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Non-Contact Skid Resistance Measurement

FINAL REPORT
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Submitted by

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16. Abstract

In this research, a correlation between the SN40R collected by locked wheel skid tester and the texture data or Mean Profile Depth (MPD) collected by a vehicle mounted laser operating at highway speeds was developed. The proposed correlation between SN40R and MPD is positive for MPD values less than 0.75 mm to reach a peak SN40R value, then it becomes a negative correlation of decreasing SN40R values with increase in MPD values until the MPD values reached 1.15 mm, which was the maximum value measured in this research. However, the slope of the negative correlation becomes smaller with increasing MPD. It was also observed that there is significant data scatter for the MPD value of 0.8mm. The test result showed a similar trend for old asphalt pavements, but with lower SN40R values due to polishing of pavement micro-texture by traffic. Based on the comparison between old and new asphalt pavements, reduction coefficients, which is a functions of road treatment time and traffic volume was developed to account for the traffic polishing effect on micro-texture of pavement.

This report also describes two field tests performed to validate the above correlation and development of an interface for the PMS to upload the predicted skid data from texture data obtained from high speed laser. During the field tests, MPD values and SN40R were collected by a vehicle mounted laser and a locked wheel skid trailer, respectively. Then the comparison between predicted SN40R by using the developed correlation between SN40R and MPD and measured SN40R are conducted. For the prediction of SN40R, reduction coefficient, which is a function of traffic volume and pavement age (treated or refurnished age), were used to take into account the polishing effect traffic on micro-texture of the pavements. The results show that the measured and predicted SN40R values match each other very well with the maximum variance between them less than 5. Based on the validated correlation between MPD and SN40R, an interface for the PMS was developed to extract and process MPD data collected by vehicle mounted laser and report predicted skid number to NJDOT pavement management system.

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LIST OF ABBREVIATIONS AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing of Materials
CTM	Circular Track Meter
DFT	Dynamic Friction Tester
DOT	Department of Transportation
ETD	Estimated Texture Depth
FHWA	Federal Highway Administration
HMA	Hot Mix Asphalt
HSTS	High Speed Texture System
ICC	International Cybernetics Corporation
IRI	International Roughness Index
JMF	Job Mix Formula
MLP	Multi-Laser Profiler
MMSD	Mean of the Sean segment Depths
MP	Mile Post
MP	Materials Procedure
MPH	Miles per hour
MPD	Mean Profile Depth
MSD	Mean Segment Depth
MTD	Mean Texture Depth
NCHRP	National Cooperative Highway Research Program
NJDOT	New Jersey Department of Transportation
PC	Personal Computer
QC/QA	Quality Control/Quality Assurance
RMS	Root Mean Square
RN	Ride Number
RSP	Road Surface Profiler
SN40R	Skid Number measured at 40MPH using ribbed tire
SPT	Sand Patch Test
TFHRC	Turner-Fairbank Highway Research Center

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INTRODUCTION

Pavement texture is the controlling factor in the skid-resistance level of roadway surfaces. Through a complex interaction of micro and macro textures at the pavement-tire interface, sufficient friction is needed for vehicles to perform routine maneuvers under normal operating conditions. To obtain more complete data on texture, a non-contact high-speed method was developed to permit the collection of pavement data from a vehicle moving at highway speeds. This method can be correlated with Circular Texture Meter (CTM) test procedure presented in ASTM E2157 to validate macro-texture measurements. These methods combine existing designs for the measurement of macro-texture. The correlation of macro-texture measurements with skid resistance values could allow the New Jersey Department of Transportation to estimate skid values of the pavement network while collecting pavement ride quality data for the PMS with one piece of equipment on an annual basis. This will significantly reduce the need for the ASTM E274 skid resistance trailer to collect the skid resistance data over a two year period. The screening of the state's pavement network would allow detailed measurement of the pavement-tire interface with ASTM E274 skid resistance trailer.

OBJECTIVES AND SCOPE OF WORK

The objectives of this study were to:

- Develop a vehicle-mounted screening device to measure variations in pavement texture using a non-contact high-speed method.
- Correlate that with CTM test procedure presented in ASTM E2157 to validate macro-texture measurements.
- Recommend development of NJDOT specification for implementation of the surface texture measurement methods.

LITERATURE SEARCH

Pavement texture is the feature of the road surface that ultimately determines most tire road interactions, including wet friction, noise, splash and spray, rolling resistance, and tire wear. Pavement texture has been categorized into three ranges based on the wavelength of its components: micro-texture, macro-texture, and mega-texture (Table 1).[50] Wavelengths longer than the upper limit of mega-texture are defined by the term roughness or evenness.

Surface roughness in highway pavements results from several differing material and construction properties.[16] The choice of rock type contributes to micro texture of the aggregate where the mixture type adopted is largely contributing to the macro-texture of the road surface, see Figure 1. The tire contact with the road surface relies principally on the micro-texture to prevent skidding and by careful selection of aggregate type. However, this micro-texture must be maintained throughout the year with various differing climatic conditions. In periods of heavy rain micro-texture can be lost by surface water.[46] Micro-texture is defined as a surface-roughness quality on the sub-visible or microscopic level. Micro-texture, a function of the aggregate particle properties, is not measured directly in the field. Micro-texture levels are commonly estimated using low speed friction measurement devices, such as the British Portable Tester[3 and 47] or the locked wheel skid trailer[2] when testing is performed at low speeds. Earlier research has indicated that measurements conducted using the ribbed tire[4] are highly sensitive to the micro-texture properties of the pavement surface and thus are good estimators of pavement micro-texture.

Table 1: Texture Classifications

Texture Classification	**Relative Wavelengths**
Micro-texture	$\lambda < 0.5$ mm
Macro-texture	0.5 mm $\lambda < 50$ mm
Mega-texture	50 mm $\lambda < 500$ mm
Roughness	0.5 m $\lambda < 50$ m

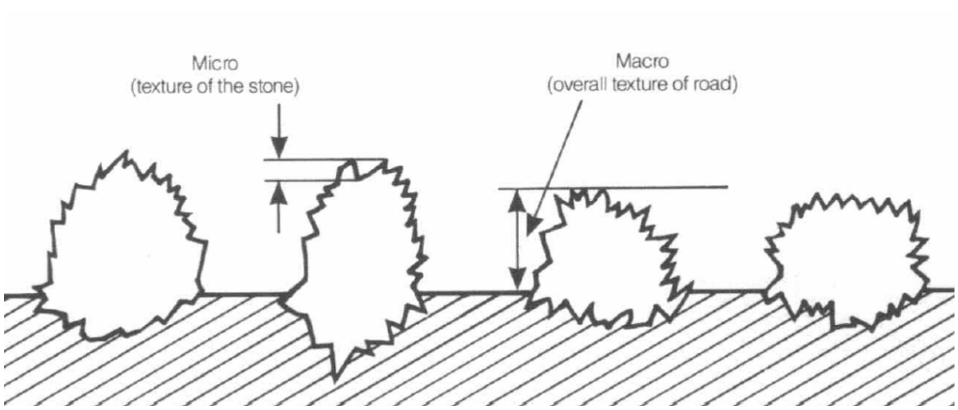


Figure 1: Micro and Macro Texture

Macro-texture is largely dependent on mixture type. Some surface treatments – such as chip seals and surface dressings can provide sufficient macro-texture. Recently, the adoption of noise reducing surfaces such as friction courses or thin surface treatments (e.g. Nova-chip and similar products) provide a macro-texture, sometimes termed as a negative macro-texture, which also allow for the rapid removal of surface water. With concrete pavements the macro-texture is achieved by tinning, grooving and other methods to provide removal of surface water. The macro-texture of a pavement surface results from the large aggregate particles in the mixture. The ability of macro-texture to contribute to skidding is adversely effected by surface water which can lead to significant reductions. Consequently, a key role of the macro-texture is to provide a means for removal of this surface water as tires transverse the pavement structure.[44]

Macro-texture is measured statically by using dynamic measurements. Common static macro-texture measurement methods include the sand patch method, the outflow meter, and the circular texture meter. The sand patch method [6] is a volumetric approach to measuring pavement macro-texture. A known volume of sand material is spread properly on a pavement surface to form a circle, which fills the surface voids with sand. The diameter of the circle on which the sand material has been spread is measured and used to calculate Mean Texture Depth (MTD). The repeatability of this test is significantly affected by the operator and choice of locations for performing the test.

Vehicle-mounted laser devices are typically used to measure macro-texture without disrupting traffic flow. A standard method for determining pavement macro-texture from a pavement profile is provided in ASTM E1845. The measured profile of the pavement macro-texture is divided for analysis purposes into segments, each having a base-length of 100mm. The slope, if any, of each segment is suppressed by subtracting a linear regression of the segment. The segment is divided in half and the highest peak in each half segment is determined. The difference between the resulting height and the average level of the segment is calculated. The average value of these differences for all segments making up the measured profile is reported as Mean Profile Depth (MPD).

The primary objective is to estimate the skid resistance via measurement of pavement texture. The skid number (SN) which is a measure of skid resistance at the measured speed is related to the pavement friction as shown below:

$$SN = 100\mu = 100\left(\frac{F}{W}\right) \tag{1}$$

where;

SN = Skid number
μ = Friction coefficient
F = Tractive force applied to the tire
W = Vertical load applied to the tire

Traffic flow will significantly effect the polishing of a surface and reduction of skidding resistance. The use of an aggregate type which resists the polishing will greatly enhance the maintenance of any skidding performance over time. The effect of polishing will not necessarily be captured by texture measuring devices, which capture the macro-texture but are more dependent upon the aggregate types used. In the northern part of New Jersey aggregates used are hard rock. Consequently, it is possible that local deviations in texture and skidding performance will exist. In addition, several mixture types have been used from dense graded asphalt to open textured surfacing. Each material type and aggregate type may need to have a specific correlation developed or a modified form of a general model.

SURFACE TEXTURE MONITORING METHODS

The surface texture measurement can be made with traditional method such as sand patch test [6], circular track meter test [8] or immerging methods such as using LASER with vehicles traveling at highway speeds. A brief description of each method is given below.

Sand Patch Test (SPT)

The sand patch test (Figure 2) has been used to quantify visual observations of differences in the surface macro-texture. The ASTM E965 test method indicates that the precision of the test method is approximately one percent of the measured depth in millimeters and the operator variation is about two percent. Good correlation was found between visual observations of non-uniform textured areas and the sand patch test results for measuring surface macro-texture. The sand patch method measures the mean texture depth (MTD).

Figure 2: Sand Patch Method

Circular Track Meter (CTM)

The CTM, see Figure 3, uses a laser to measure the profile in an 800-mm circumference circle. The mean depth of texture for each 100-mm segment of the arc is computed according to ASTM standard practice. The averages of depths of the two arcs perpendicular to the traveled direction and the two arcs parallel to it are computed. The CTM consists of a charge coupled device (CCD) laser-displacement sensor which is mounted on an arm that rotates such that the displacement sensor follows a circular track having a diameter of 284 mm (11.2 in.). The CTM (Figure 3) is designed to measure the same circular track that is measured by the Dynamic Friction Tester (DFT).

The CTM can be used both for laboratory investigations as well as in the field on actual paved surfaces. The software developed for the CTM reports the Mean Profile Depth (MPD) and the Root Mean Square (RMS) values of the macro texture profiles. The values stated in SI (metric) units are to be regarded as standard. Hanson and Prowell, 2004 conducted an extensive evaluation of this device with comparisons against sand patch measurements. They concluded that “the CTM produces comparable results to the ASTM E965 Sand Patch Test. When open-graded mixtures were excluded, this study indicated that the offset was non-significant between CTM and Sand Patch test results. The slope of the best fit line comparing the results was statistically significant, and ranged from 0.93 to 1.01. Thus, when comparing CT Meter and Sand Patch test data, the CTM data should be multiplied by a factor of 0.93 (2003 data) or 1.01 (2000 data) to produce comparable Sand Patch MTD values.”

Figure 3: Circular Track Texture Meter

LASER With Vehicles Traveling At Highway Speeds

Over the past twenty years the use of laser technology to define surface texture has been gaining wide popularity. The basic concept of the measurement system is illustrated in Figure 4. Using mathematical algorithms, the distance to the surface at a discrete point is obtained. The measurements are conducted very rapidly as the vehicle drives along the pavement enabling measurements at points that can be typically separated by 0.25 mm (1/100-inch) defining a surface profile as illustrated in Figure 4. The sampling rate of commonly used lasers is 62.5 kHz. Liu et al., 2001 developed a laser that operates at 178 kHz. Figure 5 shows a photo of Selcom laser, which is a widely used brand.

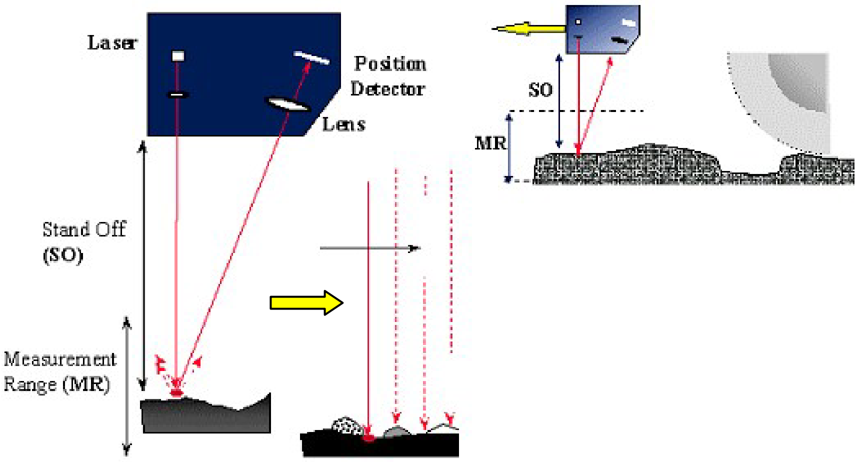


Figure 4: Schematic Representation of Surface Texture Laser

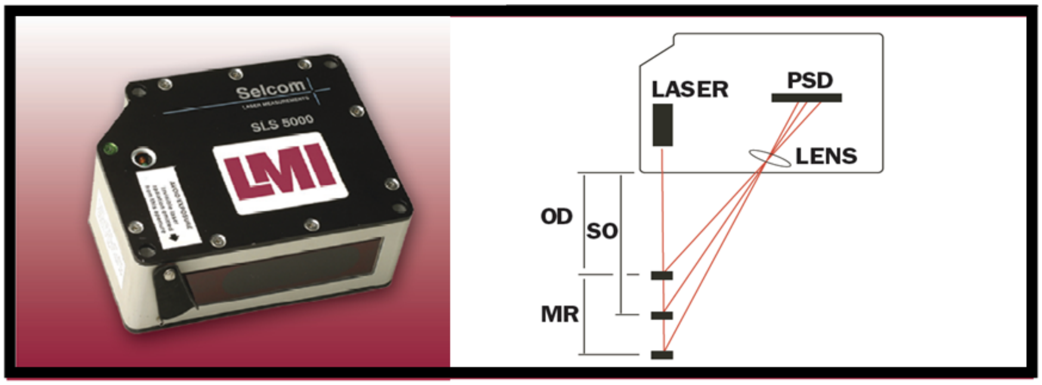


Figure 5: Selcom Laser

Selcom laser is based on high speed triangulation principle and has sophisticated fast automatic light control. It is designed for high accuracy measurements on difficult target materials with most flexible sensor available. It has a built-in processor for data averaging and filtering allows for a variety of data and analog outputs. Fast sampling rate at 62.5 kHz provides information other sensors might miss and has rugged industrial package. Applications exist for diffuse, shiny and dark targets demanding high accuracy and reliability in such industries as electronics, steel, semi-conductors, pulp and paper and building products. While not a complete system, lasers of this type are routinely used within the transportation industry for texture measurement. The assessment of texture with vehicle mounted laser measuring devices is well established and a number of commercial devices are available. Several companies' market equipment that can be vehicle mounted. A few of these are briefly summarized in the following pages, with abstracts from the manufacturer's information.

Dynatest

The Dynatest Road Surface Profiler (RSP) (Figure 6), Denmark, is designed to provide an advanced automated high quality pavement roughness and related measurement solution for engineers world-wide. The RSP performs continuous highway-speed measurements of longitudinal and transverse profile, including real-time roughness (IRI and Ride Number), rut depth and texture evaluation, GPS, and geometrics. This product line is available in several levels of sophistication, ranging from top-of-the-line version (with 11 laser sensors standard or up to 21 lasers on special order) down to 1 laser, single wheel path version for real-time longitudinal profile/IRI/RN (and optionally texture) evaluation only. The automated system for distress survey covers 100% of pavement surface at the transverse resolution of about 4,000 pixels, produces crack map (location & geometries), and classifies longitudinal, transverse, block, & alligator cracks. Both data acquisition and processing can be conducted real-time on-board at speed up to 60 MPH. It applies distress protocols & indices such as the AASHTO protocol, Universal Cracking Indicator (CI), and Texas DOT method. It is able to detect 1-mm wide cracks. The INO LRIS combines a line scan camera with laser illumination requiring only 200 Watts. Some of the features of Dynatest RSP are:

- High resolution digital images for pavement surface and right-of-way (ROW).
- Automated distress analyzer (ADA, 1mm resolution automated crack analysis).
- Longitudinal and transverse profiling (IRI and rutting)
- Differential GPS, inertial positioning, distance measurement instrument (DMI).
- Multimedia based highway information system (MHIS) and report writer.

Figure 6: Dynatest RSP

<u>Greenwood Engineering</u>

The Profilograph system, manufactured by Greenwood Engineering, Denmark (Figure 7), is installed in a standard vehicle. The Greenwood Profilograph is a pavement survey system used by road authorities and national road research institutes for pavement condition surveys. Transversal and Longitudinal profile combined in one 3D profile. The high precision sensors, digital data acquisition and processing enables highest possible result quality. The devise can be configurable to meet customer requirements. Configurations can include; full inertial system with more than 40 lasers, texture sensors and GPS. The digital data acquisition is Ethernet based and allows subsystems, such as GPS, Surface

Imaging and ROW Imaging, to be added and synchronized. Profile analysis equipment is essential to modern pavement maintenance optimization. The Profilograph system uses up to 48 laser profile sensors combined with advanced data acquisition and analysis techniques to provide detailed 3D information about pavement surface conditions. Plug-ins with user-specified algorithms can be delivered. Reports include longitudinal and transverse profiles, rut depth, cross-fall and gradients, radius of curvatures (vert. and horiz.), IRI, APL, SV, straight edge, and GPS.

Figure 7: Greenwood Engineering Profilograph

ARAN

The ARAN Automatic Road Analyzer (Figure 8) manufactured by Roadware, Canada and now Fugro-Roadware, was first delivered to Autostrade, Italy, in 1984. Today, over seventy-five agencies in over fifteen countries use ARAN's state-of-the-art technologies to increase the cost effectiveness of their data collection activities. ARAN provides information to support better management decisions by collecting consistent, accurate data quickly and cost effectively. A wide variety of data can be collected continuously at highway speeds.

Figure 8: ARAN Automatic Road Analyzer

The ARAN Automatic Road Analyzer can collect the following information while traveling at highway speeds.

- Longitudinal profile/roughness (IRI).
- Transverse profile/rutting.
- Grade, cross-slope.
- Pavement texture (ARAN, 2000).
- Pavement condition or distress.
- GPS coordinates.
- Panoramic right-of-way video (tape or disk).
- Pavement video.
- Feature location.

WDM – Multifunction Road Monitor

WDM, United Kingdom manufactures a Multi-Function Road Monitor that includes a High Speed Texture System (Figure 9) that has been designed to provide an economic method of routinely monitoring the macro texture of road networks. WDM has also developed a hand-held device, which measures texture at walking speed. The Multifunction Road Monitor measures and records in a single pass at normal traffic speeds:

- Roughness in the left-hand wheel path.
- Texture in both wheel paths and lane center.
- Gradient, horizontal radius of curvature and cross-fall.
- Wheel path ruts.
- Video record at 5m intervals.

Figure 9: WDM – Multi-function Road Monitor

Mandli Road Surface Profiler

The Road Surface Profiler (RSP) (Figure 10) is capable of real-time continuous highway speed measurements of longitudinal profile elevations, International Roughness Index (IRI), Slab Faulting, and Texture. The RSPs longitudinal profile measurement is based on the South Dakota method. The system allows the operator to view real-time profile data in both wheel paths in a graphical display allowing for verification of data collection. System will include the following specifications:

- System ambient operational temperature range: 0^0C to + 40^0C(+32^0F to +105^0 F).
- Two laser sensors are transversely adjustable to any width of 1.50m to 2.00m (60ft to 79ft).
- Vertical displacement measuring resolution of the laser sensors: 0.05mm (+/- 2 mil).
- System collection speed: 22 to 110 km/h (15 mph to 70 mph).
- Texture wavelengths: Min: 0.2 inch to Max: 2 inch.

Figure 10: Mandli Road Surface Profile (RSP)

<u>ARRB</u>

Australian Road Research Board (Figure 11) manufactures a range of laser profilers that include a multi-laser and a more limited portable system. The 2000 series is a professional, highly featured and highly specified range of survey products designed to meet the most demanding of survey applications. Typically fitted to a dedicated survey vehicle, the modular, yet integrated design allows for complete scalability and growth. The 2000 series consists of a suite of individual packages designed to provide seamless options. This enables user to choose the exact product mix to suit their immediate budget and need. The Digital Profiler Package (DP) package can be configured with a variety of sensor systems to enable the collection and reporting of data for Longitudinal Road Profile, Road Roughness, Slab Faulting, Macro-texture, Transverse Profile and Rutting. Modular design allows for product expansion to meet growing needs and the adoption of new technologies

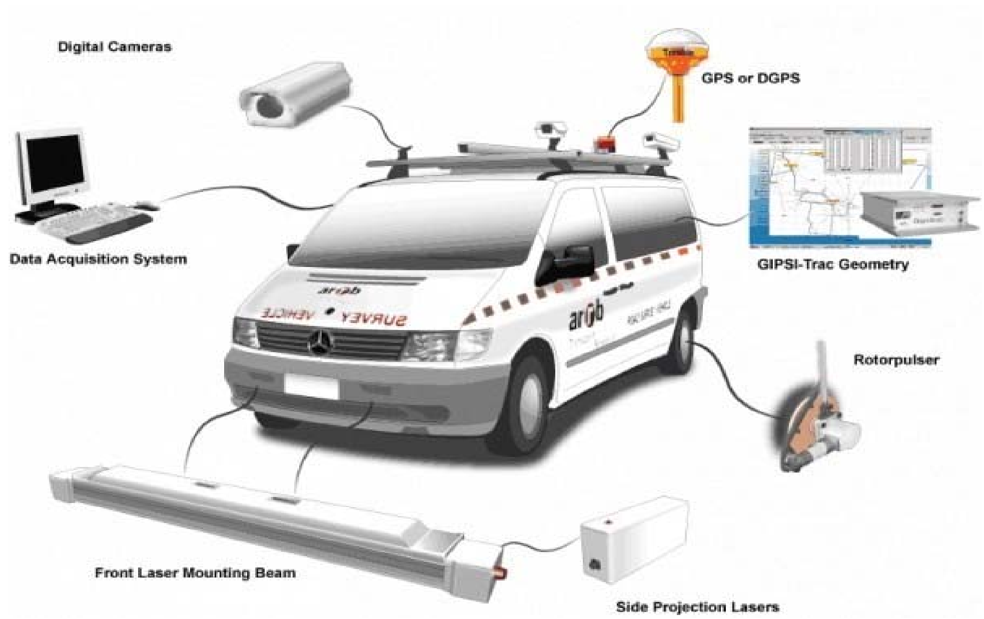


Figure 11: ARRB Multi-Laser Profiler

SSI High Speed Profiling Systems

Collects surface profile data safely at speeds from 5 mph to 70 mph with SSI's ASTM E950 certified Class I Profiler (Figure 12). Guaranteed to meet or exceed agency specifications and certification requirements (including TXDOT Test 1001-S and AASHTO PP51-02). SSI's high speed profiler is proven to be more accurate than any profiler in the industry in re-creating actual surface profile and the physical dimensions of localized roughness. The SSI high speed profiling system is offered in a variety of configurations, including (1) Robust Front Mount System installed on the front or rear of industry standard vehicles (Figure 12), (2) a portable rear mount system that transmits profile data by RF radio, requiring no wiring other than a 12V power supply, or (3) a custom mid-mount system with data collection modules embedded between the cab an rear wheels of standard pick-up trucks. SSI representatives assist with installation and configuration of the high speed systems, which consist of collection sensors (lasers and accelerometers), a distance measurement subsystem, a proprietary data collection computer, and an in-cab operator station. Windows based software routines can be safely operated by one person using touch-screen controls, on-screen viewing of data collection and immediate test results. Single laser systems can display dual wheel paths (patented). The optional GPS subsystem correlates profile data with GPS coordinates. The system allows easy transfer of electronic format data for downloading in field or viewing on desktop computer.

Figure 12: SSI High Speed Profiling System

SKID RESISTANCE MONITORING METHODS

Skid resistance is the force developed when a tire that is prevented from rotating slides along the pavement surface. Skid resistance is an important pavement evaluation parameter because:

- Inadequate skid resistance will lead to higher incidences of skid related accidents.
- Most agencies have an obligation to provide users with a roadway that is "reasonably" safe.
- Skid resistance measurements can be used to evaluate various types of materials and construction practices.

Skid resistance changes over time. For asphalt pavements, it typically increases over the first two years following construction as the asphalt binder is worn away by traffic, then decreases over the remaining pavement life as aggregates become polished. Skid resistance is also typically higher in the fall and winter and lower in the spring and summer. This seasonal variation is quite significant and can severely skew skid resistance data if not properly compensated. Skid resistance can be measured using a variety of devices, some of which are described below:

Locked Wheel Skid Trailer (ASTM E 274)

The locked wheel skid trailer (Figure 13) is used mostly to estimate the skid resistance. It measures wet friction at slip speed which is equal to velocity of test vehicle. Ribbed tire allows for differentiation of macro texture effects on friction.

Figure 13: Locked Wheel Skid Tester

Dynamic Friction Tester (DFT) (ASTM E-1911)

The Dynamic Friction Tester (Figure 14) conforms to Standard Test Method for Measuring Paved Surface Frictional Properties. The DFT has three rubber sliders that are spring-mounted on a horizontal rotary disk at a distance of 350mm. The disk is initially suspended above the pavement surface and is driven by a motor until the tangential speed of the sliders is 90 km/h. Water is then applied to the pavement surface by the device, whereupon the motor is disengaged and the disk is lowered to the test surface. The three rubber sliders contact the surface and the friction force is measured by a transducer as the disk spins down. The friction force and the speed during the spin down are saved to a file. This results in a continuous spectrum of dynamic coefficients of friction. The equipment reproduces actual speeds between 0-80 km/hr and surface bearing loads of vehicles commonly in use.

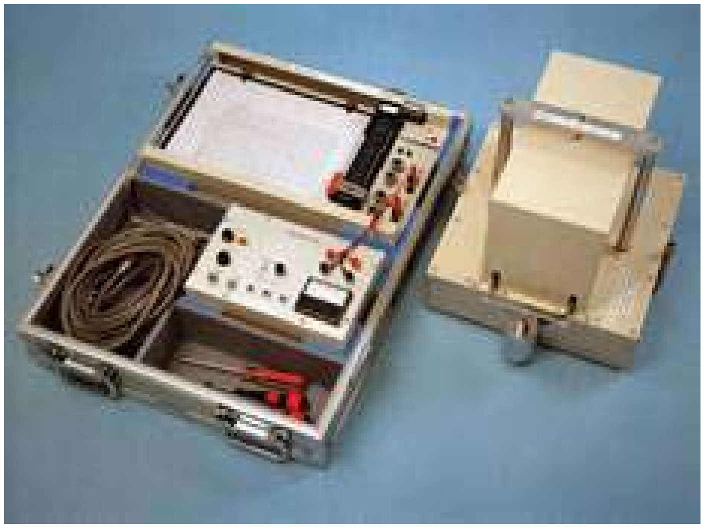


Figure 14: Dynamic Friction Tester

Sideway-force Coefficient Routine Investigation Machine (BS 7941-1:2006)

The SCRIM device (Figure 15) was developed by the Transport and Road Research Laboratory in the United Kingdom and is used to measure the wet skidding resistance of a road surface. The measurements of skidding resistance recorded by the SCRIM can be used to identify lengths of road that are at or below investigatory levels defined for particular road categories. The SCRIM device is in use in several countries around the world, such as New Zealand, Australia and other locations with close ties to the United Kingdom. The device is ideal for network skidding resistance surveys and has a daily survey capacity of 200 to 300 km’s depending upon road type.

Figure 15: SCRIM device

PAVEMENT SKID RESISTANCE AND TEXTURE MEASUREMENT CORRELATIONS

The measurement of roadway frictional properties can be accomplished by using the various types of equipment described above. The most common method in use in the USA is the locked wheel device as described by ASTM E274. However, other devices are often used such as the British Portable Tester [(3)] also referenced as Portable Skid Resistance Tester (SRT).

Do et al., 2000 demonstrated that laser measured texture can be related to friction as determined by the SRT (Portable Skid Resistance Tester). This result, although based on limited data shows the potential of using laser, with a small dot size, data to screen highways systems. The dot size being very small may be more related to the micro-texture of the stone rather than a macro-texture and some caution should be used with this data. A correlation of 0.84 was reported which is reasonable for data of this kind.

A study conducted by Virginia Tech on mixtures used in surface courses on the Virginia Smart Road project has yielded relationships between mixture parameters and mean profile depth (MPD) which has been related to frictional parameters. In this study the locked wheel friction measurement device [(2)] was used to determine the fraction characteristics and an International Cybernetics Corporation laser texture device was used to measure the texture properties.

A limited study that assessed the relationship between MPD and texture depth measured with sand patch was also conducted. In this study the results indicated that a different relationship may apply than that given in ASTM E1845 as illustrated in Figure 16. [(34)]

In the analysis conducted by Davis, 2001, relationships have been established between key mixture variables, texture and skidding. These are briefly described as follows:

Mean Profile Depth Analysis - The regression analysis of the laser MPD measurements resulted in a relationship between aggregate nominal maximum size (NMS) and voids in mineral aggregate (VMA) with a r^2 value of 0.965 (RMSE = 0.123), as follows:

$$\mathrm{MPD} = -2896 + 0.2993(\mathrm{NMS}) + 0.0698(\mathrm{VMA}) \qquad (2)$$

Where:

MPD = Mean Profile Depth (mm)
NMS = Nominal maximum size of aggregate (mm)
VMA = voids in the mineral aggregate (%)

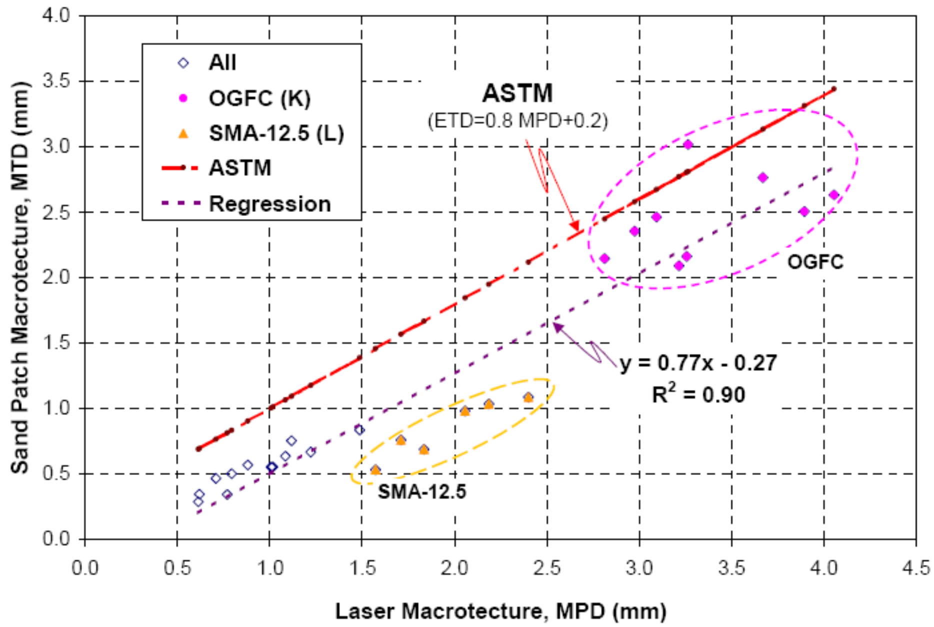


Figure 16: Correlation between Sand Patch and Laser Macro texture Measurements

The analysis of the calibrated Friction Number F60 led to the development of the equation as follows:

$$F60 = 0.38189 - 0.02962(\text{Tire}) + 0.01295(\text{Binder}) + 0.00911(\text{PP200}) + 0.00897(\text{VTM}) \qquad (3)$$

Where:

F60 = Friction parameter of the International Friction Index
Tire = Tire type, (0 or 1 depending on smooth or ribbed)
Binder = Binder code (Binder Type: (-1) for PG 64-22, (0) for PG 70-22, (1) for PG 76-22)
PP200 = Percent passing #200 sieve, and
VTM = Total voids in the mixture.

It should be noted that above equation has a relatively low value of correlation and in addition the correlation (r^2 = 0.412, RMSE = 0.048). However, this does establish that the measurements from laser texture devices can be directly translated into skid numbers.

Flintsch et al., 2003 further developed this study by reviewing the work produced by Stroup-Gardiner and an earlier relationship with ETD (estimate of the MTD using the ROSAN laser) which related the predicted texture to seven aggregate gradation parameters. Flintsch et al., 2003 concluded that the earlier relationship did not work adequately (Figure 17) when applied to the range of mixtures used in the Virginia Smart Road project.

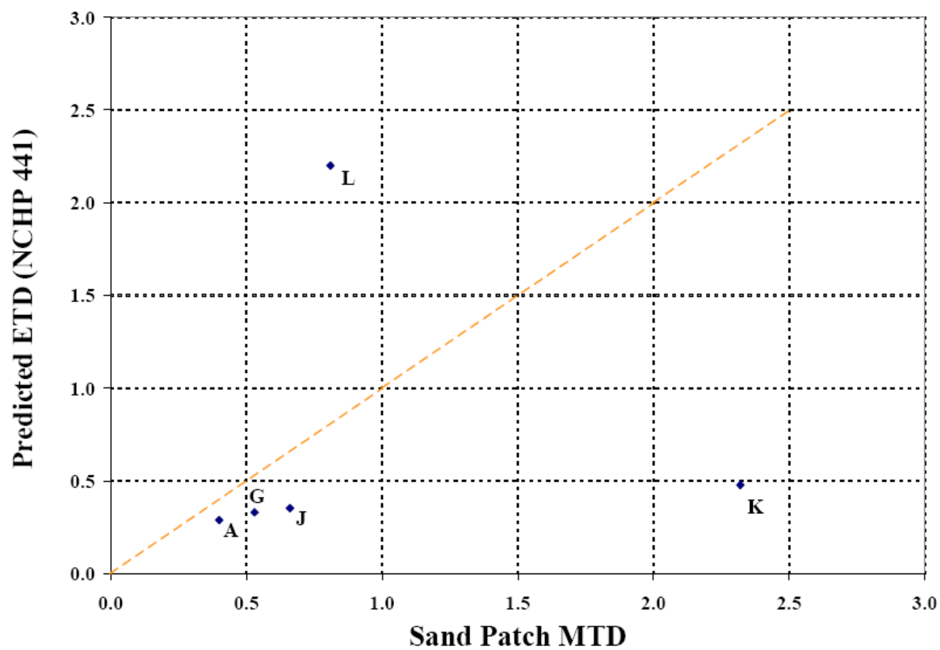


Figure 17: Measured versus Predicted Microtexture using NCHRP 441 Model

Previous work conducted at NJIT presented similar data with a laser technique was used to evaluate texture on roads in New Jersey but in this instance, the laser is used to detect segregation in pavement structures. This study presented the data in terms of an evaluation of frequencies distributions of data for a limited number of sites in New Jersey.

Recently, a study was conducted by Viner et al., 2006 relating texture and skidding performance in the United Kingdom. Viner et al., 2006 suggested that the measurement of texture does not correlate to skidding. However, they also point out that the two methods of measurement they considered are really more appropriate for low speeds. In addition, it should be noted that a large range of materials have been included in this study and when various material factors are considered then the correlations that can be produced may improve.

RESEARCH METHODOLOGY

Our literature search shows that when pavements are wet collisions occur at a rate 3.9 to 4.5 times higher than that on dry pavements.[40] Though wet skid resistance alone can't predict the accident rates as many other factors contribute to accidents, including pavement condition state, prevailing speed, and traffic volume .[30 and 49] There is a statistically significant correlation between skid resistance and the wet accident rate, where the wet accident rate increases with decreasing skid numbers. Cairney, 1997 and Giles et al., 1962 found that the risk of a skid related crash was small for friction values above 60 but increased rapidly for skid resistance values below 50. Meanwhile, McCullough and Hankins, 1966 recommended a minimum desirable friction coefficient of 0.4 measured at 50 km/h (30 mph) from a study of 571 sites in Texas. Their study examined the relationship between skid resistance and crashes and found that a large proportion of crashes occurred with low skid resistance and relatively few occurred with high skid resistance. Several transportation agencies have developed specific road friction threshold values that defined the lowest acceptable road friction condition after which surface restoration should occur. For example, Maine, Washington, and Wisconsin use 35, 30, and 38, respectively, as their cutoff values. Tighe et al., 2000 has identified the main pavement engineering relationships associated with road safety and incorporated it to pavement management. Recently, tire pavement skid resistance, especially wet skid resistance has been recognized as an important parameter to be used in network surveys for pavement management, evaluation of surface restoration, specifications for new construction, accident investigations, and winter maintenance of highways etc. However, what is still not known is the exact mechanism that causes the decrease in pavement friction when a film of water covers the road surface and the effect of pavement surface texture on it. As a result, efforts to better understand the contribution of pavement texture to skidding, and its incorporation in the pavement safety equation appears to be a promising direction. [39]

Wet skid resistance can be measured directly through full-scale friction measuring devices such as the locked wheel trailer (ASTM Standard E247). In this method, a rib or smooth tire is towed at 40 mph. The wheel is locked and allowed to slide for a certain distance, usually the left wheel path in the tested travel lane. The operator applies the brakes and measures the torque for one second after the tire is fully locked then computes the correspondent friction value. The measurement is reported as Skid Number SN40R or SN40R defined as in Equation #1. The characters 'S' and 'R' in 'SN40S' and 'SN40R' represent smooth tire and rib tire, respectively. In this research ribbed tires [4] are used; as a result, SN40R values are reported in this report.

Skid resistance between tire and pavement interface is due to two major components: adhesion and hysteresis. [14] Adhesion results from the shearing of molecular bonds formed when the tire rubber is pressed into close contact with pavement surface. These interactions are often dominated by weak Van der Waals forces. Hysteresis results from energy dissipation when the tire rubber is deformed and passed across the asperities of a rough pavement surface. The two components of skid resistance are related to the two key properties of asphalt pavement surfaces, which are micro-texture and macro-texture. Micro-texture is a surface texture irregularity which is measured at the micro scale of harshness and is known to be a function of aggregate particle mineralogy for given conditions of weather effect, traffic action and pavement age while macro-texture refers to the large-scale texture of the pavement as a whole due to the aggregate particle arrangement, which controls the escape of water under the tire and hence the loss of skid resistance at high speeds. [42]

Micro-texture values are commonly estimated using low speed friction measurement devices such as the British Portable Tester (BPT), the Dynamic Friction Tester (DF Tester), and the locked wheel skid trailer when test is performed at low speeds. [49] These measurements always disturb or disrupt the traffic flow. Macro-texture measurements can be divided into two main classes: static measurements and dynamic measurements. Common static macro-texture measurement methods include the sand patch method, the outflow meter, and the Circular Texture Meter (CTM). Flintsch et al., 2003 and McGhee and Flintsch, 2003, correlated CTM measurement data and Sand Patch Test data and found strong correlation between them. The dynamic measurement is conducted by vehicle-mounted laser devices which can collect data at highway speeds, which is a promising method for collecting macro-texture data of pavement.

As mentioned, skid resistance can be measured directly by locked wheel trailer. However, this method is very expensive and disturbs the traffic flows during the test. So it is not a practical and economical method to continually monitor road surface. The surface macro-texture is a predominant contributor to wet-pavement safety [12 and 32] and a coarse macro-texture is very desirable for safe wet-weather travel as the speed increases. [23] Micro-texture and adhesion contributes to skid resistance at speeds less than 30 mph. Therefore, a friction coefficient prediction model that only uses road macro surface texture measured by contact less method without disrupting the traffic would allow efficient routine surveys of the road network. The use of macro-texture to collect the skid resistance data will significantly reduce the need for the ASTM E274 skid resistance trailer.

There are several regression models[20, 28 and 29] relating pavement surface micro/macro-texture with SN values. However, most of them include the data of the micro-texture and such measurements will disrupt the traffic. In addition, most of the models failed to take into account the effect of the water film on the skid resistance while analyzing the correlation.

The water film thickness is a significant contributing factor that should be included when building a correlation between skid number and pavement texture. Persson, et al., 2005 studied rubber friction at low sliding velocities on wet rough substrates, where it has been observed that the friction is typically 20%–30% smaller than that for the corresponding dry surfaces and by using fluid film lubrication theory, they proved that the above reduction couldn't be completely due to hydrodynamic effects. Claeys, et al., 2001 defined two different hydroplaning: viscous hydroplaning and dynamic hydroplaning. They modeled the fluid at the interface as viscous and used the Navier-Stokes equation to determine the sink dynamics of the tire (squeezing of water). The effective tire/road contact surface is a function of the time taken by the tire to achieve contact with the ground. Water clearance time, or time of sink, which is the main contributor of the hydroplaning, vary for different wheel speeds; tread stiffness, ground pattern characteristics, etc. This is the theoretical basis for sealing off water pool: namely, regions on the substrate filled with water as shown in Figure 18. The Figure 18 shows a wet substrate the water trapped in the large valley forming a pool preventing the rubber from penetrating into the valley. A simple method for understanding the sealing off of a water pool is the use of the analogy between the behavior of the tire in the squeeze film area and the sink of a flat plate over a randomly rough surface area. Considering the sink of a flat plate over a rough surface, there is a bulk flow of fluid escaping between the plate and the asperity tips, and an open channel flow between asperities. As the plate approaches the peaks of the asperities, there is virtually no bulk flow and the channel flow becomes closed because the plate provides an upper boundary in this position and the water is sealed off in the cavity of the road surface. Hence aggregates in this valley would not contribute to the friction force. This rubber sealing effect reduces the sliding friction. [41]

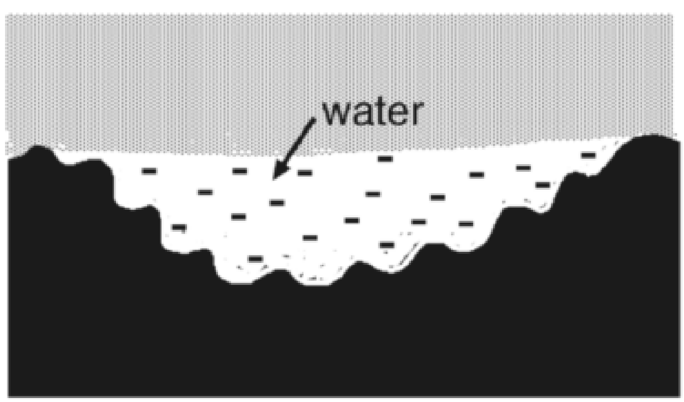


Figure 18: Illustration of sealed off water pool in the pavement surface

In this research, SN40R and Mean Profile Depth (MPD) values were collected from several asphalt pavements in New Jersey and used to develop a rational mechanism and a supporting correlation between SN40R and MPD values. While analyzing the test data, the water film thickness during the friction test was calculated and critical MPD values were defined. The effect of sealed off water pool on the SN40R was discussed. Finally a comparison was made between predicted SN40R values for new and old asphalt pavements, and reduction coefficients accounting for the polishing effects due to traffic on micro-texture was developed.

Water film thickness during the friction test and critical MPD

The pavement wetting system used during the skid resistant measurement, releases 4.0 gal ± 10% per minute per inch of wetted width (600ml/min.mm ± 10%) at 40mph. Thus the average water film thickness at a test speed of 40mph is approximately 0.55mm, which means that if the volumetric Mean Texture Depth (MTD) of the pavement is less than 0.55mm then the pavement surface is completely covered with water during the skid resistance test. The following correlation between the MTD and MPD, where MTD and MPD are in mm, can be used to compute equivalent MPD.

$$ETD = 0.8MPD + 0.2 \qquad (4)$$

When the ETD (estimated texture depth) is equal to 0.55mm, the corresponding MPD is about 0.375mm. Here the critical MPD is defined as a depth at which the water just filled all the cavities in the pavement surface. Hence according to equation 5, the critical MPD is 0.375mm. However, the MPD in the equation 5 does not describe the method of obtaining a measured profile and its calculation is based on straight line profile. In this research the dynamic macro-texture measurement by non contact laser at traffic speeds was used. Hence the above correlation between ETD and MPD should be modified. Flintsch et al., 2003 provided the correlation between MTD (by sand patch test) and MPD by non-contact laser (International Cybernetics Corporation (ICC) laser) as follows with a correlation coefficient of 0.884:

$$MTD = 0.7796MPD - 0.379 \qquad (5)$$

According to equation 5, the critical MPD measured by ICC laser is about 1.19mm. McGhee and Flintsch, 2003 also provides correlation between MTD and MPD by ICC laser with correlation coefficients 0.9028 and 0.7309, according to which the corresponding critical MPD by ICC laser are 1.26mm and 1.15mm respectively. Based on the above calculation, we can reasonably estimate the critical MPD by ICC laser to be approximately 1.2mm.

It should be noted that at low velocities (30km/h), there is sufficient time for the water to squeeze out from the contact regions between the tire and road surface, except for water trapped in road cavities and sealed off by the road-rubber contact at the upper boundaries of the cavities. According to the calculation of Persson et al., 2005 it is still the case at velocity of 64km/h (40mph). So during the skid resistance test with the MPD smaller than critical MPD, every valley will be filled with water up to the maximum level where the water still remains confined and all the other extra water will be squeezed out. As a result, it is reasonable to infer that the primary effect of water on skid resistance during the test is the sealed off water pool effect instead of hydroplaning. This effect will be employed to explain the test result in the following sections of this report.

Skid Number (SN40R) Collection and Processing

The skid number was collected by full-scale friction measuring devices – Locked Wheel Trailer conducted in accordance with ASTM Standard E247. During the test, a ribbed tire (E-501) was towed at 40 mph and the left wheel path in the travel lane was tested. At each milepost, water was delivered ahead of the test tire and the braking system was actuated to lock the test tire for one second. Please note that in New Jersey there is a milepost at 1/10 of a mile (161m). The traction force (f_h) and dynamic vertical load (f_v) were measured and the skid number was calculated automatically in real time as shown in equation 6.

$$sn(t) = \left(\frac{f_h(t)}{f_v(t)}\right) \times 100 \qquad (6)$$

Then SN can be calculated as:

$$SN = \int_0^1 sn(t)dt \qquad (7)$$

The SN in equation 7 is reported as skid number at the corresponding milepost. For the wheel fully locked for about 1 second, the reported SN is the average skid number for each 18m length at each milepost (with 9 meter on each side). Three trials were run at each site and thus three SN40R at each milepost were reported.

Texture Data Collection and Processing

Texture data (profile depth) of pavement surface was collected using a vehicle mounted laser at traffic velocity. The vehicle mounted laser device contains Selcom 62.5 KHz Laser, which is manufactured by International Cybernetics Corporation (ICC). The measurement starts manually when the front window of the laser mounted vehicle crossed the starting milepost and the laser collected the profile depth of the pavement surface at an interval of approximately 0.2mm when operated at highway speeds. The measurement was stopped manually when the testing vehicle passed the ending milepost. Five trials were run for each pavement section.

The software provided by the laser vehicle vendor was used to process the collected laser data and reported MPD value for each 100mm section of the pavement according to ASTM E1845. The MPD of 20-meter-length section of pavement at each milepost (with 10 meters on each side) was extracted and averaged. Please note that for the purpose of taking into account the operating error in skid resistance test, 20 meters instead of 18 meters is chosen for calculating the average MPD corresponding to each SN40R.

CORRELATION BETWEEN SN40R AND MPD

Correlation for Newly Constructed or Resurfaced Asphalt Pavement

The skid number and mean profile depth (MPD) data from five new asphalt pavements with average pavement age less than two years with no other surface treatment after paving were collected by a locked wheel skid trailer[(2)] and a vehicle mounted laser. The vehicle mounted laser has Selcom 62.5 KHz Laser system which conforms to ASTM E1845 and manufactured by International Cybernetics Corporation- ICC. The five new asphalt pavements sections with age and traffic volume are shown in Table 2. While developing the correlation between the SN40R and MPD, the following procedure was followed and the correlation obtained is shown in Figure 19:

- Calculated the average and the standard deviation of three SN40R at every milepost and discarded the SN40R with standard deviation greater than 2 or discarded the SN40R values among three trials varying from the other two trials by more than 5%.
- Calculated the average of MPD for the five trials and check the standard deviation. If the standard deviation was high, the original file was checked to determine which trial among the five trials should be dropped.
- Correlated the average SN40R at every milepost with the corresponding average MPD.

Table 2: Routes information for the correlation

Route NO.	Route Section	Treat Year	Total Traffic volume / per lane
Rt.29	MP 7.0-6.18 S Ln2	2007+1/2	5149511
Rt.29	MP 7.0-8.0 N Ln2	2008	1179680
Rt.29	MP 8.0-7.0 S Ln2	2008	1179680
Rt.29	MP 2.0-1.0 S Ln2	2007+1/2	5149511
Rt.73	MP 22.0-23.0 N Ln2	2008	3689967
Rt.27	MP 13.0-15.0 N Ln2	1995	49167142
Rt.27	MP 13.0-15.0 S Ln2	1995	49167142
Rt.175	MP 0.25-1.0 N Ln2	2000	3173310
Rt.175	MP 0.25-1.0 S Ln2	2000	3173310

From Figure 19, it can be observed that the SN40R and MPD values do not have a positive linear relationship as expected. There are two obvious characteristics of the curve as described below:

- There is no positive correlation between MPD and SN40R. From the above graph peak of SN40R value occurred when MPD value was around 0.75mm and after that SN40R values decreased with increasing MPD values until MPD value equal to about 1.1mm which is close to the critical MPD of 1.2mm. The above trend of SN40R with MPD is similar to that published by Jackson. However, the correlation proposed by Jackson, 2005 had a peak SN40R value at MPD equal to 1.3mm (0.05inches) which is quite different from 0.8mm in Figure 19 and there was also an increasing trend of SN40R after MPD values higher than 3.81mm (0.15inches). The probable reason for the difference between two studies may be the calibrations of lasers used. Hence, it is suggested that future research should provide calibration information of non-contact laser data using Sand Patch test or by CTM to obtain MPD values for comparison by other researchers and the laser can be calibrated.

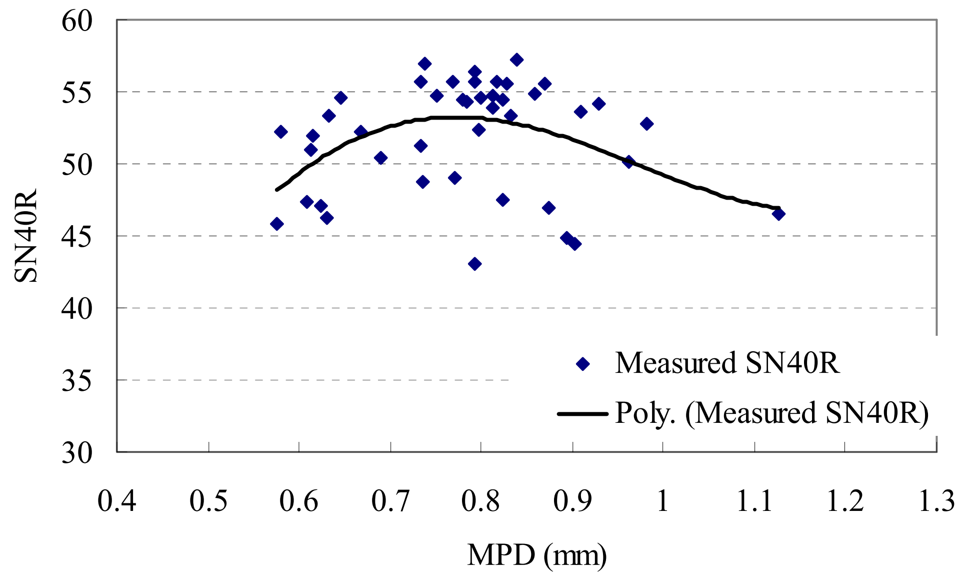


Figure 19: Correlation between SN40R and MPD

- Figure 19 also show that SN40R values fluctuated at a MPD value around 0.8mm. This phenomenon is consistent with the published data by Khasawneh and Liang, 2008 where the SN64R also fluctuated at MPD equal to 0.5mm. It should be noted that, Khasawneh and Liang collected MPD values using CTM. According to the two correlations with correlation coefficients of 0.74 and 0.91, respectively between CTM measurement and ICC laser measurement proposed by McGhee and Flintsch, 2003 a CTM measurement of 0.5mm is equivalent to ICC laser measurement of 0.85mm and 1.13mm, respectively. But the average value which is about 1mm is still different from 0.8mm observed in this study. The main factor accounting for the difference is the error of the calibration information for the ICC laser.

In order to better understand and explain the effect of macro-texture and water film on the skid resistance, the correlation in Figure 19 was divided into three separate sections as shown in Figure 20 and discussed each in the following sections.

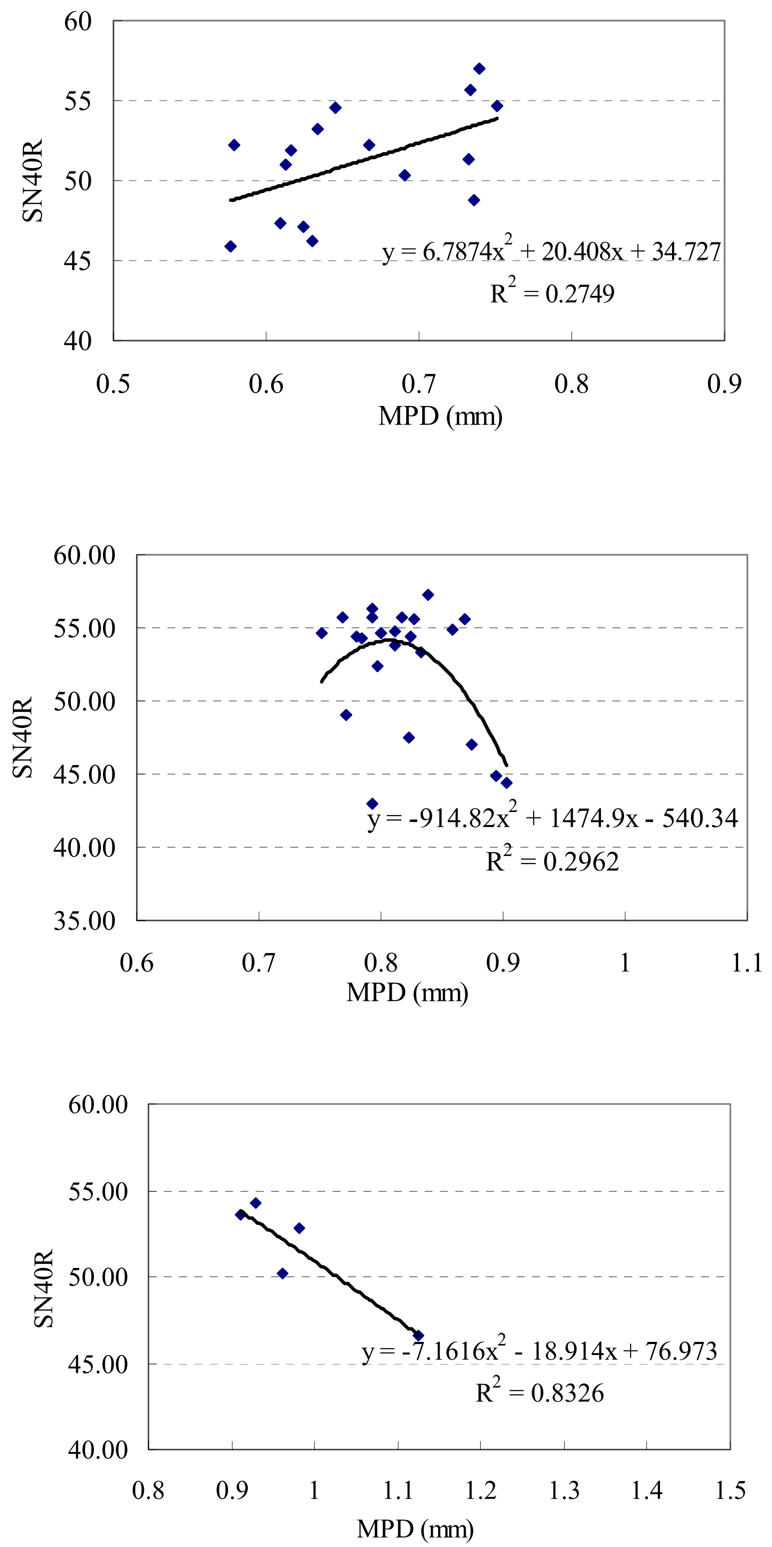


Figure 20: Correlation between SN40R and MPD Separated into Three Sections: Section 1 MPD <0.75mm, Section 2 0.75mm≤MPD≤0.9mm and Section 3 0.9mm<MPD <1.15mm

Based on the previous discussion, for MPD values less than the critical MPD value of 1.2mm the pavement surface is completely covered by water during the skid test. But as mentioned before, there is sufficient time for the water to be squeezed from the contact regions between the tire and road surface at test speeds, so the hydrodynamic effect of water may be negligible and the sealed off water pool effect which is related to the roughness of pavement surface may become the main factor affecting the skid resistance. Here the macro-texture has two effects on the SN40R, first the hysteresis and the other is related to the sealed off water pool effect. It should also be noted that increasing the macro-texture will lead to decrease of the contact area between the tire and pavement.

In section 1, as shown in Figure 20-1 there is a positive correlation between SN40R and MPD. The probable explanation for this section may be that the pavement surface is relatively smooth. As a result, the sealed off water pool effect is not significant and the slightly increased MPD values do not lead to significant decrease in contact area. Thus the primary effect of MPD on skid resistance is its contribution from hysteresis which is the main contributor to the skid resistance at high speed. That is why SN40R increases with the increase of MPD in this section (positive correlation). However, as shown in the Figure 20-1, the correlation is not very strong with the correlation coefficient of only about 0.3 and there is significant data fluctuation although the fluctuation is not high except at the MPD value of 0.8mm. The main factor accounting for the low correlation coefficient and the data fluctuation is the sealed off water pool effect which will be explained below.

Compared with the section 1, it is obvious that the correlation between SN40R and MPD becomes negative in this section as shown in Figure 20-2. According to the earlier discussion of effect of macro-texture on the skid resistance, it can be stated that with the increasing MPD, the contribution from the sealed off water pool effect and decreased contact area is increased and become greater than the contribution from the macro texture (hysteresis). Hence when the MPD is increased, the SN40R shows an inversely proportional relationship.

In Figures 20-1 and 20-2, there is a significant fluctuation of SN40R values near MPD value equal to 0.8mm which is also the reason for low correlation coefficients for both sections. The main contributing factor for the data fluctuation is the sealed off water pool effect as shown in Figure 21, with two possible pavement profiles. According to the ASTM E 1845-01 (calculating pavement macro-texture mean profile depth), the two pavements have the same MPD, but the sealed off water pool effects of the two pavement are significantly different. As shown in the Figure 21-2, pavement 2 has more cavities on its surface compared to pavement 1. As a result, pavement 2 has a larger sealed off water pool. It is also true that the pavement 2 has higher hysteresis contribution due to the protrution on the surface. However, as mentioned before, in this section (0.75≤MPD≤0.9) the effect of hysteresis on the skid resistance is not as great as that of sealed off pool and contact area, so the contribution to skidding from hysteresis is less than that from sealed off pool effect. As a result, SN40R value for pavement 2 should be lower than that for pavement 1 shown in Figure 21. This should explain why SN40R fluctuates at MPD value of 0.8mm. When MPD is smaller than 0.8mm, the road is relative smooth, so the sealed off pool effect is not that important, while for MPD values greater than 0.8mm, the increasing MPD decreased contact area becomes an important factor affecting the skid resistance. Hence the sealed off pool effect is the most influential contributor to SN40R for MPD values around 0.8mm. That is why the SN40R fluctuated near the MPD values equal to 0.8mm. In order to better under understand this phenomenon and to estimate the skid resistant of the pavements at MPD values near 0.8mm, it is proposed that Root Mean Square (RMS) value be incorporated into the correlation. Then the comparison of the RMS and MPD can indicate detailed texture, that is, whether it is provided by aggregate protruding from the surface or by cavities in the surface. For example, for two pavements having the same MPD value (Figure 21-1 and 21-2), the pavement with the higher RMS (pavement 2) will have more cavities and protrudes than pavement 1. Hence by combining RMS value with MPD, it is possible to decide whether the sealed off water pool effect is significant or not.

Figure 20-3 shows that there is a similar downward trend of SN40R with increasing MPD values from 0.9 to about 1.15mm as that in Figure 20-2 However, the slope of the decreasing SN40R is just about half of that for figure 20-2. When the MPD value is greater than 0.8mm, the effects of decreased contact area and increased hysteresis resulting from increasing MPD values become the principal contributor for the SN40R. Compared with section 2, the MPD values in section 3 is higher, as a result, the hysteresis becomes more important. Hence, the SN40R decreases slower with increasing MPD in section 3. That explains why the slope of the SN40R versus MPD curve in Figure 20-3 becomes half of that in Figure 20-2. It can be expected that with higher MPD values (greater than 1.15mm which is the maximum size in this research), the hysteresis will becomes even more important than the effect of decreased contact area leading to increase in SN40R with further increase in MPD values as reported by Khasawneh and Liang, 2008. Khasawneh and Liang, 2008 reported that the SN40R versus MPD curve has a positive slope for the MPD values larger than 1.5mm which means pavement is much rougher. However additional data is needed to validate this observation.

Figure 20-3 shows a high correlation coefficient with no data fluctuation when compared with that for Figures 20-1 and 20-2. This observation is consistent with the proposed inference that the sealed off water pool effect is the main contributing factor to the data fluctuation and a low correlation coefficient in

Figures 20-1 and 20-2. In Figure 20-3, because the MPD values are higher the sealed off water pool effect becomes relatively insignificant. As a result, the correlation coefficient is higher.

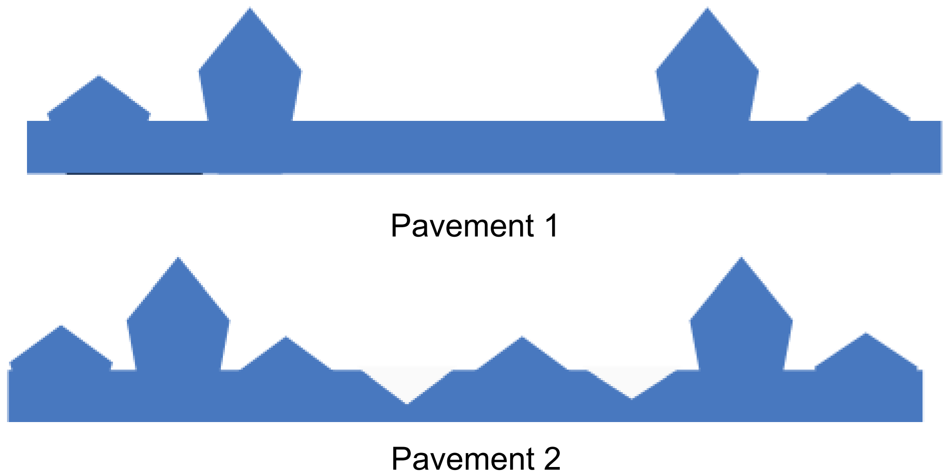


Figure 21: Illustration to Show the importance of Root Mean Square Value of Texture

Comparison Between Newly Constructed or Resurfaces Asphalt Pavements and Older Pavements

In order to further understand the contribution of micro-texture on the skid resistance, the comparison between SN40R-MPD correlation for new and old asphalt pavements is presented. The SN40R and MPD data were collected from four older asphalt pavements with an average road age of over 20 years. The four pavement sections with age and traffic volumes are also listed in Table 2. The comparison of results is shown in Figure 22.

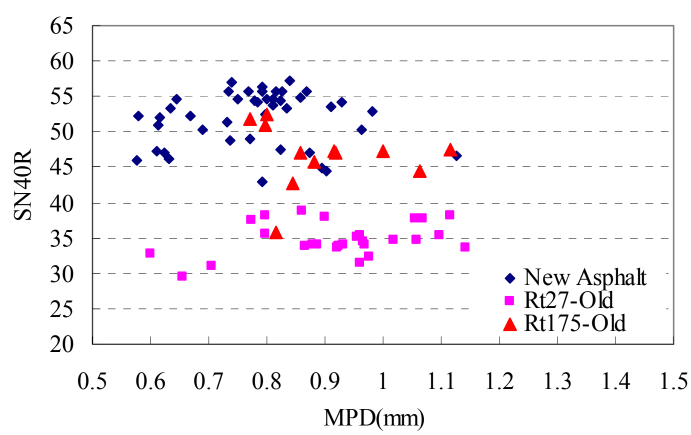


Figure 22: Comparisons between New and Old Asphalt Pavements

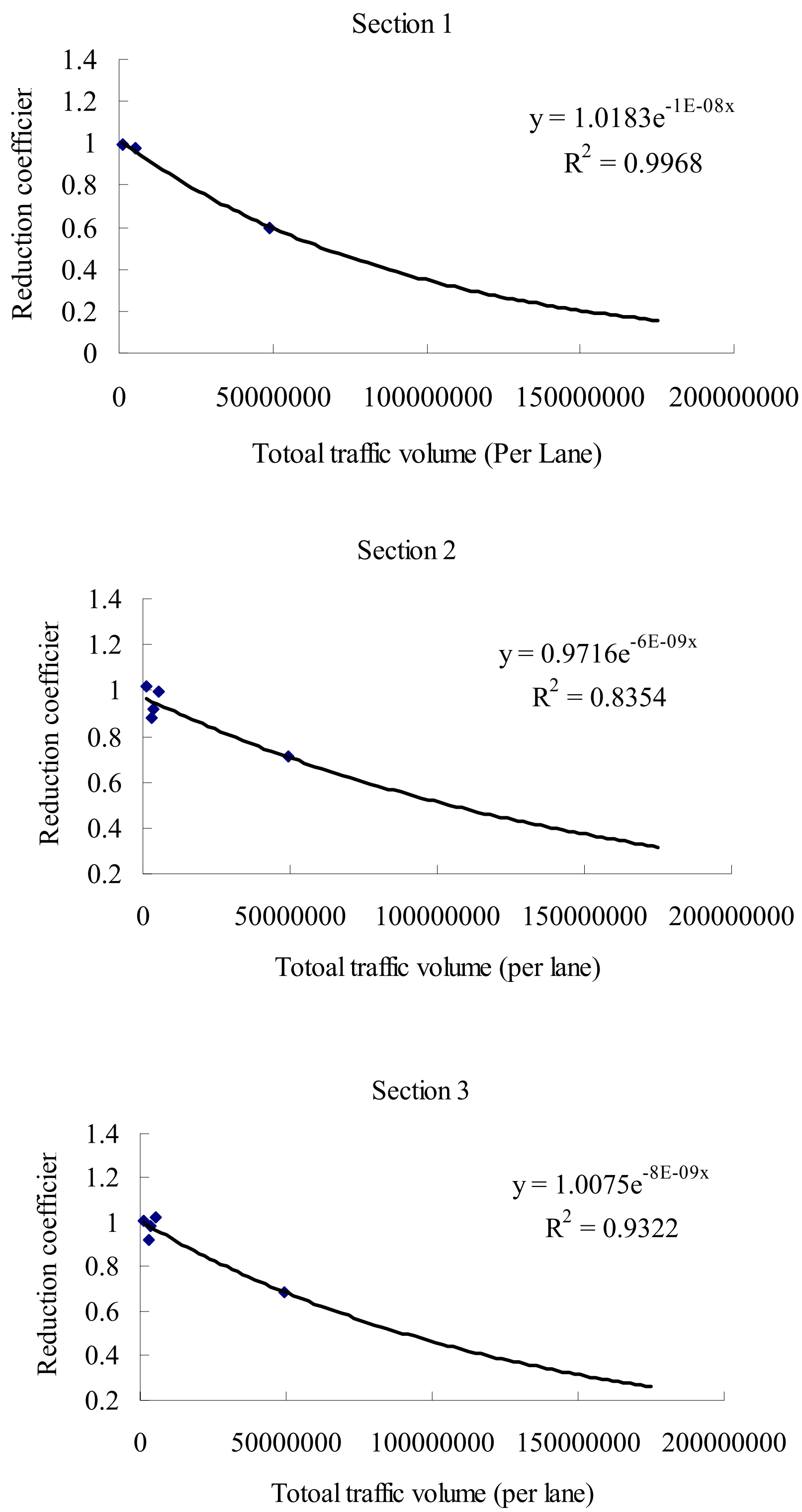


Figure 23: Reduction coefficient for Cumulative Traffic Volume for Three sections; Section 1 MPD<0.75mm, Section 2 0.75mm≤MPD≤0.9mm and Section 3 0.9mm<MPD<1.15mm

From Figure 22, one can find that the four old asphalt pavements for two roads show much different skid resistance values. The SN40R values of Rt. 175 were much higher than that for Rt. 27. The correlation between SN40R and MPD values for Rt. 175 is similar to that for a new asphalt pavement (SN40R values fluctuated around MPD value equal to 0.8mm and the correlation was similar to that of the new asphalt for MPD values greater than 0.9mm). The relationship between SN40R and MPD values for Rt. 27 is similar to that of a new asphalt pavement (the trend is almost parallel to that of a new asphalt pavement) but the SN40R values were much lower. The main factor accounting for the difference is the traffic volume.

According to the data published by NJDOT, the Annual Average Daily Traffic (AADT) volume for Rt. 27 was 38487 in 2003 which is almost 19 times that of Rt. 175. The vehicular traffic cause polishing of the pavement surface and consequently a reduction of skid resistance. That is the reason for much lower SN40R values obtained for Rt. 27, when compared with those for Rt. 175 and other new asphalt pavements. Also with traffic volume of 1932 for Rt. 175, which is also much lower than that for all seven new asphalt pavements with average traffic volume of 42000, there is minimal polishing of aggregates. As a result, based on road age, though it is treated as an old pavement, based on cumulative traffic volume and its impact on the Rt. 175 is insignificant and hence Rt. 175 can be considered as a new asphalt pavement based on cumulative traffic volume.

In this research a reduction factor was developed to account for the traffic volume. It is the ratio of the measured to predict SN40R values for the dense graded asphalt pavement and it is compared with the cumulative traffic volume. The total traffic volume for each pavement is calculated as equal to the reported daily traffic volume $\times$(2009-treated year)*365/number of lanes (both directions). Based on the treated year and traffic volume for each pavement (supplied by NJDOT), the correlation between total traffic volume per lane (count from treat year) and reduction coefficient was developed and is shown in Figure 23.

From Figure 23, it can be observed that there is a common trend for the reduction coefficient curve for all three sections that it starts from a value of 1 and decrease exponentially with the increasing total traffic volume. This is consistent with the findings of Do et al., 2000. Also, by comparing the reduction coefficient for three sections in Figure 23, it can be observed that the reduction coefficients for sections 2 and 3 with high MPD values are slightly higher than those for the section 1 with low MPD values under the same cumulative traffic volume which means the polishing of aggregates for pavement with high mean profile depth value is not so high as that for a pavements with low mean profile depth value. This is consistent with the explanation for the correlation between MPD and SN40R presented before. The skid resistance is due to adhesion and hysteresis which are related to the micro-texture and macro-texture of the pavement, respectively. For very rough surfaces (high MPD values), the hysteresis will dominate while the adhesion related to the micro-texture will become less important. As a result, the reduction coefficient reflecting the polishing of the micro-texture becomes higher and hence less important for pavements with high MPD values than those with low MPD values. However, it should also be noted that the difference between three reduction coefficients are not obvious. The reduction coefficients for section 1 and 2 are just slightly lower than that for section 3 under the same traffic volume. The reason for the above is that for pavements with low MPD values, the drainage of surface is not as good as those with high MPD values, and hence part of micro-texture may be contributing during the skid test. As a result, the traffic polishing effect on micro-texture can not be reflected completely in the reduction coefficient.

Figure 24 show the Comparison between New and Old Asphalt Pavements Corrected for the Traffic Volume. It can be seen from Figure 24 that with the proposed reduction coefficient one could use the same correlation to predict the skid resistance of an old pavement using the texture data obtained from the high speed laser.

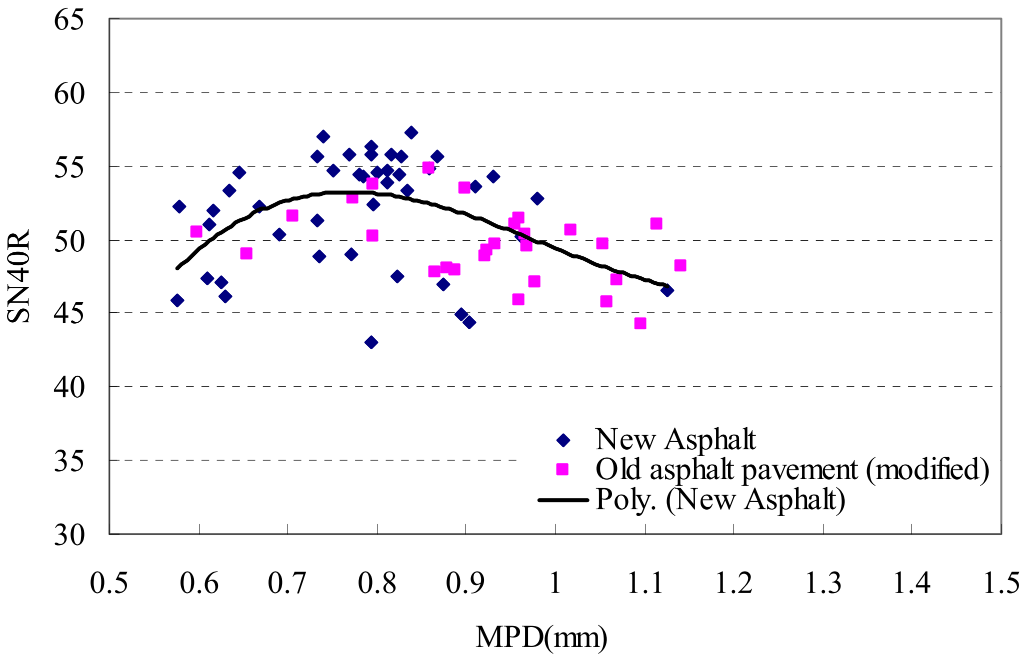


Figure 24: Comparison between New and Old Asphalt Pavements Corrected for the Traffic Volume

The above correlation will be used by the NJDOT to screen all the roadway pavements belonging to the state of New Jersey using high speed laser and the predicted skid numbers will be included in their Pavement Management Database. Hence with the predicted skid numbers NJDOT could reduce the use of expensive locked wheel skid tester saving thousands of taxpayer dollars.

It should be noted that the proposed correlation is both site and equipment specific. All pavements used were constructed with 9.5mm trap rock with similar micro texture values and used ICC laser to develop the proposed correlation. However, attempt was made to provide a mechanistic explanation so that a similar correlation could be developed for other locations and equipment enabling transportation agencies to develop rapid screening tool to evaluate the skid resistance of their pavements in the network.

FIELD DEMONSTRATION

In order to verify the above correlation, two detailed field tests are performed on dense graded fine/coarse asphalt pavement (Rt.156 and Rt.68). The information of the two roads is shown in Table 3. Representatives of the pavement management group at the NJDOT identified two field test sites. The first test site was on Route 156 from Mile Post (MP) 0.7 to 1.1, southbound lane, of two lane highway. The second test site was Route 68 MP 6.0 to 7.0 east bound slow lanes.

Table 3: Information of Two Pavements used for the Field Tests

Route No.	Route Type	Treat Year	Total Annual Traffic volume per lane (vehicles)
Rt.68	Dense graded course	1993	18556600
Rt.156	Dense graded fine	1992	5665165

The field-testing program consisted of the following components:

- Locked Wheel Skid Trailer. [2]
- Dynamic Friction Test.
- Circular Texture Meter (CTM) Test.
- Texture profile measurement using the ICC laser.
- Sand Patch Test.

The wet skid resistance is measured directly through full-scale friction measuring devices - locked wheel trailer conducted in accordance with ASTM Standard E247 (Figure 13). It measures wet friction at slip speed which is equal to the velocity of a test vehicle. In this method, a ribbed tire is towed at 40 mph. The wheel is locked and allowed to slide for a certain distance, usually the left wheel path in the tested travel lane. The operator applies the brakes and measures the torque for one second after the tire is fully locked then computing the correspondent friction value. The measurement is reported as Skid Number SN40R defined as the traction force divided by the dynamic load on the tire and it is multiplied by a constant (100) as defined in equation 1.

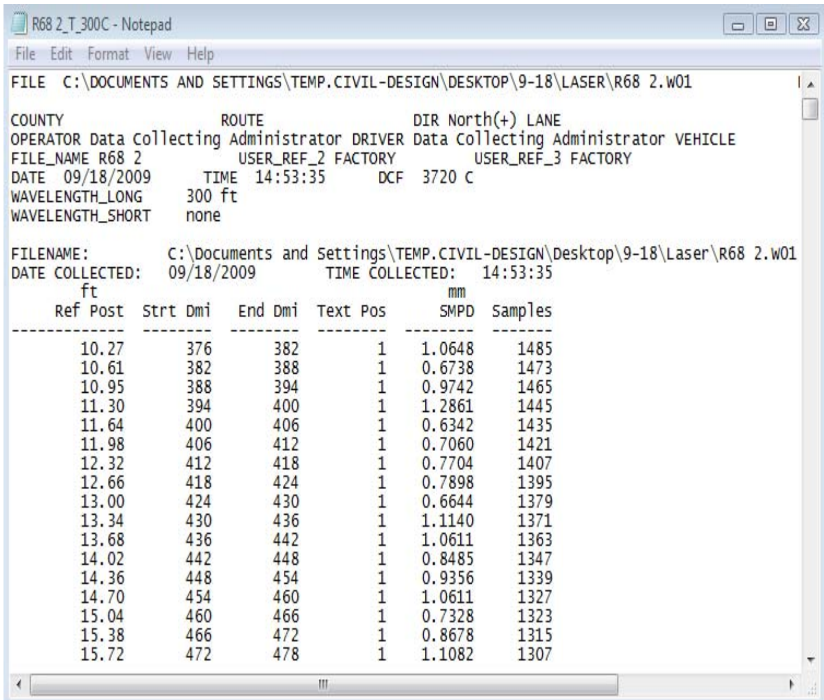
The Dynamic Friction Test conforms to Standard Test Method for Measuring Paved Surface Frictional Properties. The DFT has three rubber sliders that are spring-mounted on a horizontal rotary disk at a distance of 350mm. The disk is initially suspended above the pavement surface and is driven by a motor until the tangential speed of the sliders is 90 km/h. Water is then applied to the pavement surface by the device, whereupon the motor is disengaged and the disk is lowered to the test surface. The three rubber sliders contact the surface and the friction force is measured by a transducer as the disk spins down. The friction force and the speed during the spin down are saved to a file. This results in a continuous spectrum of dynamic coefficients of friction. The equipment reproduces actual speeds between 0-80 km/hr and surface bearing loads of vehicles commonly in use.

The Circular Texture Meter (CTM) uses a laser to measure the profile in an 800-mm circumference circle. The mean depth of texture for each 100-mm segment of the arc is computed according to ASTM standard practice. The averages of depths of the two arcs perpendicular to the traveled direction and the two arcs parallel to it are computed. The CTM consists of a charge coupled device (CCD) laser- displacement sensor which is mounted on an arm that rotates such that the displacement sensor follows a circular track having a diameter of 284 mm (11.2 in.). The CTM is designed to measure the same circular track that is measured by the Dynamic Friction Tester (DFT). The CTM can be used both for laboratory investigations and in the field on actual paved surfaces. The software developed for the CTM reports the Mean Profile Depth (MPD) and the Root Mean Square (RMS) values of the macro texture profiles. The values stated in SI (metric) units are to be regarded as standard. The inch-pound equivalents are rationalized, rather than from exact mathematical conversions.

Texture data (profile depth) of pavement surface was collected using a vehicle mounted laser. The vehicle mounted laser is a Selcom 62.5 KHz Laser system which conforms to ASTM E1845 and manufactured by International Cybernetics Corporation (ICC) (Figure 25). The measurement starts manually when the front window of the laser mounted vehicle crossed the starting milepost and the laser collected the profile depth of the pavement surface at an interval of approximately 0.2mm when operated at highway speeds. It reports the MPD values at every 0.34ft calculated according to ASTM as shown in Figures 26 and 27. The measurement was stopped manually when the testing vehicle passed the ending milepost. Five trials were run for each pavement section.

The sand patch test has been used to quantify visual observations of differences in the surface macro-texture. The ASTM E965 test method indicates that the precision of the test method is approximately one percent of the measured depth in millimeters and the operator variation is about two percent. Good correlation was found between visual observations of non-uniform textured areas and the sand patch test results for measuring surface macro-texture. The sand patch method measures the mean texture depth (MTD).

Figure 25: Vehicle mounted ICC laser



R68 2_T_300C - Notepad

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DATE COLLECTED:    09/18/2009         TIME COLLECTED:    14:53:35
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ft Ref Post	Strt Dmi	End Dmi	Text Pos	mm SMPD	Samples
10.27	376	382	1	1.0648	1485
10.61	382	388	1	0.6738	1473
10.95	388	394	1	0.9742	1465
11.30	394	400	1	1.2861	1445
11.64	400	406	1	0.6342	1435
11.98	406	412	1	0.7060	1421
12.32	412	418	1	0.7704	1407
12.66	418	424	1	0.7898	1395
13.00	424	430	1	0.6644	1379
13.34	430	436	1	1.1140	1371
13.68	436	442	1	1.0611	1363
14.02	442	448	1	0.8485	1347
14.36	448	454	1	0.9356	1339
14.70	454	460	1	1.0611	1327
15.04	460	466	1	0.7328	1323
15.38	466	472	1	0.8678	1315
15.72	472	478	1	1.1082	1307

Figure 26: Sample Macro-texture report of Route 68

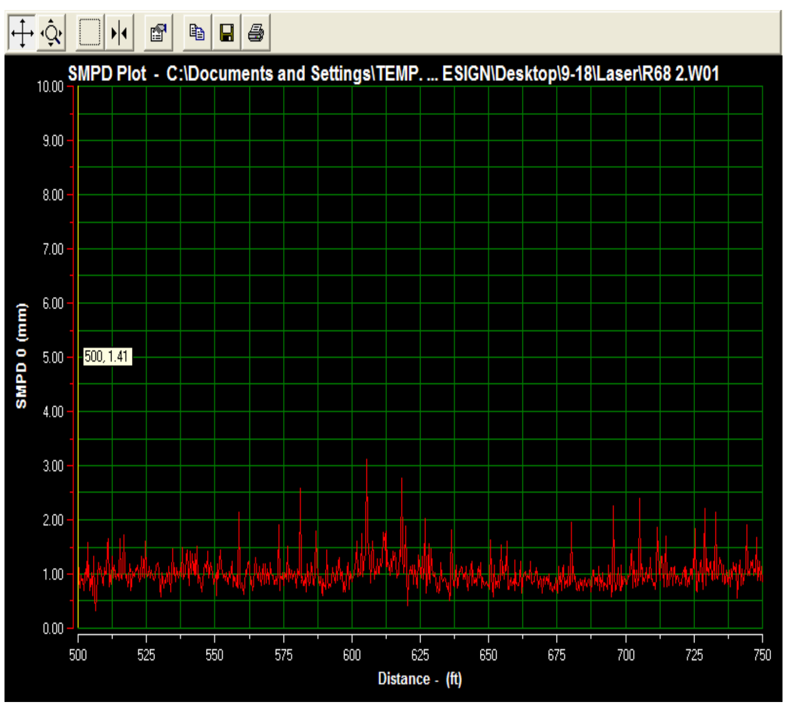


Figure 27: Sample report of mean profile depth of Route 68

The Route 156 Site: The data collection program was carried out on September 17, 2009. The test section of Route 156 was closed from 10.00 AM to 3.00 PM to accommodate the testing program.

Figure 28: Site Preparations for Field Test Location of the Skid Test

The Route 68 Site: The data collection program was carried out on 18 September 2009. The test section of Route 68 was closed from 10.00 AM to 3.00 PM to accommodate the testing program.

Once the test site was closed for traffic, the test site was prepared for the tests by marking the pavement at 100 feet intervals to enable location referencing. During the field tests, the locations where the SN40R values were collected are marked as shown in Figure 28 and the MPD data are collected in the exactly same locations. Texture measurements were performed on five separate runs along the subject lane of the Route 156 from MP 0.6 to 1.1 and for Route 68 from MP 6 to 7. The ICC texture software recorded texture depths and the distance corresponding to each measurement. The CTM, DFT and Sand Patch Tests were performed at the locations where the SN40R values were collected. The measured SN40R values were compared against the predicted SN40R values to check the correlation between SN40R and MPD (Please note that the reduction coefficients have been taken into account when predicting the SN40R values). Tables 4 and 5 summarize the test results from Routes 156 and 68 respectively.

Table 4: Data from Route 156

MP	SN40R	MPD(mm)	Reduction Coefficient	Predicted SN40R	DFT20	CTM
1.1	51.588	0.927623	0.96286	51.28723	0.514	0.652
1.0	49.147	0.969357	0.96286	49.98127	0.518	0.624
0.9	49.368	1.268987	N/A	N/A	0.528	0.773
0.8	48.630	1.108553	0.96286	45.45181	0.518	0.705
0.7	49.232	0.71894	0.962	52.16219	0.532	0.696

Note: DFT20 and CTM data are collected in the middle of each section. It is the average of three continuous points in the middle.

Table 5: Data from Route 68

MP	SN40R	MPD(mm)	Reduction Coefficient	Predicted SN40R	DFT20	CTM
6.9	40.4125	0.909723	0.86923	38.47619677	0.52	0.903
6.8	41.7175	0.906622	0.86923	38.97492602	0.51	0.805
6.7	43.185	1.062564	0.86851	42.37453564	0.533	0.80
6.6	45.0575	0.988299	0.86851	44.54182053	0.578	0.84
6.5	43.0525	1.000566	0.86851	44.18856791	0.532	0.98
6.4	47.445	1.06923	0.86851	42.17663991	0.59	1.05
6.3	42.665	1.065513	0.86851	42.28704604	0.575	1.16
6.2	43.08	1.133589	0.86851	40.23761278	0.545	1.10
6.1	44.105	0.988556	0.86851	44.53442721	0.502	1.02

Note: DFT20 data and CTM data are collected in the middle of each section. It is the average of three continuous points in the middle.

The predicted and measured SN40R for dense graded asphalt pavements are compared in Figures 29, 30 and 31. Figure 31 show that the measured and predicted SN40R values match each other very well. The maximum variance between them is less than 5 which is acceptable according to ASTM. Figure 32 shows the relationship between MPD values obtained from CTM and sand patch test for Route 68.

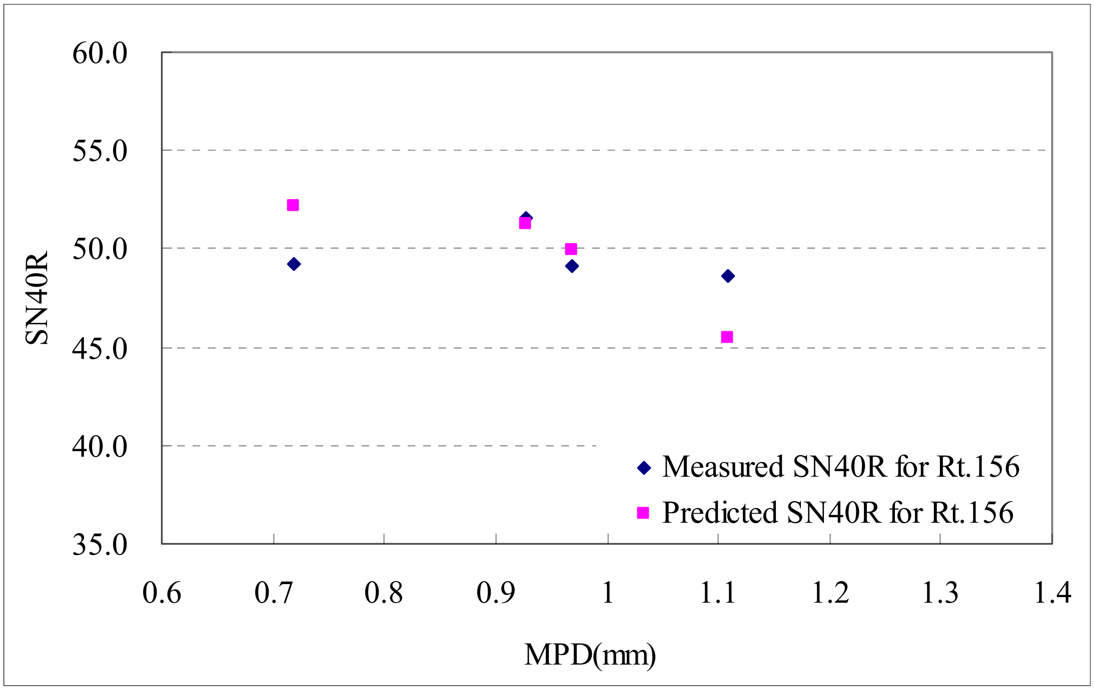


Figure 29: Comparison of Predicted and Measured SN40R Values for Rt.156

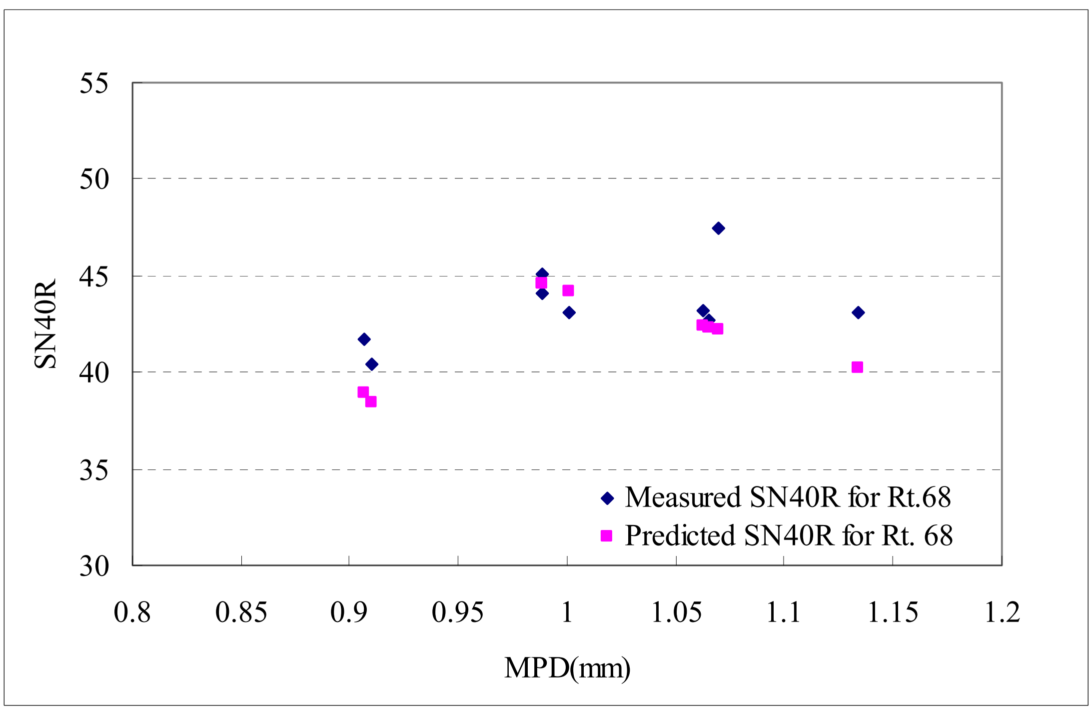


Figure 30: Comparison Predicted and Measured SN40R Values for Rt.68

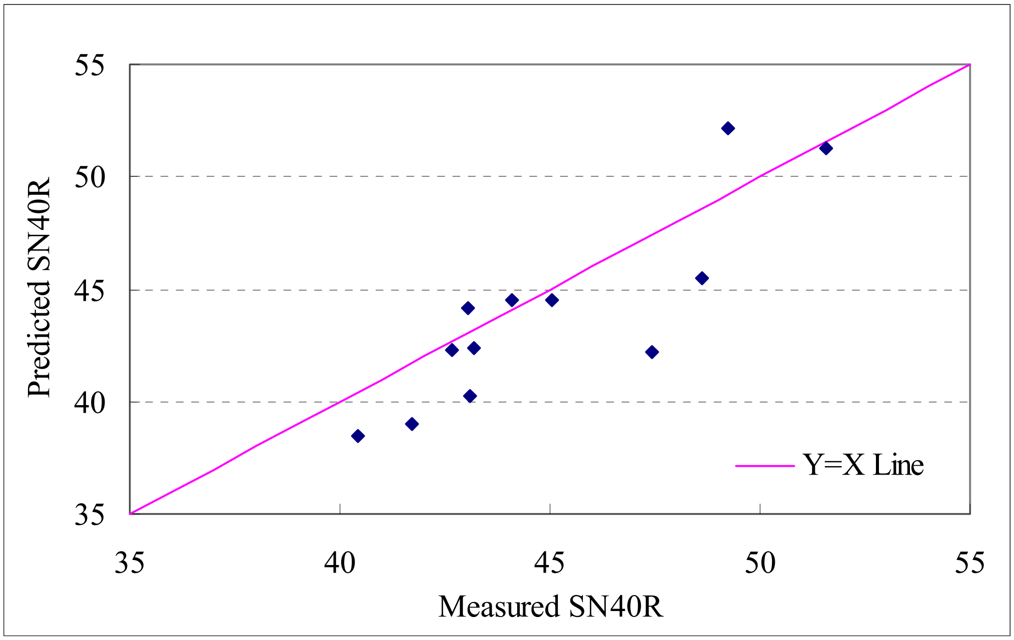


Figure 31: The Verification of the Correlation between SN40R and MPD

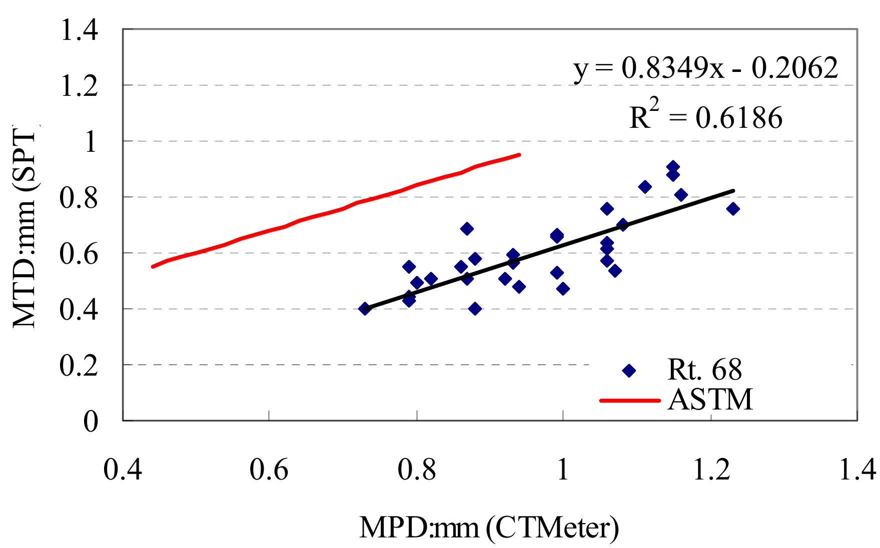


Figure 32: Variation of MPD values from CTM and Sand Patch Test

DFT20 values were collected for the two pavements Rt.156 and Rt.68 using Dynamic friction Tester (ASTM E-1911). The DFT20 value is the friction coefficient at the velocity of 20km/h and it is used as an indicator of micro-texture of the pavement surface. As a result, it may be used to reflect the traffic polishing effect on the pavement. The measured DFT20 and CTM values from Rt.156 and Rt.68 are shown in Figure 33. There seems to be a linear correlation with significant scatter. From Figure 33, one can also observe that the average DFT20 values for Rt.68 are slightly higher than that for Rt.156. However, due to the traffic volume and age, there is polishing of aggregates in Rt.68 when compared with those in Rt.156, which means the micro-texture of the Rt.68 should be lower than that of Rt.156. However, it is not the case according to Figure 33. At low velocity values, the main component of friction between tire and pavement surface is adhesion which mainly relies on the micro-texture of the pavement surface. However, this does not mean that DFT20 values of different pavements can be compared without considering the macro-texture or MPD values. Wet pavements with high MPD values have better drainage and micro-texture is fully accounted during the test. For the pavement with low MPD values there is a higher chance of not capturing all micro-texture during tests. As a result, even if a pavement new DFT20 may be lower than that of old pavement, which is the case based on Figure 33. The Rt.68 has an average MPD value of 1.02mm which is much higher than that for Rt.156 with an average MPD value of 0.70 mm. So even with the polishing of aggregates due to traffic is less for Rt.156 when compared with that for Rt.68, due to the inability of DFT20 test to capture the complete micro-texture of pavements. It is suggested here that when DFT20 are used to account for the micro-texture of the pavement, the macro-texture should also be considered. Only the pavements with similar MPD and DFT20 values are comparable.

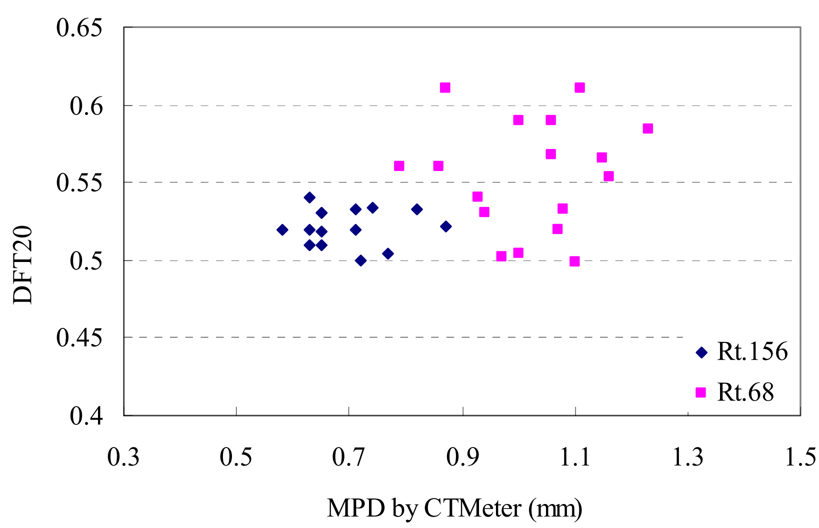


Figure 33: Variation of MPD values from CTM and DFT20 from DFT

APPLICABILITY TO OTHER PAVEMENT TYPES

As indicated before, the proposed correlation between SN40R and MPD is only valid for dense grade asphalt pavements with maximum size 9.5mm or NJ I-6 mixes. During our testing programs we also tested the following pavement types:

- Open Grade Asphalt Concrete.
- Dense Grade Coarse Aggregate Asphalt Concrete.
- Cement Concrete Pavements.
- Surry Sealed Surface Treated Asphalt Concrete.

However, we only tested one section of each of the above pavement types, so there is limited data to build any meaningful correlations. Hence in a separate demonstration project we propose to develop separate correlation for the above four pavement types. The data of the above mentioned four types of pavements are presented in the following sections. The comparison between the data of dense graded asphalt pavements based on which we build the correlation and the data of the four types of pavements are conducted to check the application of the correlation to these types of pavements.

Open Grade Asphalt Concrete

We tested the I-95 MP 3.0 to 4.0 on NB lane #3. It was open graded asphalt concrete pavement. Using the locked wheel skid tester and the laser mounted vehicle the SN40R and MPD values of open graded asphalt pavement were collected. This open graded asphalt pavement was constructed in 1973 and was treated in 2006. It has total traffic volume of 10383885 per lane. The test data is shown in Table 6 and plotted in Figure 34.

Table 6 SN40R and MPD Values of Open Graded Asphalt Pavement

SN40R	MPD (mm)	SN40R	MPD (mm)
47.02333	1.124661	49.10333	1.175252
48.16833	1.134383	47.83833	1.176494
44.97333	1.137648	49.185	1.212606
47.15333	1.164923	48.48333	1.354318

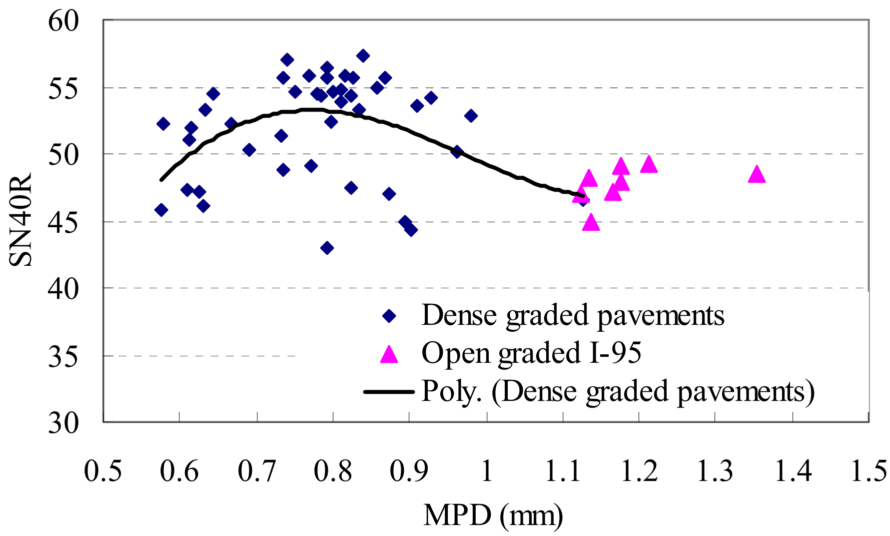


Figure 34 SN40R and MPD Values of Open Graded Asphalt Pavement

Based on the above table most of MPD values of I-95 were greater than 1.15mm. Please see Figure 34. Hence the proposed correlation between SN40R and MPD for dense graded asphalt pavements can not be employed to predict the SN40R values. As a result, further research is needed to develop a specific correlation for open graded asphalt pavements.

Dense Grade Coarse Aggregate Asphalt Concrete

We tested the I-195 MP 13.0 to 12.0 on WB lane #2. It was dense graded coarse aggregate asphalt concrete pavement with maximum size of 12.5mm. Using the locked wheel skid tester and the laser mounted vehicle the SN40R and MPD values of open graded asphalt pavement were collected. This dense graded asphalt pavement was constructed in 1999. It has total traffic volume of 175151820 per lane. The test data is shown in Table 7 and plotted in Figure 35.

Table 7 SN40R and MPD Values of Dense Graded Coarse Aggregate Asphalt Pavement

SN40R	MPD (mm)	SN40R	MPD (mm)
57.44166	0.650687	57.91166	0.779426
57.15666	0.81602	54.40166	0.829635
58.565	0.711642	56.83	0.735486
58.88833	0.772135		

Based on the above table most of SN40R values of I-195 was greater than that we obtained for the fine aggregate pavements see Figure 35. Hence the proposed correlation between SN40R and MPD for dense graded asphalt pavements can not be employed to predict the SN40R values. As a result, further research is needed in developing a specific correlation for dense graded asphalt pavements with coarse aggregates.

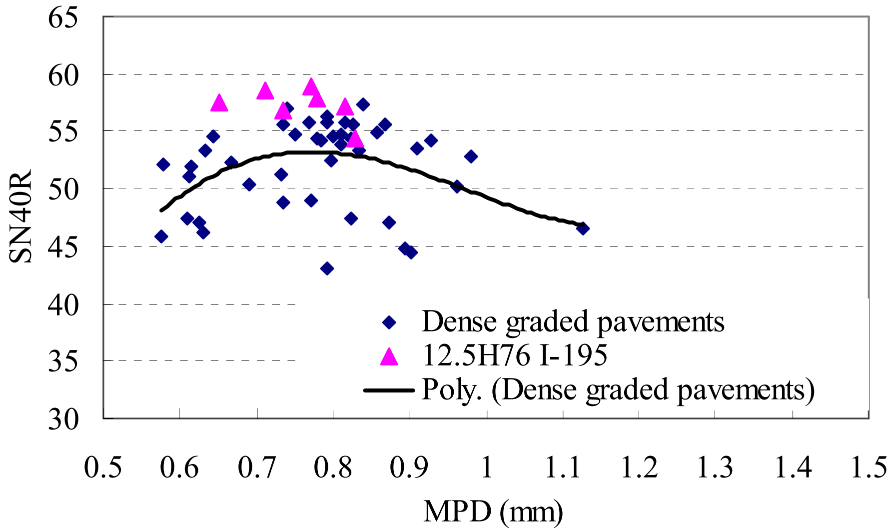


Figure 35 SN40R and MPD Values of Dense Graded Coarse Aggregate Asphalt Pavement

Cement Concrete Pavements

Two cement concrete pavements, one older and one newer were also tested. The routes MP and year of construction of these two pavements are listed in Table 8. The Skid numbers and MPD values of the two concrete pavements were also collected. The test result is shown in Figure 36. From Figure 36, it can be observed that for both routes, the SN40R values did not change with the variation of MPD values, which means the SN40R of concrete pavement is not very sensitive to MPD. When the new concrete pavement (I-295) is compared with the old concrete pavement (Rt.130), we can observe that the new concrete pavement has low MPD values with the average of about 0.65mm, but its SN40R values were higher than that of old concrete pavement (Rt.130) which had an average MPD value of 1.15mm. This is not the case for asphalt pavements. Hence we can preliminarily conclude that the skid resistance of concrete pavements relies more on the micro-texture than on macro-texture and hence needs further research.

Table 8 Routes information for the Two Cement Concrete Pavements

Route type	Route No.	Construction Year	Test site
Concrete New	I-295	1969	MP 45.0-44.0 SB Ln3
Concrete Old	Rt.130	1950	MP 59.8-58.8 SB Ln2

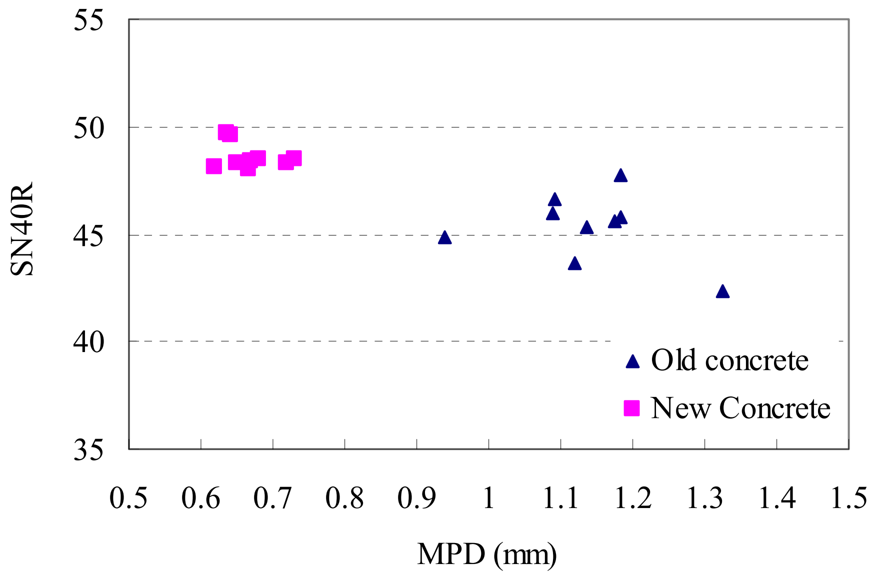


Figure 36 Correlation between MPD and SN40R for concrete pavement

Surry Sealed Surface Treated Asphalt Concrete

NJDOT had manual distress and FWD test performed on Route 202 from MP 3.9 to 3.4. Route 202 is a slurry sealed asphalt pavement treated in 2008 with the total traffic volume of 1126846. Since traffic control was used we were asked to use the same section for our detailed field tests. No pavement information was provided before we arrived at the site. Upon examination it was found that the pavement was recently treated with slurry seal. Since slurry seal has fine sand and no aggregates the pavement texture is much different from dense grade asphalt concrete. The field-testing program consisted of following components:

- Locked Wheel Skid Trailer[2].
- Dynamic Friction Test.
- Circular Texture Meter (CTM) test.
- Texture profile measurement using the ICC laser.
- Sand patch test.

The above developed correlation and reduction coefficient are applied to the pavement to predict the SN40R. The results are shown in the Table 9.

Table 9 Test Data for Rt. 202

SN40R	MPD(mm)	Reduction Coefficient	Predicted SN40R
58.403	0.84446	0.9651	52.87694811
62.928	0.700108	1.0069	53.79086684
57.907	0.683914	1.0069	53.36657654
61.405	0.616887	1.0069	50.47997521
67.228	0.615818	1.0069	50.41920019

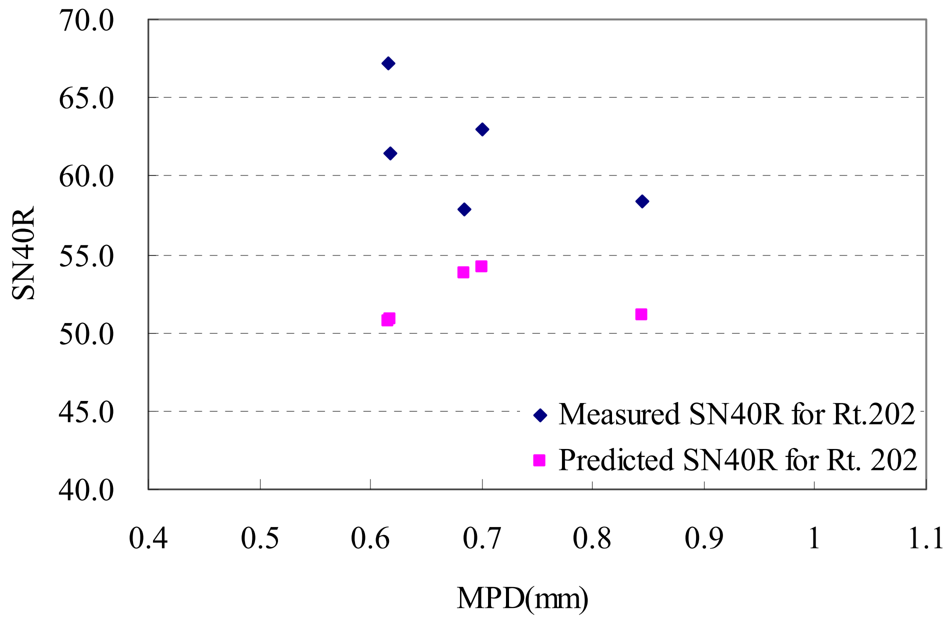


Figure 37 Comparisons between Measured and Predicted SN40R values from Rt.202

From Figure 37, we can observe that, the predicted MPD do not match the measured MPD. The trends of the initial parts of the two correlations even contradict each other. The average variance between them is greater than 5, which is not acceptable by ASTM. As a result, it can be concluded that, the correlation between SN40R and MPD developed for dense graded asphalt pavement may not be applicable to slurry sealed asphalt pavement. There are many factors accounting for this conclusion, among which the main factor is the different composition of two types of pavements. The different composition of the pavements results in the varied density and angularity which are import to skid resistance of pavement.

Table 10 Correlation between MPD and SPT

MPD by CTM (mm)	SPT (mm)	MPD by CTMeter (mm)	SPT (mm)
0.83	0.62	0.75	0.6091
0.79	0.6125	0.79	0.6091
0.7	0.6537	0.58	0.3612
0.7	0.5124	0.61	0.4319
0.87	0.7	0.68	0.4696

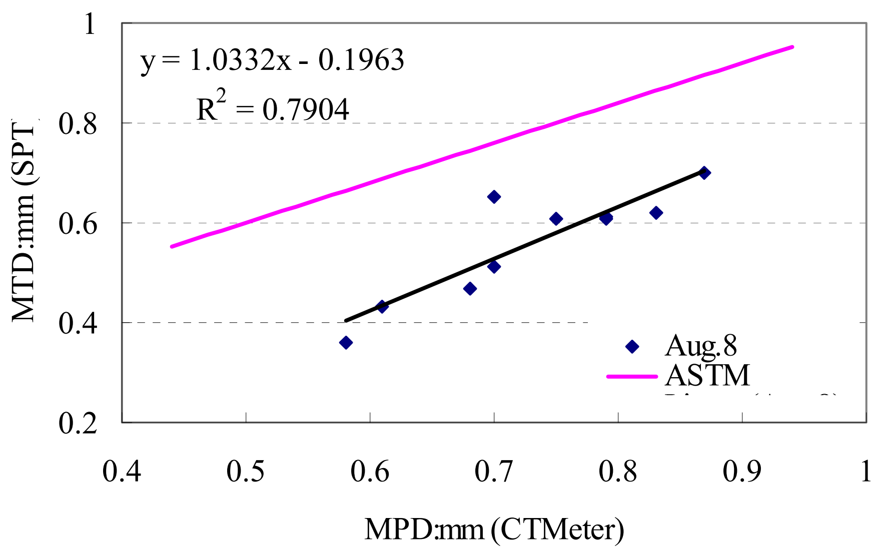


Figure 38: Correlation between MPD and SPT

Table 10 provides a comparison of MPD values obtained from CTM and the MTD measured using Sand Patch Test and Figure 38 plots those data. Please note that the correlation shown in Figure 38 is much different than that developed for Route 68, which means for different type of pavements, the measured MPD (by ICC Laser or CTM) are not comparable. As a result, the correlation between SN40R and MPD can not be shared by different type of pavements other than the dense grade fine aggregate asphalt pavements. However, we also noticed that both the correlations are parallel to the ASTM line which means it is possible to find the relationship of MPD for different types of roads.

INCORPORATION OF PREDICTED SKID NUMBERS TO PMS

The FHWA data bank indicates that each of the 50 states, the District of Columbia, and Puerto Rico have some kind of a pavement management system. The dominant forms of distress being measured and included in respective PMS databases are rutting, faulting, and cracking. The New Jersey Department of Transportation (NJDOT) in addition to the above measure and store surface friction information in NJDOT PMS. Surface friction or the skid resistance is the force developed when a tire that is prevented from rotating slides along the pavement surface. Skid resistance is an important pavement evaluation parameter because:

- Inadequate skid resistance will lead to higher incidences of skid related accidents.
- Most agencies have an obligation to provide users with a roadway that is "reasonably" safe.
- Skid resistance measurements can be used to evaluate various types of materials and construction practices.

Using texture data files generated from ICC’s WinRP software, seen in Figure 39 (refer to the WinRP User’s Manual for step-by-step instructions), the Pavement Management System allows importing of Texture data collected from laser tests and quickly performs the necessary SN40R analysis.

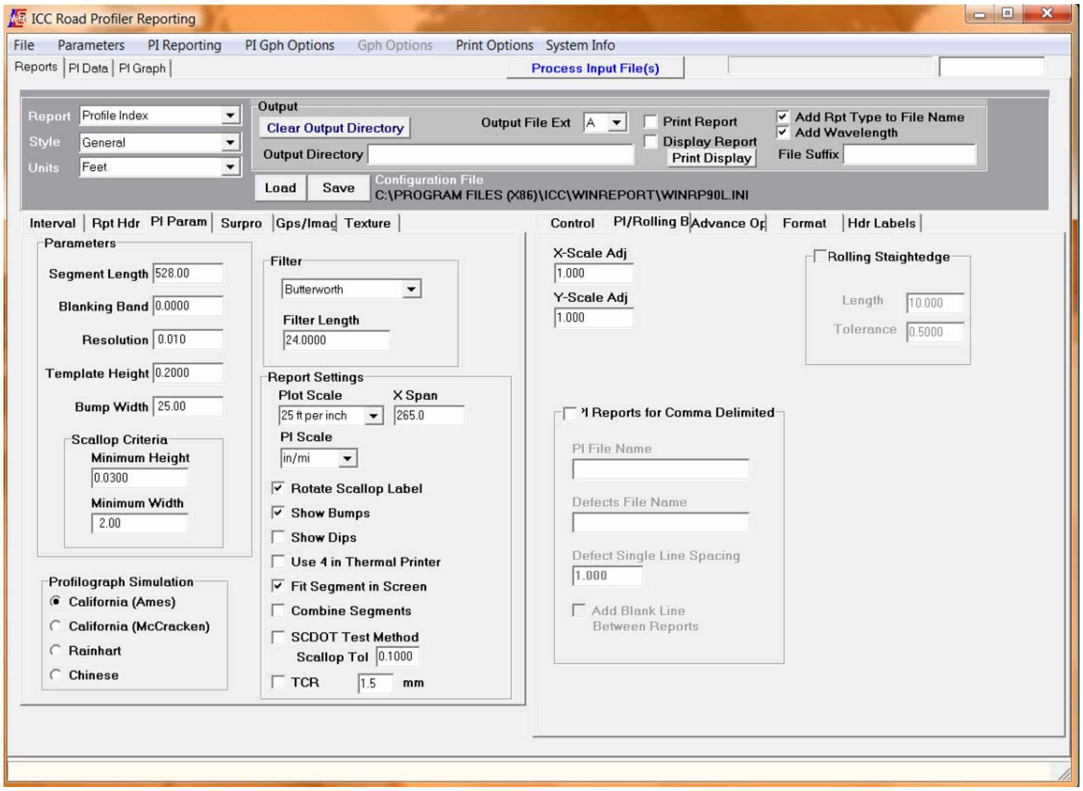
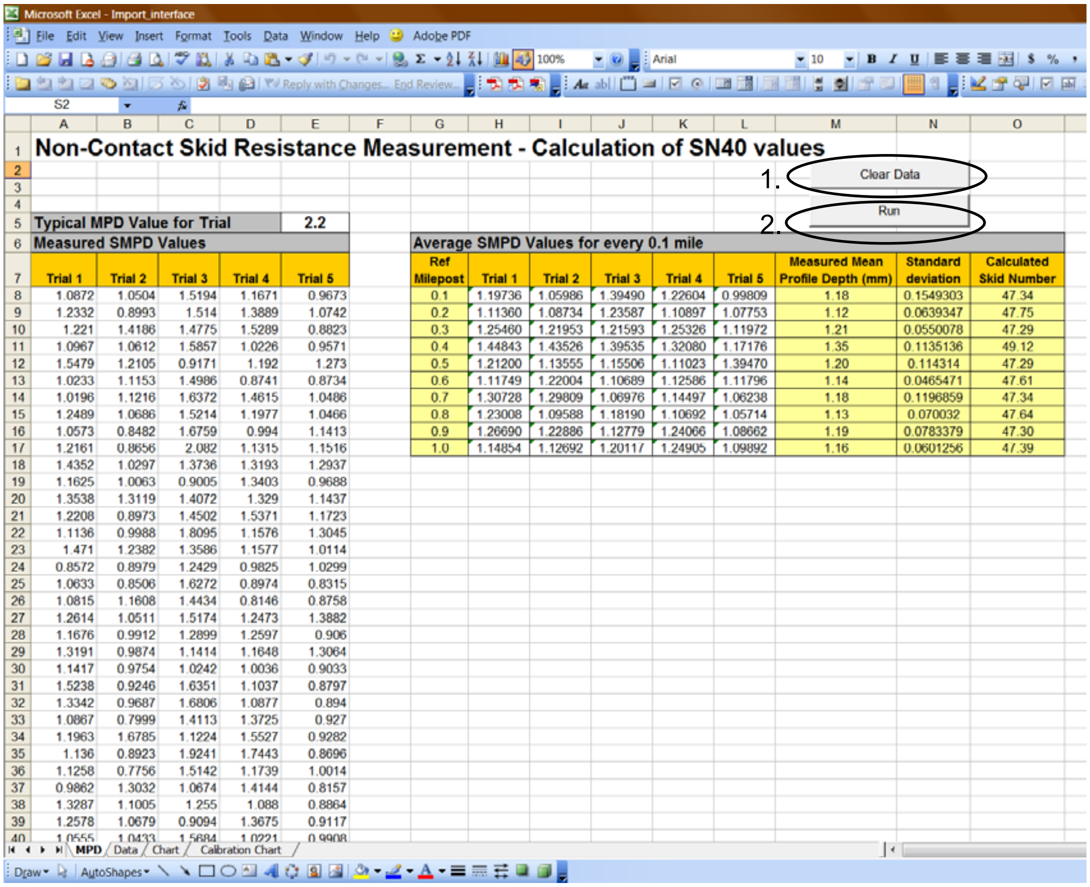


Figure 39: WinRP software by ICC

The interface developed based the correlation presented in the research, the Non-Contact Skid Measurement software for generating SN40R values for importing into the NJDOT Pavement Management System (Figure 40 and 41) allows users to import raw laser test files directly into a spreadsheet to display the results clearly and to obtain both the calculated and predicted SN40R values. The software consists of a MS Excel macro spreadsheet allowing importing of texture data and summary of the laser test data. The software also summarizes the MPD for each 0.1 mile of a given length test route.



Non-Contact Skid Resistance Measurement - Calculation of SN40 values

Typical MPD Value for Trial	2.2

Measured SMPD Values

Row	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
8	1.0872	1.0504	1.5194	1.1671	0.9673
9	1.2332	0.8993	1.514	1.3889	1.0742
10	1.221	1.4186	1.4775	1.5289	0.8823
11	1.0967	1.0612	1.5857	1.0226	0.9571
12	1.5479	1.2105	0.9171	1.192	1.273
13	1.0233	1.1153	1.4986	0.8741	0.8734
14	1.0196	1.1216	1.6372	1.4615	1.0486
15	1.2489	1.0686	1.5214	1.1977	1.0466
16	1.0573	0.8482	1.6759	0.994	1.1413
17	1.2161	0.8656	2.082	1.1315	1.1516
18	1.4352	1.0297	1.3736	1.3193	1.2937
19	1.1625	1.0063	0.9005	1.3403	0.9688
20	1.3538	1.3119	1.4072	1.329	1.1437
21	1.2208	0.8973	1.4502	1.5371	1.1723
22	1.1136	0.9988	1.8095	1.1576	1.3045
23	1.471	1.2382	1.3586	1.1577	1.0114
24	0.8572	0.8979	1.2429	0.9825	1.0299
25	1.0633	0.8506	1.6272	0.8974	0.8315
26	1.0815	1.1608	1.4434	0.8146	0.8758
27	1.2614	1.0511	1.5174	1.2473	1.3882
28	1.1676	0.9912	1.2899	1.2597	0.906
29	1.3191	0.9874	1.1414	1.1648	1.3064
30	1.1417	0.9754	1.0242	1.0036	0.9033
31	1.5238	0.9246	1.6351	1.1037	0.8797
32	1.3342	0.9687	1.6806	1.0877	0.894
33	1.0867	0.7999	1.4113	1.3725	0.927
34	1.1963	1.6785	1.1224	1.5527	0.9282
35	1.136	0.8923	1.9241	1.7443	0.8696
36	1.1258	0.7756	1.5142	1.1739	1.0014
37	0.9862	1.3032	1.0674	1.4144	0.8157
38	1.3287	1.1005	1.255	1.088	0.8864
39	1.2578	1.0679	0.9094	1.3675	0.9117
40	1.0555	1.0433	1.5684	1.0221	0.9908

1. Clear Data

2. Run

Average SMPD Values for every 0.1 mile

Ref Milepost	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Measured Mean Profile Depth (mm)	Standard deviation	Calculated Skid Number
0.1	1.19736	1.05986	1.39490	1.22604	0.99809	1.18	0.1549303	47.34
0.2	1.11360	1.08734	1.23587	1.10897	1.07753	1.12	0.0639347	47.75
0.3	1.25460	1.21953	1.21593	1.25326	1.11972	1.21	0.0550078	47.29
0.4	1.44843	1.43526	1.39535	1.32080	1.17176	1.35	0.1135136	49.12
0.5	1.21200	1.13555	1.15506	1.11023	1.39470	1.20	0.114314	47.29
0.6	1.11749	1.22004	1.10689	1.12586	1.11796	1.14	0.0465471	47.61
0.7	1.30728	1.29809	1.06976	1.14497	1.06238	1.18	0.1196859	47.34
0.8	1.23008	1.09588	1.18190	1.10692	1.05714	1.13	0.070032	47.64
0.9	1.26690	1.22886	1.12779	1.24066	1.08662	1.19	0.0783379	47.30
1.0	1.14854	1.12692	1.20117	1.24905	1.09892	1.16	0.0601256	47.39

Figure 40: Pavement Management System

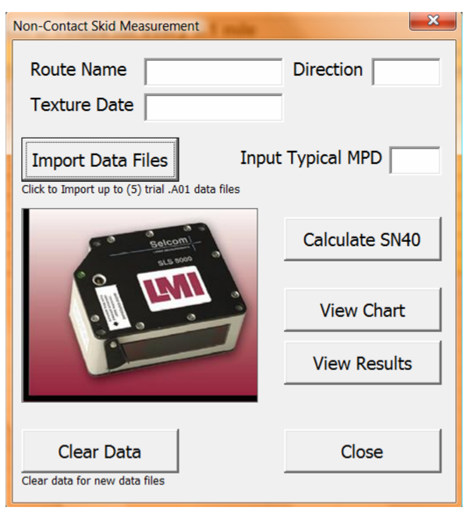


Figure 41: Pavement Management System Interface

The Pavement Management System contains the following user functions:

- 'Clear Data' – First, click on the 'Clear Data' button to clear the spreadsheet to begin a new session and import new Texture Data files.
- 'Run' – Click on 'Run' to execute the program interface as seen in the Figure 40.

Features of the Non-Contact Skid Measurement System Interface:

- Route Name – Input name of the Route/Highway/Location where the laser data is collected from (i.e. Route 68, I-95 etc.)
- Project Date – Specify date of the data collection from which the laser data was generated.
- Direction – Specify direction of travel for the route tested (i.e. East, West, North, South).
- Import Data Files – Select up to 5 trial laser test runs by clicking on the Import button. The software supports .A01 texture data files generated from the WinRP software. A File Open dialog window will open allowing the user to specify the directory of saved texture data files and select a single texture data file. If no file is selected, a warning dialog box will appear to confirm no selection. Repeat by clicking 'Import' to upload subsequent trial files.
- Typical MPD value – Specify the typical MPD values (2 decimal value) for the route tested (i.e. 1.75), used as data filter.
- Total No. of lanes – Specify the total number of lanes in both directions of travel for the route tested.
- Pavement Year – Input the year when the test route was last repaved or treated.
- Traffic volume – Input the Average Daily Traffic volume for the route tested. Refer to NJDOT Straight Line Diagrams.
- Calculate SN40 – Click on the button to display the Calculated Skid Numbers (SN40R) on the spreadsheet corresponding to the Measured MPD.
- View Chart – Click to view a graph representing the correlation between Measured MPD values, Measured SN40R and predicted SN40R values.
- View Results – Click to return to the spreadsheet showing the detail data summary including Standard Deviation.
- Return to Predicted SN40 – Click to return to the Pavement Management System Interface.
- Clear Data - Click to clear the spreadsheet to begin a new session and to import new Texture Data files.
- Close – Close the Pavement Management System interface.

SUMMARY AND CONCLUSIONS

In this research a mechanistic explanation and a correlation between skid number (SN40R) and Mean Profile Depth (MPD) for asphalt pavements were proposed based on texture data collected from high speed laser for five new asphalt pavements. The correlation is positive for the first part for MPD values less than 0.8mm, where SN40R value reaches a maximum around MPD value of 0.8mm. Then the data trend shows a negative correlation with increasing MPD values. It is also found that there is a significant fluctuation of SN40R values around MPD value of 0.8mm; the sealed off water pool effect seems to account for the data fluctuation. The proposed correlation between SN40R with MPD values is similar to that proposed by other researchers. However, there were some inconsistencies between the data from this research and those from the published data because of the difference in calibrations of vehicle mounted laser. In order to reduce the data fluctuations at a certain MPD value in the proposed correlation due to the sealed off water pool effect, it is proposed to include Root Mean Square (RMS) texture values with the MPD values to represent the macro-texture of the pavement.

The comparison of data between old and new asphalt pavements is also presented in this manuscript. The result shows that the trend of correlation for old asphalt pavements is similar to that of new asphalt pavements, but the SN40R for the old pavements are lower than that of the new pavements which reflects the polishing of aggregates due to traffic. Reduction coefficients which are the function of pavement age and traffic volume was developed and incorporated into the correlation to reflect the polishing of micro-texture due to traffic volume.

In addition to the correlation between skid numbers (SN40R) and Mean Profile Depth (MPD) values for asphalt pavements was validated using a detailed field study in this research. The field study included testing of two New Jersey Highway pavement sections, a relatively newer and older pavement, using the following tests: Locked Wheel Skid Trailer[(2)]; Dynamic Friction Test (DFT); Circular Texture Meter (CTM) test; Texture profile measurement using the ICC laser and Sand patch test. The test results showed that the measured and predicted SN40R values matched each other very well. The maximum variance between them was less than 5% which is considered acceptable according to ASTM. After confirming the validity of the correlation between skid number (SN40R) and Mean Profile Depth (MPD) for asphalt pavements and a software interface was developed to process the texture data obtained using high speed laser and report the predicted SN40R to Pavement Management System (PMS). In addition to the verification of the proposed correlation, the field test data showed that laser devices should be properly calibrated before use and that DFT test may not fully capture the micro-texture of pavements, especially those with low MPD values. The proposed correlation and the PMS interface will be used by the NJDOT to screen all the roadway pavements belonging to the state of New Jersey using high speed laser and the predicted skid numbers will be included in the NJDOT Pavement Management Database. Hence with the predicted skid numbers NJDOT could reduce the use of expensive locked wheel skid testers saving thousands of taxpayer dollars.

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APPENDIX 1 - MATERIALS PROCEDURE

<table>
<tr><td>NEW JERSEY DEPARTMENT OF TRANSPORTATION

MATERIALS PROCEDURE</td><td>DATE: December 2009</td></tr>
<tr><td colspan="2">SUBJECT: NON-CONTACT SKID RESISTANCE MEASUREMENT USING VEHICLE-MOUNTED LASER</td></tr>
</table>

1 SCOPE

1.1 This method describes the procedure for collecting and processing Texture data (profile depth) of pavement surfaces using a vehicle-mounted laser.

1.2 This test method uses a Selcom 62.5 KHz Laser, and a measuring system manufactured by International Cybernetics Corporation, operated at traffic velocity to measure the profile depth of a longitudinal profile of a pavement section.

1.3 The laser collects profile depth of the pavement surface at an interval of 0.34 ft.

1.4 Five trials runs are performed for each pavement.

1.5 The value stated in millimeters is to be regarded as the standard.

1.6 The laser measurements are to be correlated with Skid number SN40R values collected by full-scale friction measured using Locked Wheel Skid Trailer.

1.7 *This standard may involve hazardous materials, operations, and equipment. It does not purport to address all of the safety problems associated with its use. It is the responsibility of anyone using this practice to consult and establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to its use.*

2 REFERENCED DOCUMENTS

2.1 AASHTO Standards

2.2 PP51-02 "Standard Practice for Certification of Profiling Systems"

2.3 ASTM Standards

2.4 E274-06 "Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire"

2.5 E501-06 "Standard Specification for Standard Ribbed Tire for Pavement Skid-Resistance Tests"

2.6 E965-96 "Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique"

2.7 E1845-01 "Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth"

2.8 British Standards Institution

2.9 BS 7941-1 “Methods for measuring the skid resistance of pavement surfaces. Sideway-force coefficient routine investigation machine”

2.10 Texas Department of Transportation “Operating Inertial Profilers and Evaluating Pavement Profiles”

3 TERMINOLOGY

3.1 *Mean Profile Depth (MPD):* is the mean depth of the pavement macro-texture profile collected using ASTM standard practice E1845.

3.2 *Mean Texture Depth (MTD):* is the mean depth of the pavement surface macro-texture determined by the volumetric technique of ASTM test method E965.

3.3 *Skid Number (SN40R):* is the wet skid friction resistance value measured by full-scale friction measuring devices (i.e. Locked Wheel Trailer) and defined as the tractive force divided by the dynamic load on the tire. The character ‘R’ represents use of ribbed tires for skid measurements.

4 APPARATUS

4.1 Using Selcom 62.5 KHz Laser with the device manufactured by International Cybernetics Corporation and mounted on a vehicle

4.2 Software- WinPro and WinRP application software (International Cybernetics Corporation) for collecting and analyzing laser texture data

5 PROCEDURE

5.1 Start the data collection process manually using the WinPro software when the front windows of the vehicle cross the starting milepost (for rear-mounted lasers).

5.2 WinPro software automatically collects the profile depth measurements of the pavement surface measured by the laser.

5.3 Stop the measurement manually using WINPRO when the vehicle passes the end milepost.

5.4 Five trials runs are performed for each route/pavement.
5.5 Thus five data files for each route at each milepost (every 0.1 miles) are reported

6 DATA PROCESSING

6.1 The ICC's WinRP software processes the original data and reports MPD value for each 100 mm section of the pavement.
6.2 WinRP software will generate .A01 data files to be used with the Non-Contact Skid Measurement data processing software
6.3 The MPD values of each 20-meter long section of pavement at each milepost (10 meters on each side) are selected and averaged.
6.4 (Note: a length of 20 meters instead of 18 meters is chosen for calculating the average MPD corresponding to each SN40R value to take into account any operating error in skid resistance tests)
6.5 Five trials are run.

7 CALCULATION

7.1 Calculate the average and standard deviation of three SN40R values at every 0.1 milepost
7.2 Reject any SN40R values with a standard deviation greater than 2.
7.3 Calculate the average MPD value from the five laser trials laser
7.4 Check the standard deviation. If the standard deviation is high, check the original file and determine which trial among the five trials should be disregarded in the average. .
7.5 Reduction coefficient is calculated as the SN40R of old asphalt pavement based on the cumulative traffic volume which is calculated based on the number of years in service of the pavement after construction or resurfacing multiplied by the traffic volume /year /lane.
7.6 Correlate the average SN40R incorporating the reduction factors at every 0.1 milepost with the corresponding average MPD

8 REPORT

8.1 Calculate the average and standard deviation of three SN40R values at every 0.1 milepost

8.2 The report shall include the following information:

8.3 Summary tables

8.4 Average Measured Mean Profile Depth (MPD) value per each milepost along a given route

8.5 SN40R values based on measured MPD

8.6 Predicted SN40R values

8.7 Chart showing MPD vs. Calculated SN40 values

8.8 Chart showing MPD vs. Predicted SN40 values

8.9 Calibration Chart

9 PRECISION AND BIAS

9.1 The nature of this test does not follow for a round-robin testing program. Consequently, the precision and bias of this test are unknown at this time.

APPENDIX 2 - WINRP SAMPLE TEST RESULTS FOR I-95 NORTHBOUND

FILENAME: D:\Documents and Settings\Administrator\Desktop\6.14.09\I-95N(2).W01
DATE COLLECTED: 2009/06/14
DATE COLLECTED: 06/14/2009
TIME: 12:23:34
OPERATOR: Data Collecting Administrator
COUNTY:
ROUTE:
LANE:
SEGMENT LENGTH: 528.00
DIRECTION: North(+)
BEGINNING REF: 0+00
UNITS: ENGLISH
DCF: 3719.8
USER REF 1: I-95N(2)
USER REF 2: FACTORY
USER REF 3: FACTORY
USER REF 4:
USER REF 5:
USER REF 6:
USER REF 7:
DRIVER: Data Collecting Administrator
VEHICLE:
EQUIPMENT: HIGH SPEED
WAVELENGTH-LONG: none
WAVELENGTH-SHORT: none
SAMPLE DISTANCE: 0.6811 in (1)
SAMPLE DISTANCE: N.A.
PROFILE MA LEN: none
DIST CAL DATE: 09/13/2008
DIST CAL TIME: 12:27:31
SENSOR CAL DATE: 01/01/2004
SENSOR CAL TIME: 00:00:00
SYSTEM: ICC
MAX DELTA PROF: 3.0000 in
SPEED LIMIT: 1.0 mph
REPORT TYPE: Texture Data
BAR LENGTH: N.A.
BAR TOLERANCE: N.A.
RPT VERSION: 2.1.4.4
MDR VERSION: WP3.7.6.0
IRI SCALE: in/mi
RUTTING TYPE: Neg Rut
DISTANCE UNITS: ft
DATA UNITS: in
ELEVATION PROFILE:On

DOS FILTER: Off
WEATHER COND:
HIGH PASS FIL: 0.04
ACCEL CNT: 1
COLUMN FORMAT: _
LASER CNT: 1
IRI MA LEN: 15.00 ft
RUN TYPE: General
WHEELPATH: L
TIME-STRT COLLEC: 12:23:34
AIR TEMPERATURE: 0øF
AVG SPEED: 67.8 mph
VIN NUMBER: 1J4FJ68SXWL144270
DISTRICT:
COMMENT1:
COMMENT2:
VEHICLE MAKE: JEEP
VEHICLE MODEL: CHEROKEE
VEHICLE YEAR: 1998
START METHOD: MANUAL
STOP METHOD: MANUAL
STOP DISTANCE: 0.00
ENDING REF: 5176.88
CERT CODE:
CERT DATE:
SYS SERIAL NUM:
RUNOPTION1:
RUNOPTION2:
RUNOPTION3:
RUNOPTION4:
RUNOPTION5:
RUNOPTION6:
RUNOPTION7:
RUNOPTION8:
RUNOPTION9:
RUNOPTION10:
RUNOPTION11:
RUNOPTION12:
RUNOPTION13:
RUNOPTION14:
RUNOPTION15:
RUNOPTION16:
RUNOPTION17:
RUNOPTION18:
RUNOPTION19:
RUNOPTION20:

OUTPUTFILENAME: E:\6.14.09\I-95N(2)_NOF.A01
ACCEL CAL DATE: 08/14/2008
ACCEL CAL TIME: 17:09:46

ft Ref Post	Strt Dmi	End Dmi	Text Pos	mm SMPD	Samples
0.06	13511	13517	1	1.0504	229
0.40	13517	13523	1	0.8993	229
0.74	13523	13529	1	1.4186	229
1.08	13529	13535	1	1.0612	233
1.42	13535	13541	1	1.2105	229
1.76	13541	13547	1	1.1153	229
2.10	13547	13553	1	1.1216	229
2.44	13553	13559	1	1.0686	225
2.78	13559	13565	1	0.8482	229
3.12	13565	13571	1	0.8656	225
3.46	13571	13577	1	1.0297	229
3.80	13577	13583	1	1.0063	229
4.14	13583	13589	1	1.3119	225
4.48	13589	13595	1	0.8973	229
4.82	13595	13601	1	0.9988	233
5.17	13601	13607	1	1.2382	229
5.51	13607	13613	1	0.8979	229
5.85	13613	13619	1	0.8506	225
6.19	13619	13625	1	1.1608	233
6.53	13625	13631	1	1.0511	233
6.87	13631	13637	1	0.9912	237
7.21	13637	13643	1	0.9874	233
7.55	13643	13649	1	0.9754	229
7.89	13649	13655	1	0.9246	229
8.23	13655	13661	1	0.9687	233
8.57	13661	13667	1	0.7999	231
8.91	13667	13673	1	1.6785	229
9.25	13673	13679	1	0.8923	229
9.59	13679	13685	1	0.7756	231
9.93	13685	13691	1	1.3032	229
10.27	13691	13697	1	1.1005	225
10.61	13697	13703	1	1.0679	231
10.95	13703	13709	1	1.0433	225
11.30	13709	13715	1	1.1618	231
11.64	13715	13721	1	1.2305	233
11.98	13721	13727	1	1.0946	229
12.32	13727	13733	1	0.9280	229
12.66	13733	13739	1	1.0445	229
13.00	13739	13745	1	1.0299	229
13.34	13745	13751	1	0.9810	229

13.68	13751	13757	1	1.1430	237
14.02	13757	13763	1	1.0722	237
14.36	13763	13769	1	0.9822	233
14.70	13769	13775	1	0.8390	229
15.04	13775	13781	1	1.3741	233
15.38	13781	13787	1	1.1477	229
15.72	13787	13793	1	0.9303	233
16.06	13793	13799	1	1.5117	229
16.40	13799	13805	1	0.9464	229
16.74	13805	13811	1	1.3931	229
17.08	13811	13817	1	1.1031	229
17.43	13817	13823	1	1.1347	229
17.77	13823	13829	1	0.9872	229
18.11	13829	13835	1	1.2309	225
18.45	13835	13841	1	0.8170	229
18.79	13841	13847	1	1.0298	229
19.13	13847	13853	1	0.9140	233
19.47	13853	13859	1	1.3443	229
19.81	13859	13865	1	0.8508	229
20.15	13865	13871	1	1.2514	229
20.49	13871	13877	1	1.0608	229
20.83	13877	13883	1	0.8661	237
21.17	13883	13889	1	0.8793	233
21.51	13889	13895	1	0.9642	237
21.85	13895	13901	1	0.7788	233
22.19	13901	13907	1	1.2285	233
22.53	13907	13913	1	0.9654	229
22.87	13913	13919	1	1.0165	235
23.21	13919	13925	1	1.2493	229
23.55	13925	13931	1	0.9203	235
23.90	13931	13937	1	1.0015	229
24.24	13937	13943	1	1.0350	229
24.58	13943	13949	1	0.8937	233
24.92	13949	13955	1	1.2276	225
25.26	13955	13961	1	1.0459	225
25.60	13961	13967	1	1.0170	229
25.94	13967	13973	1	1.0682	229
26.28	13973	13979	1	1.0767	233
26.62	13979	13985	1	1.0743	233
26.96	13985	13991	1	0.6842	229
27.30	13991	13997	1	0.9035	229
27.64	13997	14003	1	0.9646	229
27.98	14003	14009	1	1.4201	233
28.32	14009	14015	1	0.9749	237
28.66	14015	14021	1	0.8620	237
29.00	14021	14027	1	0.9699	237

29.34	14027	14033	1	0.9188	229
29.68	14033	14039	1	1.2063	233
30.03	14039	14045	1	0.8009	233
30.37	14045	14051	1	0.9867	233
30.71	14051	14057	1	0.9963	233
31.05	14057	14063	1	0.9625	229
31.39	14063	14069	1	1.2488	233
31.73	14069	14075	1	0.8928	229
32.07	14075	14081	1	1.1541	225
32.41	14081	14087	1	1.2310	229
32.75	14087	14093	1	1.5204	229
33.09	14093	14099	1	0.8935	229
33.43	14099	14105	1	0.7954	229
33.77	14105	14111	1	1.0579	233
34.11	14111	14117	1	0.9735	233
34.45	14117	14123	1	1.0332	229
34.79	14123	14129	1	1.0469	229
35.13	14129	14135	1	1.0121	235
35.47	14135	14141	1	1.7299	237
35.81	14141	14147	1	1.2197	237
36.16	14147	14153	1	1.2495	237
36.50	14153	14159	1	1.1105	233
36.84	14159	14165	1	0.8233	229
37.18	14165	14171	1	0.9635	237
37.52	14171	14177	1	1.4382	229
37.86	14177	14183	1	1.1794	233
38.20	14183	14189	1	1.3121	233
38.54	14189	14195	1	0.8195	233
38.88	14195	14201	1	1.2239	229
39.22	14201	14207	1	1.2115	229
39.56	14207	14213	1	1.1353	225
39.90	14213	14219	1	0.8747	233
40.24	14219	14225	1	1.3420	229
40.58	14225	14231	1	0.9825	229
40.92	14231	14237	1	0.9755	237
41.26	14237	14243	1	0.9152	229
41.60	14243	14249	1	1.0053	229
41.94	14249	14255	1	0.9484	229
42.29	14255	14261	1	1.1550	233
42.63	14261	14267	1	0.9887	237
42.97	14267	14273	1	1.0418	237
43.31	14273	14279	1	1.0990	237
43.65	14279	14285	1	1.1126	235
43.99	14285	14291	1	0.8648	233
44.33	14291	14297	1	1.3875	233
44.67	14297	14303	1	1.0369	233

45.01	14303	14309	1	1.1218	233
45.35	14309	14315	1	1.1826	233
45.69	14315	14321	1	0.7939	233
46.03	14321	14327	1	1.3908	229
46.37	14327	14333	1	1.1765	229
46.71	14333	14339	1	1.0079	225
47.05	14339	14345	1	0.8900	229
47.39	14345	14351	1	1.2892	229
47.73	14351	14357	1	1.0509	237
48.07	14357	14363	1	1.4234	233
48.42	14363	14369	1	1.0852	229
48.76	14369	14375	1	1.1846	229
49.10	14375	14381	1	0.9052	229
49.44	14381	14387	1	1.1160	233
49.78	14387	14393	1	1.4589	237
50.12	14393	14399	1	0.8567	241
50.46	14399	14405	1	1.0253	237
50.80	14405	14411	1	1.2225	229
51.14	14411	14417	1	1.1476	233
51.48	14417	14423	1	1.0867	233
51.82	14423	14429	1	1.1911	235
52.16	14429	14435	1	1.3212	233
52.50	14435	14441	1	1.2682	233
52.84	14441	14447	1	0.8683	233
53.18	14447	14453	1	1.2319	229
53.52	14453	14459	1	0.9046	225
53.86	14459	14465	1	1.3566	225
54.20	14465	14471	1	1.2329	229
54.55	14471	14477	1	1.4596	229
54.89	14477	14483	1	1.1571	233
55.23	14483	14489	1	0.8592	233
55.57	14489	14495	1	1.1490	229
55.91	14495	14501	1	0.7222	225
56.25	14501	14507	1	0.8790	229
56.59	14507	14513	1	0.7631	237
56.93	14513	14519	1	1.0618	241
57.27	14519	14525	1	0.7799	237
57.61	14525	14531	1	1.0339	233
57.95	14531	14537	1	1.0503	233
58.29	14537	14543	1	0.9183	233
58.63	14543	14549	1	1.0849	233
58.97	14549	14555	1	1.0323	233
59.31	14555	14561	1	0.9627	233
59.65	14561	14567	1	1.2804	233
59.99	14567	14573	1	1.0283	233
60.33	14573	14579	1	1.3291	229

60.68	14579	14585	1	1.0948	225
61.02	14585	14591	1	1.0886	229
61.36	14591	14597	1	0.8274	229
61.70	14597	14603	1	0.9660	229
62.04	14603	14609	1	1.0416	235
62.38	14609	14615	1	0.9359	229
62.72	14615	14621	1	1.2860	233
63.06	14621	14627	1	0.9348	229
63.40	14627	14633	1	1.0608	229
63.74	14633	14639	1	0.9266	233
64.08	14639	14645	1	1.0781	237
64.42	14645	14651	1	0.6903	237
64.76	14651	14657	1	1.4587	237
65.10	14657	14663	1	1.0059	233
65.44	14663	14669	1	0.9065	233
65.78	14669	14675	1	0.8794	233
66.12	14675	14681	1	0.8439	233
66.46	14681	14687	1	0.8732	237
66.81	14687	14693	1	1.1373	233
67.15	14693	14699	1	0.9959	229
67.49	14699	14705	1	1.0984	233
67.83	14705	14711	1	1.2683	225
68.17	14711	14717	1	1.0910	229
68.51	14717	14723	1	1.2289	229
68.85	14723	14729	1	0.8007	229
69.19	14729	14735	1	1.0652	233
69.53	14735	14741	1	1.0256	233
69.87	14741	14747	1	1.0035	229
70.21	14747	14753	1	1.0718	229
70.55	14753	14759	1	0.9211	229
70.89	14759	14765	1	0.9208	233
71.23	14765	14771	1	0.9215	239
71.57	14771	14777	1	1.0601	237
71.91	14777	14783	1	0.8961	237
72.25	14783	14789	1	1.1058	233
72.59	14789	14795	1	1.0001	233
72.94	14795	14801	1	0.6590	237
73.28	14801	14807	1	0.6480	233
73.62	14807	14813	1	0.8034	233
73.96	14813	14819	1	0.9010	233
74.30	14819	14825	1	0.8825	233
74.64	14825	14831	1	0.7958	233
74.98	14831	14837	1	0.9920	225
75.32	14837	14843	1	0.9549	229
75.66	14843	14849	1	0.9625	229
76.00	14849	14855	1	0.9285	229

76.34	14855	14861	1	0.9594	233
76.68	14861	14867	1	1.2900	233
77.02	14867	14873	1	0.8228	229
77.36	14873	14879	1	0.9344	229
77.70	14879	14885	1	1.0344	229
78.04	14885	14891	1	0.8622	233
78.38	14891	14897	1	1.0223	237
78.72	14897	14903	1	0.9790	237
79.07	14903	14909	1	1.0074	239
79.41	14909	14915	1	0.8708	233
79.75	14915	14921	1	1.0790	233
80.09	14921	14927	1	0.7318	237
80.43	14927	14933	1	0.9198	233
80.77	14933	14939	1	1.0826	237
81.11	14939	14945	1	0.9441	233
81.45	14945	14951	1	0.9582	233
81.79	14951	14957	1	1.2153	233
82.13	14957	14963	1	1.3196	229
82.47	14963	14969	1	1.1380	229
82.81	14969	14975	1	1.0730	229
83.15	14975	14981	1	1.0641	225
83.49	14981	14987	1	0.8700	233
83.83	14987	14993	1	0.9619	233
84.17	14993	14999	1	0.9876	229
84.51	14999	15005	1	0.9652	229
84.85	15005	15011	1	0.8971	229
85.20	15011	15017	1	0.9389	229
85.54	15017	15023	1	1.2019	237
85.88	15023	15029	1	1.4651	237
86.22	15029	15035	1	1.1020	241
86.56	15035	15041	1	1.0388	233
86.90	15041	15047	1	0.8727	235
87.24	15047	15053	1	0.7676	237
87.58	15053	15059	1	0.8130	237
87.92	15059	15065	1	0.9306	233
88.26	15065	15071	1	1.0800	237
88.60	15071	15077	1	1.0825	233
88.94	15077	15083	1	1.0864	233
89.28	15083	15089	1	0.7920	229
89.62	15089	15095	1	0.9786	225
89.96	15095	15101	1	1.1416	229
90.30	15101	15107	1	0.9758	229
90.64	15107	15113	1	1.1025	229
90.98	15113	15119	1	0.7307	237
91.33	15119	15125	1	1.1329	229
91.67	15125	15131	1	1.1578	229

92.01	15131	15137	1	0.9645	225
92.35	15137	15143	1	1.2430	229
92.69	15143	15149	1	0.7900	237
93.03	15149	15155	1	0.8706	241
93.37	15155	15161	1	1.0020	237
93.71	15161	15167	1	0.8549	233
94.05	15167	15173	1	0.9430	237
94.39	15173	15179	1	1.3510	235
94.73	15179	15185	1	0.8178	237
95.07	15185	15191	1	1.2163	233
95.41	15191	15197	1	1.0123	241
95.75	15197	15203	1	0.9829	233
96.09	15203	15209	1	1.3698	233
96.43	15209	15215	1	1.1728	229
96.77	15215	15221	1	1.2449	225
97.11	15221	15227	1	1.0433	229
97.46	15227	15233	1	0.9736	229
97.80	15233	15239	1	1.0073	229
98.14	15239	15245	1	0.9826	237
98.48	15245	15251	1	0.9932	225
98.82	15251	15257	1	0.9846	229
99.16	15257	15263	1	0.8795	225
99.50	15263	15269	1	1.0627	233
99.84	15269	15275	1	1.0869	233
100.18	15275	15281	1	1.0969	241