The trend in Figure 5-32 shows that mean annual average temperature (averaged over past 20-year) has no effect on the variation of AC pavements skid resistance over the long term. The trend in Figure 5-33 shows that skid resistance will decrease marginally over the long term if the pavement is wet for a longer period. However, the trend is not shown to be strong (statistically significant) enough to draw any useful conclusion regarding the effect of precipitation on long term skid resistance variation.

The effect of the long term weather on PCC pavements skid resistance variation is shown in Figures 5-34 and 5-35. Both trends are shown to be constant indicating that neither long term temperature nor precipitation has a noticeable effect on the variation of PCC pavements skid resistance over time.

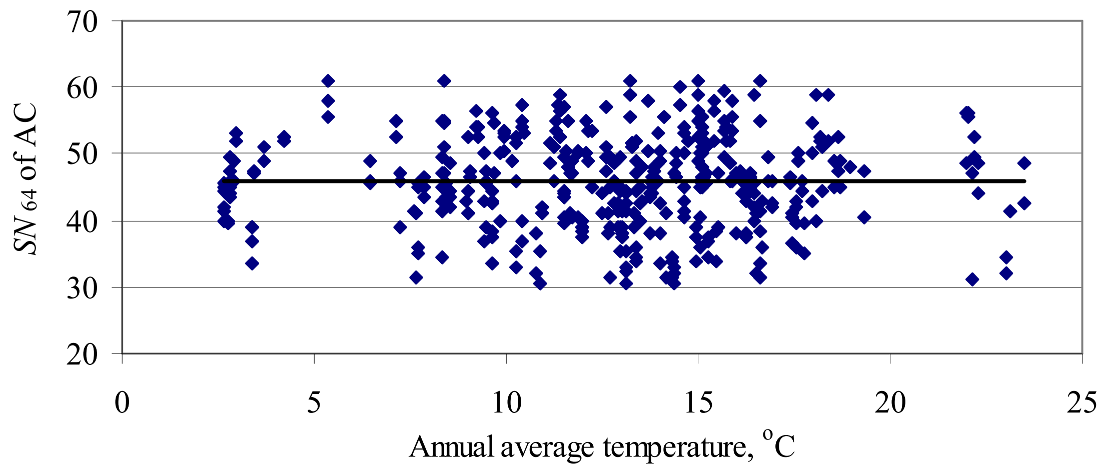

Figure 5-32 Effect of Temperature on AC Skid Resistance Variation Over Long Term.

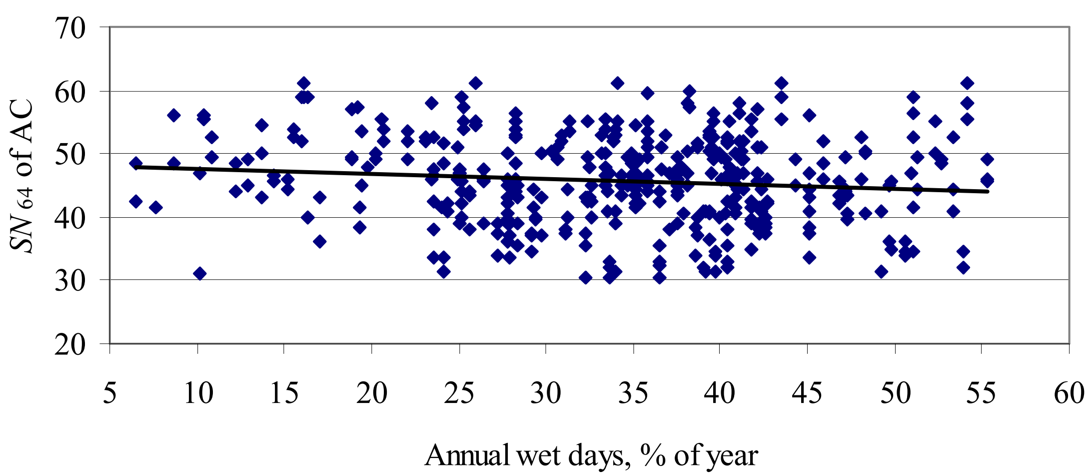

Figure 5-33 Effect of Precipitation on AC Skid Resistance Variation Over Long Term.

5.3.7 Effect of Vehicle Speed on Skid Resistance Variation

The trend for changes in AC pavement surface friction with changes in vehicle speed is shown in Figure 5-36. The correlation indicates that skid resistance decreases at 2.5 *SN*, on average, for each 10 km/h increase in vehicle speed. Such a trend is shown to resemble the trend of skid resistance at the CPATT test tracks where a reduction of 2.6 *SN* (on average) for each 10 km/h increase in speed was noted.

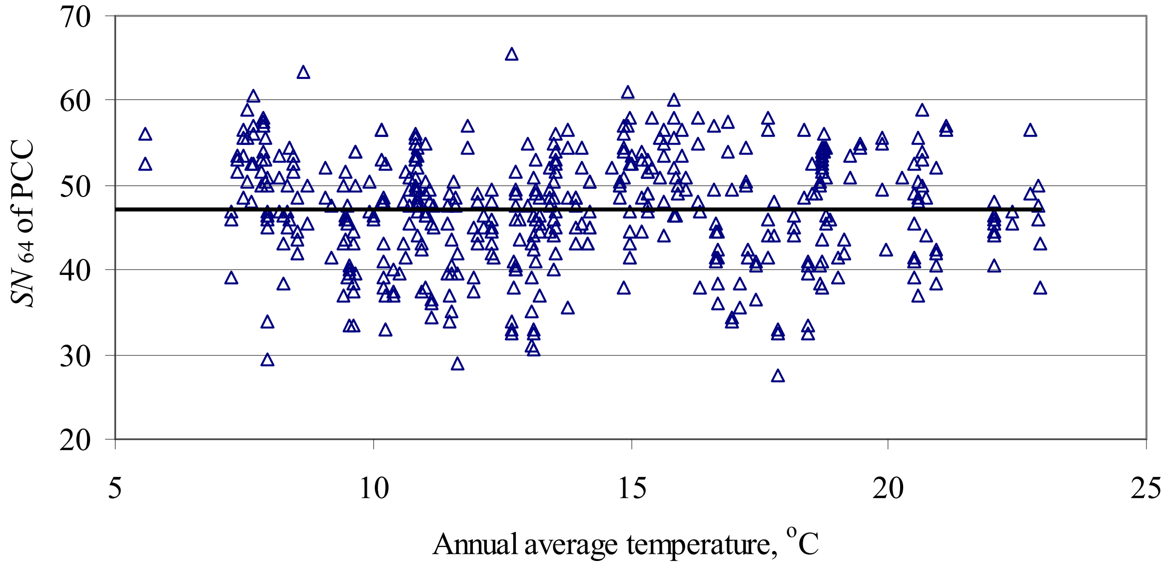

Figure 5-34 Effect of Temperature on PCC Skid Resistance Variation Over Long Term.

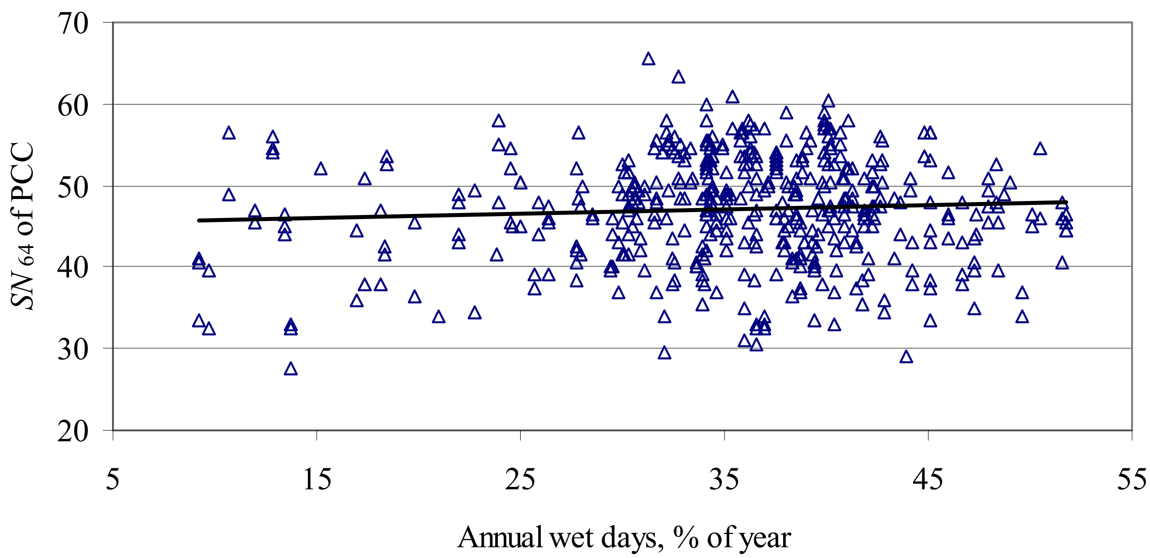

Figure 5-35 Effect of Precipitation on PCC Skid Resistance Variation Over Long Term.

Figure 5-37 shows two trends of skid resistance variation on PCC pavement surfaces having steel tined and dragged (burlap, broom, and astroturf) textures, respectively. These trends also show that skid number-speed gradients are not the same for all surfaces. This agrees with the relevant findings from testing at the CPATT test sites. The trends in Figure 5-37 indicate that PCC pavement available surface friction decreases at 3.2 *SN* and 1.5 *SN* for each

10 km/h increase in vehicle speed on surfaces that have received tine and drag textures, respectively. These trends thus indicate that the rate of loss of available skid resistance with increase in the speed of the vehicle is higher on tined/grooved PCC pavement surfaces as compared to that on drag type textured surfaces

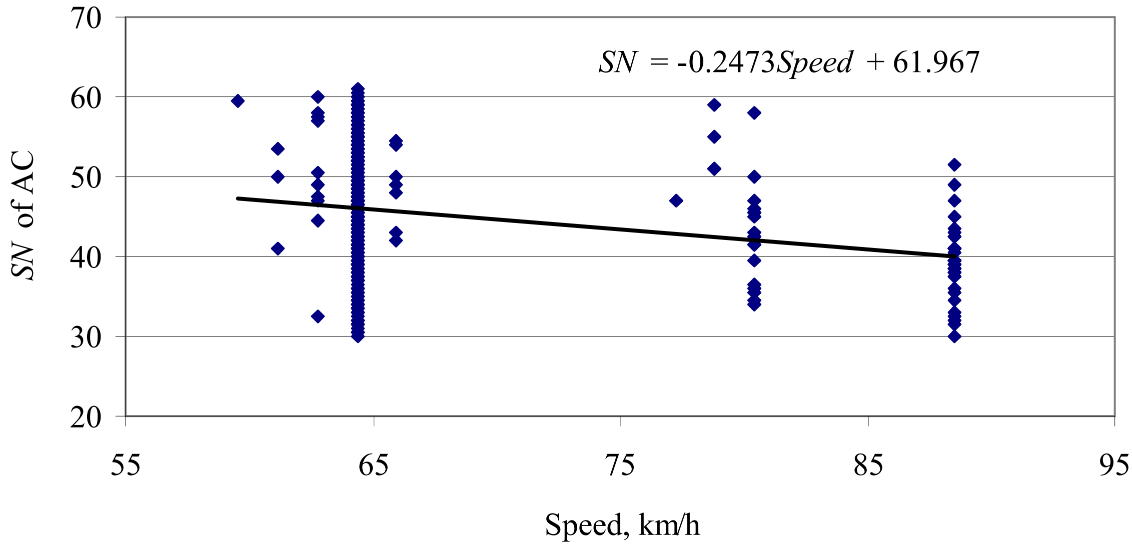

Figure 5-36 AC Pavement Skid Resistance Variation with Speed.

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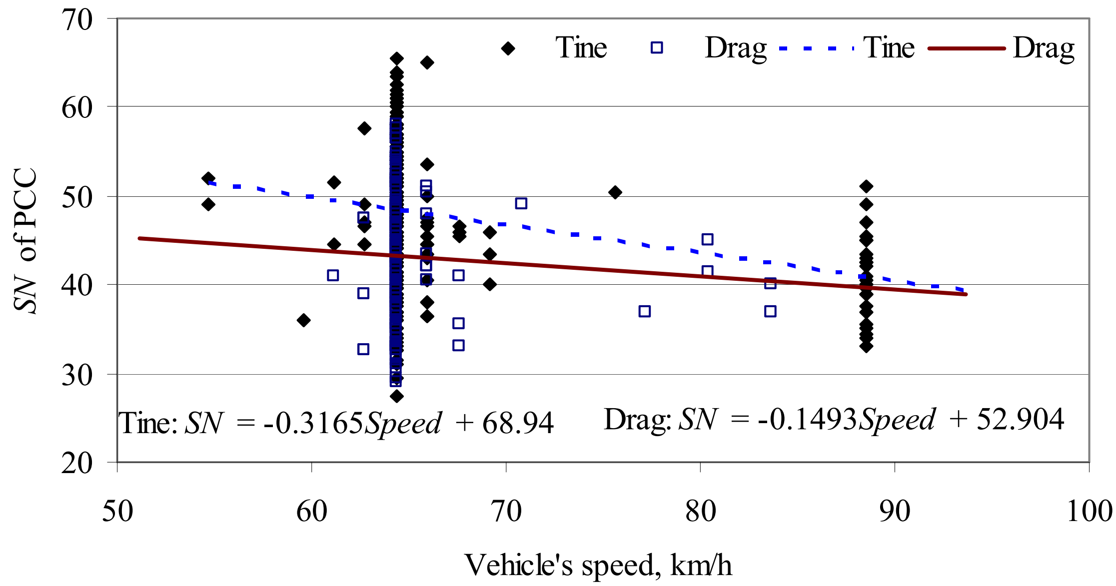

Figure 5-37 PCC Pavement Skid Resistance Variation with Speed.

5.4 TIRE-PAVEMENT NOISE AND SOUND ABSORPTION (PART IV)

5.4.1 Summary of CPX, In-Vehicle and Pass-By Noise

The summary of the CPX, in-vehicle and pass-by noise levels for the tested 32 pavements surfaces (arranged by pavement type and speed) are presented in Tables 5-1A to 5-1D. As shown in the tables, the tire-pavement noise increases with an increase in vehicle speed for all types of pavements. The variation of near field (CPX), in-vehicle and pass-by noises are not identical. In other words, a high CPX noise does not necessarily mean that in-vehicle or pass-by noise is also high. In fact, as mentioned in Chapter 2, tire-pavement noise generation and propagation are complex functions of many characteristics of pavement and tire including their interaction mechanisms and air escaping from or blocking (i.e., compression) underneath the tire-pavement contact patch that result in sound amplification or reduction. In general, the in-vehicle noise peak occurs at very low frequencies (indicated by "Freq" in Table 5-1) while the pass-by noise peaks at slightly higher frequencies. The frequencies at peak CPX noise levels are somewhat in between in-vehicle and pass-by peak noise frequencies. Typical noise-frequency curves for tire-pavement interaction near-field, pass-by, and in-vehicle noise have been presented in Appendix A.

The noise data indicate that the isolation of the test vehicle from surrounding traffic is important to characterize pavement with respect to tire-pavement noise levels. A few examples are presented in the summary tables with asterisk (*) mark to show how measured noise can be influenced by other traffic even though they are at some distance away.

Table 5-2 shows the comparison of CPX noise measured in the winter 2007 and the spring 2008. In general, observed sound levels in the spring are shown to match well with that in winter with few exceptions. The exceptional cases are sites where the wind speeds were high during the spring measurements. Variation of test spots, especially for PCC pavements, and traffic might also have contributed to the differing noise levels for these few exceptional cases.

The tested sites have shown a section-to-section variation in CPX noise of up to six dBA for same age PCC and up to three dBA for same age AC pavements. However, within a pavement, section-to-section variation of in-vehicle noise was shown to be up to three dBA for PCC and up to two dBA for AC pavements. The variation in measured noise from the same age pavement one site or section to another probably is caused by the variation in actual surface condition, mainly the texture. For example, the consistency in supplied concrete mix and consolidation, weather condition, texturing time, pressure on tine rake, angle of tine rake placement, tining speed, post tining surface refinishing, etc. will highly affect the surface texture, and thereby the noise. Similarly, variation of AC surface texture due to segregation, over compaction, roller marks, or batch-to-batch variation in AC mix will contribute to tire-pavement noise variation. It should, however, be noted that the CPX noise is not heard by the human ear. The section-to-section variation of in-vehicle noise (heard by the driver) for the same age PCC pavements are considered to be just perceptible (3 dBA).

5.4.2 Comparison of *L*max and *L*eq Noise

Figure 5-38 shows the variation of near-field (CPX) and in-vehicle *L*max and *L*eq noise levels at 100 km/h for the tested surfaces. As shown in the figure, the variation of *L*max and *L*eq are similar for all pavements. On average, the *L*eq was shown to be 3 dBA lower than the *L*max. To reduce the complexity, subsequent analysis uses only the *L*max noise levels.

5.4.3 Variation of Tire-Pavement Noise with Speed

Figure 5-39 shows the variation of tire-pavement average CPX (near-field), in-vehicle, and pass-by noise on AC pavement surfaces with changes in speed of the vehicle from 80 km/h to 100 km/h. On AC pavement surfaces, CPX noise was shown to increase at 2.3 to 2.4 dBA (average 2.35 dBA) for each 10 km/h increase in vehicle's speed. Alternatively, the in-vehicle and pass-by noise were shown to increase at 1.6 to 1.9 dBA (average 1.75 dBA) and 1.2 to 1.6 dBA (average 1.4 dBA), respectively, for each 10 km/h increase in vehicle speed.

Table 5-1 Summary of CPX, In-Vehicle and Pass-By Noise Levels (Part A)

Site No.	Highway No.	Surface Age	Pavement Surface Type	Test Speed (km/h)	CPX Noise				In-Vehicle Noise				Pass-By Noise			
					*L*max		*L*eq		*L*max		*L*eq		*L*max		*L*eq	
					Freq	SPL	Freq	SPL	Freq	SPL	Freq	SPL	Freq	SPL	Freq	SPL
3	Reg. 11	3	SMA	70									1000	71.9	1000	69.8
1	Reg. 11	3	ROFC	80	504	101.5	715	98.7	299	62.9	299	60.0	1000	74.0	1000	72.4
2	Reg. 11	3	ROGC	80	608	102.6	565	99.2	299	61.7	299	58.8	900	73.3	900	71.7
3	Reg. 11	3	SMA	80	461	99.8	640	95.7	315	62.2	365	59.5	933	73.6	933	72.1
4	Reg. 11	3	HL3	80	583	100.3	1179	96.4	299	59.8	315	57.2	1000	71.6	1000	70.3
1	Reg. 11	3	ROFC	90	508	102.7	540	99.0	299	64.0	315	60.8	900	75.7	900	74.1
2	Reg. 11	3	ROGC	90	583	105.9	625	102.9	454	64.0	454	61.4	800	75.3	800	73.6
3	Reg. 11	3	SMA	90	515	101.8	558	98.5	315	64.4	315	61.9	1000	74.9	1000	73.5
4	Reg. 11	3	HL3	90	920	102.0	1179	98.8	454	62.2	533	60.2	1400	74.2	1400	72.6
1	Reg. 11	3	ROFC	100	598	107.0	565	103.8	315	64.6	299	62.2	900	77.2	900	75.4
2	Reg. 11	3	ROGC	100	615	105.9	683	103.3	283	64.6	283	62.2	715	76.1	715	75.1
3	Reg. 11	3	SMA	100	540	103.8	658	100.4	299	65.9	299	62.9	800	76.1	800	74.9
4	Reg. 11	3	HL3	100	583	104.7	625	101.7	299	63.9	299	62.3	800	75.1	800	73.8
7	401EB	0	SP12.5FC2	80	429	100.5	750	96.7	413	61.3	325	58.2				
7A	401WB	0	SP12.5FC2	80	500	100.9	633	96.7	272	60.6	372	57.5	1000	*74.9	1000	*73.4
8	6 (WR)	1	SP12.5FC2	80	600	99.7	715	95.5	358	61.4	658	58. 28	800	77.7	800	75.6
9	402WB	2	SP12.5FC2	80	805	95.9	933	93.7	477	58.8	477	56.7	1000	73.1	1000	71.3
10	402EB	3	SP12.5FC2	80	800	100.9	800	96.6	279	61.2	400	58.8	1000	73.8	1000	72.3
5	6 (CR)	4	SP12.5	80	463	105.9	475	102.0	351	61.4	366	58.8	1000	73.2	1000	71.6
7	401EB	0	SP12.5FC2	90	529	102.3	720	98.7	575	63.5	500	60.6				
7A	401WB	0	SP12.5FC2	90	450	102.3	515	98.8	388	61.6	508	59.1	800	71.2	630	69.9
8	6 (WR)	1	SP12.5FC2	90	604	103.4	608	99.2	408	63.8	533	61.1	1025	78.6	900	76.2
9	402WB	2	SP12.5FC2	90	743	98.6	800	95.9	500	61.8	500	60.1	1000	74.9	1000	73.7
10	402EB	3	SP12.5FC2	90	700	101.1	772	98.1	500	63.8	500	62.1	900	74.7	900	72.8
5	6 (CR)	4	SP12.5	90	578	108.1	527	105.1	433	63.5	421	60.9	815	74.8	630	73.1
7	401EB	0	SP12.5FC2	100	515	105.7	506	102.3	313	64.3	250	61.0				
7A	401WB	0	SP12.5FC2	100	630	104.7	500	101.7	516	63.6	429	60.7	900	74.7	900	73.1
8	6 (WR)	1	SP12.5FC2	100	608	106.1	625	102.3	436	67.1	436	63.2	1000	80.4	1600	78.6
9	402WB	2	SP12.5FC2	100	715	102.5	800	99.3	250	63.9	250	61.5	1000	76.6	1000	74.8
10	402EB	3	SP12.5FC2	100	743	103.2	800	100.3	250	64.2	250	61.5	1000	76.7	1000	75.1
5	6 (CR)	4	SP12.5	100	576	109.4	595	106.6	308	65.3	296	62.5	1000	76.2	1000	74.6

* Indicate readings are not reasonable (probably influenced by vehicles in opposite direction)

Table 5-1 Summary of CPX, In-Vehicle and Pass-By Noise Levels (Part B)

Site No.	Highway No.	Surface Age	Pavement Surface Type	Test Speed (km/h)	CPX Noise				In-Vehicle Noise				Pass-By Noise			
					*L*max		*L*eq		*L*max		*L*eq		*L*max		*L*eq	
					Freq	SPL	Freq	SPL	Freq	SPL	Freq	SPL	Freq	SPL	Freq	SPL
11	401WB	1	SMA	80	715	99.9	715	97.1	666	59.3	772	57.3				
11A	401EB	1	SMA	80	755	98.4	800	95.7	833	59.4	833	57.7	1250	*76.5	1250	*76.1
12	401WB	2	SMA	80	630	102.1	800	97.4	557	60.1	568	58.1	1000	73.9	1000	72.1
13	401EB	3	SMA	80	800	97.9	800	95.7	553	59.6	634	57.4	800	73.6	800	72.2
11	401WB	1	SMA	90	736	101.5	800	98.7	469	61.8	550	60.1				
11A	401EB	1	SMA	90	758	100.9	743	98.3	900	61.1	950	59.2	1250	*80.4	1250	*77.2
12	401WB	2	SMA	90	772	104.2	772	100.4	575	62.0	575	60.2	630	74.1	800	72.6
13	401EB	3	SMA	90	804	100.9	800	98.4	438	62.0	500	60.1	800	74.3	800	73.1
11	401WB	1	SMA	100	715	103.3	800	101.1	763	62.7	863	60.8				
11A	401EB	1	SMA	100	720	103.0	779	100.5	694	62.6	788	60.8	940	76.6	940	76.2
12	401WB	2	SMA	100	800	106.3	800	103.2	451	63.1	728	60.9	800	74.8	800	73.8
13	401EB	3	SMA	100	720	102.9	800	100.3	587	63.0	624	60.6	800	75.3	800	73.8
20	132	0	SP9.5Fine	80	486	101.3	508	97.1	553	62.0	450	60.0	1000	75.3	1600	73.0
21	TIP	0	SP12.5Fine	80	589	99.1	598	95.1	355	60.4	433	58.1	953	70.4	1200	69.0
22	15	1	SP12.5FC1Fine	80	483	101.1	703	95.5	315	61.8	315	56.2	810	72.9	1010	71.6
23	401EB	2	SP12.5FC2Fine	80	624	99.3	699	95.8	315	60.0	400	58.2	630	67.9	630	66.1
24	15	3	SP12.5FC1Fine	80	715	105.8	743	102.9	272	60.2	315	57.6	1000	76.7	1000	75.8
20	132	0	SP9.5Fine	90	515	106.4	570	101.9	500	64.4	500	62.6	630	77.9	630	75.4
21	TIP	0	SP12.5Fine	90	657	101.1	603	97.8	357	62.0	368	59.5	630	72.7	1087	70.9
22	15	1	SP12.5FC1Fine	90	650	104.6	560	101.3	293	63.7	438	60.4	815	75.4	815	74.4
23	401EB	2	SP12.5FC2Fine	90	633	100.4	699	97.6	299	60.9	315	58.6	1000	75.7	1000	74.4
24	15	3	SP12.5FC1Fine	90	679	108.6	800	105.8	315	62.4	500	62.4	1083	77.9	1083	76.2
20	132	0	SP9.5Fine	100	577	106.9	593	103.1	313	66.0	326	63.7	800	79.2	715	76.7
21	TIP	0	SP12.5Fine	100	647	104.7	597	100.7	299	64.6	307	62.3	800	74.1	800	72.2
22	15	1	SP12.5FC1Fine	100	640	106.4	625	102.1	315	65.4	315	62.2	900	75.9	800	74.2
23	401EB	2	SP12.5FC2Fine	100	650	102.4	715	99.5	266	63.9	299	61.4	800	71.5	800	70.0
24	15	3	SP12.5FC1Fine	100	543	111.2	587	109.5	335	64.7	335	62.0	800	78.8	800	77.2
32	417EB	5	SP12.5FC1Fine	100	720	105.2	715	101.2								
32A	417WB	5	SP12.5FC1Fine	100	772	105.0	772	101.5								
31	407EB	8	AC	100	850	101.9	900	98.7								

Table 5-1 Summary of CPX, In-Vehicle and Pass-By Noise Levels (Part C)

Site No.	Highway No.	Surface Age	Pavement Surface Type	Test Speed (km/h)	CPX Noise				In-Vehicle Noise				Pass-By Noise			
					*L*max		*L*eq		*L*max		*L*eq		*L*max		*L*eq	
					Freq	SPL	Freq	SPL	Freq	SPL	Freq	SPL	Freq	SPL	Freq	SPL
18	10	1	Micro-Surf-Fine	80	629	99.5	715	96.6	311	60.9	361	58.4	1125	72.7	1000	71.5
19	10	2	Micro-Surf-Fine	80	596	97.9	760	94.8	311	61.9	300	59.1				
28	416NB	1	Micro-Surf-Coarse	80	672	99.4	788	95.7	250	65.5	250	61.5	1000	71.4	900	69.4
27	416SB	2	Micro-Surf-Coarse	80	680	100.2	736	96.7	266	68.0	250	63.9	800	72.2	800	70.7
18	10	1	Micro-Surf-Fine	90	746	101.7	772	98.2	261	62.3	283	59.6	1000	73.7	1000	72.2
19	10	2	Micro-Surf-Fine	90	697	100.7	786	98.2	297	62.6	275	60.2				
28	416NB	1	Micro-Surf-Coarse	90	715	102.5	715	99.6	250	66.3	283	63.3	800	72.6	1000	70.7
27	416SB	2	Micro-Surf-Coarse	90	593	102.0	715	98.4	250	70.5	250	65.7	800	73.5	800	71.4
18	10	1	Micro-Surf-Fine	100	699	103.9	772	100.8	272	64.4	261	61.9	1000	75.5	933	74.3
19	10	2	Micro-Surf-Fine	100	722	103.9	786	100.9	250	64.9	250	62.7				
28	416NB	1	Micro-Surf-Coarse	100	729	105.5	758	101.6	250	67.0	283	62.3	1000	74.6	1000	73.1
27	416SB	2	Micro-Surf-Coarse	100	715	103.5	736	101.0	250	70.6	272	67.0	715	75.6	800	73.9
15	401WB	0	PCC-Longitudinal	80	667	104.2	867	101.8	315	63.5	315	60.9	900	78.5	1000	76.8
6	410SB	0	PCC-Transverse	80	590	100.3	980	96.9	1250	62.2	1250	59.7	1125	76.0	1125	73.4
6A	410NB	0	PCC-Transverse	80	379	102.7	529	98.5	250	62.2	250	60.2				
14	401EB	0	PCC-Transverse	80	475	102.6	425	99.7	289	62.6	319	59.6	1000	75.9	1000	73.8
14A	401WB	0	PCC-Transverse	80	510	102.1	405	98.7								
16	401EB	1	PCC-Transverse	80					266	64.1	266	61.0				
16A	401WB	1	PCC-Transverse	80	760	104.3	633	101.6	276	64.5	315	62.1	1000	77.9	1000	76.1
17	401EB	2	PCC-Transverse	80	423	102.9	1150	99.8	250	63.7	266	59.5	1000	79.3	1250	77.3
17A	401WB	2	PCC-Transverse	80	646	104.9	1050	101.9								
25	417WB	3	PCC-Transverse	80	688	107.1	605	103.2	1000	67.8	1000	63.3	1000	75.9	1000	74.6
26	417EB	5	PCC-Transverse	80	917	101.4	1000	99.1	1000	67.0	1000	64.4	1250	77.0	1000	75.1
29	402EB	0	PCC-Transverse	80	758	100.8	850	97.7	250	64.4	250	60.8				

Table 5-1 Summary of CPX, In-Vehicle and Pass-By Noise Levels (Part D)

Site No.	Highway No.	Surface Age	Pavement Surface Type	Test Speed (km/h)	CPX Noise				In-Vehicle Noise				Pass-By Noise			
					*L*max		*L*eq		*L*max		*L*eq		*L*max		*L*eq	
					Freq	SPL	Freq	SPL	Freq	SPL	Freq	SPL	Freq	SPL	Freq	SPL
15	401WB	0	PCC-Longitudinal	90	525	108.0	720	105.3	266	64.8	386	61.7	1000	82.5	900	80.1
6	410SB	0	PCC-Transverse	90	440	103.0	440	99.1	500	63.5	625	60.4	1000	78.4	1000	76.1
6A	410NB	0	PCC-Transverse	90	400	106.2	450	102.8	313	63.9	300	61.3				
14	401EB	0	PCC-Transverse	90	506	105.6	506	102.5	261	65.7	272	62.2	1000	77.5	1000	76.4
14A	401WB	0	PCC-Transverse	90	579	105.8	460	101.9								
16	401EB	1	PCC-Transverse	90					315	65.2	250	62.2				
16A	401WB	1	PCC-Transverse	90	549	106.1	652	102.7	263	66.2	289	63.0	1000	79.3	1000	77.1
17	401EB	2	PCC-Transverse	90	466	104.5	1440	101.3	250	64.2	272	61.4	1000	81.1	1000	79.3
17A	401WB	2	PCC-Transverse	90	740	107.8	1000	104.8	650	64.7	663	62.1				
25	417WB	3	PCC-Transverse	90	613	108.7	660	105.2	1000	65.8	1000	63.1	1000	76.9	1125	75.8
26	417EB	5	PCC-Transverse	90	858	104.5	892	101.5	1250	65.1	1000	63.0	1000	78.6	1000	76.4
29	402EB	0	PCC-Transverse	90	743	102.3	772	99.8	272	65.0	250	62.0				
15	401WB	0	PCC-Longitudinal	100	672	109.5	730	107.2	289	66.3	593	63.5	1000	83.4	1000	81.0
6	410SB	0	PCC-Transverse	100	492	104.2	680	100.6	250	64.5	250	62.1	1000	79.0	1000	77.0
6A	410NB	0	PCC-Transverse	100	532	108.7	526	105.8	266	66.4	250	63.8				
14	401EB	0	PCC-Transverse	100	565	107.5	500	104.5	266	68.4	388	64.7	630	82.3	630	80.1
14A	401WB	0	PCC-Transverse	100	532	108.6	578	105.9								
29	402EB	0	PCC-Transverse	100	850	107.1	800	104.1	250	68.0	250	65.3				
16	401EB	1	PCC-Transverse	100	578	107.5	526	104.8	276	66.6	250	63.8				
16A	401WB	1	PCC-Transverse	100	540	108.2	480	105.1	276	67.5	289	64.5	1000	81.0	800	81.0
17	401EB	2	PCC-Transverse	100	486	108.6	506	105.6	266	66.8	525	63.9	900	82.5	900	81.1
17A	401WB	2	PCC-Transverse	100	632	109.5	926	106.4	276	65.4	360	62.7				
25	417WB	3	PCC-Transverse	100	875	111.1	858	107.3	250	68.5	250	65.6	1300	77.6	1250	75.3
26	417EB	5	PCC-Transverse	100	643	107.3	847	103.9	583	65.8	1250	63.7	1300	80.6	1425	79.0
30	407EB	12	PCC-Transverse	100	833	104.8	950	101.0								
30A	407WB	12	PCC-Transverse	100	705	104.5	833	100.8								

Table 5-2 Comparison of CPX Noise Measurements in Winter (2007) and Spring (2008)

Test Site No.	MTO Contract No.	Regional Highway No.	Year of Const.	Age at Test	Pavement Surface Mix	Vehicle's Speed, km/h	Winter (2007) CPX Noise		Spring (2008) CPX Noise		Spring (2008) Temperature (°C)		Spring (2008) Wind, km/h
							*L*max	*L*eq	*L*max	*L*eq	Pavement	Air	
7	2005-3031	401EB	2007	0	SP12.5FC2	100	105.7	102.3	103.1	99.5	20.0	11.2	15.9
7A	2005-3031	401WB	2007	0	SP12.5FC2	100	104.7	101.7	103.6	99.5	18.0	8.0	18.5
11	2006-3037	401WB	2006	1	SMA	100	103.3	101.1	103.7	100.6	21.0	9.4	18.3
11A	2006-3037	401EB	2006	1	SMA	100	103.0	100.5	101.3	98.7	21.0	9.4	18.3
12	2004-3021	401WB	2005	2	SMA	100	106.3	103.2	101.2	99.1	20.0	9.2	22.9
13	2004-3021	401EB	2004	3	SMA	100	102.9	100.3	102.8	99.7	20.0	9.2	22.9
15	2005-3046	401WB	2007	0	PCC-Longitudinal	100	109.5	107.2	110.0	107.5	12.0	14.1	20.2
16	2005-3047	401WB	2007	0	PCC-Longitudinal	100			104.4	102.8	12.0	14.1	20.2
6	2006-2018	410SB	2007	0	PCC-Transverse	100	104.2	100.6	107.1	102.6			
6A	2006-2018	410NB	2007	0	PCC-Transverse	100	108.7	105.8	107.0	103.5			
14	2005-3046	401EB	2007	0	PCC-Transverse	100	107.5	104.5	102.1	98.8	12.0	6.6	
16	2005-3001	401EB	2006	1	PCC-Transverse	100	107.5	104.8	103.8	100.6	16.0	10.0	12.0
16A	2005-3001	401WB	2006	1	PCC-Transverse	100	108.2	105.1	108.2	105.8	13.2	9.0	10.9
16A	2005-3001	401WB	2006	1	PCC-Transverse	100			105.0	102.7	13.2	9.0	10.9
17	2004-3002	401EB	2005	2	PCC-Transverse	100			102.8	100.1	15.0	11.9	20.2
17	2004-3002	401EB	2005	2	PCC-Transverse	100	108.6	105.6	103.4	100.5	15.5	12.5	20.2
17A	2004-3002	401WB	2005	2	PCC-Transverse	100	109.5	106.4	109.3	107.1			
25	2003-4029	417WB	2004	3	PCC-Transverse	100			107.2	103.9	14.0	12.6	5.2
25	2003-4029	417WB	2004	3	PCC-Transverse	100			109.3	106.8			
25	2003-4029	417WB	2004	3	PCC-Transverse	100	111.1	107.3	111.6	107.8	16.0		
25	2003-4029	417WB	2004	3	PCC-Transverse	100			106.3	103.0	15.0		
26	2000-0025	417EB	2002	5	PCC-Transverse	100	107.3	103.9	108.2	104.2	21.3	10.0	7.1
26	2000-0025	417EB	2002	5	PCC-Transverse	100			105.4	102.0			
26	2000-0025	417EB	2002	5	PCC-Transverse	100			105.0	101.6	16.0	11.0	7.2

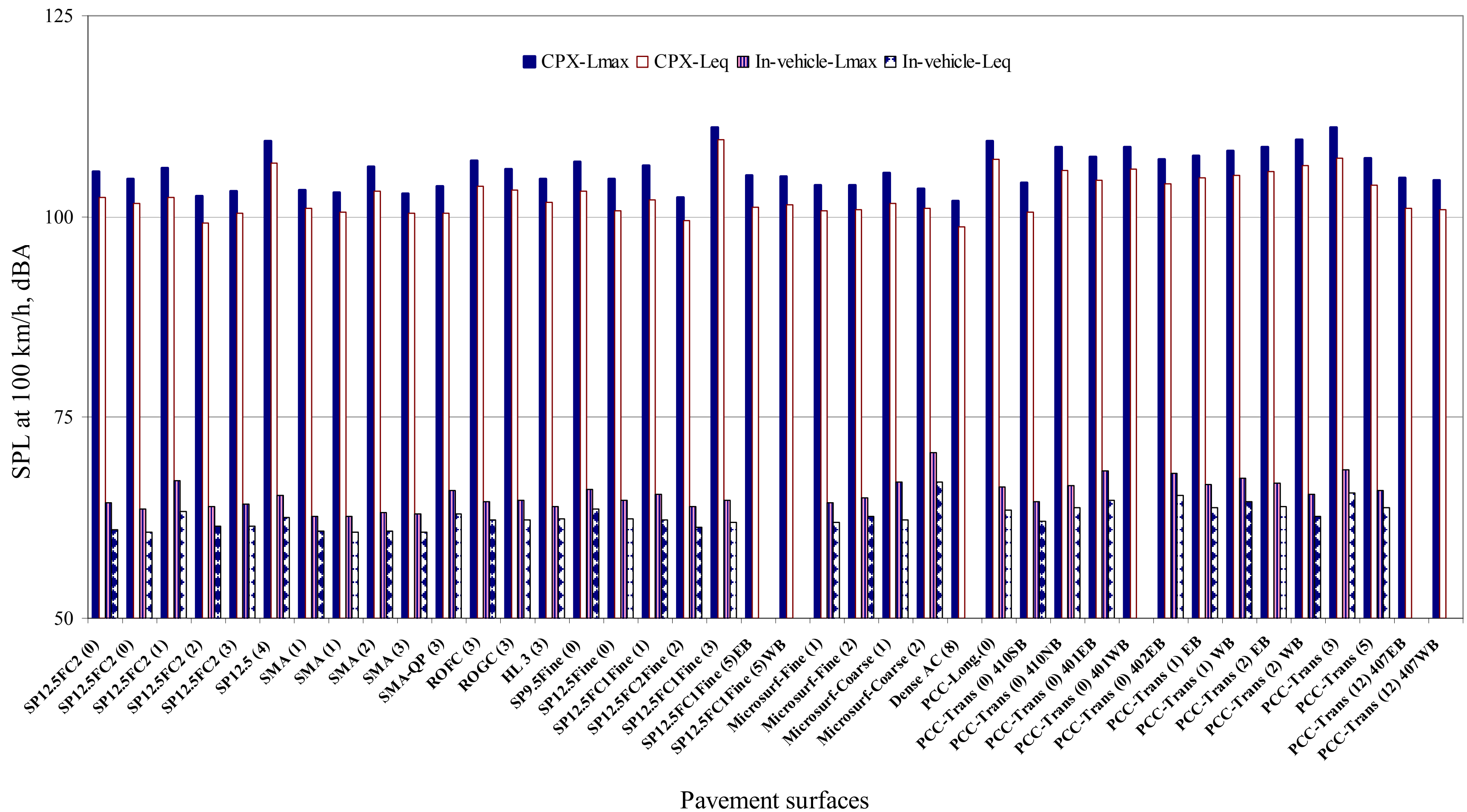

Figure 5-38 Comparison of *L*max and *L*eq.

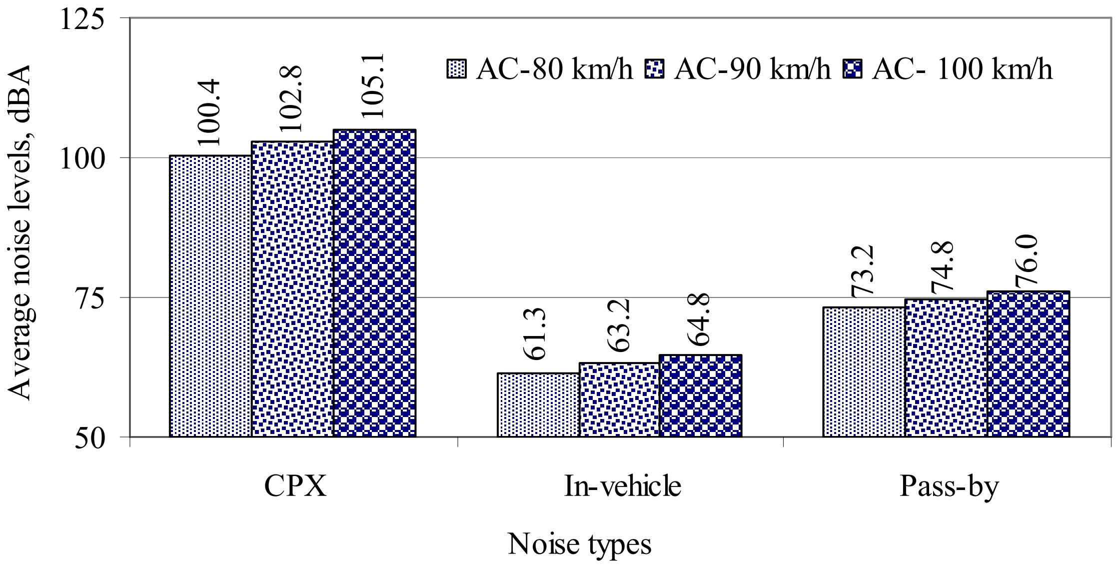

Figure 5-39 Variation of Tire-Pavement Noise with Vehicle Speed on AC Surfaces.

The variations of tire-pavement average CPX (near-field), in-vehicle and pass-by noise levels with the speed of vehicle from 80 km/h to 100 km/h for the tested PCC pavement surfaces are shown in Figure 5-40. The CPX noise was shown to increase at 2.0 to 2.7 dBA (average 2.35 dBA) for each 10 km/h increase in speed of the vehicle. The average variation was shown to be similar to that observed for AC pavement surfaces. The in-vehicle noise on PCC pavement surfaces was shown to increase at an average rate of 1.25 dBA (0.7 to 1.8 dBA) as compared to average 1.75 dBA on AC pavement surfaces. Finally, the increase in pass-by noise level on PCC surface was shown to be 1.7 to 2.0 dBA (average 1.85 dBA) for each 10 km/h increase in vehicle speed as compared to an average 1.40 dBA for AC pavement surfaces. Overall, combining the AC and PCC pavement surfaces, the increase in CPX, in-vehicle and pass-by noise levels were shown to shown to be 2.4 dBA, 1.6 dBA and 1.5 dBA, respectively, for each 10 km/h increase in vehicle speed.

Figures 5-39 and 5-40 show that on average PCC pavements are 2.7 dBA louder than the AC pavements when CPX noise levels are compared. The differences were shown to be 2.2 dBA (PCC surfaces louder than the AC surfaces) if the in-vehicle noise and 4.4 dBA if the pass-by noise levels are compared. It should be noted that a difference of five dBA is a noticeable change while a difference of three dBA is just perceptible. A difference of less than three dBA is barely noticeable. Therefore, the measured difference in average noise levels between the PCC and AC pavements may be regarded as noticeable (pass-by case) to hardly noticeable (in-vehicle case).

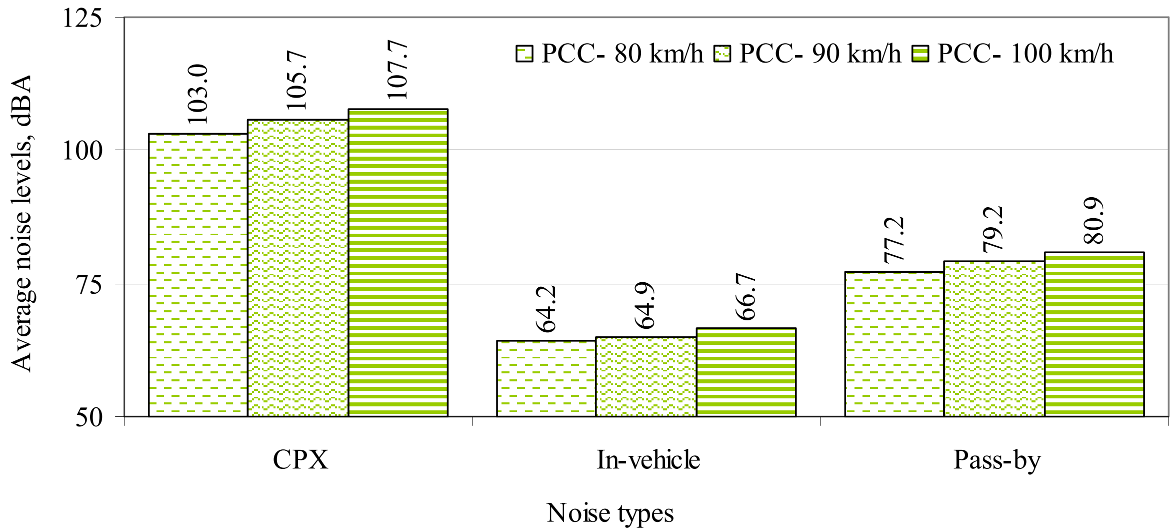

Figure 5-40 Variation of Tire-Pavement Noise with Vehicle Speed on PCC Surfaces.

The tested PCC pavements were surface textured with transverse tining, with the exception of the trial longitudinal tined section. The tine width, depth, and spacing were specified as 3 mm (±1 mm), 4 mm (±1 mm) and 16 mm (±3 mm) c/c (uniform spacing), respectively, for both transverse and longitudinal directions according to OPSS 350 (1998). Studies have shown that tire-pavement noise increases as the tine depth, width, and spacing increase. A 3.2 mm deep and 3.2 wide tine texturing is generally specified in the US. Specified transverse tine spacing varies from 13 mm to 38 mm. However, 19 mm spacing are preferred because of lower tire-pavement noise. The current trend is the longitudinal tining that has shown a further noise reduction as compared to transversely tined surfaces. In fact, a wide variation in tire-pavement noise levels has been observed despite the same tine specifications is being used for different pavement sections (refer to Chapter 3, Literature Review).

Findings in this and other research indicate that the current MTO specified 16 mm tine spacing is fine with respect to tire-pavement noise if texturing in the field is uniformly applied. However, the tine depth may be reduced to 3.2 mm for further reduction of tire-pavement noise, if skid resistance is adequate. Longitudinal tining may be taken as a standard for further reducing the tire-pavement noise. However, as mentioned earlier, uniform texturing is important to achieve the noise reduction benefit and reduce the variability among pavement sections. MTO may also consider diamond grinding. In California, grinding of transverse tined bridge decks reduced the noise by 3 to 10 dB while a reduction of nine dBA was achieved in Arizona (Scofield 2006). Plastic bristle brushed surfaces have shown to be quieter PCC (similar to AC surface) in Europe (Snyder 2006). According to Scofield (2006), noise on PCC surfaces can span 16 dB depending on surface texture. PCC pavements therefore could be constructed or retextured to perform quietly.

5.4.4 Comparison of CPX Noise on Pavements of Varying Age

Figures 5-41 and 5-42 show the comparison of tire-pavement near-field (CPX) *L*max noise levels at 100 km/h for various AC and PCC surfaces, respectively. The values in the parenthesis indicate the ages of various surfaces. The near-field noise level for each surface is indicated on the top of each bar. As shown in the figures, it is not possible to compare the variation of tire-pavement noise level with variation of age of the pavement surfaces tested in this study. Figure 5-41 shows that the near-field noise produced by two new (less than one year old, referred to as 0-year old in this study) 12.5FC2 surfaces (on Highway 401 in the West Region) constructed under the same contract (2005-3031) differs by 1.0 dBA between the east and west bound travel directions. Alternatively, 2-year and 3-year old SP12.5FC2 surfaces (on Highway 402 in the West Region) constructed under the same contract in two different years (one year age difference) have shown to produce noise levels with a difference of only 0.7 dBA.

Figure 5-41 also shows that two same age (1-year old) SMA surfaces (on Highway 401 in the West Region) have exhibited almost equal near-field noise levels (only a difference of 0.3 dBA). A 2-year old SMA surface was shown to be louder than both 1-year and 3-year old SMA surfaces. Similar variation has been observed for the fine graded Superpave mixes in the East Region. Such inconsistent variation in noise levels is likely to be associated with variation in surface macrotexture of various surfaces as shown in the pictures taken from the pavement surfaces (Figures 4-13 through 4-15). Nearby traffic was an influential factor for the SP12.5FC2 on Highway 6 in the West Region where isolation from other traffic was next to impossible. Traffic may also have some influences in the measured noise levels for some other sites, especially for 400 series highways, despite every effort being made for isolation from other vehicles. However, overall results and observation of test sites indicate that tire-pavement noise variation with pavement ages may not accurately be estimated unless the same section is tested in repeated years with isolation from surrounding traffic.

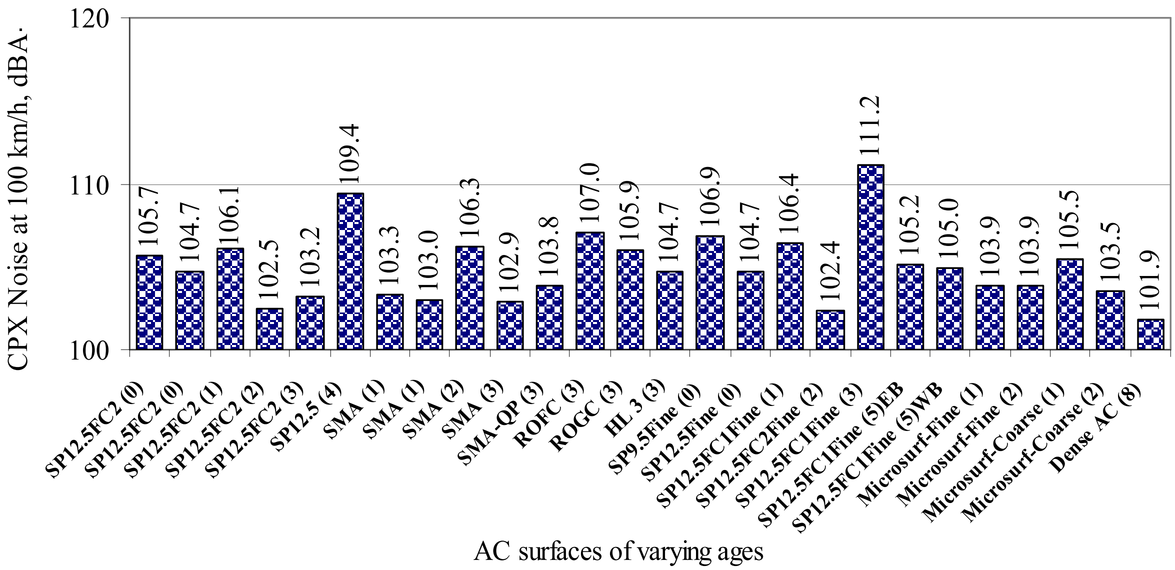

Figure 5-41 CPX Noise of Various AC Surfaces of Varying Age.

Among the same age (0-year old) PCC pavement surfaces with transverse tining, the variation of near-field noise (Figure 5-42) was shown to be up to 4.5 dBA, even for the same contract (e.g. Highway 410). A 3-year old PCC pavement surface was shown to be louder than 0-year to 2-year old PCC pavement surfaces. Alternatively, a 5-year old PCC surface was shown to be 3.8 dBA quieter than a 3-year old PCC surface while the 12-year old PCC surfaces were shown to be 2.5 to 2.8 dBA quieter than the 5-year old PCC. Therefore, it was difficult to quantify the variation in noise levels among the PCC surfaces of similar or varying age because of variation in as-built surface texture.

As mentioned earlier, construction variation (e.g. consistency in texture application and its effectiveness) is a key player in the variation of observed noise levels. Field observation has also shown some variations in surface texture from section to section such as deep and shallow grooves. Longitudinal texture on some spots of transversely tined sections was also noted. It is therefore important to include surface texture measurement with all noise measurements. This will allow for examining the effect of variations in actual surface texture and/or pavement age on the variation of tire-pavement noise. A number of texture measurement techniques have been presented in Chapter 2. A texture laser such as a high-speed laser mounted with the ARAN could be used for measuring the surface macrotexture without interrupting the traffic.

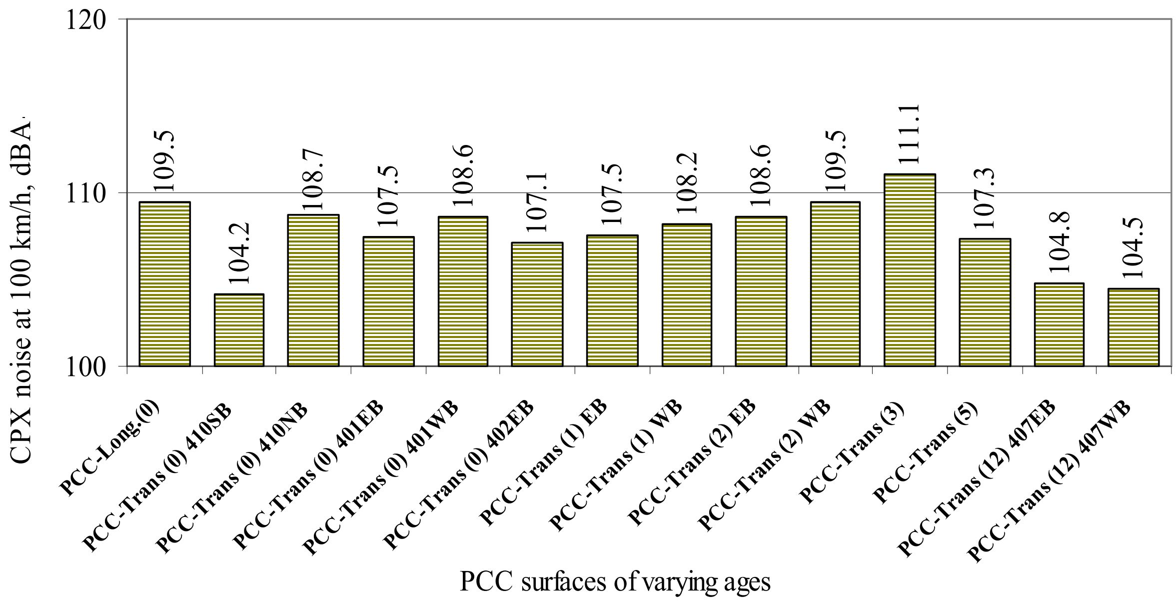

Figure 5-42 CPX Noise on Various PCC Surfaces of Varying Age.

Figures 5-41 and 5-42 show that the 8-year old dense AC surface is the quietest pavement among the test surfaces included in this study. However, the mix information for this section was unavailable due to some practical limitations. Furthermore, MTO no longer supports using these old dense mixes for highways in their jurisdictions. Therefore, this section has been excluded for comparison of noise level with that of other surfaces. Excluding this older dense AC surface, a 2-year old fine graded SP12.5FC2 and a 3-year old fine graded SP12.5FC1 (both in the East Region) were shown to be the quietest and loudest pavements, respectively, when the near-field (microphones attached in the vicinity of tire-road interface) noise levels are compared. As mentioned earlier, some texture is needed for reducing air compression underneath the tire-pavement contact patch (reduction of sound generation). Therefore, a fine graded mix does not necessarily mean a quieter pavement, specifically when the tire-pavement near-field (CPX) noise is compared.

Tables 5-1A to 5-1D also show that the variation of near-field, in-vehicle and pass-by noise levels are not identical. Several other studies have also found that variation of pass-by and near-field noise levels are not identical (e.g. Rasmussen et al. 2008b, Rasmussen 2008). This is probably because of complex mechanisms of noise generation and propagation, variation in frequencies corresponding to peak noise levels that is perceived at roadside, within the vehicle or near the vehicle's tire and the distance of microphone(s) from the noise source (tire-road interface). As the in-vehicle and pass-by noise levels are of prime concern for the travelers and nearby residents, the in-vehicle and pass-by noise levels for various surfaces should mainly be taken into account in selecting the pavement types for different applications e.g. urban and rural contexts.

Although traffic noise is a growing concern throughout the world, no public agency specifies a desirable maximum noise level for the selection of pavement type. An end-result specification can incorporate criteria for the desirable maximum tire-pavement noise level as well as section-to-section variation. It may not be appropriate to set a maximum or range of textures for reduced noise because a specified maximum texture may not provide adequate skid resistance. Each transportation agency should develop a comprehensive database of tire-pavement noise, texture and skid resistance levels for available materials and mixes in their jurisdictions should an end result specification be established. The developed database will help in the selection of a surface with specified maximum noise level and a limit of allowable variation from section to section. The surface with desirable maximum noise level, however, must meet the skid resistance requirements as safety is of paramount importance. Frameworks for the selection of pavement surface with desirable minimum skid resistance and maximum in-vehicle as well as pass-by noise levels have been presented by Ahammed and Tighe (2008a).

5.4.5 Comparison of In-vehicle Noise from Various Surfaces

The variation of in-vehicle *L*max noise levels at 100 km/h for various AC pavement surfaces is shown in Figure 5-43 while that for PCC pavement surfaces is shown in Figure 5-44. Under the same contract, two new (0-year old) SP12.5FC2 surfaces were shown to differ in in-vehicle noise levels by 0.7 dBA. Two 1-year old SMA surfaces were shown to differ in in-vehicle noise levels by 0.1 dBA. Alternatively, a 3-year old SP12.5FC2 surface was shown to be 0.3 dBA louder than a 2-year old SP12.5FC2 surface while a 3-year old SMA surface was shown to be 0.1 dBA quieter than a 2-year old SMA surface with respect to perceived in-vehicle noise. A 2-year old coarse Microsurfacing on Highway 416 was shown to be the loudest (6.7 dBA louder than similar age regular SP12.5) while a 1-year old 12.5 mm SMA was shown to be the quietest (1.3 dBA quieter than the same age regular SP12.5) among the tested AC and PCC pavements surfaces. The fine graded Superpave with 9.5 mm nominal maximum size aggregate (SP9.5Fine) was shown to be 1.4 dBA louder than same age (0-year old) fine graded Superpave with 12.5 nominal maximum size aggregate (SP12.5Fine).

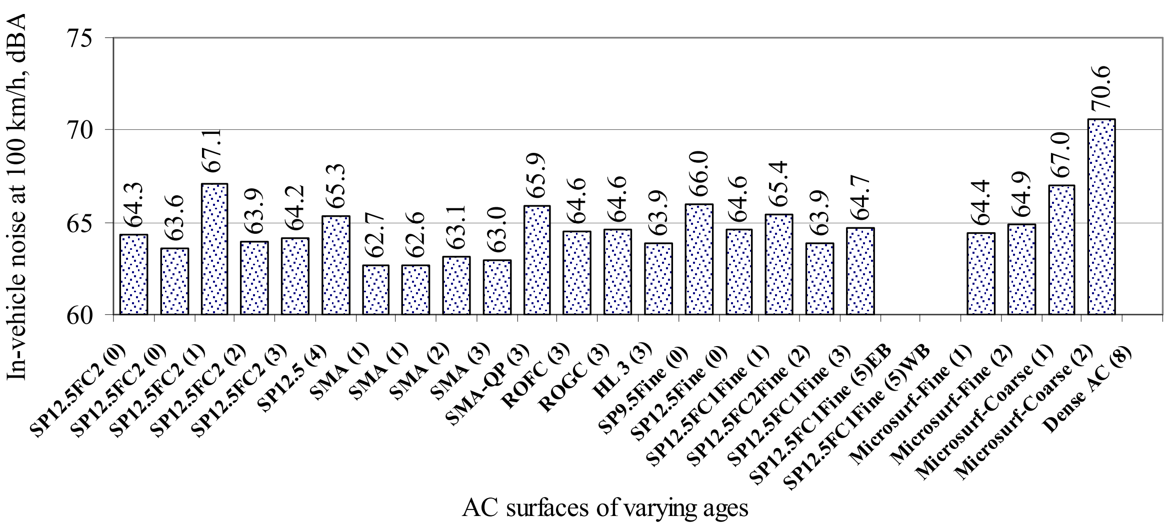

Figure 5-43 In-Vehicle Noise from Various AC Surfaces of Varying Age.

Among the PCC pavement surfaces alone, a less than one-year (0-year) old transversely tined surface on Highway 410 (SB direction) was shown to be the quietest surface with an in-vehicle noise level of 64.5 dBA. The northbound direction (Highway 410NB) of the same highway was shown to be 1.9 dBA louder than the southbound direction with in-vehicle noise level of 66.4 dBA. Same age (0-year old) PCC pavement surfaces on Highway 401 and Highway 402 were shown to be 3.9 and 3.5 dBA, respectively, louder than Highway 410SB. A 2-year old PCC surface was shown to be quieter than both 1-year and 3-year old surfaces making it difficult to generalize the result.

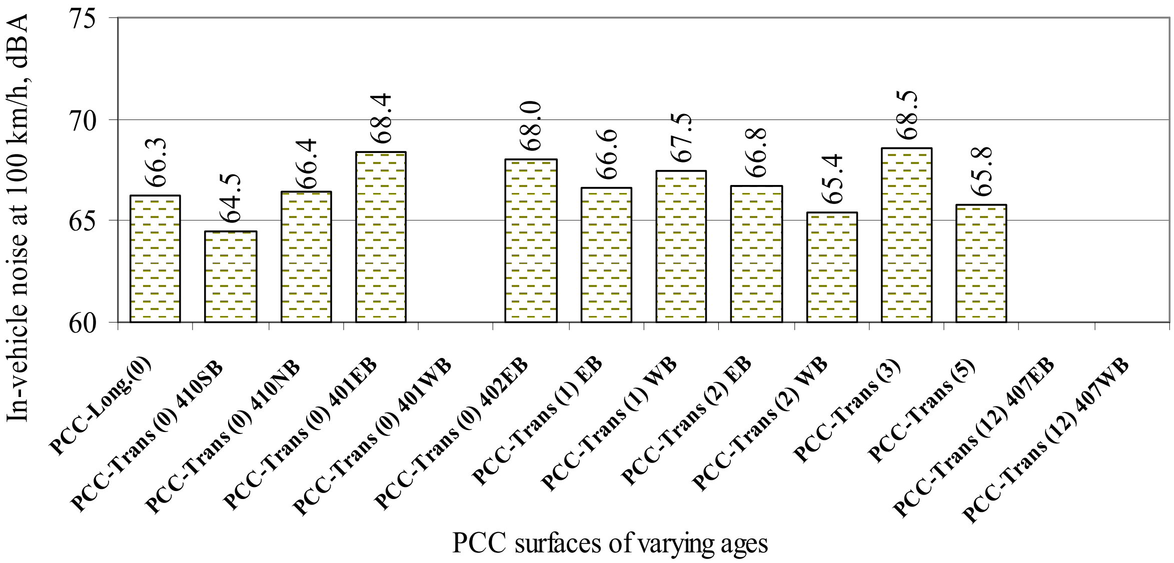

Figure 5-44 In-Vehicle Noise from Various PCC Surfaces of Varying Age.

As mentioned in the case of CPX noise, because of the variation in as-built surface texture, it is also not possible to quantify the variation of in-vehicle noise levels with time/age of any of the AC and PCC pavements surfaces included in this study. This further emphasizes that the same section should be tested in repeated years for estimating noise deterioration or reduction over time. A database of macrotexture and tire-pavement noise levels as well as skid resistance properties of various pavement surfaces will be helpful in developing a best practice guide for field quality control and end-result specification incorporating these aspects of pavement surface characteristics.

5.4.6 Comparison of Pass-By Noise from Pavements of Varying Age

Figures 5-45 and 5-46 show the variation of pass-by noise levels from various AC and PCC surfaces tested in this study. A 2-year old SP12.5FC2Fine surface on Highway 401 in the

East Region was shown to be the quietest pavement (5.1 dBA quieter than similar age regular SP12.5FC2) among the tested surfaces while the SP9.5Fine surface on Highway 132 was shown to be the noisiest pavement (4.5 dBA louder than same age regular SP12.5) among the asphalt pavement surfaces. The trial section of longitudinal tining on PCC pavement was shown to be the loudest surface among the pavements tested with a pass-by noise level of 8.7 dBA greater than the same age regular SP12.5 surface. It should, however, be noted that the contractor was unable to successfully texture this section as specified in the MTO specification (tine depth is substantially greater than the specified 4 mm ± 1 mm).

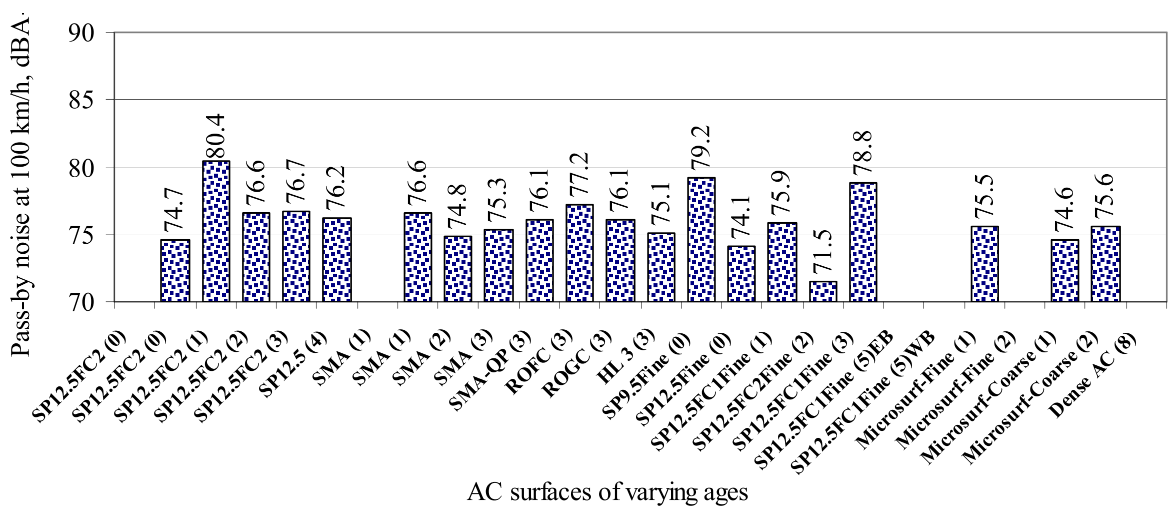

Figure 5-45 Pass-By Noise from Various AC Surfaces of Varying Age.

The variation of pass-by noise levels was also shown not to follow any pattern with variation of surface age for the same reasons mentioned in the cases of near-field and in-vehicle noise levels. Figures 5-41 through 5-46 also show that the variations of near-by (CPX), in-vehicle and pass-by noise levels are not identical. For example, a 2-year old SP12.5FC2Fine was shown to be the quietest surface with respect to the near-field (CPX) while a 1-year old 12.5 mm SMA was shown to be the quietest with respect to the in-vehicle noise levels. Alternatively, a 2-year old SP12.5FC2Fine was shown to be the quietest pavement with respect to the pass-by level. A 3-year old SP12.5FC1Fine, a 2-year old coarse Microsurfacing and the longitudinal tined PCC surfaces were shown to be the loudest pavements with respect to near-field, in-vehicle, and pass-by noise levels, respectively. Such inconsistent variation is not unusual for the tire-pavement interaction noise levels because of the complex mechanisms of noise generation, amplification/reduction, and propagation to receiver points.

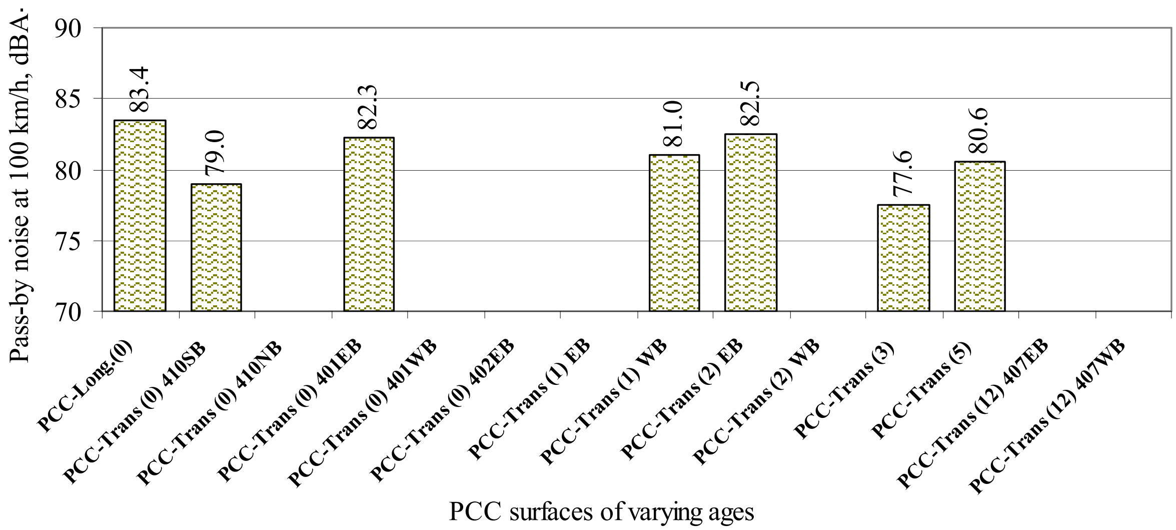

Figure 5-46 Pass-By Noise from Various PCC Surfaces of Varying Age.

It should be noted that the CPX (i.e., near-field) noise is measured with microphones mounted near the tire of the vehicle, in-vehicle noise is measured with microphone(s) mounted near the ear of driver within the vehicle, and pass-by noise is measured with microphone(s) mounted at 15 m off the highway right lane centre line. As the measured noise levels using these three methods are not identical, the choice of a measurement method will depend on its use, regardless of the cost of each method. The near-field (CPX) noise is not heard by the human ear, and therefore it is of less importance for travelers and neighbouring residents. If a road section is located in rural area, it is being recommended that the highway agency should give priority to in-vehicle noise measurement. Alternatively, if a roadway section passes through a residential community, priority should be given to pass-by noise measurement and use in the selection of the pavement surface.

5.4.7 Benchmarking Various Surfaces for Tire-Pavement Noise

As mentioned earlier, the tire-pavement noise variation with age of the tested pavements was not shown to follow any trend. Therefore, the average noise of each type of AC mix or PCC texture of varying age has been used for benchmarking various pavements with respect to the tire-pavement noise performance. As the measured noise level for 1-year old SP12.5FC2 on Highway 6 in the WR was shown to be greatly influenced by other traffic, this section has been excluded in determining the average noise level of regular Superpave. Alternatively, the 5-year old SP12.5FC1Fine on Highway 417 in the ER has been excluded in determining the average noise level of fine graded Superpave because of apparent surface distress (transverse and longitudinal cracks) that might have influenced the measured noise level. The average CPX noise level of 12-year old PCC on Highway 407 has been presented separately because this study has mainly focused to 0-year to 5-year old pavements.

Figures 5-47 through 5-49 show the variations of average near-field, in-vehicle, and pass-by noise levels, respectively, for various AC and PCC surfaces. The average age of various surfaces are shown in the parenthesis as usual. For example, the SMA-QP (3) represents the 3-year old SMA at the CPATT Quiet Pavement (QP) test site. SMA (1.8) represents the SMA on Ontario Provincial Highways having average age of 1.8 years.

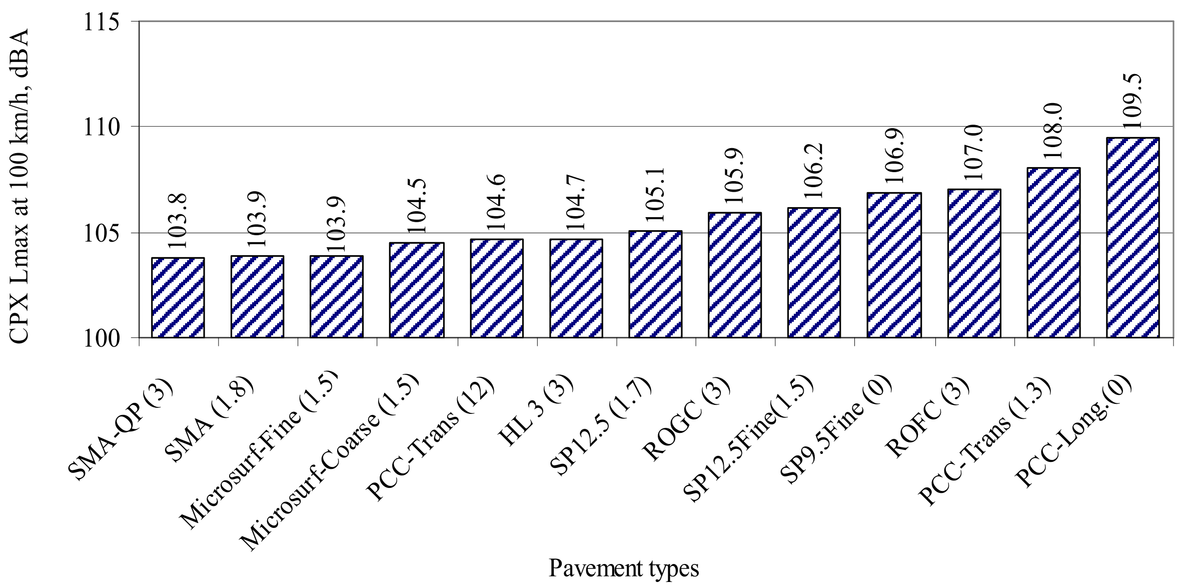

Figure 5-47 Average CPX Noise Levels of Various Pavements.

As shown in Figure 5-47, SMA with 12.5 mm nominal maximum size aggregate is the quietest pavement with respect to the near-field noise among the pavements included in this study. Assuming the regular 12.5 mm Superpave (SP12.5) mix as the reference surface, the SMA surfaces were shown to be 1.2 dBA (on average) quieter than the SP12.5 surfaces. Although open graded mixes were quieter immediately after construction, their noise reducing properties diminished in just three years.

Figure 5-47 also shows that the longitudinal tined trial PCC is the loudest pavement followed by the transversely tined PCC pavements. The longitudinal tined PCC section was shown to exhibit 4.4 dBA greater while the transversely tined PCC pavements (0 to 5-year old) were shown to exhibit 2.9 dBA (on average) greater near-field noise as compared to the SP12.5 surfaces. The SP9.5Fine was shown to be louder than other AC surfaces further indicating that some textures are essential for noise reduction. However, poor surface condition (micro-cracks and rough spots) that are probably associated with a fine mix holding problem during the placement and compaction and/or reflection cracks may also have contributed to higher tire-pavement noise in the case of SP9.5Fine surface.

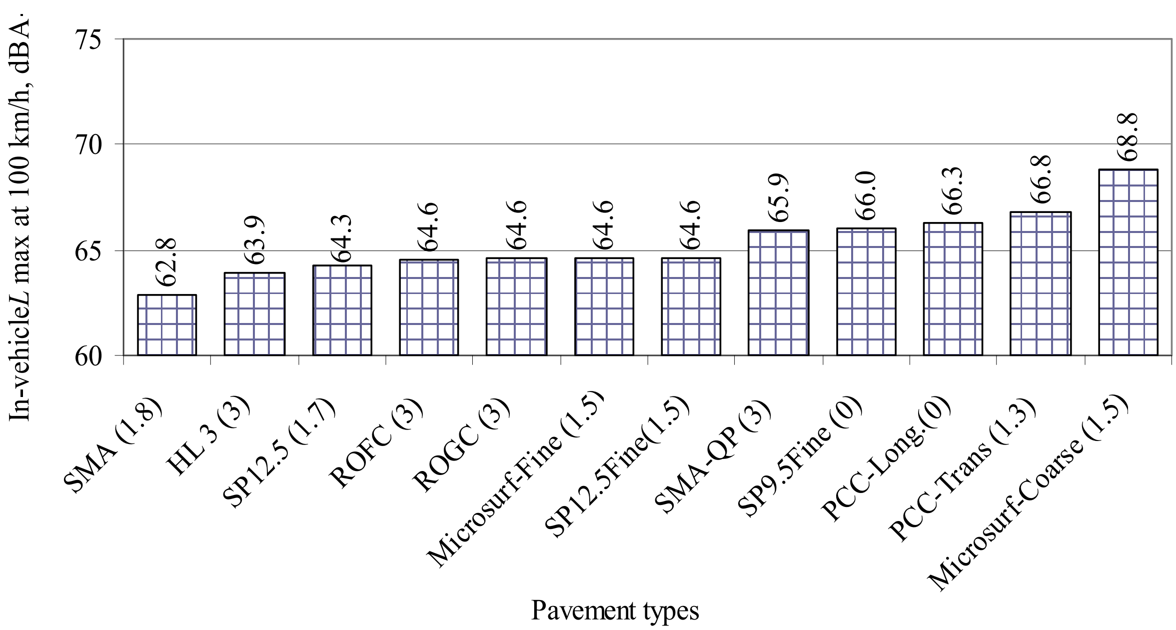

Figure 5-48 Average In-Vehicle Noise Levels of Various Pavements.

When the average in-vehicle noise levels of various pavements are compared, as shown in Figure 5-48, the 12.5 mm SMA has again shown to be the quietest pavement. The 12.5 SMA surfaces on Provincial highways were shown to be on average 1.5 dBA quieter than the regular SP12.5 surfaces. Traditional (Waterloo Regional) HL3 mix was shown to be just 0.4 dBA quieter than the regular SP12.5 surfaces. The 16 mm ROFC, 16 mm ROGC, fine Microsurfacing, and fine graded 12.5SPsurfaces were shown to exhibit similar in-vehicle noise, just 0.3 dBA greater than the regular SP12.5 surfaces. The 16 mm SMA at the quiet pavement test site was shown to be 3.1 dBA louder than the 12.5 mm SMA and 1.6 dBA louder than the regular SP12.5 surfaces. The SP9.5Fine on Highway 132 was shown to be 1.7 dBA louder than the regular 12.5SP surfaces.

Figure 5-48 also shows that coarse (Type III Modified) Microsurfacing is the noisiest pavement among the pavements tested in this study. It was shown to be 4.5 dBA louder than the SP12.5 surfaces and 2.0 dBA louder than the transversely tined PCC surfaces. It should be noted that Microsurfacing is expected to become quieter with age as traffic smoothes the surface. However, the condition of underlying pavement on which it is applied and developed surface distresses with age or traffic uses may be an influencing factor in noise increase over time. The transversely tined PCC pavement surfaces were shown to be 0.5 dBA (on average) louder than the longitudinal tined trial surface. The transverse and longitudinal tine textures on PCC pavements were shown to be 2.5 dBA and 2.0 dBA louder, respectively, than the SP12.5 surfaces.

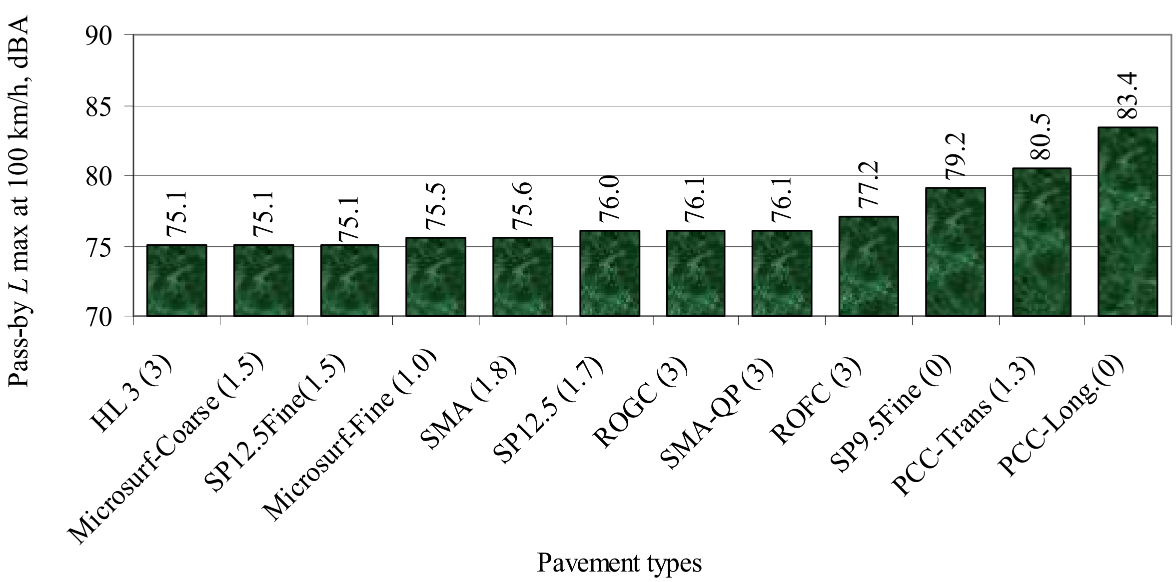

Figure 5-49 Average Pass-By Noise Levels for Various Pavements.

In the case of pass-by noise (Figure 5-49), the traditional 16 mm HL3, fine graded SP12.5, and coarse Microsurfacing pavements were shown to exhibit similar noise. These surfaces were shown to be on average 0.9 dBA quieter than the regular 12.5SP surfaces. The 12.5 mm SMA was shown to be just 0.4 dBA (on average) quieter while the 16 mm SMA was shown to be 0.1 dBA louder than the regular SP12.5 surfaces. The 9.5 mm fine graded Superpave (SP9.5Fine) was again shown to be 3.2 dBA louder than the regular SP12.5 surfaces.

The longitudinal tined trial PCC pavement was shown to be the noisiest surface with a pass-by noise of 7.4 dBA greater than the regular SP12.5 and 2.9 dBA greater than the transversely tined PCC surfaces. However, it should be noted that the trial longitudinal tined PCC surface was inconsistent in terms of texture depth with some aggressive texturing i.e., greater texture depth than the specified 4 mm ± 1 mm. Such inconsistent and aggressive texture is the cause of the high of tire-pavement noise. In other words, although this section is expected to become quieter as traffic smoothes the texture, it does not adequately or accurately depict what the surface and its noise level would be if it were textured properly.

It should be noted that in studies carried out in the US and elsewhere (refer to Chapter 3), the longitudinal tined PCC surfaces were shown to be quieter than similar transversely tined surfaces. Therefore, this is now becoming a standard texturing practice for PCC pavements in the US. With a new Technical Advisory dated June 17, 2005, the US FHWA dropped the requirement for transverse tine and stated that tire-pavement noise should also be considered when specifying the pavement and bridge surfaces while safety consideration is paramount. The paving contractors need to be trained to ensure that texture is applied consistently and within the specified tolerance to attain the noise reduction benefit of longitudinal tining.

5.4.8 Sound Absorption of Various Pavements

Sound Absorption of Various AC Pavement Mixes

The summary of average sound absorption coefficients for various AC pavement cores obtained from as-built surface layers before opening for traffic movement is shown in Table 4-6. The regular 12.5 mm Superpave mixes in the West and Central regions were shown to absorb 4.8% to 7.9% of sound (absorption coefficient of 0.048 to 0.079) with an average sound absorption of 6.3%. The 12.5 mm SMA was shown to absorb 7.5% of sound. Alternatively, the fine graded 12.5 mm Superpave mixes in the East Region were shown to absorb 6.8% to 9.2% of sound with an average sound absorption of 8.5%. On average, the fine graded 12.5 mm Superpave mixes were shown to absorb 2.2% higher sound as compared to similar regular Superpave mixes. These results closely agree with other similar studies e.g. Crocker et al. (2004) and Leung et al. (2006).

Figure 5-50 shows the variation of sound absorption with the variation of BRD of Superpave mixes (excluding the SMA). The SMA was shown to be deviant from the trend of Superpave possibly because of variation in mix constituents (cellulose and/or rich binder in SMA) and/or texture. As shown in Figure 5-50, the sound absorption of AC mixes decreases with an increase in density of the mixes. With this trend, the sound absorption was shown to decrease by 1.4% for each 0.1 increase in *BRD*. The correlation (r = 0.54) was shown to be statistically significant at the 5% level of significance.

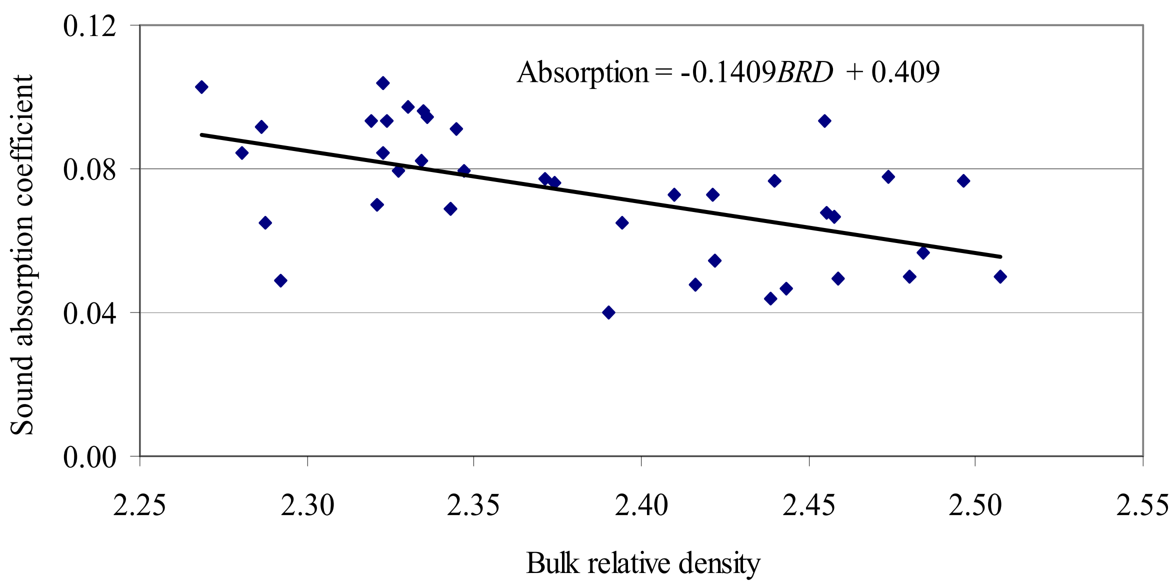

Figure 5-50 Variation of Sound Absorption with Variation in *BRD* of AC Mixes.

Figure 5-51 shows the variation of sound absorption of Superpave AC mixes with the variation of layer thickness. A negligible increase in sound absorption has been observed with an increase in AC layer thickness. The correlation (r = 0.09) between the sound absorption and AC pavement layer thickness was not shown to be statistically significant at the 5% level of significance. This indicates that the variation of sound absorption with the variation in layer thickness of dense AC mixes is of minimal importance. The variation of air voids of dense AC mixes tested in this study was also not shown to produce any statistically significant effect for the variation of sound absorption.

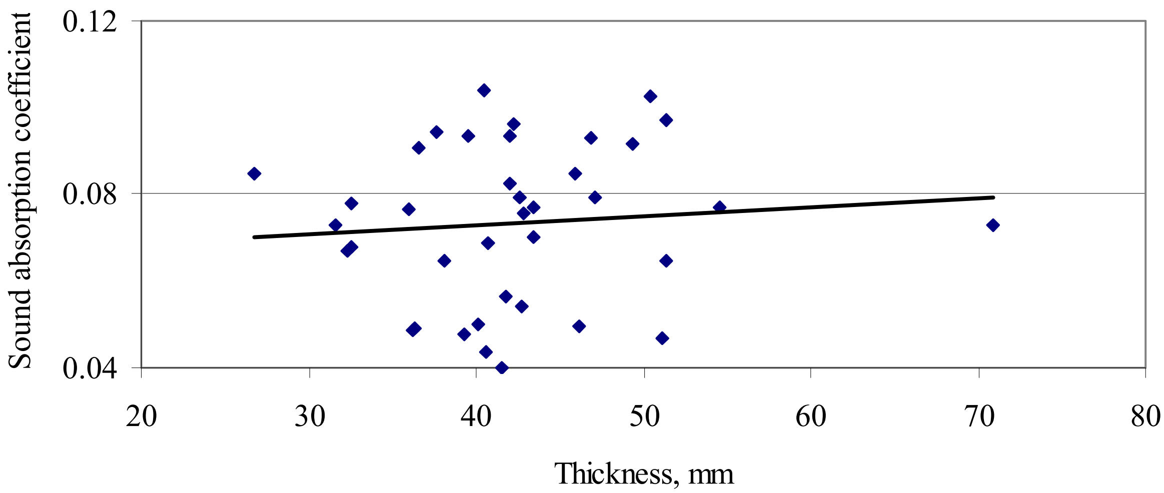

Figure 5-51 Variation of Sound Absorption with AC Layer Thickness.

Sound Absorption of Various PCC Pavement Surfaces

PCC slabs of varying thickness (260 mm, 200 mm, and 76 mm) have shown no noticeable difference in sound absorption with peak absorptions of 3% to 4%. Figure 5-52 shows the variation of sound absorption of PCC samples prepared in the laboratory with different surface texturizations. The textured PCC surfaces were able to absorb 5% to 6% of the sound. The surface texture type was shown to be insignificant for the variation of sound absorption. The slightly higher sound absorption of cylindrical samples as compared to that of the slab is probably associated with variation in compaction (density) of two sample types (vibrator was used for consolidation of slabs versus tamping rod for cylindrical samples).

It should be noted that sound generation and sound absorption are two different measures. Sound is generated due to the complex interaction of the tire and pavement surface that depends on the stiffness as well as tire tread and surface texture patterns. Alternatively, the absorption of generated sound depends on the interconnected voids in the pavement surface layer. For the same texture levels, a porous surface will absorb higher percentage of sound than a non-porous surface. In such cases, the porous surface is expected to produce lower tire-pavement interaction noise that is transmitted to a roadside or on-road receiver.

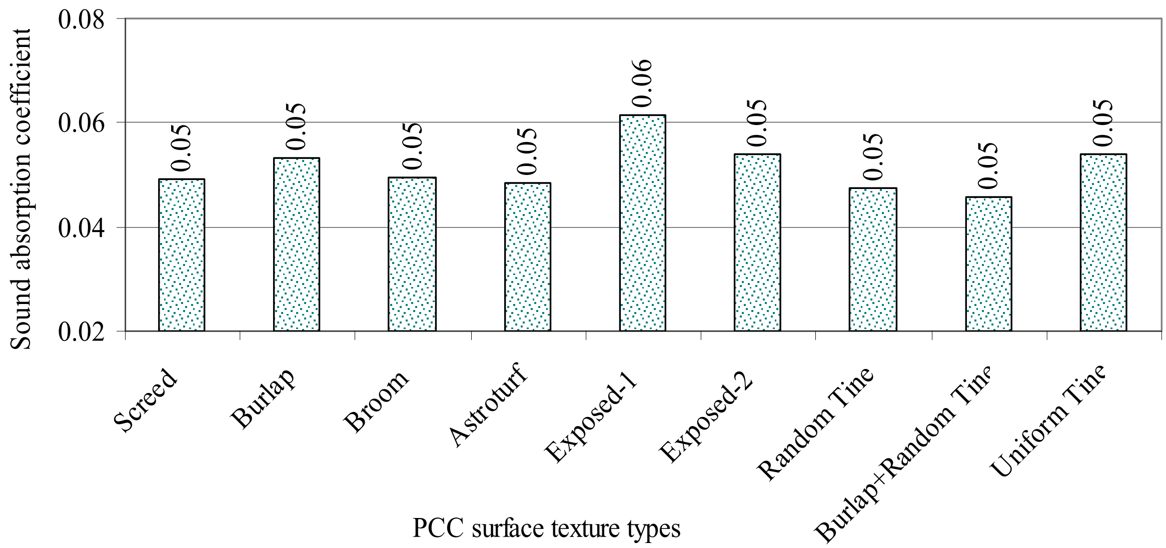

Figure 5-52 Sound Absorption of Different PCC Surfaces.

5.5 SURFACE TEXTURE, SKID RESISTANCE AND NOISE

5.5.1 Pavement Surface Texture and Noise Relationship

Figure 5-53 shows the variation of near-field (CPX) noise with a variation of texture for four AC pavement surfaces at the CPATT quiet pavement test site. As shown in the figure, CPX noise increase slightly with an increase in the *MTD* and the relationship is very weak. In a UK study, the variation in traffic noise with changes in skid resistance was also shown to be independent of the surface texture pattern or surfacing materials (Phillips and Kinsey 2000). However, in this study, the variations of pass-by and in-vehicle noise levels have shown stronger relationships, compared to the CPX noise, with the variation of *MTD*. The trends in Figures 5-54 and 5-55 show noticeable increase of pass-by and in-vehicle noise levels, respectively, with an increase in texture depth.

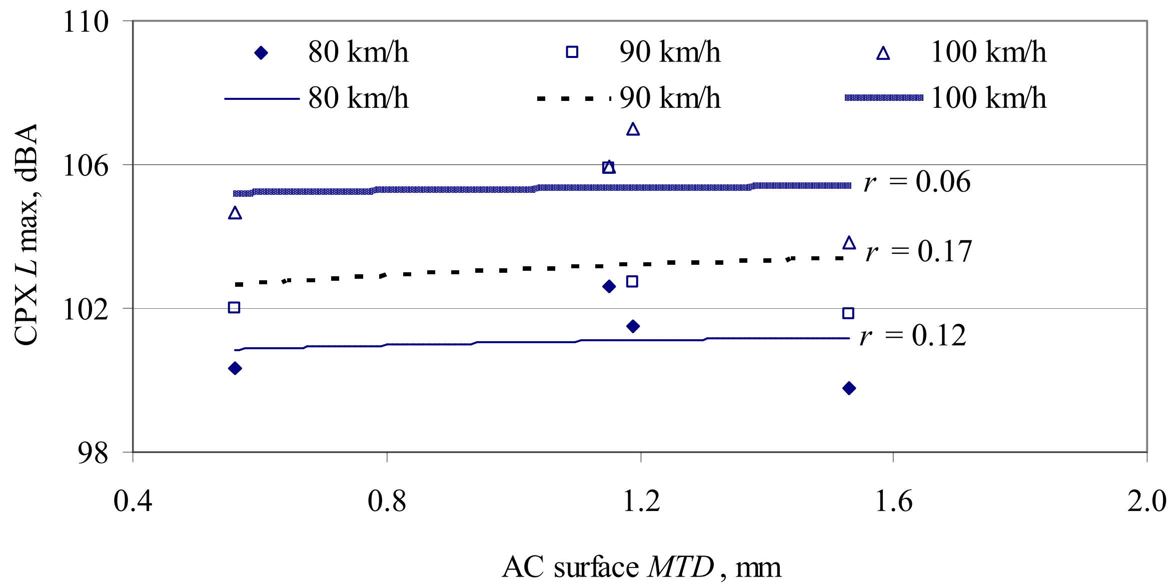

Figure 5-53 Variation of CPX Noise with Pavement Surface Texture.

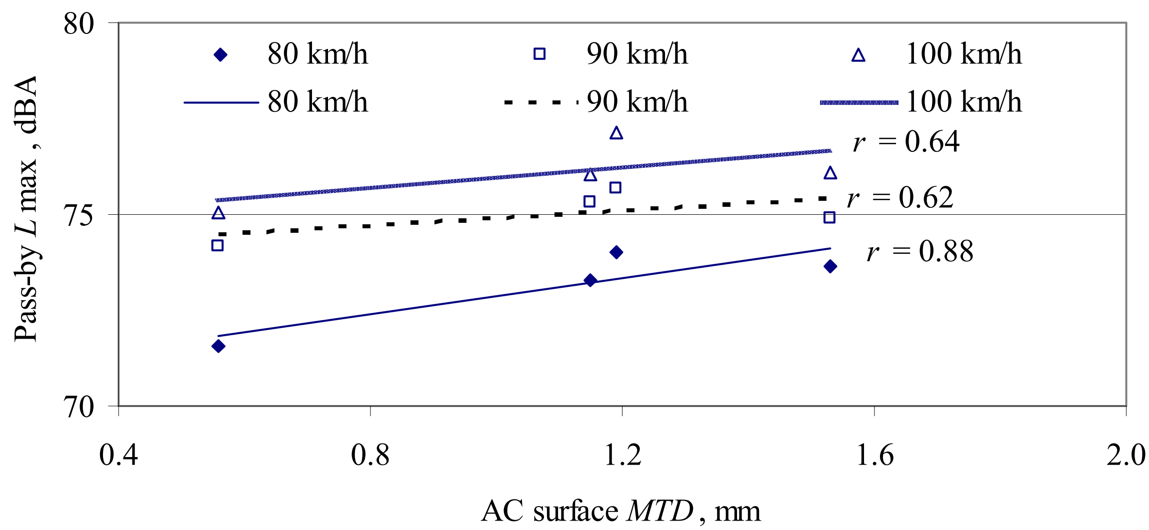

Figure 5-54 Variation of Pass-by Noise with Pavement Surface Texture.

5.5.2 Pavement Surface Friction and Noise

No direct correlation has been found in this study between the pavement surface friction and CPX noise. The correlations between the pass-by noise and surface friction (Figure 5-56), and between the in-vehicle noise and surface friction (Figure 5-57) are not strong although both pass-by and in-vehicle noise levels were shown to increase with an increase in pavement surface friction. However, in general, the trends show that safety and noise are negatively correlated i.e., increased safety (*SN*) is associated with an increased (undesirable) noise.

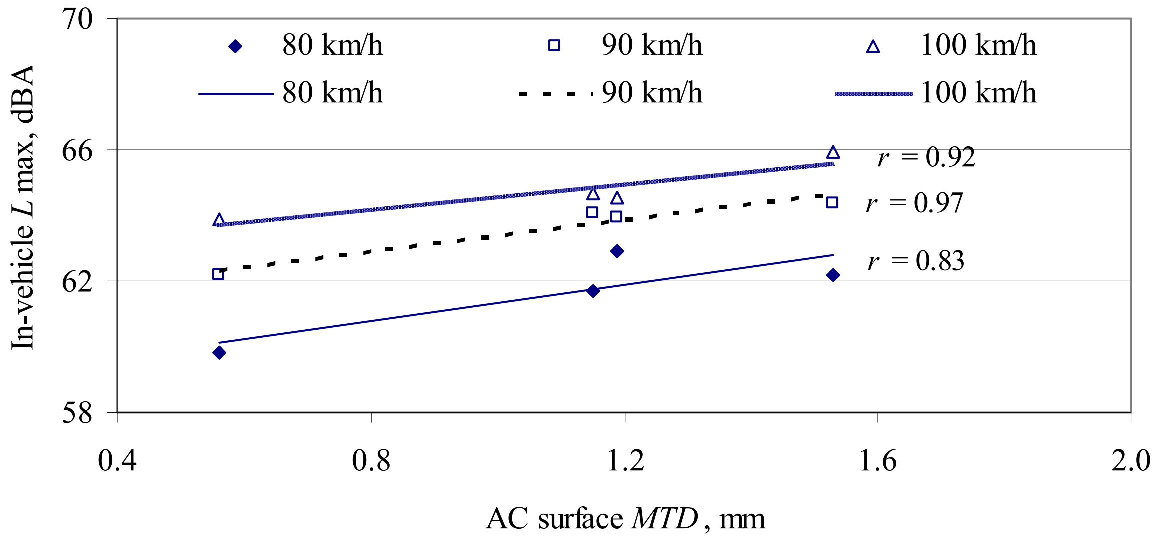

Figure 5-55 Variation of In-vehicle Noise with Pavement Surface Texture.

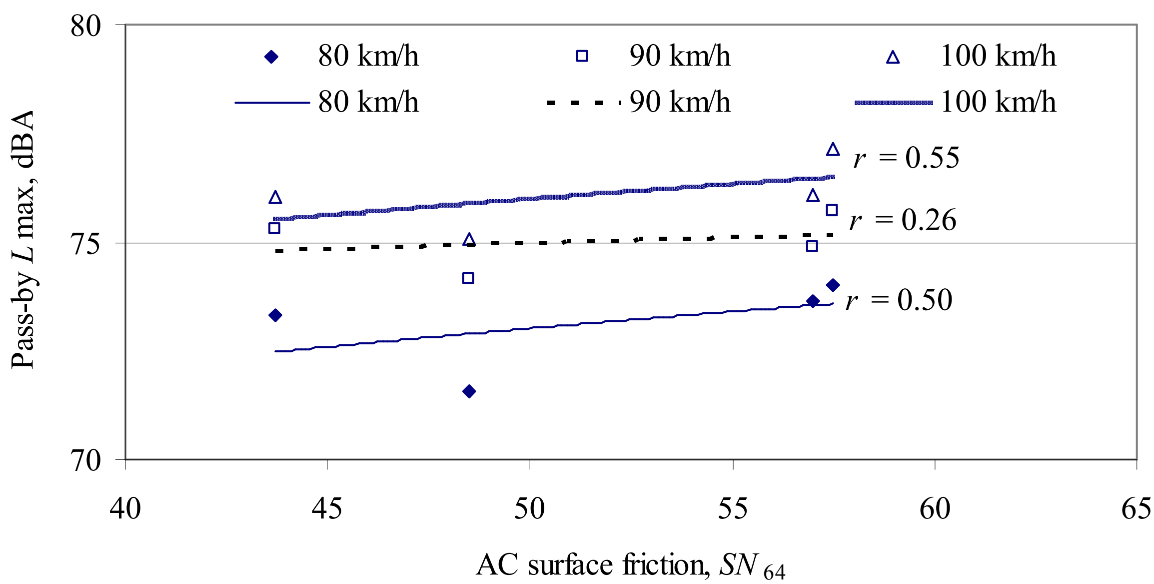

Figure 5-56 Variation of Pass-by Noise with Pavement Surface Friction.

Figures 5-58 through 5-60 show the comparison of skid numbers with near-field (CPX), pass-by and in-vehicle maximum noise (*L*max) levels, respectively, at 100 km/h for five test surfaces. The noise for Superpave (SP) represents the average levels of regular SP surfaces on provincial highways while the surface friction of SP represents the measured *SN* at the CPATT landfill site. When the CPX noise levels are compared, both ROFC and ROGC were shown to be louder than the SP, SMA, and HL3 surfaces. Between the HL3 and SMA, the SMA surface was shown to exhibit far better skid resistance with the lowest tire-pavement noise level. The SP surface was shown to provide the highest skid resistance with slightly greater noise than the SMA or HL3. Given the seasonal fluctuation of surface friction and long term wear/polishing of pavement surface, both SMA and SP seem to be better choices.

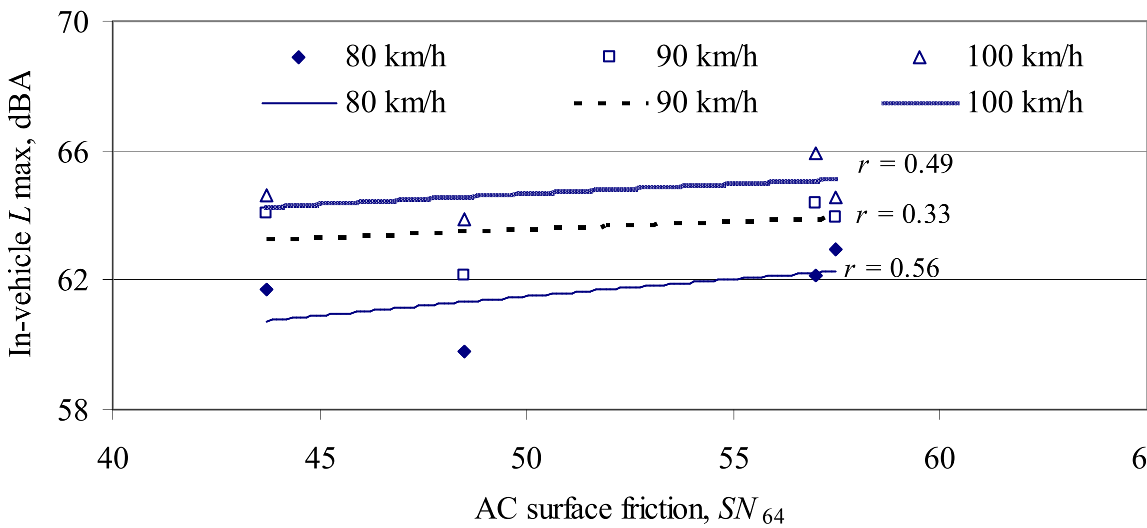

Figure 5-57 Variation of In-Vehicle Noise with Pavement Surface Friction.

When the pass-by noise levels are compared, both SMA and SP surfaces were still shown to be better choices considering the skid resistance and noise. For in-vehicle noise, the SP surface was shown to be quieter than the SMA and other surfaces, except HL3 that is no longer supported by the MTO. The SP, which was developed in Strategic Highway Research Program (SHRP) to better match different traffic and environmental conditions, and asphalt mixing process, has appeared to be a better choice in terms of skid resistance i.e., safety.

As the surface texture influences greatly the in-vehicle and pass-by noise levels, a low textured SMA surface (can be achieved using lower maximum size aggregate) is likely to reduce both the pass-by and in-vehicle noise levels and further reduce the CPX noise level.

For instance, a 12.5 mm and 9.5 mm SMA may reduce 1-3 dBA and 2-6 dBA, respectively, as compared to 19 mm (FHWA Team 2005) with adequate friction on high-speed facilities.

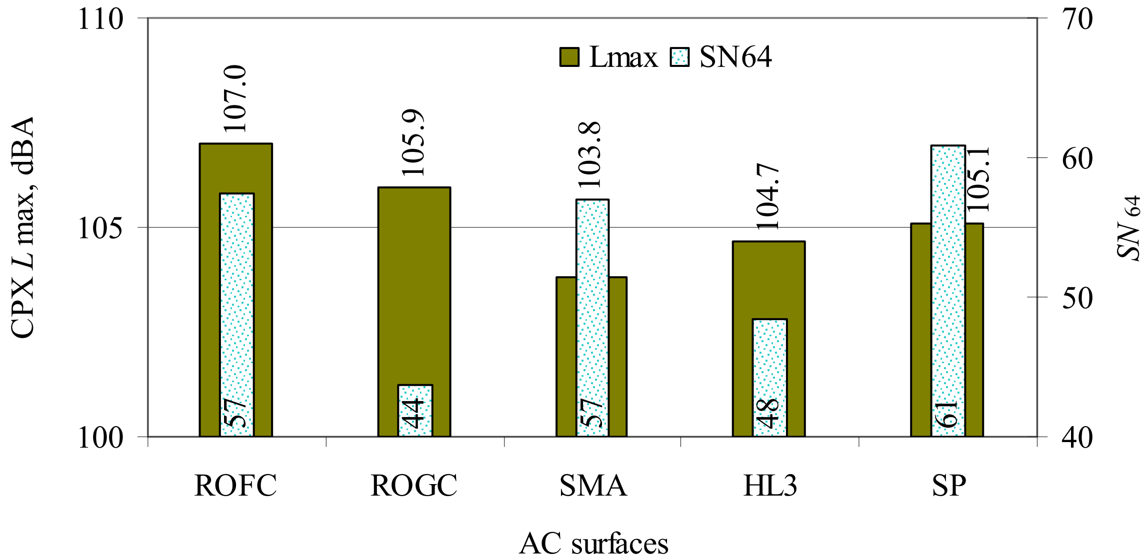

Figure 5-58 Comparison of Surface Friction and CPX Noise Levels.

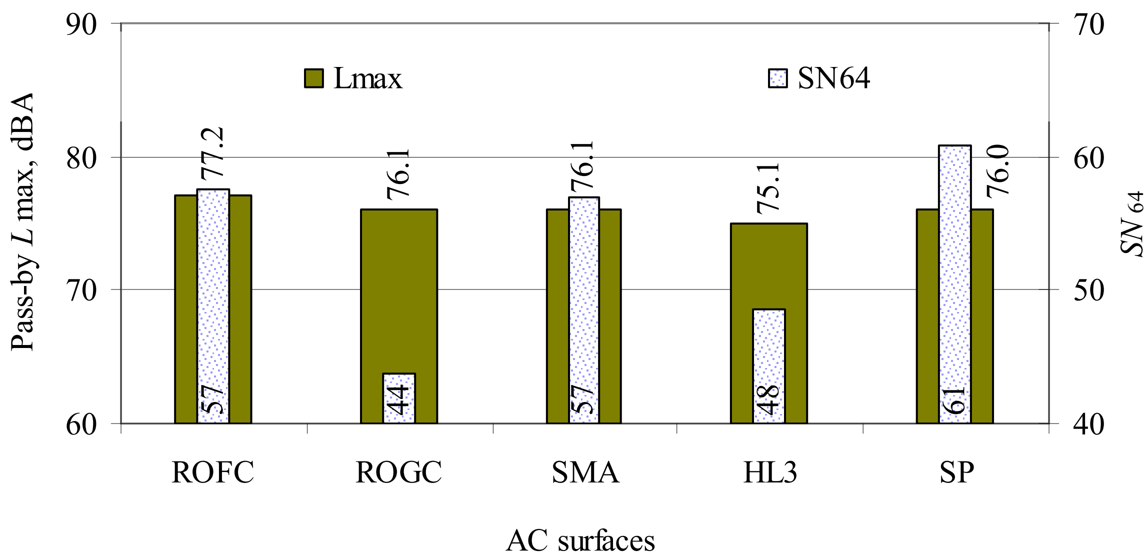

Figure 5-59 Comparison of Surface Friction and Pass-by Noise Levels.

It has been seen that SMA with deeper texture is quieter with respect to CPX noise while HL3 with the lowest texture is quieter with respect to pass-by and in-vehicle noise levels. All these further indicate that noise generation and propagation, for a given vehicle and tire condition, is not simply a function of a single attribute but rather a complex function of many variables of tire-pavement interaction and pavement surface as well as mix properties.

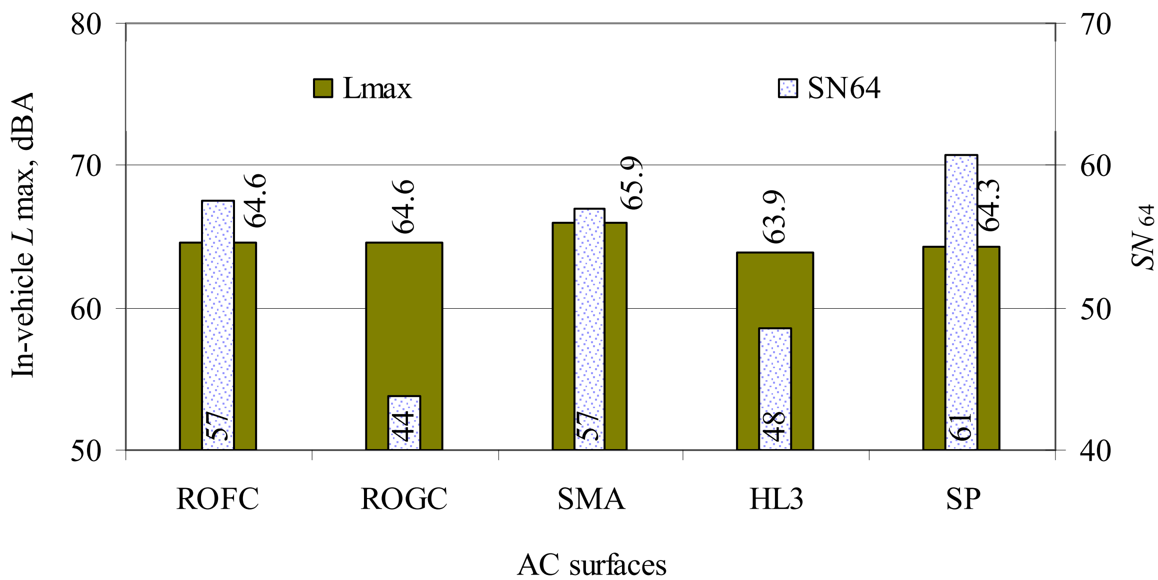

Figure 5-60 Comparison of Surface Friction and In-vehicle Noise Levels.

5.6 ANALYSIS AND RESULTS SUMMARY

The available surface texture or friction is highly dependent on the control of construction/ finishing practices, not just the specifications. Transversely textured PCC surfaces provide better skid resistance than the longitudinal textured surfaces. A high level of texture does not necessarily purport a high level of skid resistance. The quality of aggregates is of prime importance for high skid resistant surfaces.

The seasonal variation of both AC and PCC pavements surface friction seemed to be mainly dependent on prevailing ambient or surface temperature. Both AC and PCC surface friction increases for a short period following the construction and friction decreases thereafter due to traffic use. A very low textured surface does not necessarily produce a quiet surface. The SMA and Superpave mixes with premium aggregates (maximum 12.5 mm size) can produce low noise surfaces with good skid resistance. However, careful materials selection and placement are important to attain the noise reduction benefit without sacrificing the safety.

Chapter 6 Performance Models and Surface Characteristics into PMS

This chapter presents the multiple regression models for the estimation of both AC and PCC pavements surface texture and friction including the seasonal and long term variations. As no texture information was available for the provincial highways and noise variation did not show any trend with the variation of surface age, no multiple regression model for the tire-pavement noise has been feasible. The framework for optimization of surface texture through selection of minimum skid resistance and maximum acceptable noise, and the strategy for incorporating the surface characteristics into the PMS have also been suggested.

6.1 REGRESSION MODEL PROCEDURE

The statistical analysis software SPSS Statistics Version 15.0 (SPSS Inc. 2006) was used for all multiple regression analysis and developing the models. The available and relevant independent variables were entered in the models and statistically significant variables were selected through proper examination of the developed models. The predictor variables that were shown to be statistically significant at the 5% level of significance, make practical sense, and improve the model predictability, were selected for building the final models.

The best correlation of each independent variable (IV) with a dependent variable was selected using the curve estimation module in SPSS. The attempted trends include linear, quadratic, inverse, logarithm, exponential and power. The trend that has shown greater correlation coefficient (r) with the dependent variable in question and made logical sense was selected for the transformation of each IV, if not linear. In all modeling attempts, the normality was checked based on the distribution of standardized residual. Observation points with standardized residual absolute values exceeding 2.0 were filtered out as outliers based on guidance in statistical analysis text (Montgomery and Runger 2006). The filtering process was repeated until normality condition is met. The multicollinearity was checked based on the variance inflation factor (VIF) where a VIF value of less than 4 to 5 indicates no multicollinearity problem (Montgomery and Runger 2006).

6.2 MODEL FOR SURFACE TEXTURE AND FRICTION (PART I)

6.2.1 Skid Resistance Prediction Model for PCC Pavement Surfaces

Several attempts were taken to develop a regression model relating the texture and skid resistance using the SPSS software. In all cases, the quadratic relationship exhibited the best correlation considering the model predictability, statistical significance, and logical sense. In the first model, an attempt was made to correlate the *BPN* and *MTD* using data from individual specimens of all texture configurations. For texture direction, an indicator variable was entered in the model. The summary of the resulting model is presented in Table 6-1 and given by Equation 6-1. The developed model has shown a good coefficient of determination (R^2) of 0.87 with all the predictor variables and the model as a whole statistically significant at the 5% significance level (*p*-values of 0.000 for all independent variables including the intercept). Equation 6-1 shows that for a given *MTD*, PCC transverse texture will exhibit about 8 *BPN* (on an average) higher surface friction as compared to other textures.

$$BPN_S = 34.338 + 38.475MTD - 9.669MTD^2 + 8.290TD \qquad (6\text{-}1)$$

Where,

BPN_S = British Pendulum Number by specimen or test point

MTD = Mean Texture Depth in mm, and

TD = Texture Direction code (transverse texture = 1, other texture = 0).

A second model has been developed using the average *BPN* and *MTD* by texture configuration (sixteen surface textures) that has appeared to predict better with a R^2 of 0.91 than the model based on individual specimen. The summary of the new model is also presented in Table 6-1 and given by Equation 6-2. Equations 6-1 and 6-2 were shown to be identical with similar values of regression coefficients associated with the independent variables. However, better R^2 for Equation 6-2 emphasizes the importance of replicating the test for each physical attribute.

$$BPN_{Avg} = 34.057 + 39.507MTD_{Avg} - 10.171MTD_{Avg}^{\ 2} + 7.609TD \qquad (6\text{-}2)$$

Where,

BPN_{Avg} = Average British Pendulum Number for each texture configuration

MTD_{Avg} = Average *MTD* (mm) for each texture configuration, and

TD = Texture Direction code as indicated earlier.

Table 6-1 Skid Resistance Models for PCC Surfaces

Model	IVs	*N*	*b*	Std. Error	*t-value*	*p*-value	R^2
Equation 6-1 (BPN_S)	(Constant)		34.338	3.827	8.973	0.000	0.868
	MTD, mm	42	38.475	6.389	6.022	0.000	
	MTD^2	42	-9.669	2.347	-4.120	0.000	
	TD	42	8.290	1.184	7.001	0.000	
Equation 6-2 (BPN_{Avg})	(Constant)		34.0566	9.170	5.503	0.000	0.906
	MTD, mm	16	39.507	6.188	3.722	0.003	
	MTD^2	16	-10.171	10.614	-2.536	0.026	
	TD	16	7.609	4.010	4.600	0.001	
Equation 6-3 (BPN_{Avg})	(Constant)		34.752	5.732	6.063	0.000	0.958
	MTD, mm	14	37.829	10.564	3.581	0.005	
	MTD^2	14	-8.993	4.277	-2.103	0.062	
	TD	14	6.697	1.215	5.510	0.000	

As the exposed aggregate texture was shown to behave differently from other surfaces because of the loss of the sand microtexture with washed mortar, another attempt was made to develop a skid resistance prediction model excluding the two exposed aggregate surfaces. The resulting model is also summarized in Table 6-1 and given by Equation 6-3. All the regression coefficients were shown to be statistically significant at the 5% level of significance with very good R^2 values of 0.96, except the square term, which is statistically significant at the 6% level of significance. Equation 6-3 shows that for a given *MTD*, transversely textured surfaces will exhibit about 7 *BPN* (on an average) higher skid resistance as compared to the longitudinal textured surfaces.

$$BPN_{Avg} = 34.752 + 37.829 MTD_{Avg} - 8.993 MTD_{Avg}^{2} + 6.697 TD \quad (6\text{-}3)$$

Where,

BPN_{Avg} = Average British Pendulum Number for each texture configuration (except exposed aggregate surface).

MTD_{Avg} = Average *MTD* (mm) for each texture configuration, and

TD = Texture Direction code as indicated earlier.

6.2.2 AC Pavement Texture and Skid Resistance Prediction Models

Modeling attempts in SPSS for macrotexture of asphalt pavement surfaces has shown that the *C.A./F.A.* ratio and *VMA* (%) are statistically significant at the 5% level of significance. However, the correlation of *MTD* with *VMA* (%) was shown to be counterintuitive indicating that the *MTD* decreases with an increase in VMA (%). Therefore, a model for *MTD* has been developed correlating the *C.A./F.A.* ratio as given by Equation 6-4 and presented in Table 6-2. The model was shown to be statistically significant at the 5% significance level with good R^2 value of 0.84. The developed model indicates that an AC mix with 100% sand (i.e., fine aggregate) will produce a *MTD* of 0.50 mm (on average) while a mix with 80% coarse aggregate (16 mm maximum size) is expected to produce a *MTD* of 1.69 mm, on average.

$$MTD = 0.501 + 0.296(C.A./F.A.) \quad (6\text{-}4)$$

Where,

MTD = Mean Texture Depth in mm, and

C.A./F.A. = Coarse to fine aggregates ratio in the asphalt mix (by weight).

As the *MTD* and *C.A./F.A.* are highly correlated, both of them were not included as independent variables in a single model for the prediction of skid resistance. However, to accommodate the variation in aggregate quality (crushing), a binary code was incorporated to distinguish between the premium and normal aggregates. Another binary code was included to capture the difference between rubber/polymer modified mixes and conventional mixes with no rubber or polymer. The models for the skid resistance estimation have then been developed as given by Equations 6-5 and 6-6, and summarized in Table 6-2.

$$SN_V = 60.703 + 12.959(PREMIUM) - 0.233V \tag{6-5}$$

$$SN_V = 57.032 + 11.435MTD - 0.258V \tag{6-6}$$

Where,

SN_V = Skid Number at speed V

V = Vehicle speed, km/h

MTD = Mean Texture Depth in mm, and

$PREMIUM$ = Code for aggregate crushing (1 for 100% crushed aggregates, 0 for normal aggregates).

Table 6-2 Texture and Skid Resistance Prediction Models for AC Surfaces

Model	IVs	*N*	*b*	Std. Error	*t-value*	*p*-value	R^2
Equation 6-4 (*MTD*)	(Constant)		0.501	0.059	8.519	0.000	0.843
	C.A./F.A.	26	0.296	0.026	11.340	0.000	
Equation 6-5 (SN_v)	(Constant)		60.703	1.696	35.789	0.000	0.976
	PREMIUM	22	12.959	0.533	24.315	0.000	
	V (km/h)	22	-0.233	0.021	-11.05	0.000	
Equation 6-6 (SN_v)	(Constant)		57.032	6.638	8.592	0.000	0.558
	MTD (mm)	26	11.435	2.741	4.171	0.000	
	V (km/h)	26	-0.258	0.075	-3.426	0.002	

As shown in Table 6-2, all the parameters are statistically significant at the 5% level of significance. The model for *SN* incorporating aggregate quality (premium versus normal) and speed has shown a very good R^2 of 0.98. However, the model for *SN* as related to *MTD* and speed has shown a fair R^2 value of 0.56. The code for rubber or polymer in the mix was not shown to be statistically significant indicating that presence of rubber in AC mix has no significant effect on skid resistance. Models 6-5 and 6-6 indicate that skid resistance will decrease at an average 0.25 *SN* for each 1 km/h increase in vehicle speed. Model 6-5 indicates that AC mixes with premium aggregates will exhibit a higher surface friction of 13

SN as compared to the mix containing gravel. Alternatively, Model 6-6 indicates that skid resistance will increase by 11 *SN* (on average) for 1 mm increase in *MTD*. The developed models and preceding analysis indicate that quality of aggregates is most important in achieving good friction.

6.3 MODEL FOR SEASONAL VARIATION OF SURFACE FRICTION (PART II)

The effect of temperature during the skid testing and other variables on seasonal skid resistance variation has been presented in last chapter. Attempts were made to correlate seasonal surface friction variation with the *MTD*, mean 1-day, 3-day, 5-day and 7-day low as well high temperatures and total rainfall, and the number of dry days (dry spell) preceding the testing day. None of these variables was shown to be statistically significant at the 5% significance level. The only statistically significant variable was shown to be the temperature during the testing (i.e., driving). The prior environmental conditions were not shown as adequately capturing the variation of surface friction from month to month. All these observations indicated that the seasonal variation of surface friction may not be predicted in advance unless the temperature of that particular time and date are known. Therefore, no multivariate model has been developed for the prediction of seasonal skid resistance variation.

It should be noted that short term variation due to oil spillage, debris/dust on surface and washing out of contaminants could be significant factors for skid resistance variation depending on the extent of contamination. According to Kokkalis et al. (2002), reduction in surface friction due to surface contamination by dust, soil and debris, oil spillage, tire remnants, etc. varies with traffic, environment, season, and rainfall. The wet contaminants work as lubricant while the dry contaminants act as rollers reducing the available skid resistance on both wet and dry surfaces.

6.4 MODEL FOR LONG TERM SURFACE FRICTION (PART III)

The dependent variable (DV) for these models is the average *SN*. The predictor (independent) variables included in the modeling attempts for both PCC and AC pavements are: surface age, cumulative vehicle passes, percentage of trucks, vehicle speed, ambient temperature during the testing, annual average temperature, annual average wet days, and codes for climatic regions (dry versus wet and freeze versus no freeze). For AC pavements, additional predictor variables included are: maximum aggregate size, coarse aggregate percentage, air voids (%) and VMA (%) in asphalt mixes, and Marshall Stability and flow of the compacted mixes. For PCC pavements, additional variables include: concrete compressive strength and a texture rank code that accounts for the difference in surface texture type.

6.4.1 PCC Pavements Long Term Frictional Performance Models

The outputs of the modeling attempts for rigid pavements long term surface friction have shown that annual average temperature, annual average wet days and different climatic regions that distinguish between dry (dry freeze and dry no freeze) and wet (wet freeze and wet no freeze) weathers as well as between freeze (dry freeze and wet freeze) and no freeze (dry no freeze and wet no freeze) are statistically insignificant and/or meaningless. This indicates that the PCC pavement long term surface friction is less sensitive to prior environmental conditions.

Although cumulative passes of trucks and passenger cars were shown to be statistically significant in bi-variate analysis (Chapter 5), the number of truck passes was not shown to be statistically significant in the multiple regression models. The percentage of trucks was shown to be statistically insignificant at the 5% significance level but the cumulative traffic passes (all type of vehicles combined) as shown to be statistically significant. This is probably due to limited variability in truck count and redistribution of regression parameters in the multiple regression models. Concrete compressive strength was also shown to be statistically insignificant. Pavement age and cumulative traffic passes were shown to be statistically significant in two separate models. Two models have therefore been developed as summarized in Table 6-3 and given by Equations 6-7 and 6-8.

$$SN_S = 21.767 - 0.717Y + 40.345R - 0.198S \quad (6\text{-}7)$$

$$SN_S = 35.840 - 0.240V + 35.486R - 0.308S - 0.131T \quad (6\text{-}8)$$

Where,

SN_s = SN at speed S

S = Vehicle speed in km/h

Y = Pavement age in years after an early age increase in surface friction (age since construction minus 2½ years)

V = Cumulative traffic passes in million after an early age increase in surface friction (total traffic since construction minus traffic passes in 2½ years)

T = Temperature during the skid testing (driving) in °C, and

R = Rank for different texture configurations.

Table 6-3 Summaries of PCC Pavements Long Term Friction Performance Models

Parameters	*N*	Coefficients	*t*-value	*p*-value	*VIF*	R^2
Rigid Pavement Long Term Skid Resistance Model 6-7						
Intercept	153	21.767	3.69	0.000		0.592
Age, year	153	-0.717	-10.80	0.000	1.07	
Relative Rank	153	40.345	7.02	0.000	1.04	
Speed, km/h	153	-0.198	-6.28	0.000	1.08	
Rigid Pavement Long Term Skid Resistance Model 6-8						
Intercept	127	35.840	6.70	0.000		0.701
Cum. Traffic, million	127	-0.240	-9.61	0.000	1.02	
Relative Rank	127	35.486	6.84	0.000	1.03	
Speed, km/h	127	-0.308	-11.30	0.000	1.03	
Test Temperature, °C	127	-0.131	-4.89	0.000	1.01	

Note: N = Number of data points, VIF = Variance Inflation Factor.

The Rank (R) is an indicator variable that captures the variability in PCC texture configuration in terms of available skid resistance of each texture type relative to the average friction number exhibited by all surface textures in the network. The surface texture that had exhibited above average skid resistance based on the network has a rank above 1.0 and vice versa. The ranks for various surface textures are: astroturf drag = 0.87, burlap drag = 0.92, broom drag = 0.93, diamond ground = 0.96, astroturf drag & tining = 0.98, grooved float = 0.99, tining = 1.04 and burlap drag & transverse groove = 1.08.

As shown in Table 6-3, all the predictor variables are statistically significant at the 5% significance level (*p*-values are less than 0.05) for both models. The coefficient of determination (R^2 value) is 0.59 for Model 6-7 and 0.70 for Model 6-8. The low R^2 values do not indicate any problem if each regression coefficient is statistically significant at a pre-selected significance level, make logical sense, and regression diagnostic does not show any problem. Regression diagnostic has shown that *VIF*s range from 1.01 to 1.08, which are lower than the acceptable maximum value of 4 to 5. The errors were shown to be normally distributed about the mean (Figure 6-1) and the scatter plot of errors has shown no particular pattern (Figure 6-2) further proving the adequacy of the developed models.

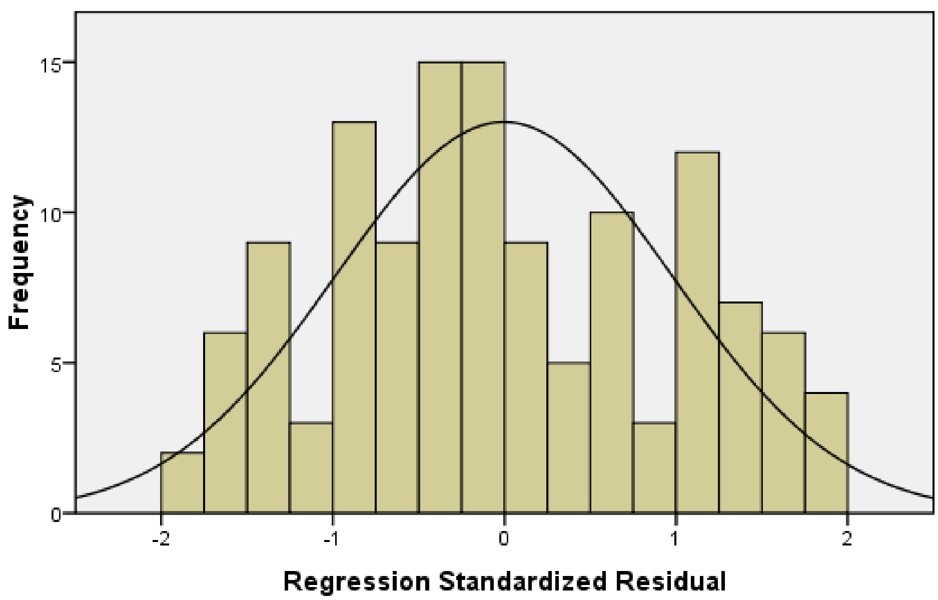

Figure 6-1 Histogram (Normal) Distribution of Error (Residual).

The regression coefficients associated with age and traffic indicate that PCC surface friction reduces at 0.7 *SN* per year or 0.24 *SN* per million vehicle movements. Surface friction increases with improved texture rank and decreases with an increase in speed as well temperature during the testing (driving). All these variations make practical sense. The developed models therefore can be used to predict the PCC pavements surface friction after about 2½ years of construction. For example, if surface friction after 10 years has to be predicted, the *Y* variable in Equation 6-7 would be 7½ years. For pavement management, it is recommended to apply both models and use the lowest friction value obtained from these two models for preventive action.

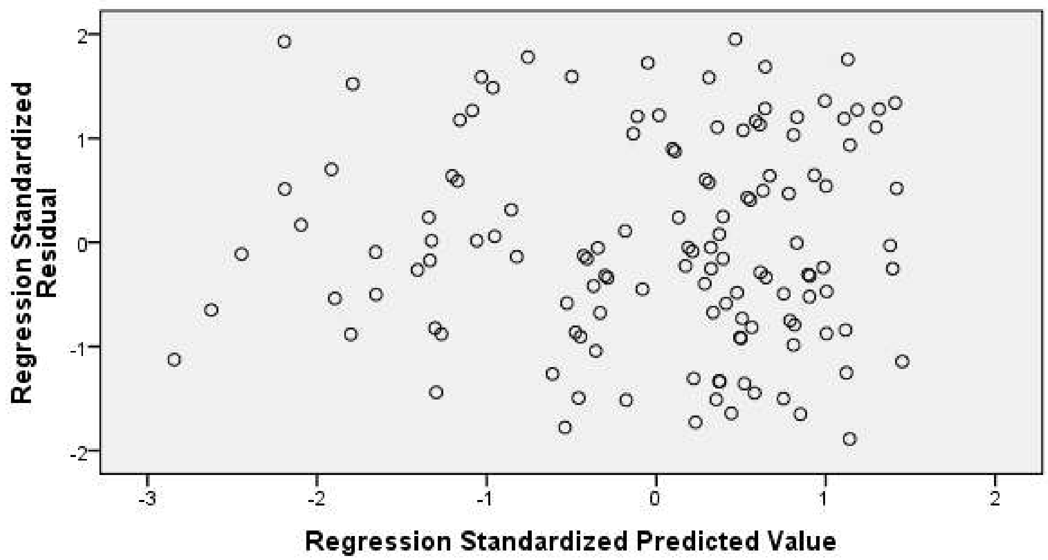

Figure 6-2 Scatter Plot of Errors.

6.4.2 AC Pavements Long Term Frictional Performance Models

In AC pavements long term surface friction models, the annual average temperature and annual average wet days were shown to be statistically insignificant resembling the PCC pavements. However, the codes defining different climatic regions were shown to be statistically significant. The correlations of surface friction with asphalt mix properties such as stability, flow, air voids, and VMA were shown to be insignificant, counterintuitive, or impractical with a very high correlation coefficient making all other IVs insignificant. The close study (Chapter 5- Part I) based on data from the CPATT test track has also shown that neither air voids or VMA have statistically significant or meaningful correlation with the *SN* for the available data. The possible reason is that both air voids and VMA are internal properties of the AC mix while the skid resistance is an external property of the pavement surface. However, more study is recommended to confirm this observation.

In all modeling trials, the coarse aggregate percentage, and maximum aggregate size were also shown to be statistically insignificant for long term surface friction variation. Pavement age and cumulative traffic passes were shown to be statistically significant in two separate models resembling the PCC pavement surfaces, and two performance models therefore have been developed. The summaries of these two models are presented in Table 6-4 and given by Equations 6-9 and 6-10.

$$SN_S = 63.079 - 1.208Y + 5.321DW + 2.697FNF - 0.179S - 0.242T \quad (6\text{-}9)$$

$$SN_S = 59.644 - 0.265V + 5.901DW + 3.691FNF - 0.133S - 0.293T \quad (6\text{-}10)$$

Where,

SN_s = Skid Number at speed S

S = Vehicle speed in km/h

Y = Pavement age in years after an early age increase in surface friction

V = Cumulative traffic passes in million after an early age increase in surface friction

T = Temperature in °C during skid testing

DW = Dry versus Wet weather code (dry weather = 1 and wet weather = 0), and

FNF = Freeze versus No Freeze weather code (no freeze = 1 and freeze = 0).

As shown in Table 6-4, the coefficient of determinations (R^2 values) for Models 6-9 and 6-10 are 0.48 and 0.41, respectively. However, all the predictor variables for both models were shown to be statistically significant at the 5% significance level (p-values are less than 0.05). Equations 6-9 and 6-10 also show that the coefficients associated with the IVs are logical. Regression diagnostic has also shown that errors are normally distributed about the mean while the scatter plot of errors has shown that errors are randomly distributed about a line with mean equal to zero with no particular trend (slope). The VIFs range from 1.03 to 1.16 indicating no multicollinearity problem. The significance of *DW* and *FNF* indicate that AC pavements surface performance is more affected by the environmental condition as compared to the PCC surfaces. More susceptibility of the asphaltic concrete to environmental changes probably explains such variation.

The developed models show that AC pavements surface friction reduces at 1.2 *SN* per year or 0.27 *SN* per million vehicle passes, which is relatively higher than the rates observed for PCC pavements. AC pavements will exhibit 5 to 6 *SN* greater surface friction if the weather is predominantly dry (dry no freeze and dry freeze) as compared to the wet weather (wet freeze and wet no freeze). If the weather is predominantly freezing (dry freeze and wet freeze), the AC pavements will exhibit 3 to 4 lower *SN* as compared to no freeze weather (dry no freeze and wet no freeze).

Table 6-4 Summaries of AC Pavements Long Term Friction Performance Models

Parameters	*N*	Coefficients	*t*-value	*p*-value	*VIF*	R^2
Flexible Pavement Long Term Skid Resistance Model 6-9						
Intercept	468	63.079	29.394	0.000		0.484
Age, year	468	-1.208	-10.00	0.000	1.03	
Dry-Wet Code (*DW*)	468	5.321	10.17	0.000	1.04	
Freeze Code (*FNF*)	468	2.697	5.34	0.000	1.13	
Speed, km/h	468	-0.179	-5.72	0.000	1.14	
Test Temperature, °C	468	-0.242	-8.74	0.000	1.08	
Flexible Pavement Long Term Skid Resistance Model 6-10						
Intercept	467	59.644	26.20	0.000		0.412
Cum. Traffic, million	467	-0.265	-3.57	0.000	1.04	
Dry-Wet Code (*DW*)	467	5.901	10.78	0.000	1.03	
Freeze Code (*FNF*)	467	3.691	6.96	0.000	1.12	
Speed, km/h	467	-0.133	-4.03	0.000	1.16	
Test Temperature, °C	467	-0.293	-10.16	0.00	1.09	

Note: N = Number of observation points, VIF = Variance Inflation Factor.

6.5 INCORPORATING THE SURFACE CHARACTERISTICS INTO THE PMS

The published literature and analysis in this research have indicated that an increased texture is desired for increased and durable surface friction, and thereby safety and economy. Increased texture, however, has shown to affect the driver/residents comfort and economy in terms of increased noise, vehicle vibration, fuel consumption, and tire and vehicle wear. In

NCHRP synthesis 291, Henry (2000) reported the result of a survey among highway agencies around the world that rated various design criteria of pavement based on relative importance. The rating was done in a scale of 1 to 3 where 1 represents "very important" and 3 represents "relatively unimportant". The summary of the average ratings from the US and other countries is presented in Table 6-5. As shown in the table, pavement durability and safety are the most important factors in selecting a pavement type.

Table 6-5 Average Ratings of Various Surface Design Criteria (Henry 2000)

Design Criteria	Average Ratings of Each Design Criteria	
	US	Other Countries
Durability	1.1	1.3
Skid Resistance (Safety)	1.2	1.4
Splash and Spray	2.0	1.8
Exterior Noise	2.4	2.2
Interior Noise (In-Vehicle)	2.4	2.4
Smoothness (Rolling Resistance)	2.7	2.7
Tire Wear	2.7	2.9

According to Snyder (2006), several other factors also need to be considered when selecting the pavement surfaces in the course of planning, design, construction, and maintenance of pavements. These include:

i) Traffic volume and mix: Affects noise
ii) Highway speed: Affects available friction (safety) and noise
iii) Pavement cross-slope: Affects surface drainage (hydroplaning)
iv) Porosity: Affects splash and spray
v) Vertical and Horizontal Curves: Affects friction requirement and safety
vi) Local Climates (rainfall, snow/ice): Affects wet weather safety, maintenance and de-icing effects

vii) Location (residential areas, hospitals, schools, etc.): Presence and absence of noise sensitive receptors

viii) Availability of materials for specific surface types, and

ix) Ambient temperature: May affect selection of specific surfaces (e.g. porous rubberized asphalt).

The cost-effectiveness is a major controlling factor in the pavement selection process. It was not included in aforementioned survey (Henry 2000) or list of factors (Snyder 2006). The pavement (highway) location may also affect the skid resistance requirement because of variation of available stopping distance (due to traffic density and intersection), slow-stop-go operations, and turning activities.

The selection of a suitable pavement is therefore a complex task as several aspects need be considered for optimizing the functional as well as structural performance and cost. The challenge is to balance noise with other more important requirements such as safety, as related to surface friction, pavement durability, structural capacity, noise mitigation and safety over time, ride quality, and economy (Snyder 2006). It is therefore time to develop a specification or guideline for the desired minimum surface texture or friction and the acceptable maximum noise level for the pavements to be newly constructed or rehabilitated. Selected pavement design must also incorporate the long term pavement performance. A PMS can incorporate all these factors for the selection of pavement surfaces during the initial construction and rehabilitation operation.

6.5.1 Minimum and Maximum Surface Texture

As mentioned earlier in Chapters 1 and 2, no specific guideline is available in North American jurisdiction with respect to the desired minimum or maximum texture levels. Some countries outside North America, however, specify the minimum surface texture as mentioned in Section 2-1. For example, the UK looks for a sensor based minimum *MTD* of 0.7 mm (Phillips and Kinsey 2000). French specifications also provided a minimum texture requirement for different highway speeds (Dupont and Bauduin 2005). Larson et al. (2008) have recommended a minimum macrotexture for Ohio, which is the same as the French specification for intervention at network level but a 1.0 mm as an investigatory (desirable) value for network as well as project levels.

The Ministry of Transportation Ontario (MTO) specifies various asphalt surface courses based on traffic levels as shown in Table 6-6. According to this directive, DFC may be replaced with Open Friction Course (OFC) for urban residential areas, if no noise barrier is used (MTO 2002). In fact, the minimum surface texture may not be as important as the safety related to the skid resistance. It has been found in this research that a good quality aggregate can ensure good skid resistance with low texture for wet pavement safety as compared to poor quality aggregates. A high texture beyond a certain level also does not mean a high skid resistance. A moderate texture with good quality aggregates is expected to provide good skid resistance and minimize the tire-pavement noise as well.

Table 6-6 Selection of Bituminous Surface Course Types (MTO 2002)

ESALS/design lane/year (or AADT/lane)				
AADT<500	AADT 500 – 2500	AADT 2500-5000	1< ESAL <3 Million or AADT >5000	ESAL>3 Million
HL 4 or Surface Treatment	HL 4 or Superpave 12.5	HL 1 or Superpave 12.5FC1	DFC or Superpave 12.5FC2	SMA

Although texture contributes to surface drainage, appropriate pavement cross slope and adequate drainage facilities can minimize water accumulation on the pavement surface. This will prevent hydroplaning as in the case of the longitudinal tine texture on PCC pavements. The safety related to splash and spray, however, may need to be considered when selecting the surface. A good drainage facility can also minimize the splash and spray.

6.5.2 Minimum Skid Resistance for Safety

Murad and Abaza (2006) mentioned that if the expected or actual wet-weather accident rate on a road segment is higher than a critical specified level, this highway section is considered at risk and need attention for possible action. The wet pavement safety is a complex function of vehicle and driver performance/behaviour and surface condition. Surface friction is a predominant factor for wet pavement safety. According to Larson et al. (2008), the probability of crashes could be reduced by managing pavement skid resistance and texture depth at the appropriate level. However, no transportation agencies in Canada or the US have set standards for minimum surface friction. This is probably because of litigation risk that may arise from skidding accidents. Setting an absolute minimum requirement is also not a simple task because of vast network of existing pavements. Furthermore, the adequacy of the existing pavements with respect to safety may be questioned. Tentative guidelines therefore have been developed by some agencies in North America. A tentative guideline, as shown in Table 2-2 in Chapter 2, had been used by the MTO to assess the surface friction level. The skid resistance guideline (Figure 6-3) in Australia specifies the criteria for bad to very good surface friction levels. The desired friction level under each criterion is also indicated for different speeds of the roadway.

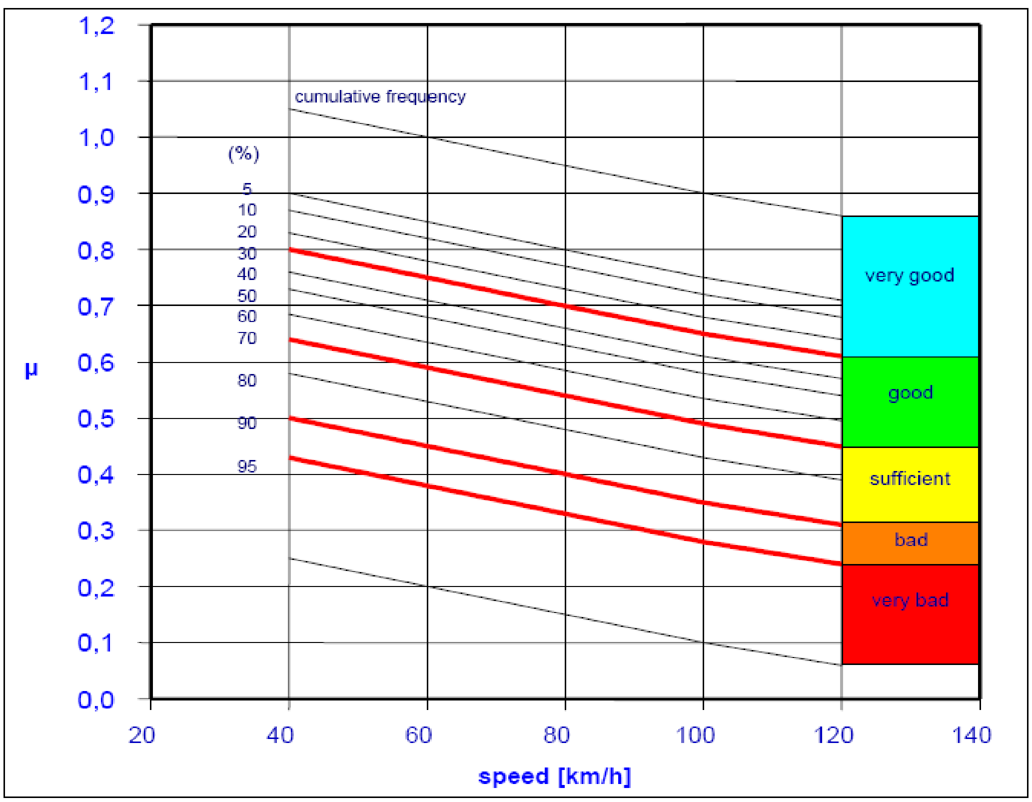

Figure 6-3 Australian Skid Resistance Evaluation Method (Maurer 2004).

Rogers et al. (2008) have recommended a ribbed tire minimum *SN* of 32 and 42 for Ohio as the intervention and investigatory levels, respectively, for road network evaluation. For the project level, the investigatory *SN* are 38 and 40 for congested freeways and intersections (signalized and unsignalized), respectively. All these criteria are subjected to a minimum wet/total accident ratio and 2 to 3-year annual average number of crashes.

Some agencies outside North America provide standards for minimum surface friction. For example, the UK provides a comprehensive standard for the desired minimum friction levels (investigatory levels) for different road classes (motorway, dual carriageway, and single carriageway), geometric condition (curve, roundabout, etc.), road gradient, and approaches (to intersection and roundabout). The investigatory level of the SCRIM friction coefficient starts from a minimum of 0.35 at 50 km/h for motorway to 0.60 at 20 km/h for sharp bend with radius ≤ 100 m (speed limit > 40 km/h) during the summer. Implementation of this standard has resulted in significant benefits in terms of accident reduction (Gargett 1990, Rogers 1991).

The Swedish specification calls for a wet surface friction of 0.5 measured using Skiddometer BV-11 or Saab Friction Tester (SFT). Finland specified acceptable surface friction values as a function of speed, measured according to Finnish standards for testing. The desired surface friction is 0.4 minimum for speeds up to 80 km/h, 0.5 for speeds up to 100 km/h, and 0.6 or more for speeds up to 120 km/h (Noyce et al. 2005).

None of the above recommendations accounts for the seasonal fluctuation and long term performance in the pavement design stage. Figure 6-4 shows a suggested general framework for selecting the desired minimum skid resistance for a new surface course or texture and selecting treatment/ rehabilitation of an existing surface. The terminal *SN* (at the end pavement service life) should be set based on road/section location and class (speed and traffic mix), cumulative traffic passes, surface polish/wear resistance, local condition of drainage and weather (rain, snow/ice and temperature variations), wet to dry accident ratio, and level of maintenance activities (drainage, snow removal and de-icing).

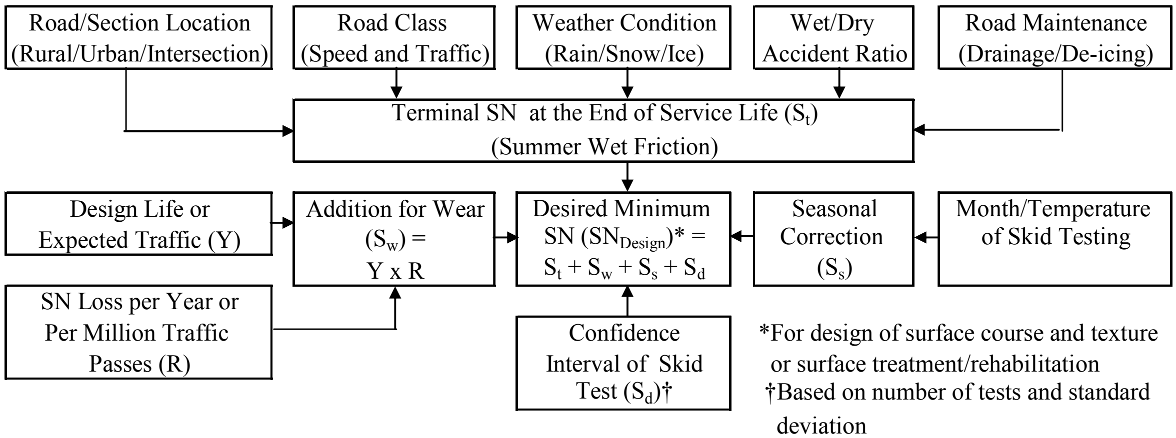

Figure 6-4 General Framework for Selection of Design *SN* or Rehabilitation Decision.

6.5.3 Acceptable Maximum Noise Level

As mentioned in Section 2.5.2, different agencies have provided criteria for noise abatement to reduce exposure at neighbourhoods given that the proposed measures are technically and economically feasible. However, no agencies in the US and Canada specify the acceptable noise level for the selection of pavement type or texture. A new technical advisory from the FHWA has recommended that tire-surface noise should be considered when specifying surface types for pavements and bridges (Gee 2005).

Several studies including this research have measured the tire-road surface noise for various AC and PCC pavements. A wide variation in as-built surfaces has resulted in a wide variation in noise among the pavement sections, even for a specified PCC texture or AC mix. Despite such variation, evaluating the noise and surface textures of 57 pavements (AC and PCC) in the United States, Kuemmel et al. (2000a) has indicated that a desirable surface should exhibit a maximum of 83 dBA exterior and 68 dBA interior noise (at 97 km/h) with a *ETD* of 0.7 mm or above. Rasmussen et al. (2008b) mentioned that an OBSI level of 100 dBA (at 97 km/h) using the SRTT is a reasonable target threshold for PCC pavements. Rasmussen et al. (2008c) set target OBSI levels for PCC surfaces (measured at 97 km/h) between 99/100 dBA and 104/105 dBA considering the construction cost, noise, surface friction, and pavement smoothness (ride quality).

The recommendations specified above are definitely useful guidance. However, they may not be applicable or adoptable for every location/agency. Furthermore, not all surfaces perform in a similar manner because of pavement deterioration over time, and variability in materials and mixes. A criterion therefore needs to be developed for each agency jurisdiction and for each class of roadway considering the public perception or noise abatement criteria. For setting the maximum acceptable in-vehicle noise, user perception survey may be conducted or maximum limit in NAC may be used as a rough guidance. In this case, the maximum acceptable limit may be increased by up to about 2 dBA (3 dBA being the perceptible difference) from that obtained/estimated from the user perception survey or the specified limit in regional noise abatement criteria.

For a maximum acceptable exterior noise, distance to the nearby community, and criteria of noise attenuation with distance and regional NAC need to be taken into account. Deterioration in noise performance over time also should be considered. Figure 6-5 shows a suggested framework for selecting the acceptable maximum noise level for a new pavement and rehabilitation or surface treatment of an existing pavement. The acceptable maximum noise level refers to the overall noise from the road traffic. However, the desired minimum surface friction i.e., safety criterion must be checked when selecting the surface texture or mixes with acceptable maximum overall noise.

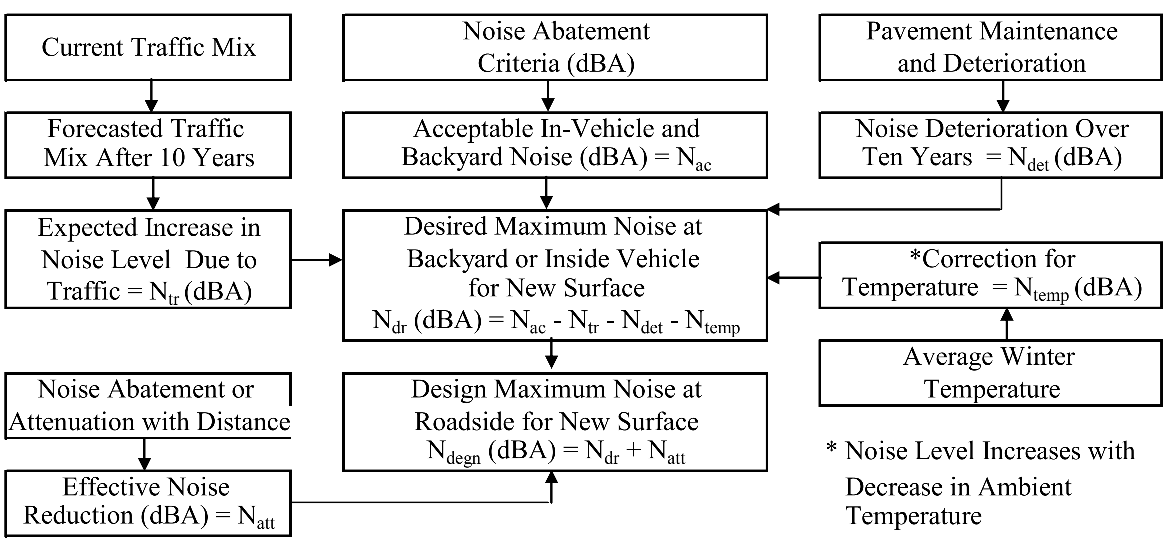

Figure 6-5 General Framework for Design Noise Level for a New Surface.

6.5.4 Surface Characteristics into Project Level PMS

It has now been learned that pavement surface friction represents a major functional performance of the highway. Routine monitoring of the surface friction is therefore essential to ensure safety of the road users, especially in wet-weather. However, although as-built construction smoothness has been incorporated into specifications of several US states, the surface texture and skid properties have not yet been quantitatively defined (Flintsch et al. 2003). Monitoring of surface friction is an important part of PMS that helps to evaluate the quality of the pavement surface (Song at al. 2006). Tighe et al. (2000) also emphasized that pavement surface properties and safety improvements must be incorporated in the PMS, and taken into account simultaneously when planning the maintenance program and selecting the treatment strategies. Although no transportation agencies in North America have set standards for minimum surface friction, different agencies have developed some criteria for identifying low friction surfaces and they are initiating possible countermeasures (refer to Sections 2.3 and 6.5.4).

On the noise side, a recent study in New Zealand found that a change in noise level of 1 dBA is noticeable and annoying to public, especially when the existing noise level is high, reverting previous knowledge that noise increase of 3 dBA is just noticeable to most people (Dravitzki 2006). Based on community survey for the degree of annoyance and disturbance, a noise guideline (Table 6-7) was then developed for changes in urban road surfaces.

Bendtsen and Schmidt (2006) also mentioned that PMS could incorporate the noise performance together with other factors like safety, comfort, durability while planning pavement maintenance or renewal activity. The noise emission, a crucial factor for quiet environment, may be evaluated following similar approaches of pavement condition data acquisition. As mentioned, a simple system like visual inspection and technical measurement like CPX trailer measurement may be used for a pavement condition and noise survey. A relationship between the noise performance and pavement surface deterioration, such as potholes, ravelling and cracking, then needs to be developed for various pavement types for inclusion in the PMS.

Table 6-7 Extent of Improvement in Noise Environment from Road Surface Change (Dravitzki 2006)

Changes in Noise Level (dBA)		<60 dBA *L*eq(24)	60-69 dBA *L*eq(24)	≥ 70 dBA *L*eq(24)
Reduction	≥ 3.6	Small Improvement	Improvement	Big Improvement
	1.1 - 3.5		Small Improvement	Improvement
	0 - 1	Little Change	Little Change	Small Improvement
No Change	0	N/A	N/A	N/A
Increase	0 - 1	Little Change	Little Change	A Little Worse
	1.1 - 3.5	A Little Worse	A Little Worse	Worse
	≥ 3.6		Worse	Much Worse

Although Bendtsen and Schmidt (2006) have focused on the AC pavement surfaces, a similar model can be developed for the PCC pavement surfaces incorporating concrete surface defects or deterioration over time. The developed model then can be used to predict noise deterioration (increase in noise emission) over time. The pavements then may be classified into five different categories, based on noise levels, using the network data. The classification from very noisy to noise reducing as suggested by Bendtsen and Schmidt (2006) are:

1) Very noisy: Noise level ≥3 dB greater than the reference pavement
2) Noisy: Noise level 1 -2 dB greater than the reference pavement
3) Normal: Reference pavement
4) Less Noisy: Noise level 1 -2 dB lower than the reference pavement, and
5) Noise Reducing: Noise level ≥3 dB lower than the reference pavement

The paper, however, did not characterize the reference pavement. Furthermore, for the same surface, within tests variability may exceed 1-2 dBA. The ranges of noise change over time needs to be more practical. A new guideline therefore is being suggested as summarized in Table 6-8. According to this guideline, the very noisy and noise reducing refer to the pavements that exhibit a noise greater or less than 5 dBA, respectively, with respect to the acceptable maximum limit as indicated in Section 6.5.3 (Figure 6-5). The needed actions for different noise levels have also been incorporated to aid the highway agencies in noise mitigation measures.

Table 6-8 Guideline for Evaluation of Pavement Surfaces at Project Level

Overall Noise Level with Respect to the Maximum Acceptable Limit	Pavement Classification	Action by the Agency
>5 dBA higher	Very noisy	Actively consider for surface change/ treatment to reduce the noise level
3-5 dBA higher	Noisy	Candidate for surface change/treatment
Within ± 2 dBA	Normal	Check at 2-year interval for potential increase
3-5 dBA lower	Less Noisy	Check every 5-year for potential increase
>5 dB lower	Noise Reducing	No action is needed

6.5.5 Value Engineering Approach for Pavement Selection

Snyder (2006) suggested a value engineering technique for the selection of pavement surface type and texture for new pavements as well as noise mitigation for existing pavements. Accordingly, the best choice for a surface layer can be identified in the decision-making through evaluation of various alternatives. An example was also given with six alternative options of PCC surface textures and AC surface mixes ranking each important factor in the scale of 0 (worst) to 100 (best). The weights for various factors were allocated as First Cost = 20, Structural Durability = 15, Safety (including wet/dry weather friction, hydroplaning potential, black ice, etc.) = 20, Interior Noise = 10, Exterior Noise = 5, Durability of Friction and Noise Reduction Characteristics = 20, Future Maintenance Costs and Options = 10.

However, the pavement smoothness was not included in the process mentioned above. As mentioned in Chapter 3, roughness affects the rolling resistance, ride quality, and vehicle-operating cost (additional fuel, tire wear, air pollution, and vehicle maintenance). In fact, the overall ride quality or condition of a pavement is judged by its surface roughness, generally computed as the International Roughness Index (IRI) (Noyce et al. 2005). As the smoothness is an important criterion, it needs to be included in the decision making process. Alternatively, pavement durability and cost are major issues in the wake of increased budget deficits for construction and maintenance of the road network, and sustainability of natural resources as well as economic development. Various papers on PMS suggest that future maintenance represents a substantial cost that needs to be incorporated into pavement life cycle analysis.

Furthermore, the exterior noise probably is more critical than interior, especially in urban areas, because of complaints from residents. In fact, a combination of costs, public perspectives, and engineering judgment of the importance/effectiveness of various factors and options should govern the decision-making process. It is also important to realize that noise alone should not be used as the criteria to distinguish between AC and PCC pavements. Overall initial and life cycle costs, constructability, maintainability, durability, comfort and economy in terms of rolling resistance and fuel consumption, and noise should be taken into account together with project location (rural/urban), roadway type (freeway/major/ local), and traffic class/mix and speed. A revised but simplified list of factors, together with their corresponding weights, is being suggested in this research (Table 6-9) for use in the decision-making process. Each factor can be assigned a score in the scale of 0-10 or 0-100 with 0 indicating most inferior and 100 or 10 denoting the most superior. The criteria for ranking different attributes have also been indicated for easy application.

6.5.6 Surface Characteristics into Network Level PMS

Bendtsen and Schmidt (2006) suggested noise management strategies for the road network as summarized below. The suggested classification of noise reducing to very noisy pavements is presented in Section 6.5.4. However, the suggested classification in this research (also presented in Section 6.5.4) may be more reasonable considering the nature of noise and its measurement variations. Furthermore, the time cycle may be revised to capture a complete life cycle of pavements at which some resurfacing/rehabilitation will be needed. This is especially important when the network is very large as in the case of North America. The suggested change (*italic*) in time cycle is also included in the summary presented below.

1) Over ten years, no pavement should be in the very noisy pavement class. *Change to 10 to 15 years that is typical service life of the overlays.*
2) Over six years, all pavements in densely populated area should be of noise-reducing types. *Change to 5 to 10 years depending on the network size.*
3) Over ten years, all pavements in areas with detached residential houses should only belong to the less noisy types. *Change to 10 to 15 years depending on the network size.*
4) For any spot increase in the maximum noise level, the road surface shall be visually inspected to determine the reason of such increase. Pavement related noise problem should be solved within two years with appropriate repair/remediation. *Change to 2 to 5 years depending on the network size.*

Table 6-9 Value Engineering Approach for Selection of Surface and Pavement Type

Pavement Attributes	Weights	Criteria for Ranking the Attributes
Initial construction cost and cost effectiveness	30	Based on bid price for alternative pavements or surfaces and expected benefits
Life cycle maintenance cost	10	Based on historical costs for similar pavements/surfaces
Structural capacity/durability	20	Based on design and/or actual service life
Safety (skid resistance, splash and spray) over the service life	20	Based on ranges of average skid resistance value and/or accident record on similar surfaces over the service life
Exterior or interior noise over the service life	10	Based on average roadside or in-vehicle noise levels over the service life for alternative surfaces, depending on roadway location
Smoothness and rolling resistance over the service life	10	Based on average IRI of alternative surfaces over the service life

Similar to noise, management strategies can also be developed for skid resistance and pavement smoothness. Based on this research, the management strategies for surface friction in the network level are being suggested as follows:

1) Over 10-15 years, no pavement should have skid resistance below the desired minimum value.

2) Over 3-5 years, all high speed (≥100 km/h) and highly traveled facilities with annual design lane ESALs of >3 million should have surface friction exceeding the desired minimum *SN*.

3) Over 5-10 years, all high speed (≥90 km/h) and highly traveled facilities with annual design lane ESALs of 1-3 million should have surface friction exceeding the desired minimum *SN*.

4) Over two years all black spot locations on a) sharp curves ≥4° for 100 km/h (60 mph) speed limit, ≥6° for 80 km/h (50 mph) speed limit, and ≥9° for 60 km/h (37 mph) speed limit; b) steep grades of >4%; c) merges; and d) approaches to stop signs and traffic signals should have surface friction exceeding the desired minimum *SN*.

5) Friction related problem at all spot locations other than specified in item 4 should be solved within 2- 5 years with appropriate treatment or rehabilitation.

Chapter 7 Conclusions and Recommendations for Future Research

7.1 CONCLUSIONS

This research has completed a comprehensive study on pavement surface characteristics namely the texture, skid resistance, and noise performances. The contributions of AC mix properties and various PCC surface texturizations on macrotexture and skid resistance, independent of variations in aggregate mineralogy and construction/uses, have been examined. The seasonal, early life and long term variations of both AC and PCC pavements surface friction have also been examined. The noise reduction potential of typical pavements that are currently being used on Ontario Highways has been evaluated through measurement of near-field, far-field, and in-vehicle noise of various PCC and AC pavements. The correlations of surface texture, skid resistance, and noise have also been examined.

This research has presented the strategies for the selection of pavement surfaces with desirable minimum skid resistance and acceptable maximum noise. The process of including the surface characteristics together with construction and maintenance costs, durability, and structural capacity in the selection of pavement surfaces has also been provided. The skid resistance and noise management strategies for project and network levels have been provided. The findings and recommendations is this research are therefore expected to aid the pavement engineers in the selection of appropriate surface texture or surface mix of the AC and PCC pavements considering the safety, comfort, cost and durability. The important conclusions from this research can be summarized as follows:

PCC Surface Mixture, Texture, and Skid Resistance

1) The available surface texture or friction was shown to be highly dependent on actual construction/finishing i.e., what actually is done in the field (not just the specifications).

2) Laboratory test in this study has indicated that a broom texture can exhibit a skid resistance as high as 83 *BPN* depending on the type of broom used.

3) For similar texture depths, exposed aggregate PCC surface was shown to exhibit a lower *BPN* as compared to the tined surfaces probably because the benefit of sand microtexture on pavement surface is lost with washed mortar.

4) For the same texture configuration, transversely textured PCC surfaces were shown to exhibit 7%-14% (average 8 *BPN*) higher skid resistance than that of longitudinal textured surfaces.

5) The trend of surface friction for the available texture range suggests that a *MTD* of about 1.8 mm is the optimum texture that provides the maximum and/or adequate resistance to skidding on textured PCC surfaces.

6) Skid resistance was shown to increase with an increase in RCA content, which is probably associated with additional sand microtexture of crushed reclaimed concrete that was used to replace the virgin coarse aggregate.

7) PCC surface *MTD* and texture direction were shown to be statistically significant for skid resistance (*BPN*) with good R^2 values of 0.87 to 0.96.

AC Surface Mixture, Texture, and Skid Resistance

1) The AC pavements surface friction was shown to be a complex function of texture, aggregate quality, and actual tire-pavement contact. In other words, a high texture does not necessarily ensure a high skid resistance.

2) In this study, the Superpave surface with premium aggregates was shown to exhibit the highest SN_{64} of 61 with a relatively low *MTD*. The SMA surfaces with the greatest *MTD* were shown to exhibit lower SN_{64} (57-58) as compared to the Superpave. ROGC with a good *MTD* was shown to exhibit the lowest SN_{64} of 44.

3) The trend for skid resistance versus *MTD* on AC surfaces (multidirectional macrotexture) was shown to be different from that on PCC surfaces (unidirectional macrotexture). However, as indicated by the *SN*-*MTD* trend of the available data, a *MTD* of maximum 1.8 mm is expected to provide adequate skid resistance.

4) AC pavements skid resistance was shown to decrease at 2.6 *SN* (on average) for each 10 km/h increase in vehicle speed.

5) Within the available data range, the skid number-speed gradient was shown to be different for each mix. It probably suggests that a separate relationship may help in best utilization of the available surface friction from each surface mix.

6) For the available data range, the *BPN* was shown to correlate well with the *SN* where the SN_{64} is fairly 77% of the *BPN* value (a *BPN* of 55 would mean a SN_{64} of 42). This suggests that *BPN* is not only an indicator of surface microtexture and low speed surface friction.

7) For AC surface *MTD,* the aggregate gradation (C.A./F.A. ratio) was shown to be statistically significant with a very good with R^2 value of 0.84.

8) The model correlating the S*N* with *MTD* and vehicle speed has shown a fair correlation with a R^2 value of 0.56 whereas the model incorporating the aggregate quality code has shown an excellent R^2 of 0.98 indicating that aggregate quality is of outmost importance for surface friction.

9) AC mix with premium aggregates was shown to exhibit 13 *SN* higher than the mix containing conventional aggregates. Skid resistance was shown to increase at 11 *SN* (on average) for a 1 mm increase in *MTD*.

Seasonal Variation of Surface Friction

1) The seasonal variation of both AC and PCC pavements wet surface friction were shown to be similar with a maximum difference of 8 *BPN* (6 SN_{64}) between the peak and the lowest values.

2) None of the prior temperature, dry days without rain (dry spell), and precipitations was shown to be statistically significant to explain the seasonal skid resistance variation for the tested pavements.

3) Overall, the wet surface friction was shown to be predictable from ambient or surface temperature during the testing (driving). The surface friction variation was shown to be 0.35 *BPN* (0.27 SN_{64}) for 1°C change in temperature. The

correlation was shown to be statistically significant at the 5% significance level.

Long Term Variation of Surface Friction

1) Based on the LTPP data, the full surface friction is expected to attain in about 1½ (AC) to 2½ (PCC) years, on an average, following the construction. The early life surface friction increase was shown to be about four SN_{64} for PCC and five SN_{64} for AC pavements.

2) PCC and AC surfaces friction was shown to decrease at 0.7 *SN* and 1.2 *SN,* respectively, per year after the early life friction increase.

3) PCC and AC surface friction was shown to decrease at 0.24 *SN* and 0.27 *SN*, respectively, per million vehicle passes.

4) Vehicle speed, pavement age or cumulative traffic passes, prevailing temperature and texture rank were shown to be statistically significant in PCC long term surface friction performance models.

5) For AC pavements long term surface friction models, the significant variables were shown to be vehicle speed, pavement age or cumulative traffic passes, prevailing temperature, and predominant weather codes.

6) Prior temperature, rainfall, and AC as well as PCC mix properties were shown to have no statistically significant or logical effect on long term skid resistance variation of the pavements in the LTPP database.

Tire-Pavement Noise

1) The variations of near-field, far-field and in-vehicle noise levels were not shown to be identical i.e., a low near-field noise may not ensure a pavement surface with low in-vehicle and/or pass-by noise.

2) A surface with a very low level of texture may not produce a quiet surface because some texture is needed for air escape from tire-pavement contact patch and noise reduction.

3) Within the same pavement, the section variation of in-vehicle noise was shown to be up to three dBA (perceptible difference) for PCC and up to two dBA (hardly noticeable difference) for AC pavements.

4) On average, 0 to 5-year old PCC pavements were shown to be 2.2 dBA (hardly noticeable) louder than similar AC pavements when the in-vehicle noise levels were compared. However, different noise frequencies on these two pavement types may cause the difference to be noticeable.

5) PCC pavements were shown to be 4.4 dBA (perceptible) louder than AC pavements when the pass-by noise levels were compared.

6) On average, the in-vehicle and pass-by noise levels were shown to increase at 1.6 dBA and 1.5 dBA, respectively, for each 10 km/h increase in vehicle speed.

7) The 12.5 mm SMA was shown to be the quietest (1.5 dBA quieter than the regular SP12.5) pavement with respect to the in-vehicle noise. The 16 mm SMA was shown to be 3.1 dBA louder than the 12.5 mm SMA.

8) In the case of pass-by noise, the HL3 and SP12.5Fine mixes were shown to be the quietest (0.9 dBA quieter than the regular 12.5SP). The 12.5 mm SMA was shown to be just 0.5 dBA louder than the SP12.5Fine.

9) Overall, the 12.5 mm SMA or 12.5 SPFine have appeared to be good choices for low in-vehicle and pass-by noise levels, especially for noise sensitive areas. However, careful placement and compaction is essential to produce a uniform low textured surface and to attain the noise reduction benefit.

10) The current MTO specified 16 mm tine spacing for PCC pavements has seemed to be appropriate but a 3.2 mm deep longitudinal tining may be taken as a standard for further noise reduction. However, uniform texturing is

important to achieve the noise reduction benefit and reduce variability among pavement sections.

Pavement Acoustic Absorption

1) On average, regular 12.5SP, 12.5 mm SMA, and 12.5SPFine mixes were shown to absorb 6.3%, 7.5%, and 8.5% of sound, respectively. Textured PCC surfaces were shown to absorb 5% to 6% of the sound.

2) The sound absorption of dense AC was shown to decrease at 1.4% for each 0.1 increase in BRD. The thickness of dense AC and conventional PCC has shown no significant effect on the variation of sound absorption.

Surface Texture, Skid Resistance, and Noise

1) Tests at CPATT quiet pavement test site have shown that although open graded mixes were quieter immediately after construction, their noise reducing properties have diminished in just three years.

2) For the CPATT test sites, no or poor correlation has been found between CPX noise and surface texture as well as friction. However, the variations of pass-by and in-vehicle noise levels with surface texture as well as friction were shown to be noticeable with increased noise with an increase in macrotexture and skid resistance.

3) Considering the noise and skid resistance including the seasonal fluctuation of surface friction and long term wear/polishing of surface, both SMA and SP seem to be better choices among the tested pavements.

4) As the pavement surface texture was shown to influence greatly the in-vehicle and pass-by noise levels, a low textured SMA surface may further reduce both these levels and provide good skid resistance.

7.2 RECOMMENDATIONS FOR FUTURE RESEARCH

Based on the observation, analysis, and results in this research, the following recommendations are proposed for future study on pavement surface characteristics:

1) Skid and texture measurements on a greater number of AC pavements containing known mixes may find the optimum surface macrotexture for maximum skid resistance.

2) The optimum macrotexture for PCC surfaces that has been found in this research should be verified using a full-scale skid tester e.g. skid trailer.

3) The correlation of *BPN* and *SN* should further be checked using data from a greater number of pavements with varying surface textures.

4) The skid number-speed gradient should be established separately for each AC mix (e.g. Superpave, SMA, DFC, OFC, Microsurfacing) and PCC texture type (e.g. longitudinal tined, transversely tined, exposed aggregate, diamond ground, burlap/broom/turf dragged) using larger data sets.

5) The correlation of laser based and sand patch texture values should be closely studied for both positive and negative textures.

6) The seasonal variation of skid resistance on designated test sections should be further examined using a full-scale skid tester on dry as well as wet conditions.

7) The long term skid testing on designated test sections may be helpful to develop models that are more reliable.

8) Designated pavement sections (clearly marked for consistent subsequent measurements) should be tested for tire-pavement noise over several years to determine the noise deterioration or noise reduction over time.

9) Future noise measurement should also include measurement of the pavement surface macrotexture for meaningful classification of pavements with respect to the tire-pavement noise levels.

10) As the leading, trailing, passing, or opposing vehicle(s) nearby the testing vehicle may influence the measured noise level, noise measurement should be conducted when isolation from surrounding vehicle(s) is possible for more reliable benchmarking of various pavement surfaces.

11) Microphone responses in near field noise measurement may not be quite reliable because of the wavelength that is required for a sound wave to develop properly, particularly at low frequencies. As the in-vehicle and pass-by noise levels are of public concerns, more emphasis should be given on the in-vehicle and pass-by noise measurements.

12) Noise measurement should be carried out during calm weather with wind speed not exceeding 10 km/h to avoid influence of wind pressure.

13) A small size car (e.g. Chevy Malibu) mounted with a standard tire (ASTM F 2493) may be used for future noise measurement. It will allow for better comparison of measured noise levels with national and international databases.

14) Surface texture, noise, and skid resistance correlation should further be examined using data from a greater number of test sections.

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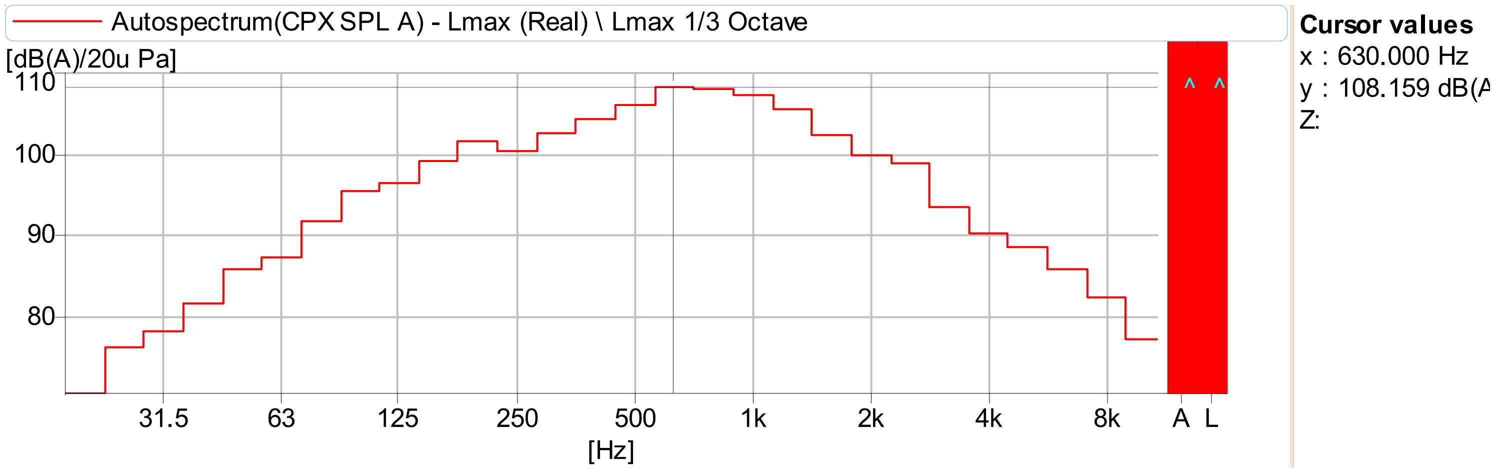
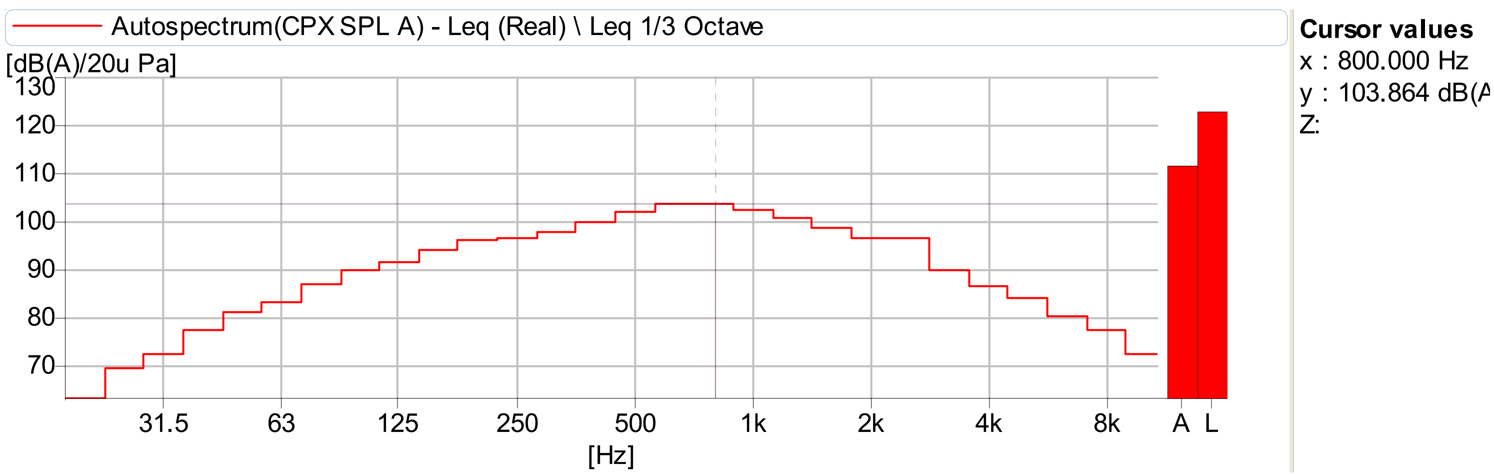
Appendix A

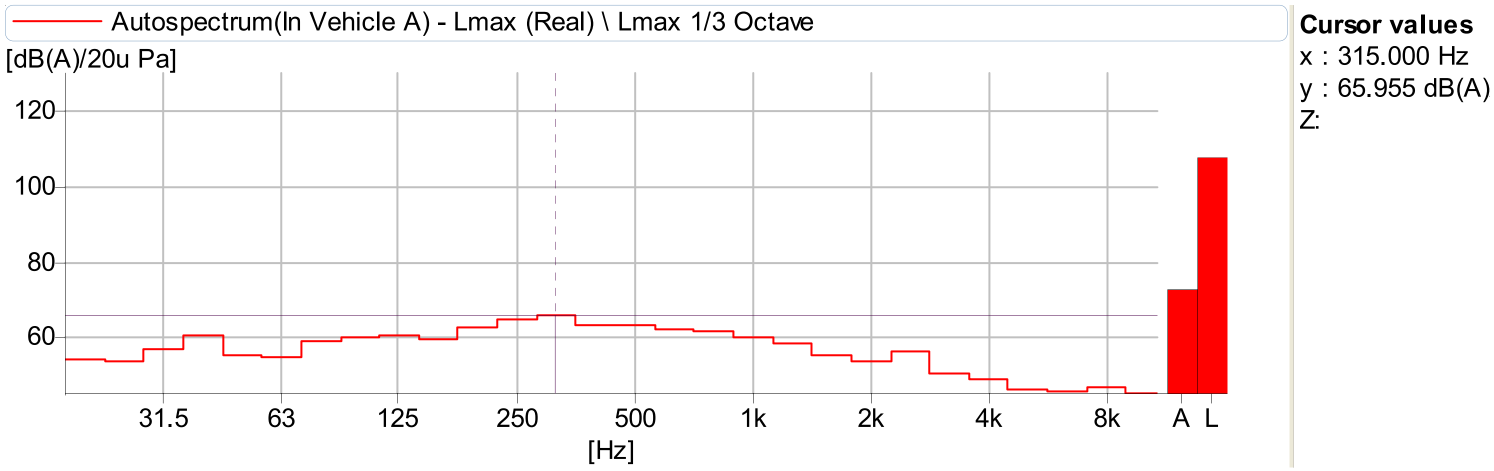
Sample Graphs of Tire-Pavement Noise at Different Frequencies



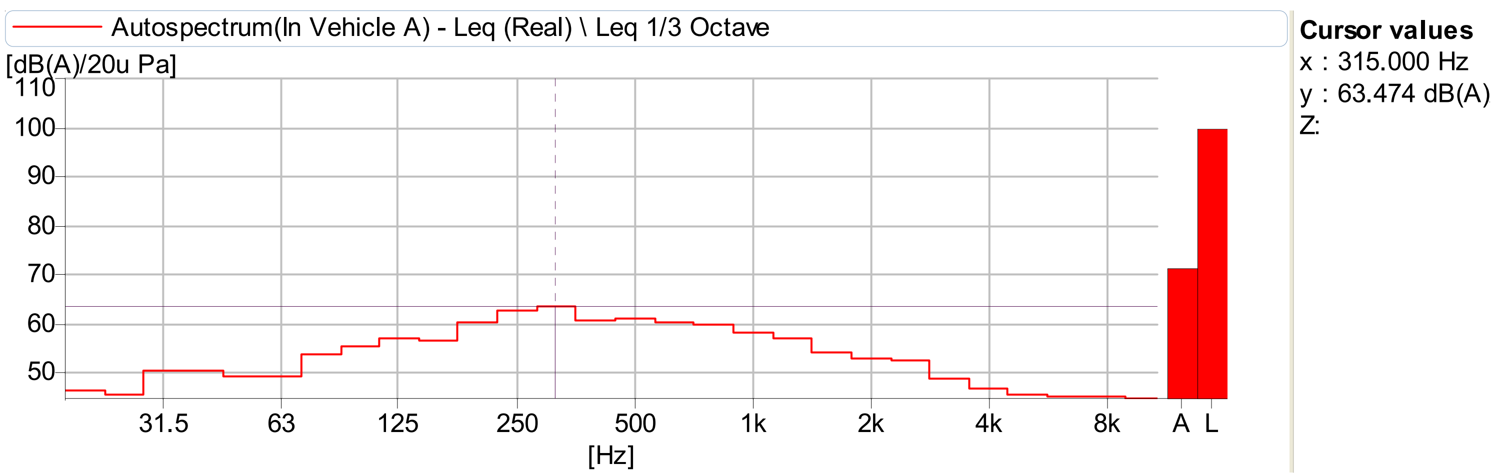
Appendix A- 1 CPX *L*max at 100 km/h for Fine Superpave in East Region (TIP).



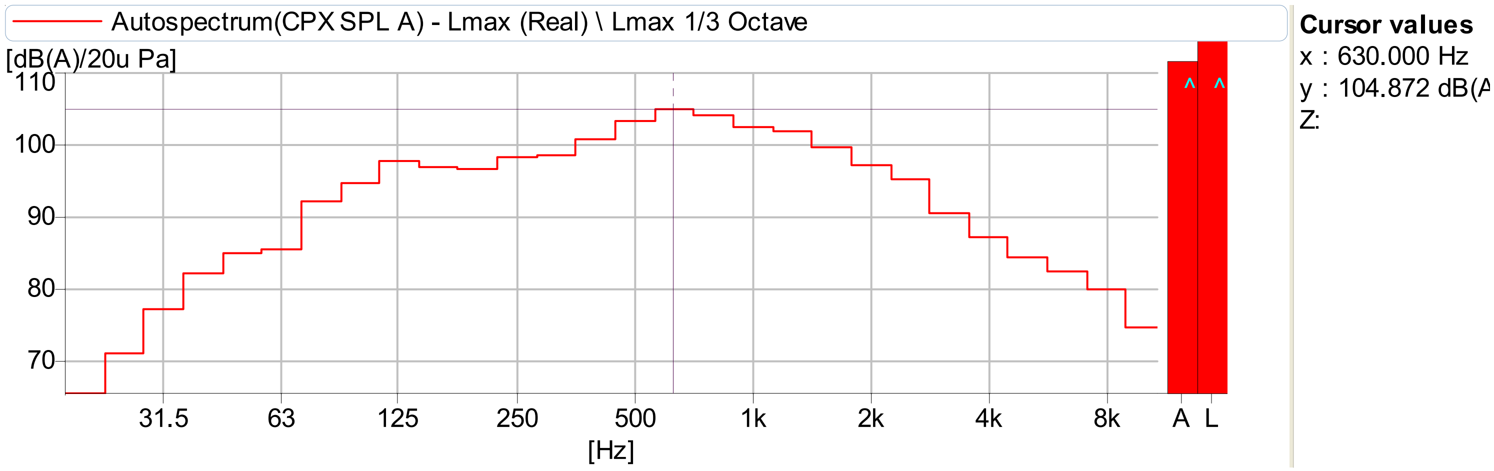
Appendix A- 2 CPX *L*eq at 100 km/h for Fine Superpave in East Region (TIP).



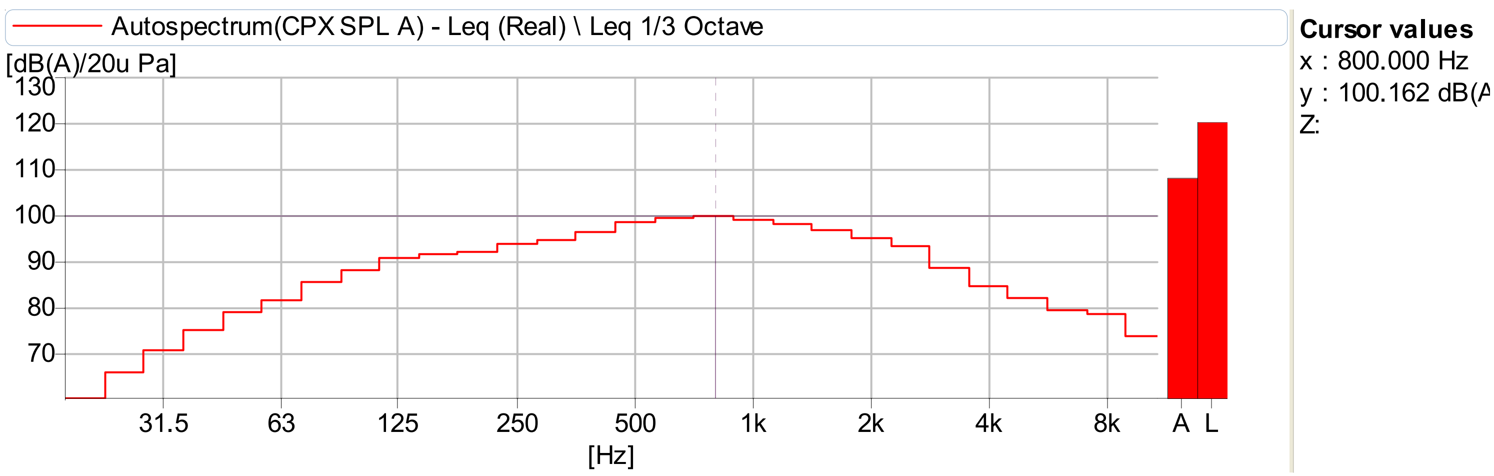
Appendix A- 3 In-vehicle *L*max at 100 km/h for Fine Superpave in East Region (TIP).



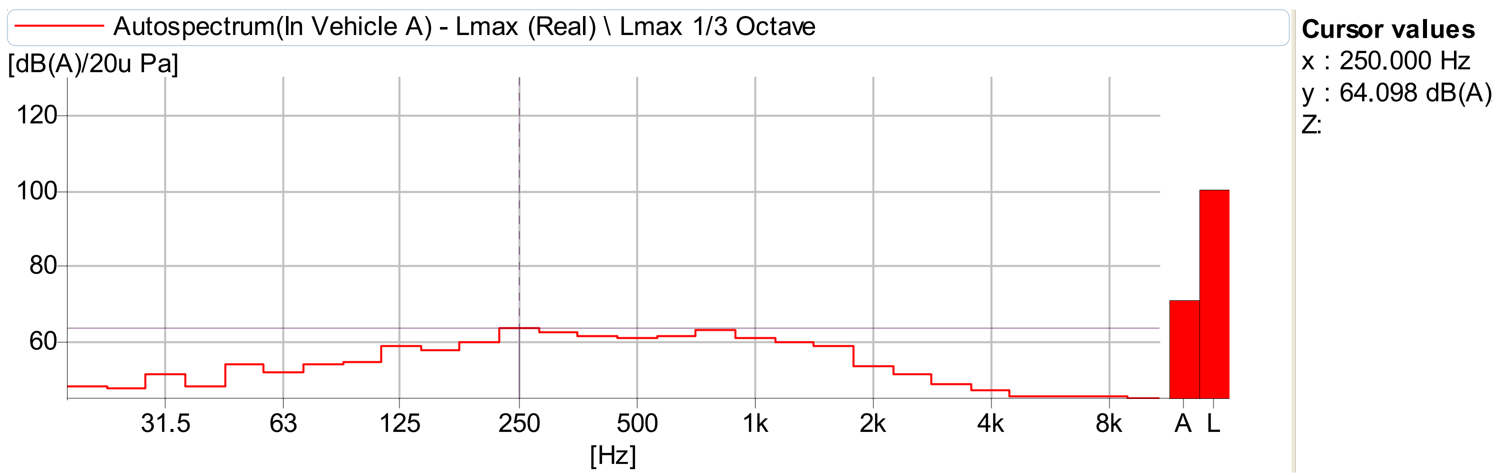
Appendix A- 4 In-vehicle *L*eq at 100 km/h for Fine Superpave in East Region (TIP).



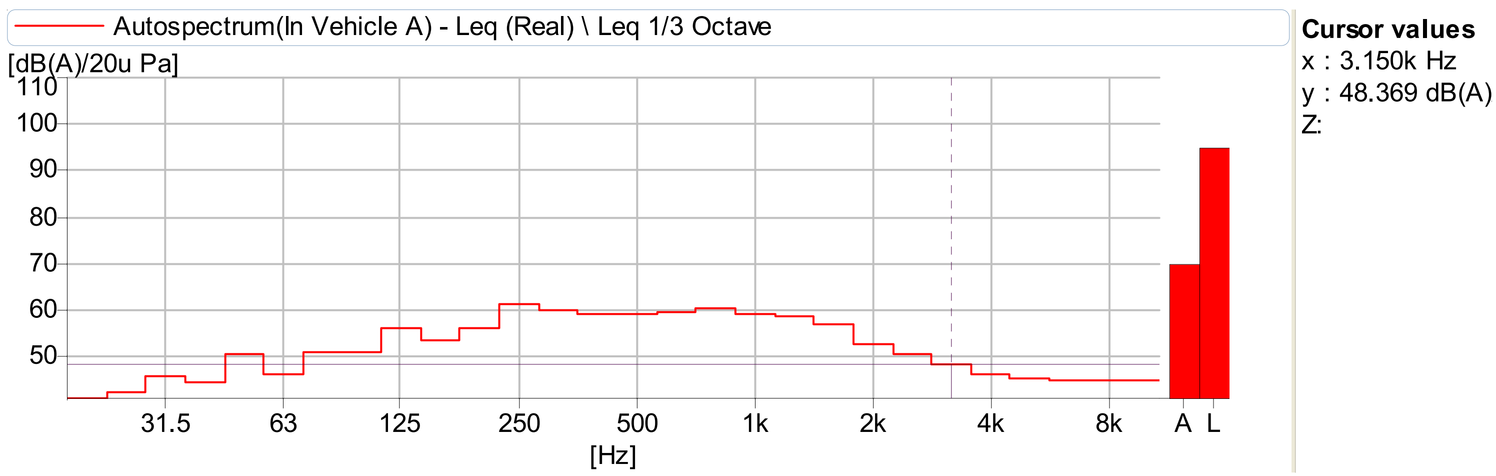
Appendix A- 5 CPX *L*max at 100 km/h for Regular Superpave in West Region (Hwy 402).



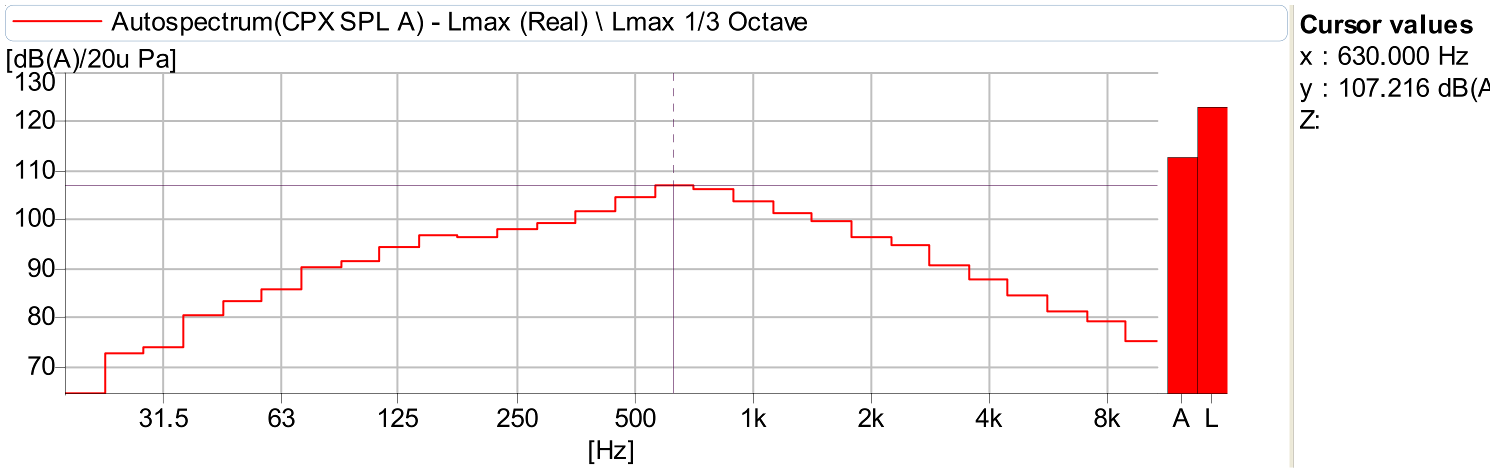
Appendix A- 6 CPX *L*eq at 100 km/h for Regular Superpave in West Region (Hwy 402).



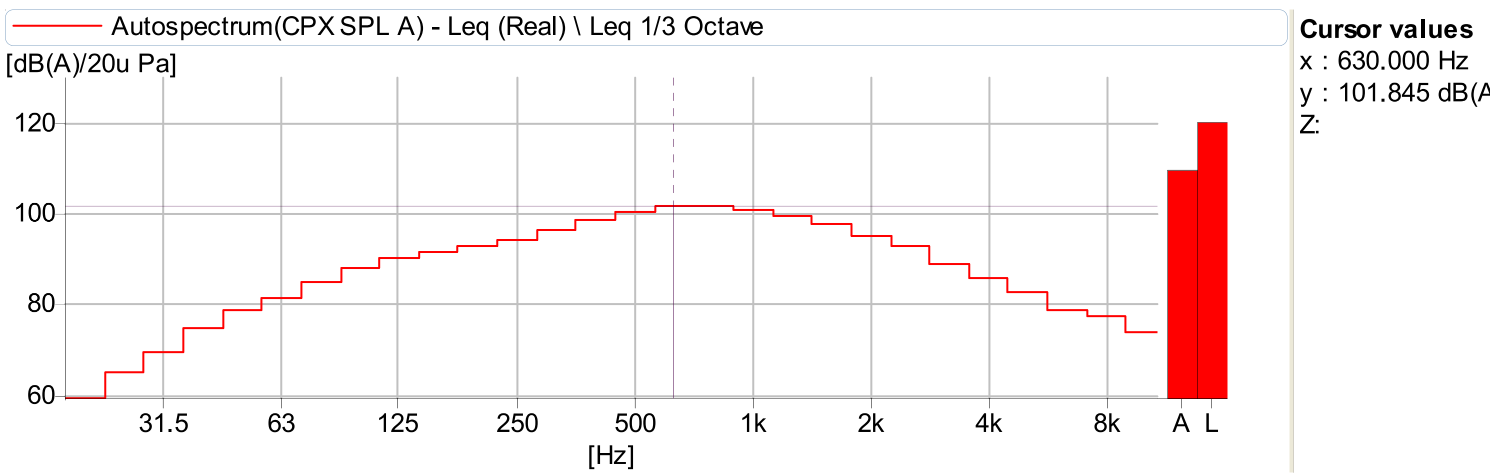
Appendix A- 7 In-vehicle *L*max at 100 km/h for Regular Superpave in West Region (Hwy 402).



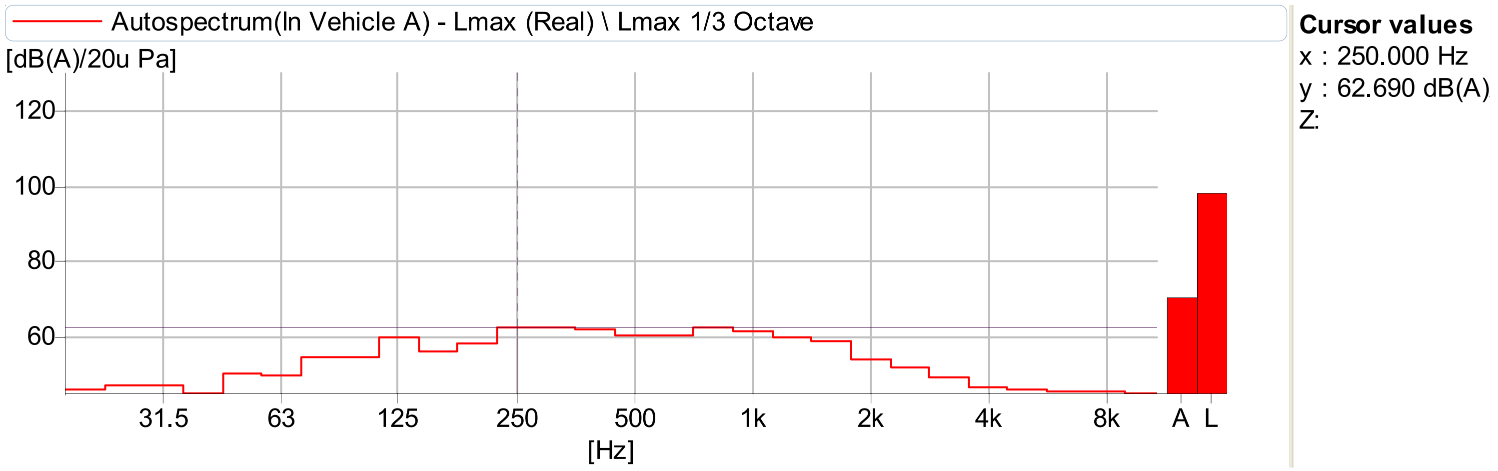
Appendix A- 8 In-vehicle *L*eq at 100 km/h for Regular Superpave in West Region (Hwy 402).



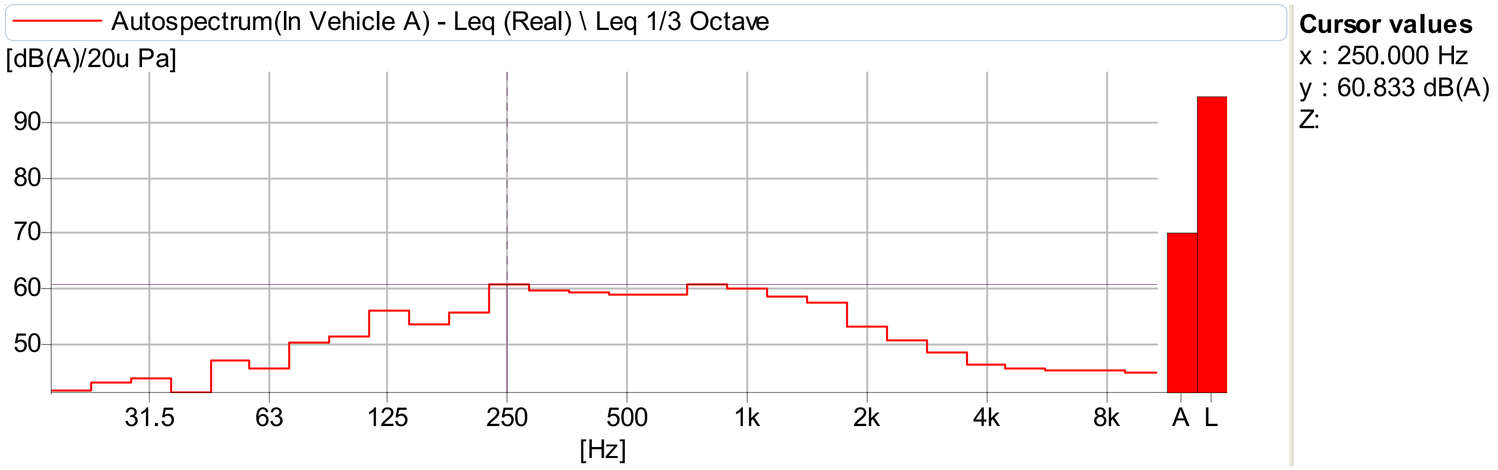
Appendix A- 9 CPX *L*max at 100 km/h for 1-Year Old SMA in West Region (Hwy 401).



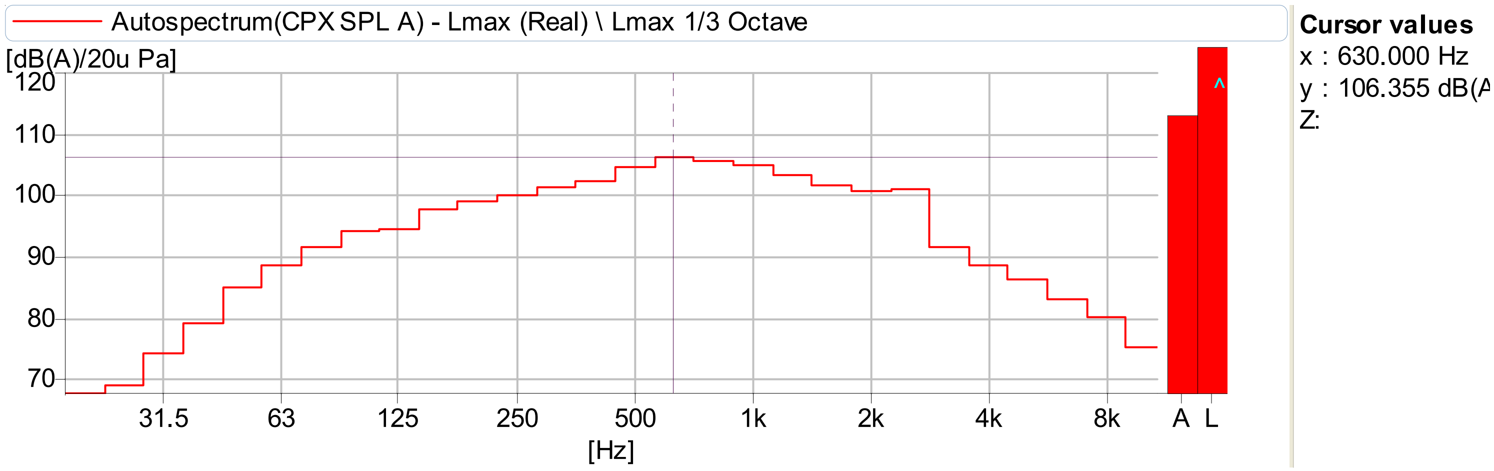
Appendix A- 10 CPX *L*eq at 100 km/h for 1-Year Old SMA in West Region (Hwy 401).



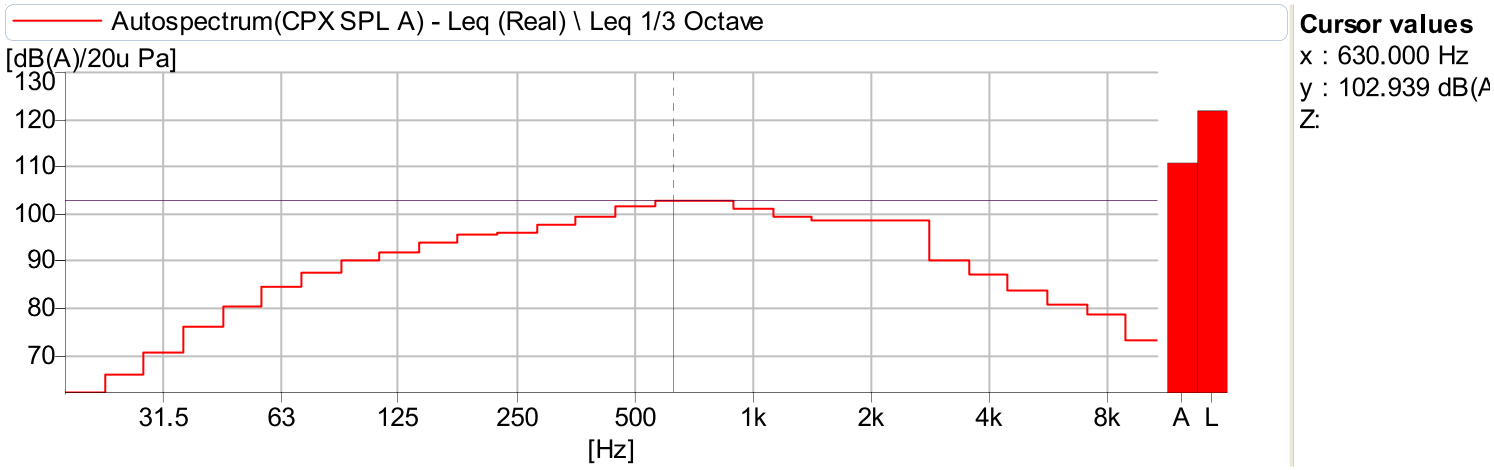
Appendix A- 11 In-vehicle *L*max at 100 km/h for 1-Year Old SMA in West Region (Hwy 401).



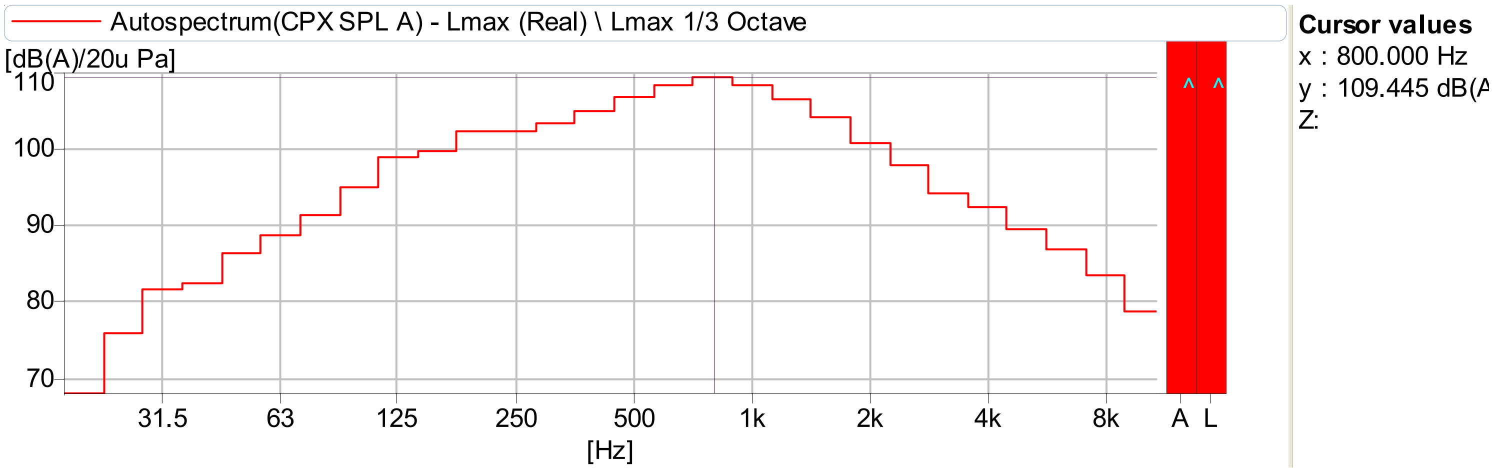
Appendix A- 12 In-vehicle *L*eq at 100 km/h for 1-Year Old SMA in West Region (Hwy 401).



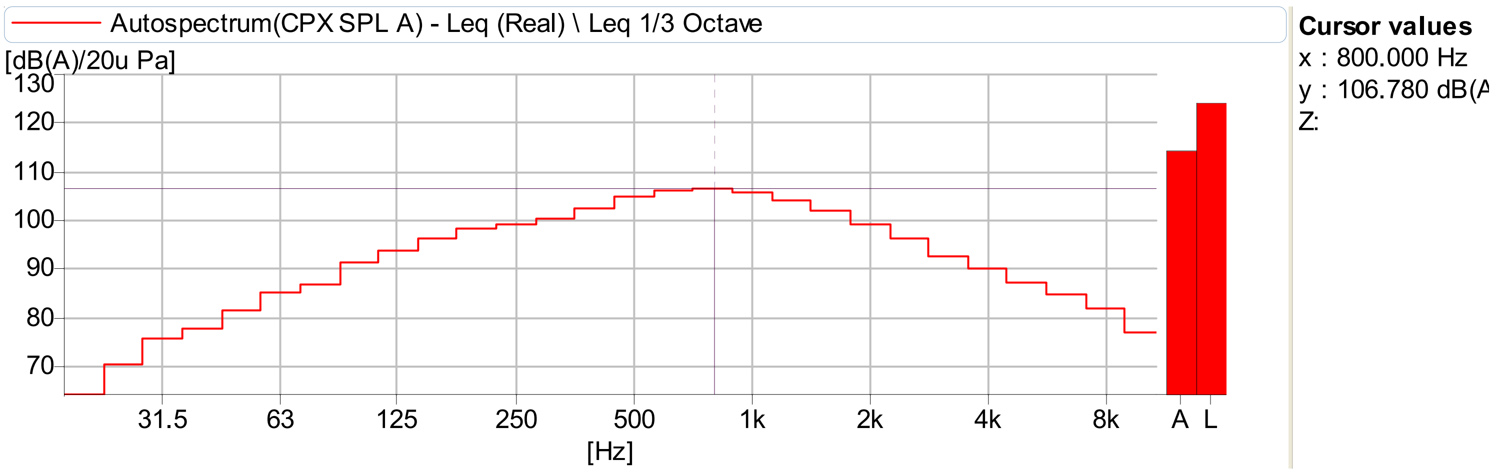
Appendix A- 13 CPX *L*max at 100 km/h for SP9.5Fine in East Region (Hwy 132).



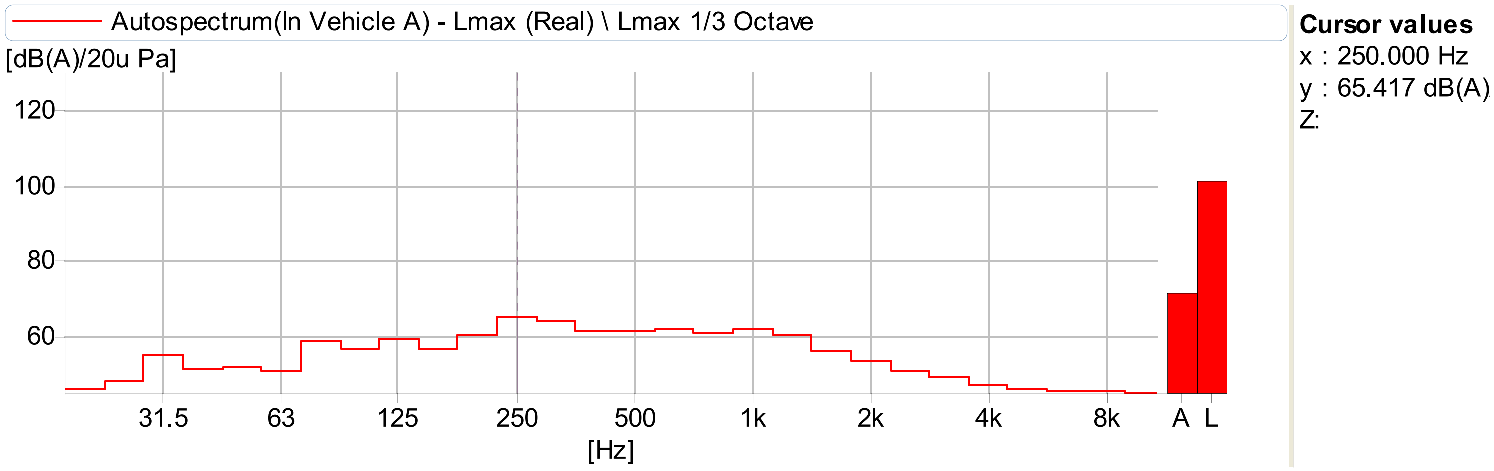
Appendix A- 14 CPX *L*eq at 100 km/h for SP9.5Fine in East Region (Hwy 132).



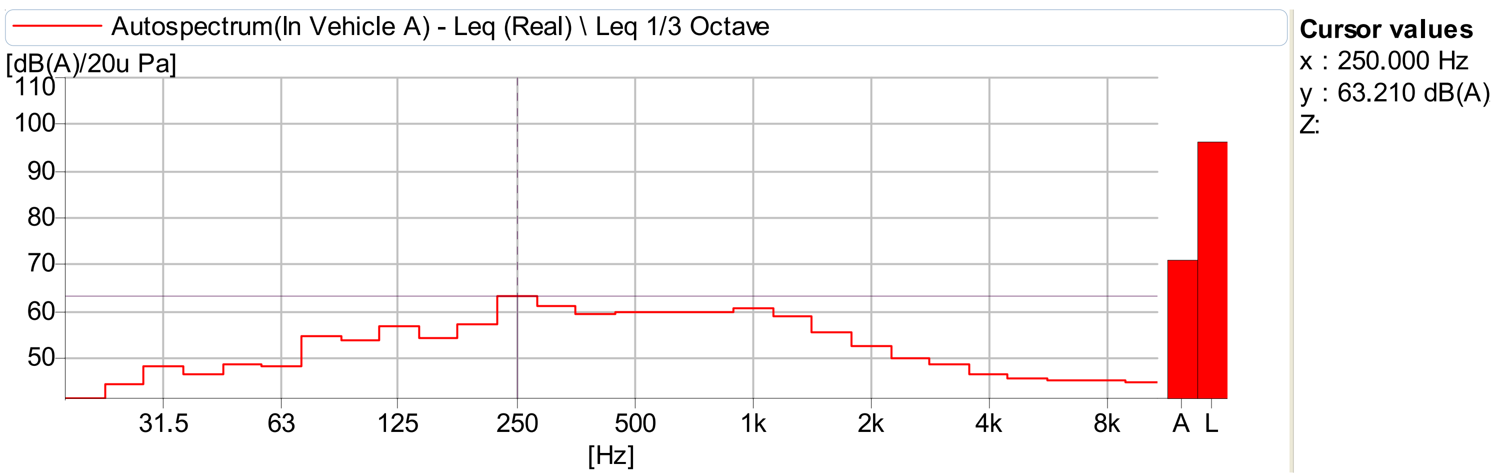
Appendix A- 15 CPX *L*max at 100 km/h for 2-Year Old Fine Microsurfacing in West Region (Hwy 10).



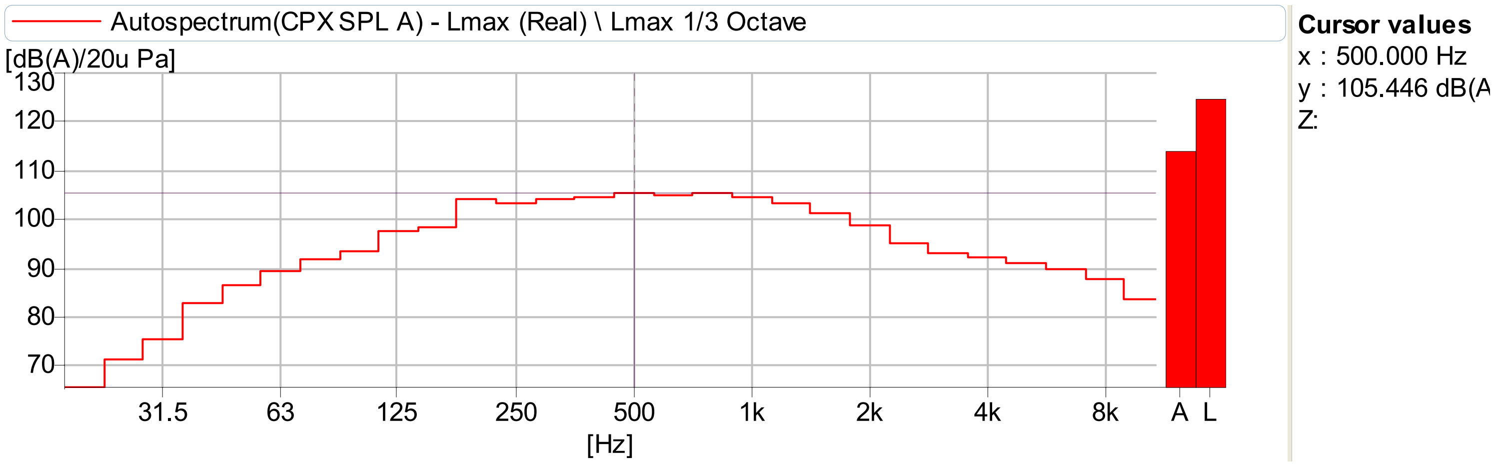
Appendix A- 16 CPX *L*eq at 100 km/h for 2-Year Old Fine Microsurfacing in West Region (Hwy 10).



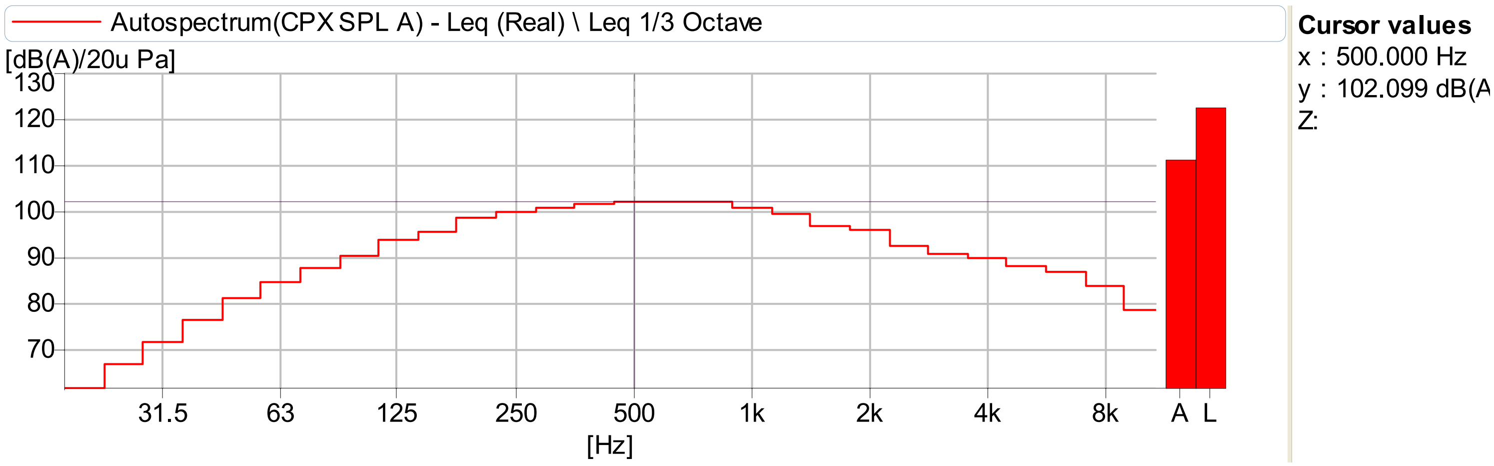
Appendix A- 17 In-vehicle *L*max at 100 km/h for 2-Year Old Fine Microsurfacing in West Region (Hwy 10).



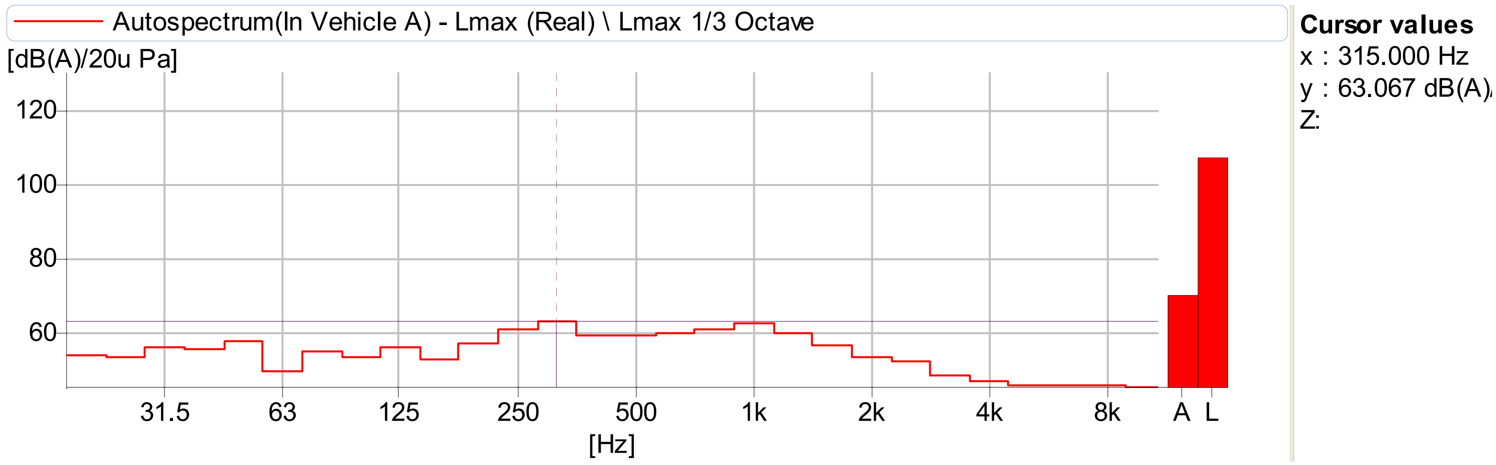
Appendix A- 18 In-vehicle *L*eq at 100 km/h for 2-Year Old Fine Microsurfacing in West Region (Hwy 10).



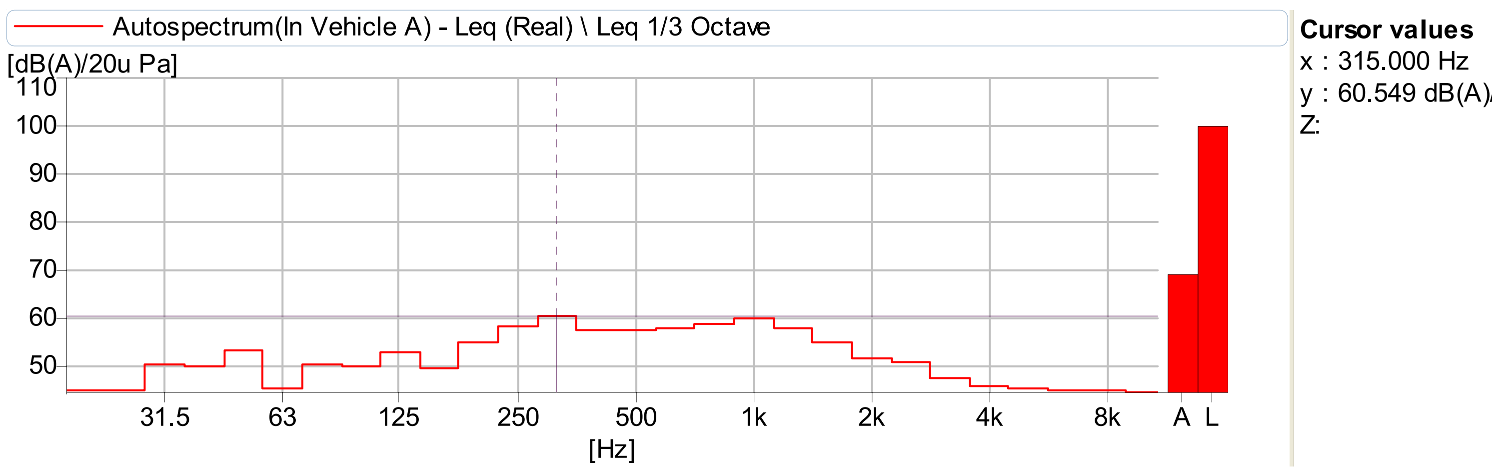
Appendix A- 19 CPX *L*max at 100 km/h for 3-Year ROFC at CPATT Quiet Pavement Test Site.



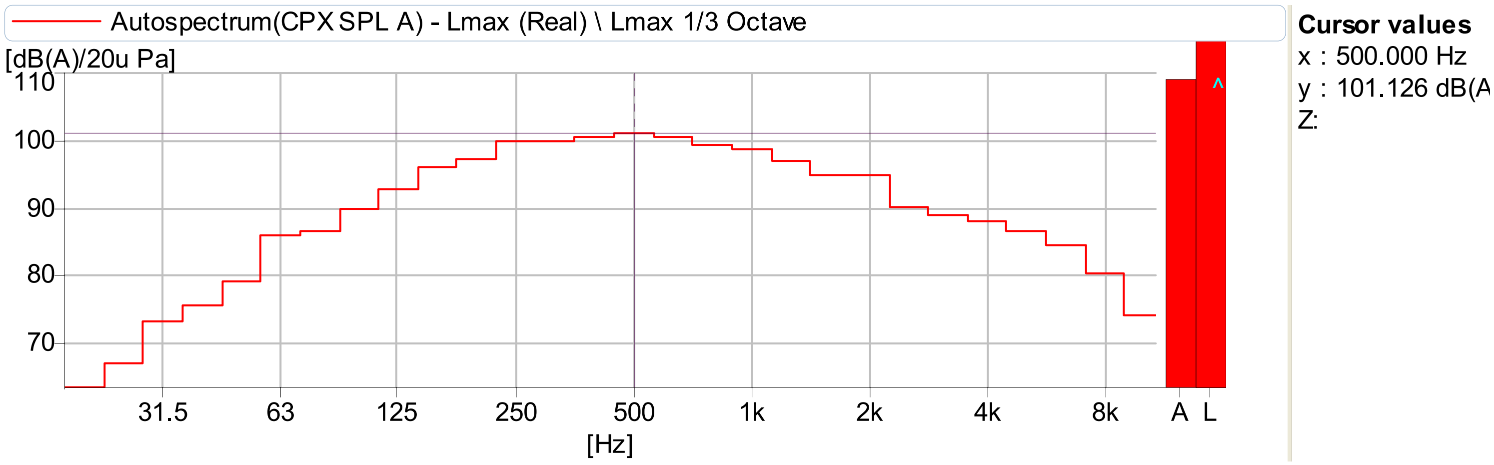
Appendix A- 20 CPX *L*eq at 100 km/h for 3-Year ROFC at CPATT Quiet Pavement Test Site.



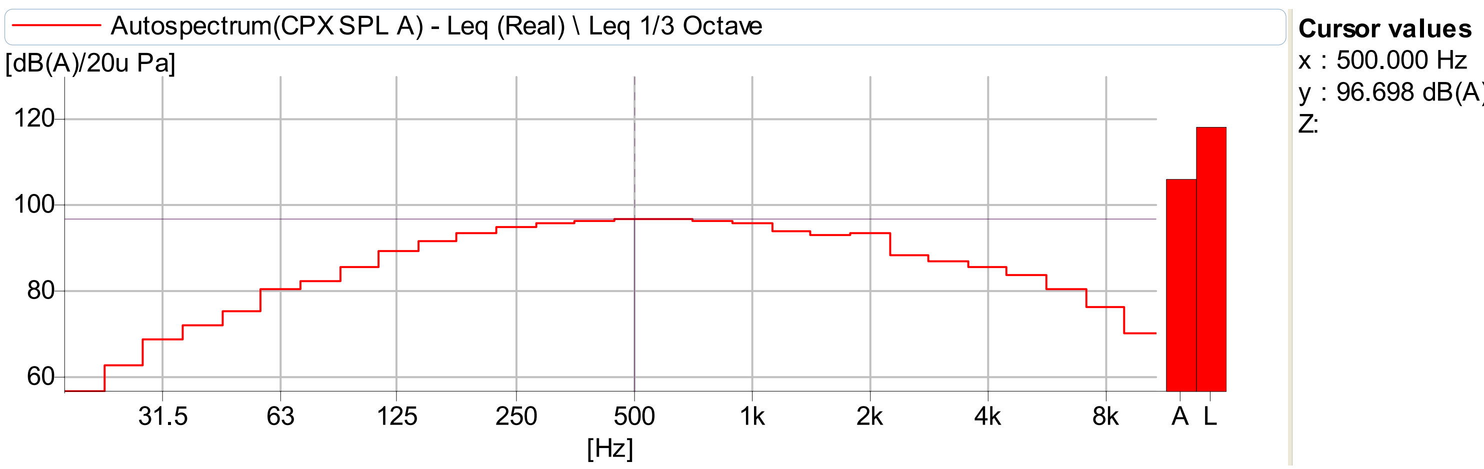
Appendix A- 21 In-vehicle *L*max at 100 km/h for 3-Year ROFC at CPATT Quiet Pavement Test Site.



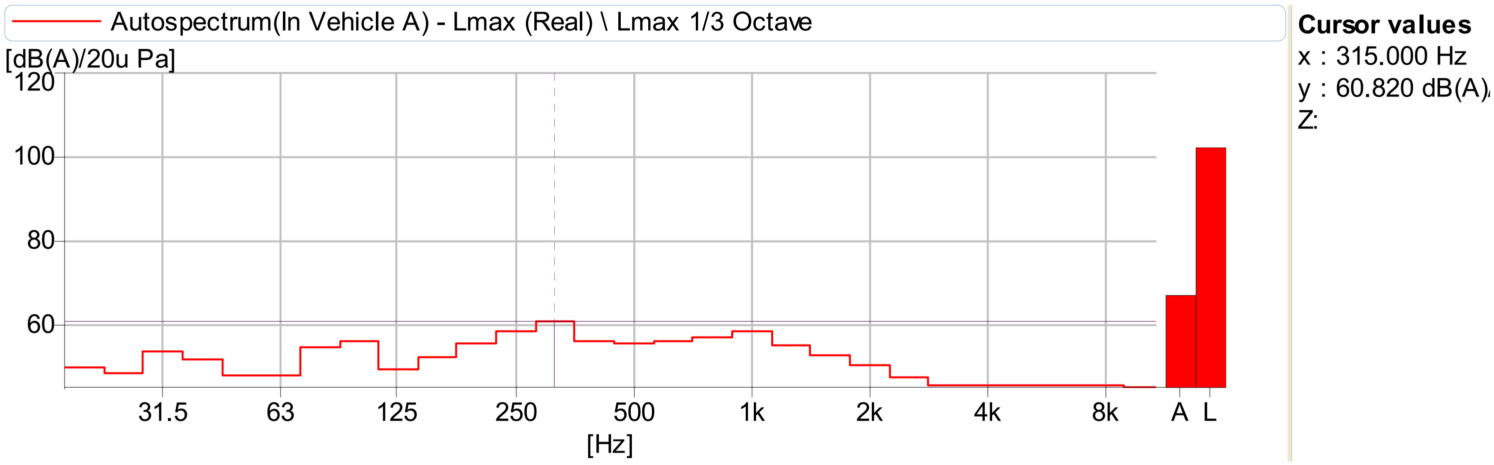
Appendix A- 22 In-vehicle *L*eq at 100 km/h for 3-Year ROFC at CPATT Quiet Pavement Test Site.



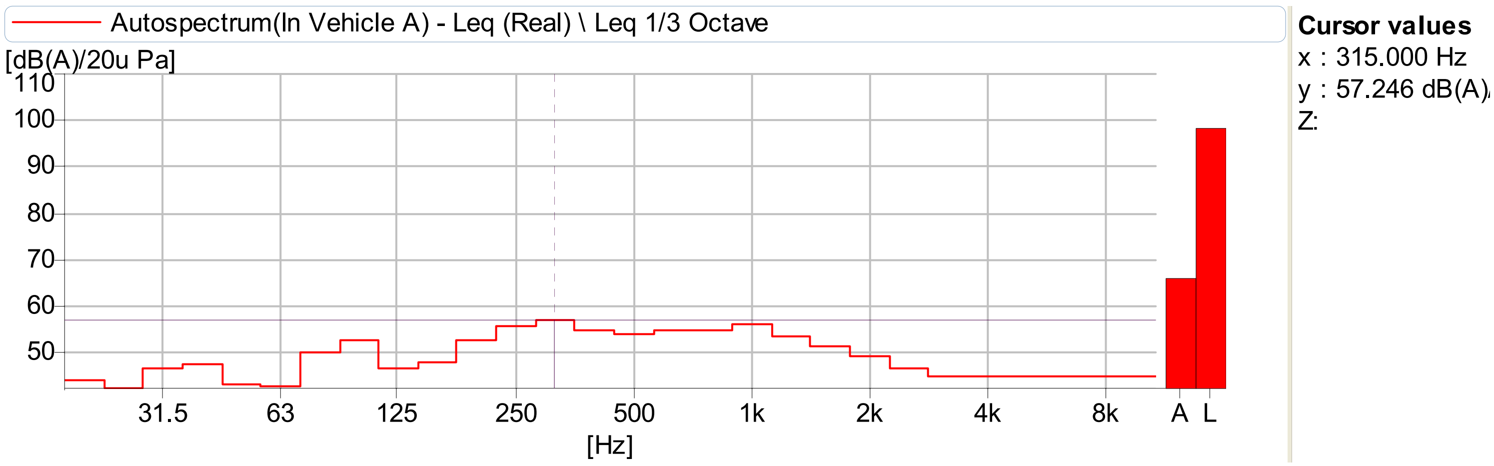
Appendix A- 23 CPX *L*max at 100 km/h for 3-Year ROGC at CPATT Quiet Pavement Test Site.



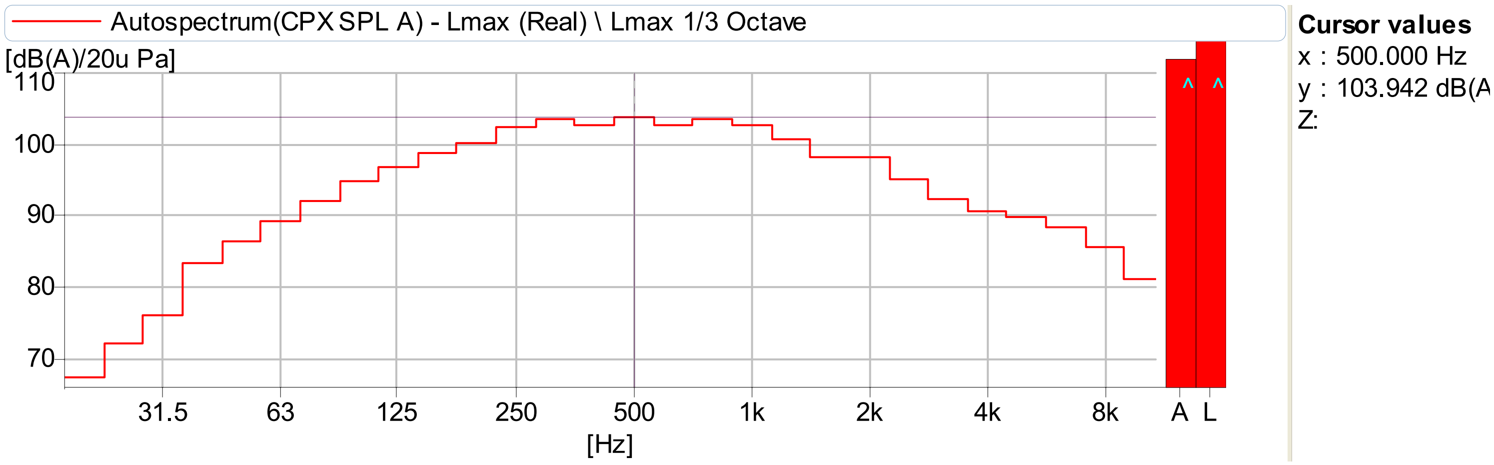
Appendix A- 24 CPX *L*eq at 100 km/h for 3-Year ROGC at CPATT Quiet Pavement Test Site.



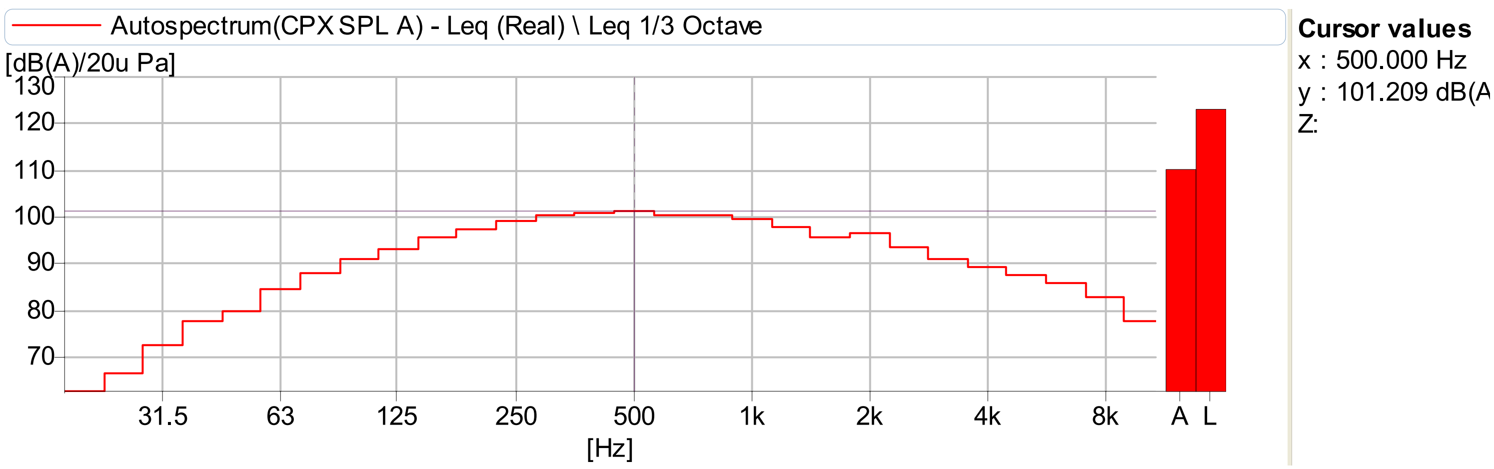
Appendix A- 25 In-vehicle *L*max at 100 km/h for 3-Year ROGC at CPATT Quiet Pavement Test Site.



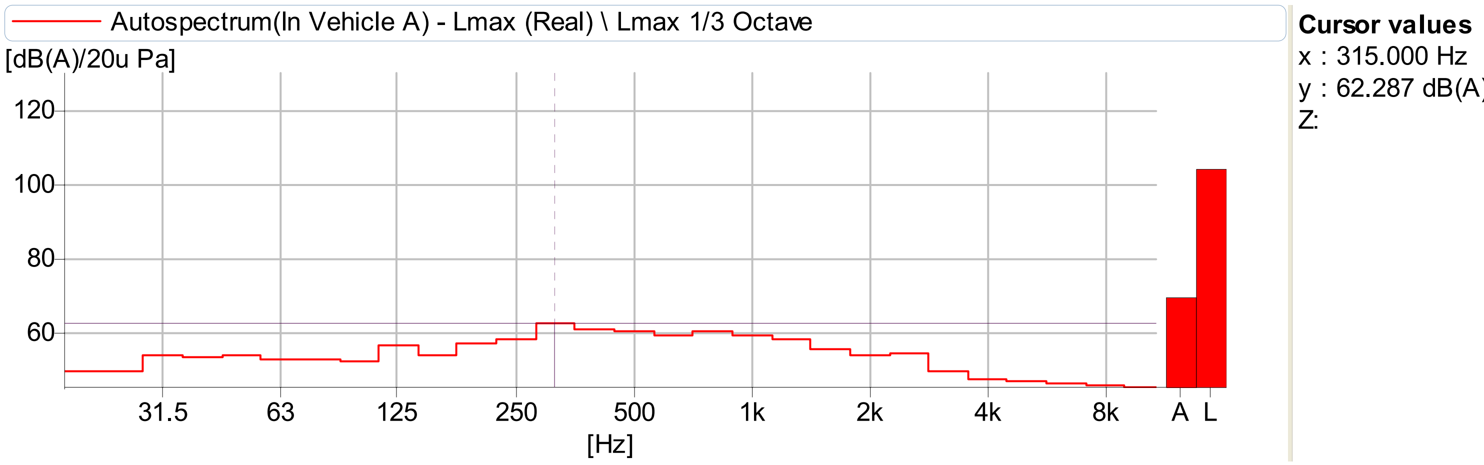
Appendix A- 26 In-vehicle *L*eq at 100 km/h for 3-Year ROGC at CPATT Quiet Pavement Test Site.



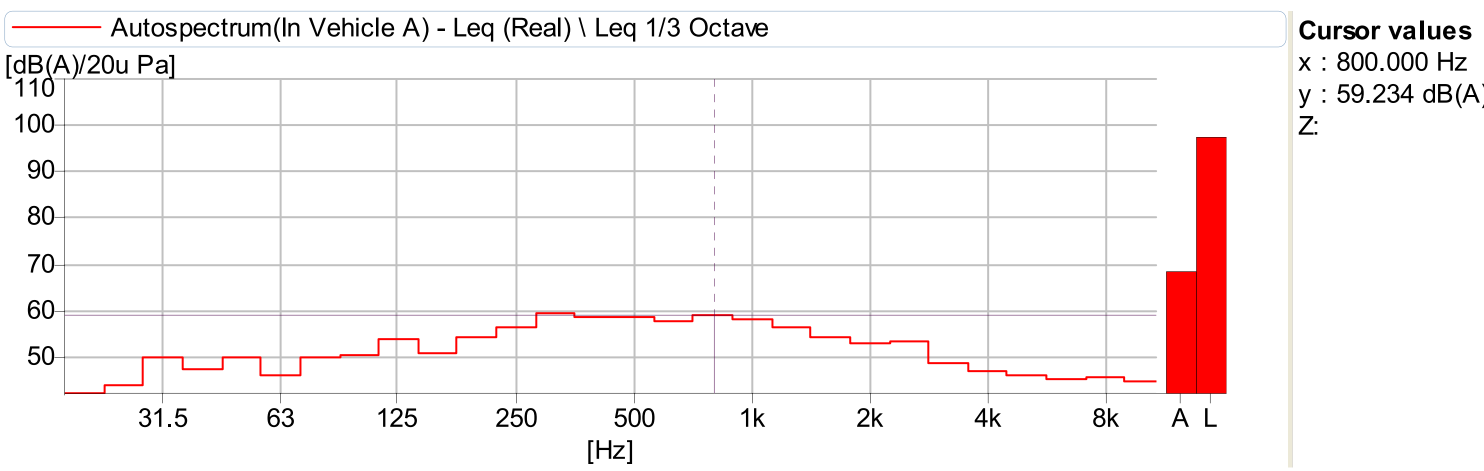
Appendix A- 27 CPX *L*max at 100 km/h for 3-Year HL3 at CPATT Quiet Pavement Test Site.



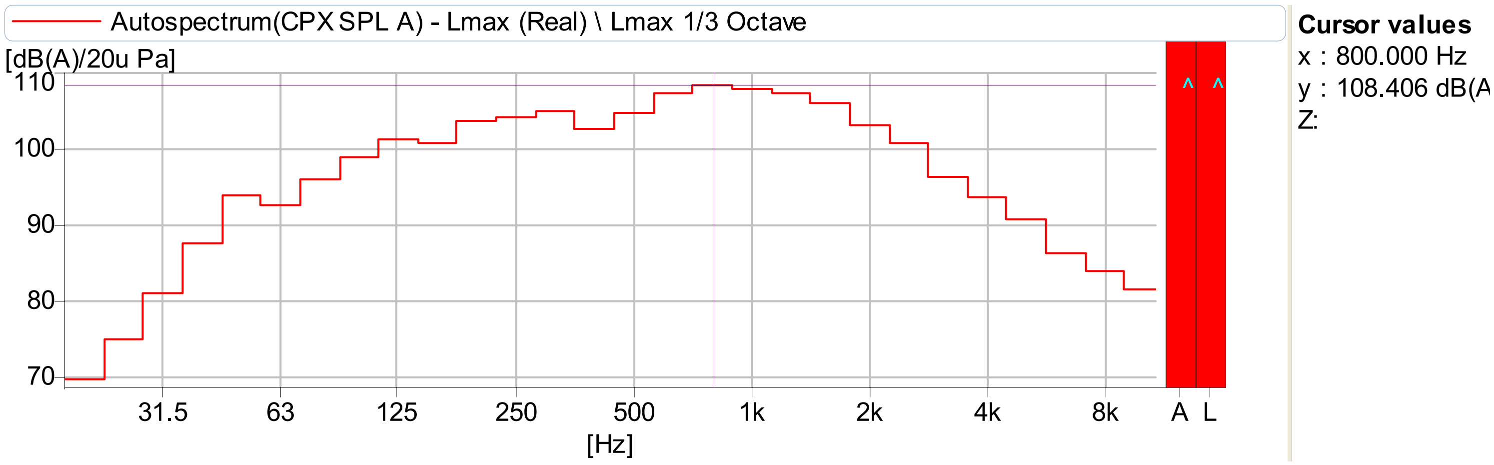
Appendix A- 28 CPX *L*eq at 100 km/h for 3-Year HL3 at CPATT Quiet Pavement Test Site.



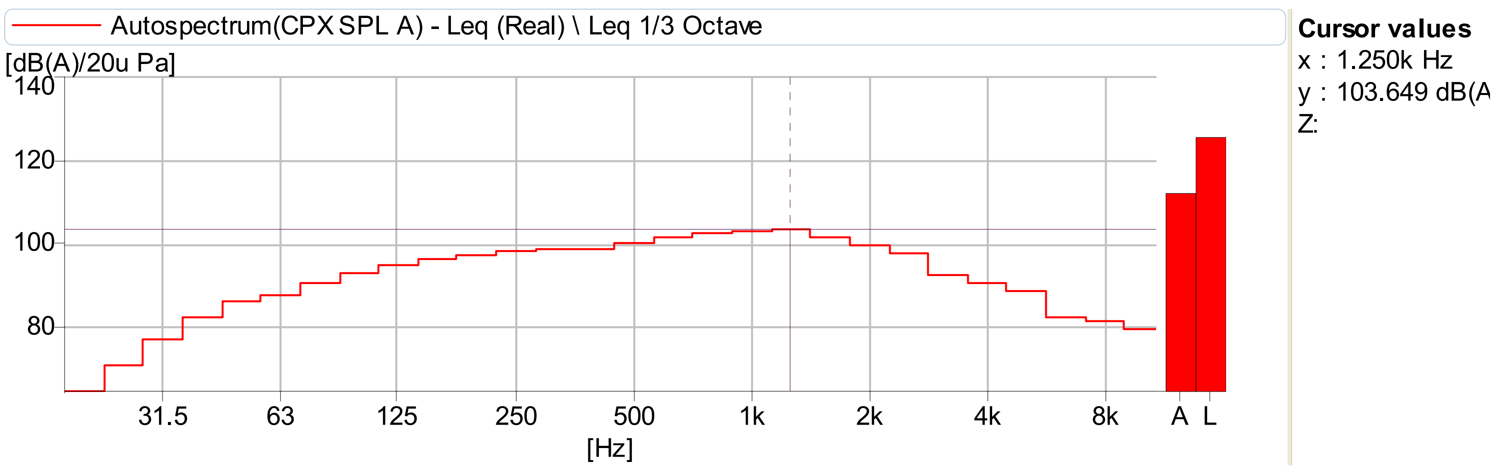
Appendix A- 29 In-vehicle *L*max at 100 km/h for 3-Year HL3 at CPATT Quiet Pavement Test Site.



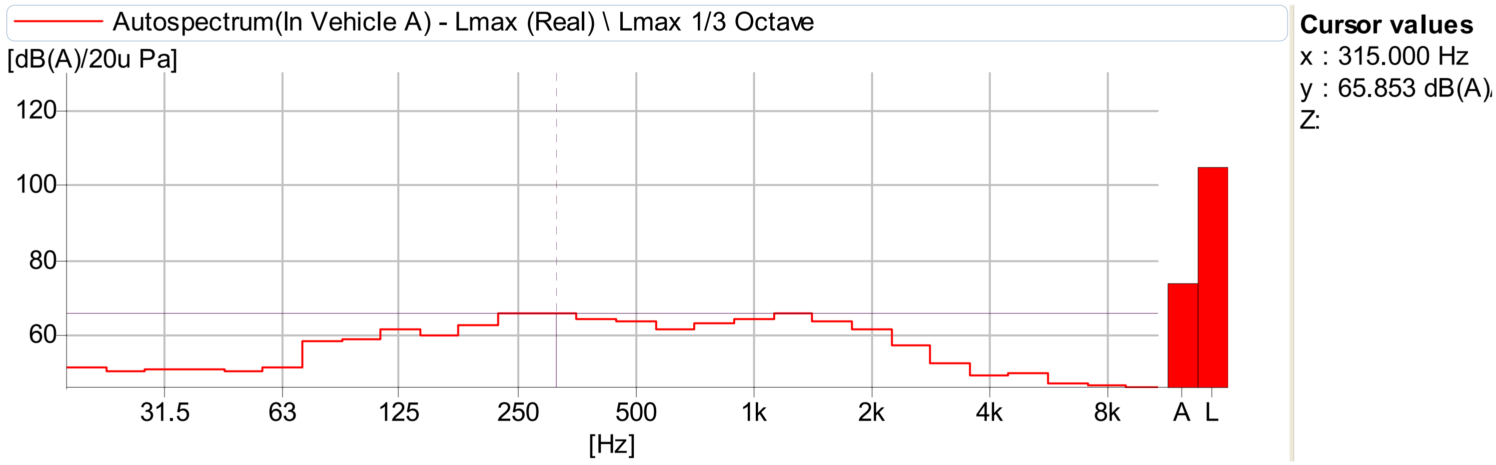
Appendix A- 30 In-vehicle *L*eq at 100 km/h for 3-Year HL3 at CPATT Quiet Pavement Test Site.



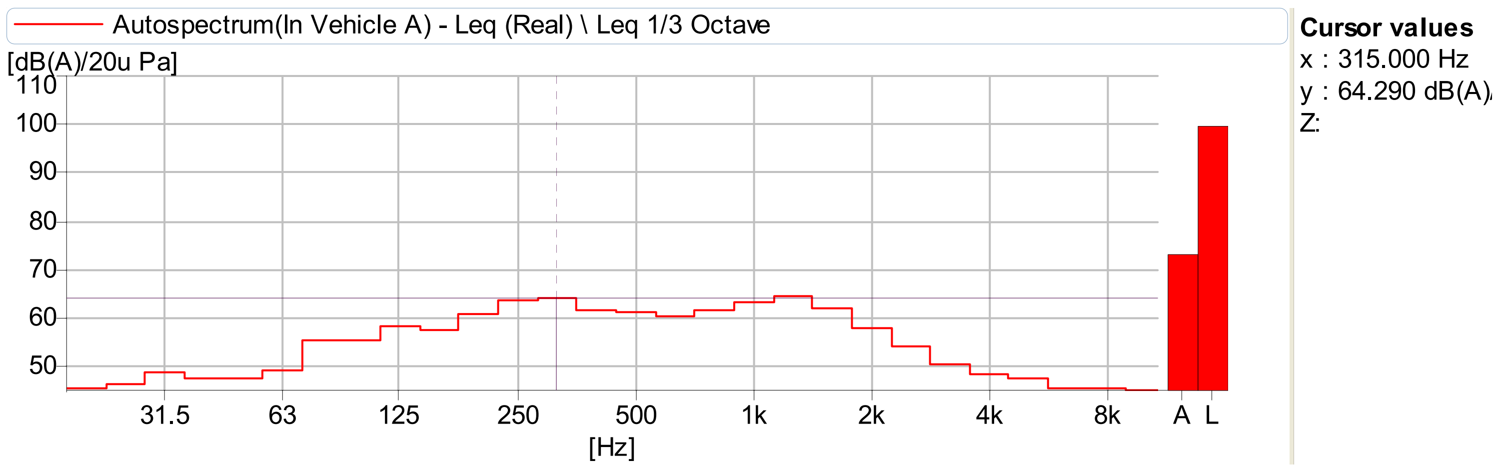
Appendix A- 31 CPX *L*max at 100 km/h for PCC Transverse Tine on Hwy 417EB in East Region.



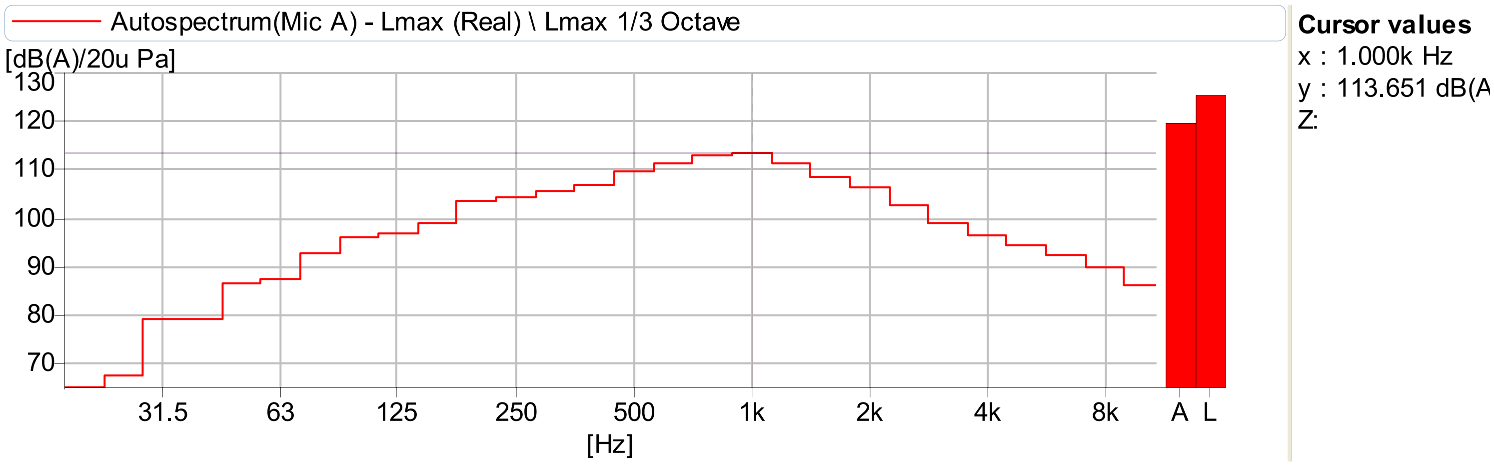
Appendix A- 32 CPX *L*eq at 100 km/h for PCC Transverse Tine on Hwy 417EB in East Region.



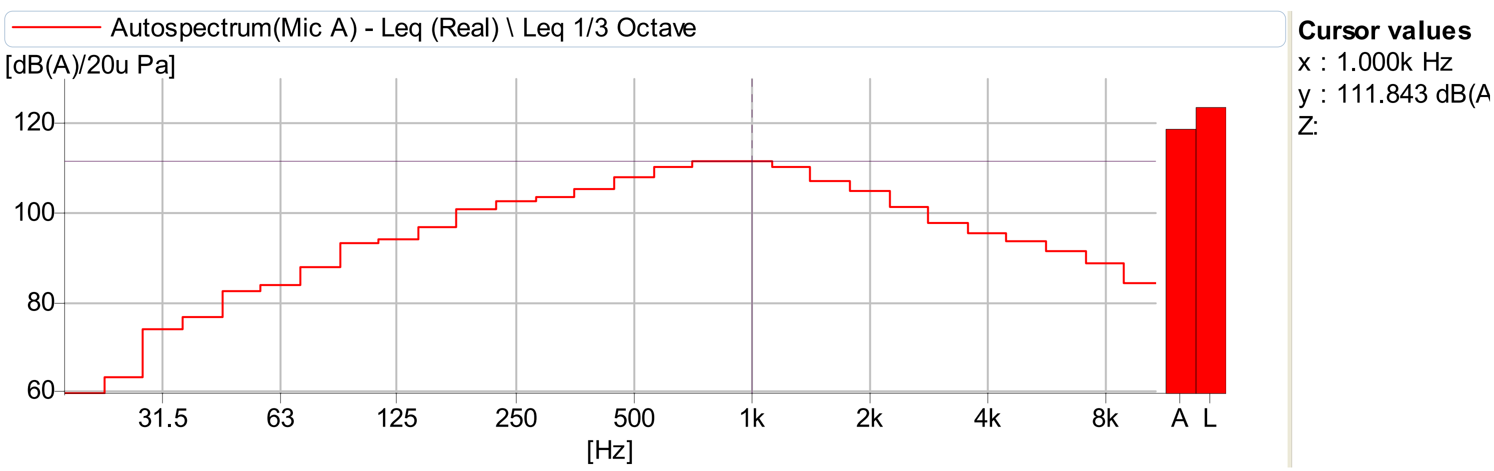
Appendix A- 33 In-vehicle *L*max at 100 km/h for PCC Transverse Tine on Hwy 417EB in East Region.



Appendix A- 34 In-vehicle *L*eq at 100 km/h for PCC Transverse Tine on Hwy 417EB in East Region.



Appendix A- 35 CPX *L*max at 100 km/h for PCC Longitudinal Tine on Hwy 401WB in West Region.



Appendix A- 36 CPX *L*eq at 100 km/h for PCC Longitudinal Tine on Hwy 401WB in West Region.

Appendix A- 37 Typical Output for Pass-by Noise (on TIP at 100 km/h) - Part I

Time	200	250	315	400	500	630	800	1	1.25	1.6	2	2.5	3.15	4	5	6.3	8	10	Max	LEQ
0.05	32.8	32.8	32.8	38.2	47.5	51.7	55.8	57.8	54.8	57.2	53.2	48.5	43.7	45.5	38.6	36.8	35.9	36.1	0	64.3
0.1	32.8	32.8	32.8	43.1	42.9	52.4	56.1	58.6	57.4	56.9	53.6	48.5	44.4	43.9	38.6	36.7	35.9	35.8	0	64.6
0.15	41.1	39.3	38.4	43.4	46.7	53.9	56.7	58.4	57.5	56.5	54.7	48.1	45.3	43.2	39.1	36.9	36.1	35.7	64.7	64.7
0.2	40.3	39.1	38.3	43.2	46.6	53.6	56.7	58	58.2	57	54.7	48.4	46.2	43	39.5	37.2	36	35.8	64.7	64.7
0.25	40	37.8	38	43.9	47.9	53.5	57.1	57.5	58	57.3	55.4	48.8	46.9	42.9	40	37.7	36.2	35.9	64.9	64.8
0.3	40.1	37.4	38.3	43.4	48.3	54.4	56.8	57.2	58.3	57.8	55	49.4	47.2	43.2	41	37.9	36.4	36	66.1	65.4
0.35	40.8	37.8	38.6	50.9	57.1	58.3	58.2	59.5	59.2	59.1	56.2	50.6	48	44.6	41.6	38.6	37	36	67.2	66
0.4	42.1	50	44.9	56.5	56.3	57.8	58.7	59.6	60.1	58.7	57.3	51.2	48.8	44.5	41.5	38.7	36.6	35.8	67.3	66.1
0.45	43.3	48	43.2	54.2	54.2	56.7	58	59.1	59.7	59.5	57.5	51.8	49.2	43.9	41.5	39	36.6	36.2	67.3	66.2
0.5	42.3	46.1	42.4	52	53.9	57.2	57.7	59.2	59.4	60	58.2	51.6	48.8	43.9	41.8	39.3	36.6	36.1	67.3	66.3
0.55	43	44.4	41.7	50.1	53	56.5	57.9	58.9	59.9	60.7	59	51.9	49.9	44.7	42.9	40.4	36.9	36.2	67.4	66.5
0.6	42.4	43.2	41.5	48.6	52.2	55.5	58.5	59.5	60.1	61.9	59.8	53	49.9	45.4	42.9	40.1	37	36.1	67.8	66.7
0.65	41.5	42.1	43	47.2	51.4	55.2	59.1	59.7	61.2	61.2	59.5	52.9	49.7	45.7	42.8	40.3	36.9	36.3	68	66.8
0.7	41.3	41.1	42	45.4	52.2	57	58.2	59.4	60.4	61.3	59.4	52.8	50.5	45.8	43.4	40.4	37.1	36.4	68	66.9
0.75	41.3	40	41.6	46.8	53	56.3	58.2	59.8	59.7	61.6	59.8	53.6	51.5	46	43.6	40.3	37.3	36.3	68.1	67
0.8	41.6	38.9	42.5	45.5	52.4	56.7	59.9	61	60.7	62.6	59.1	54.8	52	45.6	44.9	41	37.8	36.4	68.5	67.2
0.85	42.3	38.6	41.9	46.1	51.6	57.2	59.5	61.1	61.2	61.8	59.5	55.3	52.4	46.9	45.6	40.7	38	36.5	68.7	67.3
0.9	43.6	39.8	41.9	45.1	51.8	57.1	59.7	61.7	61.2	62.3	60.2	55.8	52.6	47.5	46.1	41.3	38.5	36.7	68.9	67.4
0.95	44	39.7	44.1	45.4	52.6	56.4	59.5	62.6	61.9	62.4	60.3	56.2	52.4	47.4	46.4	41.2	38.2	36.9	69.4	67.6
1	44.8	41.2	42.1	44.7	51.9	57.4	60	63.4	62.7	62.6	60.4	56	52	47.9	46.8	41.5	38.5	37.1	69.6	67.8
1.05	43.3	41.9	42	46.4	51.1	57.9	60.4	63.3	62.6	62.3	60.5	56.1	51.9	48.1	47	41.5	38.8	37.1	69.7	67.9
1.1	43.6	41.3	42.5	45.9	50.3	57.5	60.7	64.2	62.4	62.6	60.7	56.4	52.3	48.7	47.9	42.8	39.4	38	70	68.1
1.15	45	44.1	45.9	46.4	51.5	56.7	59.6	63.9	62.5	62.2	60.3	56.4	51.7	49.2	47.8	42.6	39.3	37.9	70	68.2
1.2	46.1	44.5	45.2	47.3	51.1	56.7	59.3	64.5	62.6	63.3	60.5	56.2	51.9	49.5	47.6	42.7	39.7	38.3	70.1	68.3
1.25	45.5	44	46	49.3	51.1	56.7	59.9	64.1	62	62.9	61.8	56.3	52	49.7	47.6	42.7	39.5	38.4	70.2	68.4

Note: Only Needed Information has been shown in above Table.

Appendix A- 38 Typical Output for Pass-by Noise (on TIP at 100 km/h) - Part II

Time	200	250	315	400	500	630	800	1	1.25	1.6	2	2.5	3.15	4	5	6.3	8	10	Max	LEQ
1.3	45	50.3	46.8	49.5	51.7	57.3	58	64.5	62.1	62.9	61.7	55.7	51.6	49.4	47.2	42.4	39.4	38.1	70.2	68.5
1.35	46.5	48.6	46.6	49.5	54.6	60.2	58.8	63.5	61.9	62	61.4	56.5	51.3	48.8	47.2	42	39	37.8	70.2	68.5
1.4	46.3	47.3	46.7	52.5	55.2	60.6	58.6	63.1	60.5	61.4	61	56	51.6	49.4	46.8	41.9	38.7	37.7	70.2	68.5
1.45	44.7	48.6	48.5	52.1	56.7	61.5	59.9	63.6	60.6	61	61.3	55.8	51	50.2	46.6	41.4	38.4	37.4	70.2	68.6
1.5	43.7	48.2	47.3	52	56.1	61.8	59.3	62.7	60	60.1	60.9	55.9	50.4	49.7	46	41.4	38.4	37.4	70.2	68.6
1.55	43.3	46.6	48	52.9	58.2	62.6	60.4	63.6	59.4	59.2	60.3	56.3	50.1	49	45.5	41.3	38.3	37.5	70.2	68.7
1.6	43.6	46.5	47.9	53.9	57.8	64.2	60.8	63.1	59.5	60.8	59.7	56	50	48.2	45.2	40.8	38.7	37.4	70.3	68.7
1.65	42.6	47.2	46.9	52.6	58.1	64.1	61.4	62.7	60.7	61.1	59.4	55.5	50.3	48.6	44.8	41.1	38.5	37.2	70.3	68.8
1.7	44.7	47.3	46.7	51.5	59.4	63.8	62.3	62.7	61.5	61.5	59.4	55.6	50	48.2	44.8	40.9	38.4	37.1	70.5	68.9
1.75	45.1	47.7	46.4	50.4	58.2	63.6	61.6	61.8	61.4	62	60.7	55.4	49.9	47.7	45	40.5	38	37.1	70.5	68.9
1.8	45.6	47.6	45.4	51.9	57.7	63.3	60.4	62.2	61	61.9	60	55.5	50.3	47.5	44.7	40.3	37.7	36.7	70.5	68.9
1.85	45.6	48.5	47.7	50.9	56.2	61.8	62	62.6	61.1	62.1	59.9	55.1	50.1	47.6	44.2	40.4	37.7	36.7	70.5	69
1.9	46.6	47.8	46.7	49	55.3	60.9	61.1	62.7	60.9	62.8	59.8	55.1	49.7	46.8	43.8	40.2	37.6	36.6	70.5	69
1.95	48.5	47	47.6	49.5	54.4	60.3	60.4	62.3	60.5	62.5	59.4	54.9	49.3	46.5	43.8	39.7	37.5	36.5	70.5	69
2	48.3	45.8	46.5	50.5	54	59	59.6	62.5	60.4	62.2	59.9	54.8	49.3	46.2	43.6	39.7	37.4	36.3	70.5	69
2.05	47.4	45.8	45.5	48.9	53.5	58.7	59.2	62.8	61.1	61.8	59.4	54.9	49.3	46	43.7	39.2	37.3	36.2	70.5	69
2.1	46.9	43.9	45.2	48.9	51.7	57.6	59.3	62.6	60.8	61.9	59.9	54.3	49.3	45.3	43.2	38.9	36.9	36.2	70.5	69
2.15	47.3	43.7	45.9	48.5	50.5	56.7	59.7	62.7	60	62.3	60.1	54.6	48.4	45.1	42.4	38.8	36.9	36.1	70.5	69
2.2	46.6	42.3	44.6	48	49.9	55.9	58.2	62	60.3	61.6	59.6	54	47.5	44.8	42.3	38.4	36.7	36	70.5	69
2.25	46.6	42.4	43.4	47	49.3	55.6	59.4	62.6	60.5	61.9	58.4	53.3	47.1	44.4	41.5	38.1	36.6	36	70.5	68.9
2.3	46.6	41.9	42.7	46	48	55	58.8	62	59.9	61.6	57.6	53.5	46.9	44	40.9	38.1	36.4	36	70.5	68.9
2.35	45.6	41	41.5	46.7	50.2	54	57.8	62.6	60.3	62.1	57	53	46.3	43.2	40.3	37.7	36.2	36	70.5	68.9
2.4	44.6	40.8	39.8	45.5	49.7	52.5	56.6	61.4	59.9	61.2	56.8	52.1	47	42.7	39.6	37.5	36.1	36	70.5	68.9
2.45	43.6	39.7	39.1	45.1	48.8	52.9	56.2	60.9	59.4	60.4	55.9	51.6	46.5	42.2	39.2	37.2	36.1	36	70.5	68.8
2.5	42.8	40.4	39.4	43.3	48.3	51.5	55.9	60.4	59.4	61.1	56	50.7	46.5	41.9	39.3	37.1	36	35.9	70.5	68.8
2.55	43.5	39.2	39.6	43.1	47.3	52	55.7	60.1	59.1	60	56	50	46	41.7	39.4	36.8	36.1	35.9	70.5	68.7

Appendix A- 39 Typical Output for Pass-by Noise (on TIP at 100 km/h) - Part III

Time	200	250	315	400	500	630	800	1	1.25	1.6	2	2.5	3.15	4	5	6.3	8	10	Max	LEQ
2.6	42.4	41.3	38.9	42.4	49.2	52	55.9	59.3	59	58.8	55.4	49.2	45.2	41.4	38.8	36.5	35.9	35.7	70.5	68.6
2.65	41.5	40.2	38	43	48.5	51.3	54.8	57.9	58.7	58.6	54.6	48.6	44.4	40.9	38.2	36.1	36	35.5	70.5	68.6
2.7	40.8	40.6	38.4	42.3	49.1	50.5	55.1	57	58.4	58.4	54.4	48.4	44.6	41	38	36	35.9	35.7	70.5	68.5
2.75	39.7	39.4	37.6	41.9	48.9	50	53.8	58.2	57.9	58.5	53.8	48.3	44.2	40.7	37.5	36.1	35.9	35.8	70.5	68.5
2.8	39.4	39	38.3	42	47.8	49.6	53.3	57.1	57.9	58.1	53.5	47.6	43.3	40.2	37.3	36.1	35.9	35.7	70.5	68.4
2.85	38.3	38.1	37.3	41.3	47.6	49.9	52.7	57	57.5	57.7	52.6	47.2	42.8	39.9	37	35.8	35.9	35.7	70.5	68.4
2.9	37.6	38.5	36.6	40.4	46.8	49.9	52.8	57.3	56.8	56.8	52.9	46.8	42.6	39.2	36.7	36	36	35.6	70.5	68.3
2.95	37.8	39.4	36.5	40.4	45.8	49.7	52.8	56.2	56.7	56.4	52.7	46.4	42.3	39.2	36.4	36.1	35.8	35.6	70.5	68.3
3	38.2	38.4	36.5	39.9	45.3	49.6	53	55.5	56.6	56.6	51.9	45.9	41.7	38.5	36.2	36	35.7	35.7	70.5	68.2