Influence of Road Surface Texture on Traffic Characteristics Related to Environment, Economy and Safety

A State-of-the-art Study Regarding Measures and Measuring Methods

Author: Ulf Sandberg
Research division: Road Maintenance and Operation
Project number: 20229
Project name: Measurement of road surface texture
Sponsor: Swedish National Road Administration
Distribution: Free
INFLUENCE OF ROAD SURFACE TEXTURE ON TRAFFIC CHARACTERISTICS RELATED TO ENVIRONMENT, ECONOMY AND SAFETY

A STATE-OF-THE-ART STUDY REGARDING MEASURES AND MEASURING METHODS

By Ulf Sandberg
Swedish National Road and Transport Research Institute

17 October 1998
Preface

A couple of years ago, the Swedish National Road Administration (from here the official Swedish name Vägverket is used) requested a state-of-the-art report on measures and methods to describe the influence of road surface texture on effects such as environment, economy and safety in traffic. It was agreed that the report be written in English in order to facilitate international exchange. Major parts of earlier work on the subject had been made in international cooperation and the current work within ISO and CEN further emphasized the need for working on an international level but with a strong national base. This report is intended to meet this request.

The report is based on data collection and other work made in previous years, mostly in projects sponsored by Vägverket, but also in projects sponsored by the Swedish National Road and Transport Research Institute (VTI). The author is grateful for this support.

It is acknowledged that most of the diagrams have been skilfully produced by Mrs. Meiying Dong at VTI. Mrs. Karin Nilsson, VTI, has assisted with some typing and editing.

Two more state-of-the-art reports with respect to functional properties of road surfaces have recently been produced within this programme:

**Wretling, Peter:** “Relationship between the functional properties of road surface and traffic safety”. VTI Notat No. 32A–1996, Swedish National Road and Transport Research Institute (VTI), Linköping (in English).

**Magnusson, Georg:** “Kan jämnhetsstanden hos det svenska vägnätet förorsaka fordonsskador och onödigt fordonsslitage?”. VTI Notat No. 21–1998, Swedish National Road and Transport Research Institute (VTI), Linköping (in Swedish).
CONTENTS

EXECUTIVE SUMMARY ............................................................................................. 1

SAMMANFATTNING ......................................................................................... V

1. INTRODUCTION ................................................................................................. 1

2. PURPOSE WITH THE STUDY ......................................................................... 1

3. TERMINOLOGY WITH REGARD TO PAVEMENT TEXTURE ............................... 1

4. EFFECTS OF TEXTURE .................................................................................. 4

4.1 EFFECTS IN GENERAL ................................................................................ 4

4.2 FRICTION ........................................................................................................ 5

4.3 OVERVIEW OF TEXTURE EFFECTS ON SAFETY-RELATED CHARACTERISTICS .................................................. 10

4.4 ROLLING RESISTANCE: EFFECTS ON AIR POLLUTION AND ECONOMY .................................................. 11

4.5 TYRE WEAR .................................................................................................. 13

4.6 OTHER VEHICLE WEAR ............................................................................. 16

4.7 ROAD WEAR ................................................................................................ 16

4.8 EXTERIOR NOISE ........................................................................................ 17

4.9 INTERIOR VEHICLE NOISE ...................................................................... 19

5. PREVIOUS AND CURRENT STANDARDIZATION ACTIVITIES ............................. 20

5.1 ISO — THE INTERNATIONAL STANDARDIZATION ORGANIZATION ................. 20

5.1.1 ISO 10844 — Reference surface for noise measurements / Volumetric Patch method .................................................................................................................. 20

5.1.2 ISO 11819-1 — The Statistical Pass-By method for comparison of road surfaces .................................................................................................................. 20

5.1.3 ISO/CD 11819-2 — The Close-Proximity method for comparison of road surfaces .................................................................................................................. 21

5.1.4 Reference tyres .......................................................................................... 21

5.1.5 Sound absorption measuring method for comparison of porous road surfaces .................................................................................................................. 23

5.1.6 ISO 13473-1 — Measurement of Mean Profile Depth ................................................. 23

5.1.7 Future parts of ISO 13473 — Terminology and Specifications of Profilometers .................................................................................................................. 24

5.1.8 ISO draft on "Measurement of road surface friction" ............................................. 25

5.2 CEN ............................................................................................................... 25

5.2.1 Texture measuring methods ........................................................................ 25

5.2.2 Friction measuring and harmonization methods ........................................... 26

5.2.3 Quality classes and normative values ................................................................ 31

5.2.4 Overview of standards ................................................................................. 31

5.3 OTHERS ....................................................................................................... 31

6. THE MEASUREMENT AND USE OF ROAD SURFACE TEXTURE DATA — HISTORY AND CURRENT TRENDS ........................................................................ 33

6.1 HISTORICAL REMARKS .............................................................................. 33

6.2 USE OF TEXTURE DATA IN SOME OTHER COUNTRIES .............................. 34

7. MEASURES, METHODS AND INSTRUMENTS ............................................ 37

7.1 MEASURES AND METHODS ....................................................................... 37

7.2 INSTRUMENTS AND EQUIPMENT .............................................................. 41

8. MAJOR ON-GOING OR PLANNED INTERNATIONAL AND NATIONAL RESEARCH OR DEVELOPMENT PROJECTS ........................................ 49

8.1 FRICTION .................................................................................................... 49

8.2 OTHER SAFETY-RELATED PROJECTS ......................................................... 51

8.3 ROLLING RESISTANCE AND FUEL CONSUMPTION .................................. 51

VTI notat 53A–1997
Influence of Road Surface Texture on Traffic Characteristics Related to Environment, Economy and Safety – A State-of-the-Art Study Regarding Measures and Measuring Methods

by
Ulf Sandberg
Swedish National Road and Transport Research Institute (VTI)
SE-581 95 Linköping, Sweden

EXECUTIVE SUMMARY

Surface texture is the most important feature of the road surface, affecting tyre/road interaction processes such as friction, tyre wear, exterior vehicle noise emission, interior vehicle noise emission, light reflection and rolling resistance. It follows that the description of texture is very important when trying to quantify road surface condition and/or its potential effects on safety, economy and environment. Unfortunately, practical tools for describing this surface feature have become available only recently. This report attempts to describe the current state-of-the-art regarding the effects of road surface texture, measurement technology and instrumentation, and also attempts to outline near future activities which are recommended in order to make use of the latest developments in the subject area.

The purpose with this study is to provide background information concerning the use of road surface texture data for condition surveys as well as for actions. Furthermore, near future and long-term research needs and other actions based on texture utilization are identified.

In recent years the terminology with respect to pavement texture has been reviewed and refined, essentially following current activities in international organizations such as the World Road Association (PIARC), the International Organization for Standardization (ISO) and the European Committee for Standardization (CEN). The report starts with a review of the most important terms.

The effects of texture are reviewed in the next chapter. It is first concluded that surface texture, although having great impact on several traffic parameters, has no consistent and uniform influence on them as a whole. One cannot say generally that high or low or medium levels of surface texture are desirable. It depends on the specific application, since texture affects different parameters differently. However, it seems that it is possible to optimize texture to some extent, in a way which would be beneficial for most applications.

Tyre/road friction is affected essentially by microtexture and macrotexture. Both should be high for good friction. Microtexture is needed to get a high general friction level, but macrotexture is needed in order to provide escape channels for water trapped in the tyre/road interface in wet weather, thus avoiding a high drop-off of friction with increasing speed, eventually resulting in poor safety at high-speed traffic irrespective of microtexture level. If macrotexture fails to provide this drainage, the road may be very unsafe for high-speed traffic in wet weather conditions. In recent years, as a result of an international project under PIARC, it has been
possible to find a texture measure called Mean Profile Depth (MPD), which is a good descriptor of the speed effect on friction. This is a most important achievement in this subject in recent years. The MPD makes it possible to reduce the number of friction measurements to one speed per site: If MPD is also measured, one can in principle and in many cases also practically calculate the friction level at any other speed.

Rolling resistance, and thus also vehicle fuel consumption and exhaust emissions, is affected by texture of longer texture wavelengths than those affecting friction. When texture assumes high levels in the megatexture range, rolling resistance will become high, but also macrotexture has a significant effect. It seems that both ranges of texture have an influence of about 10 % in fuel consumption and it is concluded that even if road authorities have little possibilities of playing with the entire range, there is nevertheless a significant effect on fuel consumption and thus on exhaust emissions on a national level by choice of road surface types and state of maintenance.

Research on the effects of surface texture on tyre wear is not at a stage advanced enough to provide a full and quantitative picture. However, it is not questioned that high microtexture affects tyre wear negatively (which is a conflict with friction) and there are indications that also macrotexture has an effect. Overall, it has been recorded by many that texture has significant effects on tyre wear, and thus on economy and environment.

Both exterior and interior noise are affected by macrotexture and megatexture. Megatexture has a negative effect on noise, whereas macrotexture has both negative and positive effects. Surface texture, including porosity in the wearing course, in fact affects road traffic noise equally much as the type of tyres or types of vehicles that are considered. It is equally important to limit noise emission by setting limits with regard to vehicle or tyre noise as it is to force a proper selection of road surface to avoid excessive tyre/road noise.

It is also concluded that texture affects parameters such as splash and spray, water runoff and light reflection properties. These effects influence primarily safety and environment.

The report then presents the current and past international standardization activities. These have accelerated from almost none to a high pace at the moment, mostly triggered by the availability of proper mobile texture measuring devices in recent years and by the realization among many researchers and authorities that by measuring texture, a lot of measurements and predictions of performance parameters are possible and will be even more feasible in the future. Organizations such as ISO and CEN have recently or are currently aiming at standardizing methods, measures and equipment for texture characterization. ISO has recently issued a standard for measuring MPD, which CEN has accepted, CEN has also accepted an older ISO standard for measuring texture depth with the patch method, ISO has standardized a method for characterizing noise properties and is working on another one, CEN has accepted the first one, and ISO is currently trying to specify requirements for profilometers and is defining several new measures needed for texture characterization. Work has also started with specifying reference tyres for testing of road surfaces. Finally, all these standardization activities are summarized in an overview table.

A few years ago, as mentioned above, an international experiment conducted by the PIARC committee on surface characteristics resulted in a proposal to harmonize friction measurements by different devices. In normal cases, friction coefficients measured by different types of equipment may deviate very much; an example mentioned in the report gave a friction value of 0.90 with one device and 0.33 with another device on the same road test section. Friction
measurements or intervention levels of friction can therefore not be directly compared unless the same type of equipment has been used or unless some type of conversion or harmonization has been applied.

The proposal from the PIARC researchers, which recently has been further processed in Belgium, is now subject of standardization attempts in CEN. This proposal suggests the use of an International Friction Index (IFI), alternatively a European Friction Index (EFI), which reports friction values in a uniform way, derived from measurements by any type of friction equipment that participated in the PIARC experiment. The follow-up work also suggests methods to make periodic calibrations, also making it possible for equipment which did not take part in the PIARC experiment to be calibrated for reporting IFI (or EFI). The IFI (or EFI) consists of two values for each test section; a friction coefficient at a reference slip speed (PIARC suggested 60 and the Belgian follow-up work suggests 30 km/h) as well as a speed "constant". With these two values, friction can be calculated not only at the reference slip speed but at any slip speed. One of these two components of the IFI or EFI, a parameter indicating the speed influence on friction, is a surface texture depth. Normally, it would be recommended that this parameter would be the recently standardized MPD. Thus by measuring friction and texture (and pending the result of current CEN standardization) it is now possible to:

- obtain an international/European friction index at a reference speed, a value which in principle is independent on equipment
- estimate friction at (in principle) any speed by measuring only at one speed
- from one’s own measurement of friction and texture estimate the corresponding friction values that would have been obtained with (in principle) any other major device
- compare friction measurements in a way never before possible and to establish uniform standards and/or limits throughout at least Europe, perhaps world-wide

Of course, it should be noted that the accuracy of such estimations is currently not the best, but it will probably be improved by and by. These important progress steps have been taken with essential contributions by projects sponsored by Vägverket. The procedure for applying the suggested harmonization procedure to for example the Swedish BV-11 is outlined in the report.

One chapter in the report presents some historical notes on texture measurements and reports on the use of texture data in various countries. It is concluded that road surface macrotexture measurement is applied in many countries, in some countries regulations or recommendations are already based on texture, and the use of such measures seems to be increasing. The results of the PIARC Experiment will most probably accelerate this development. *This emphasizes the need for international standardization before methods are becoming too disperse and before standardization will be politically difficult due to locked positions.*

The chapter about measures, methods and instruments, systematically lists all major known methods and instruments used for texture measurements. Examples of modern ways of presenting texture measurements, for example in terms of profile amplitude distribution and profile (frequency) spectrum, are shown. Some instruments are illustrated with photos. Modern laser profilometers are presented in some more detail.

There is also a chapter in which some selected ongoing or planned international projects in the subject area are mentioned or presented. The chapter includes a presentation of some currently applied ideas abroad utilizing performance requirements of road surface characteristics, for
example on Italian toll motorways, on which the toll charge is connected to the measured quality of the motorway - in principle the driver pays for the quality he is getting.

The author’s vision for future use of texture data in road management is presented in one chapter. It is outlined how mobile texture measurement over the micro-, macro and megatexture ranges (of which microtexture is not yet possible) can be utilized for estimation of the most important properties of the road surface just by texture measurements. This will of course require that models for the relation between these properties and texture be developed, models of which may already exist in rudimentary terms.

It is discussed at what stage in the realization of this vision that we are at the moment and the author’s best judgement of the development times required before certain parts of it can be applied are included. It is concluded that parts of this vision of a "Grand Model" for texture data utilization are realizable already now and other parts will be possible in just a few years along with ongoing or planned development. It is emphasized that by using such an approach it will be possible to replace by and by the individual measurement of most properties, for example friction and noise, which are often unsafe, uneconomical and time-consuming, by a uniform mobile texture measurement. In principle, it will be possible to survey an entire national road network, perhaps annually, at a reasonable cost and produce statistics of the network status indicating a "national quality index" for each property of the road surface, e.g. friction index, noise index, tyre wear index and fuel consumption index. This is in line with current interest to create "Environmental indicators".

The main part of the report ends with a presentation of research and development needs, for example work necessary to follow-up the PIARC experiment and to realize by and by the visionary "Grand Model". In the "Conclusions" chapter, it is emphasized how important it is that international standardization takes place efficiently. The development in the latest years shows how much progress that can be achieved if such work is made timely.

The report also includes three annexes: the first one on tyre/road noise generation mechanisms and measuring methods, the second one illustrating how quality (noise) classes for road surfaces may be specified and the third one presenting a round-up of VTI involvement in road surface texture research in recent decades.
SAMMANFATTNING

Vägytans textur påverkar viktiga interaktionsprocesser mellan däck och vägbana såsom friktion, däckslitage, extern fordonsbulleremission, intern fordonsbulleremission och rullmotstånd, och utgör därmed den viktigaste grundegenskapen hos vägytan. Därför följer att metoder och mätteknik för beskrivning av vägytetextur är mycket viktiga när man försöker bestämma vägbeläggningars kondition och/eller deras potentiella effekter på trafiksäkerhet, ekonomi och miljö. Praktiska möjligheter att beskriva denna ytegenskap har inte blivit tillgängliga förrän under senare år, i och med framtagandet av apparater som kan mäta vägytans profil kontaktlös.

Syftet med denna studie är att ge en state-of-the-art-redovisning beträffande effekterna av vägytetextur samt beträffande mätteknik och mätinstrument. Den försöker också att redovisa de huvudsakliga aktiviteterna som pågår samt de som behöver genomföras för att man skall kunna praktiskt nyttiggöra den senaste utvecklingen inom ämnedområdet. Vidare sammanfattas behoven av såväl kort- som långsiktig forskning och åtgärder som är baserade på användning av texturmått.

Under senare år har terminologin vad gäller vägytetextur reviderats och utvecklats, i huvudsak som en följd av aktiviteter inom internationella organisationer såsom the World Road Association (PIARC), the International Organization for Standardization (ISO) och the European Committee for Standardization (CEN). Rapporten börjar med en överblick över de viktigaste facktermerna. T ex brukar man numera indela texturen i tre delområden:

Mikrotekstur Den fintextur som enskilda stenar i en vägbeläggning har, vilken yttrar sig som en strävhet hos enskilda stenar

Makrotekstur Den yttektur som, i regel avsiktligt, uppkommer av blandningen av stenar (samt ofta även sand och bruk) i en vägbeläggning, och som yttrar sig som en skrovlighet hos vägytan

Megatekstur Den yttektur som, i regel oavsiktligt, uppkommer av inhomogenitet i packningen av stenar och bruk, sammanhängande stensläpp, s k "potthål", kortvägiga korrugerings samt genomslag av kortvägiga ojämnheter och skarvar hos underliggande lager

Effekterna av texturen redovisas i nästa kapitel. Först fastslås att yttektur, trots stor effekt på åtskilliga trafikpåverkande parametrar, inte har något entydigt inflytande på dem i det stora hela.
Man kan således inte allmänt säga att höga, låga eller medelhöga nivåer av yttextur är önskvärda, eftersom texturen påverkar olika parametrar på helt olika sätt. Den mest önskvärda texturen blir därmed beroende på vilken parameter eller effekt som man avser. Det tycks emellertid vara möjligt att optimera texturen i någon mån på ett sätt som skulle vara fördelaktigt för de flesta tillämpningar. En någorlunda ”optimal” vägta skulle då ha en hög mikrotexutur, låg megatextur, hög makrotexutur vid korta väglängder och låg makrotexutur vid långa väglängder. Trots att en sådan vägta skulle vara optimal utifrån de flesta synpunkter skulle den emellertid inte alls vara bra från däckslitagesynpunkt.

Däck/vägfrictionen påverkas väsentligt av mikro- och makrotexutur. För god friction är det önskvärt med hög mikrotexutur såväl som hög makrotexutur. Mikrotexuturen behövs för att få en hög allmän frictionströja, medan makrotexuturen behövs för att inte frictionen skall sjunka för kraftigt vid ökande hastighet. En hög makrotexutur ger rikligt med fria kanaler som måste finnas i kontaktytan mellan däck och väg genom vilka vattnet kan hinna från vägen och de gör däckets rullning när emot vattnet hinner undan kommer däckets kontakt med texturen att alltmer förstärkas med ökande hastighet, vilket till slut kan innebära att vattenplaning inträffar. Om makrotexuturen inte är tillräckligt hög för att ge en sådan dränning blir vägens frictionströja för låg vid hög hastighet och vatt våg.

Som resultat av ett omfattande internationellt experiment som PIARC lät genomföra för några år sedan, och genom uppföljande arbete i en ISO-grupp, har man uppfunnit ett texturmått, kallat medelprofildjup (Mean Profile Depth – MPD), som på ett utmärkt sätt beskriver hastighetens effekt på frictionen. Detta är ett mycket viktigt resultat, eftersom det innebär att man med en frictionstavling visar hur en hastighet kombinerat med en texturmåttning kan beräkna vad frictionen bör vara vid varje annan hastighet. På så vis kan man väsentligt minska behovet av frictionstavlingar vilket är fördelaktigt för såväl ekonomi som trafiksäkerhet. Man kan säga att detta är ett av de mest betydelsefulla framstegen under senare år inom området.


Forskningen om texturens effekt på däckslitaget är inte tillräckligt långt kommet för att kunna visa på säkra kvantitativa samband. Emellertid är det uppenbart att hög mikrotexutur påverkar däckslitaget negativt– vilket därmed ger ett motsatsförhållande till önskemål vad gäller frictionen – och det finns vissa indikationer på att detta i någon mån gäller även makrotexuturen. Det finns exempel på undersökningar som visar att däckslitaget kan påverkas av texturen med en faktor upp till 7 i extremfall, och i mer normala fall med en faktor 3. Även om kvantitativa beskrivningar av sambanden inte är säkerställda är det klart visat att texturen påverkar däckslitaget i hög grad; och därmed även i allra högsta grad såväl ekonomi som miljö.

Saväl det fordonsbuller som sprider sig till omgivningen (externt buller) som det som hörs inuti fordonen (internt buller) påverkas starkt av mega- och makrotexutur. Megatexuturer har en negativ effekt medan makrotexuturer kan ha såväl positiv som negativ effekt beroende på dess
vågländ. Vägtexturen inklusive ytans porositet har visat sig påverka totalbullret lika mycket som typen av fordon och typen av bildäck. Därav följer att det kan vara lika effektivt att begränsa trafikbullret med vägbeläggningsåtgärder som med de mer etablerade åtgärderna av typ gränsvärden för fordonsbuller och för däckbuller (det senare är nyligen föreslaget av EU-Kommissionen). Det finns ett stort behov av att använda ”lägbullerbeläggning”, bl a har EU-Kommissionen antytt att man är beredd att ge bidrag till sådan användning. För att få lägre trafikbulleremission med en lägbullerbeläggning är det då nödvändigt att bl a optimera texturen i förhållande till en ”normalbeläggning”.

Det konstateras även att texturen påverkar parametrar såsom vattenstänk, vattenavrinning och ljusreflektionsegenskaper, med effekter som påverkar trafiksäkerhet och miljö. Det finns också forskningsrapporter som påvisar samband mellan olycksrisk och vägtextur, på så sätt att minskad textur ökar antalet olyckor.


Som redan nämnts genomfördes i PIARC:s regi för några år sedan ett omfattande internationellt experiment för att studera friktions- och textursamband. Detta resulterade bl a i ett förslag till hur man kan harmonisera friktionsmätningar som utförs med olika mätapparater. Det är normalt att olika friktionsmätare kan ge sinsemellan mycket olika friktionsvärden på en och samma beläggning. I det nämnda experimentet förekom t ex att två olika mätare kunde ge så olika värden som 0,33 och 0,90 för mätningar utförda på samma plats och under kontrollerade förhållanden. Detta visar att friktionsjämförelser utan hänsyn till använda metoder och mätinstrument är meningslösa. Friktionsmätvärden eller acceptansnivåer kan därför inte direkt jämföras från land till land eller ens inom ett visst land, eftersom det finns en uppsjö av olika mät, metoder och mätapparatur, såvåda de inte förutsätter att man använder samma typ av mätinstrument. I vissa länder använder man högst olika friktionsmätare t o m inom landet, även om vi i Sverige i huvudsak använder BV11, BV14 eller Saab Friction Tester vilka alla bygger på samma mätprincip och i övrigt är likartade.

Det förslag till harmonisering av mätare och mätetal som presenterades av forskarna inom PIARC-projektet har nyligen vidarebearbetats i Belgien och därefter blivit föremål för standardisering inom CEN, dock än så länge på ett preliminärt stadium. Förslaget innebär att
man beräknar ett Internationellt FriktionsIndex (IFI), alternativt ett Europeiskt FriktionsIndex (EFI), vilket rapporterar friktionsvärdet på ett enhetligt och jämförbart sätt — oberoende av vilken friktionsmätare som har utnyttjats vid den bakomliggande mätningen. Ett påbörjat uppföljdande arbete syftar till att ta fram standardiserade kalibreringsmetoder så att mätapparater som inte deltog i det nämnda PIARC-experimentet kan kalibreras för rapportering av IFI eller EFI. Man har även börjat visa på hur IFI kan användas i Pavement Management.

Harmoniseringsmetodens IFI (eller EFI) kräver att man har tillgång till dels en uppmätt friktionskoefficient vid en (godtycklig) hastighet, dels ett mätt på makrotexturen (helst MPD). Därutöver behöver man känna till vissa konstanter som gäller den aktuella mätapparaturen. För varje provad vägstrecka får man då ett friktionsvärde normaliserat till en referensglidhastighet (som är 60 km/h för IFI och 30 km/h för EFI) samt en "hastighetskonstant". De två värdena tillsammans kan användas för att räkna sig fram till friktionen för vilken friktionsmätare och vilken mäthastighet som helst. "Hastighetskonstanten" är dock egentligen inte en konstant utan en parameter som beror helt och hållet av vägstreckets textur.

Sålunda kan man numera genom att mäta friktion och makrotextur:

- erhålla ett internationellt eller europeiskt friktionsindex vid en referenshastighet — ett värde som i princip är oberoende av mätapparatur eller mätmetod
- beräkna friktionen vid en godtycklig annan hastighet
- beräkna motsvarande friktion för en (i princip) godtycklig annan friktionsmätare än den man själv använt
- jämföra friktionsmätningar gjorda i olika länder/regioner och med olika friktionsmätare, samt uppställa enhetliga friktionskrav om så önskas i hela Europa (eller i princip i hela världen)

Även om noggrannheten i den harmoniserings därmed blir möjlig måste förbättras på sikt, kan man säga att PIARC-experimentets resultat medför att hittills oanade framsteg inom ämnesområdet kan göras. Det är det kanske viktigaste (och även dyreste) experiment som någonsin har utförts vad gäller vägtekarakteristik. Dessa framsteg har möjliggjorts inte minst genom Vägverkets bidrag till VTIs deltagande i experimentet samt till andra projekt som varit till hjälp inför detta.

Ett kapitel i rapporten redovisar hur texturmättekniken har utvecklats i ett historiskt perspektiv samt hur texturdatal används i några länder. Det visas att texturdatal används på ett eller annat sätt i ett flertal länder — i flera fall finns t.o.m regler eller rekommendationer som grundar sig på texturvärden — och användningen av sådana mätt tycks vara starkt accelererande. Bl a PIARC-experimentet och standardiseringssträvandena kommer sannolikt att påverka den utvecklingen i hög grad. Detta påvisar vikten av internationell standardisering innan mätt och metoder i olika länder blir alltför olika och innan det gör så långt att man i vissa länder läser fast sig ”politiska” eller ”prestigemässigt” till de nationellt välda mätten och metoderna.

I ett kapitel om mätt, mätmetoder och mätinstrument vad avser vägtextur, redovisas i tabeller systematiskt alla kända sådana. Vad gäller mätinstrumenttyper dominerar olika laserprofillometrar eller liknande apparater som grundar sig på kontaktlös avkänning av vägtexturen medelst laserteknik. Det finns troligen över 100 sådana mätfordon idag i världen. Några mätinstrument och metoder, med viss tonvikt på laserprofillometrar, presenteras bl a med foton och blockschema. Några moderna exempel på texturdatalpresentation redovisas även, t ex texturprofilens statistiska amplitudfördelning och dess profilspets. Några av
dessa mått kommer sannolikt i framtiden att användas för prediktering av olika effekter av texturen, på samma sätt som MPD redan kan användas för viss prediktering av friktionstal.

Pågående eller planerad forskning om ämnet sammanfattas, bl a nämns några idéer utomlands som f n undersöks eller redan används beträffande användning av vägytedata, t ex på några italienska avgiftsbelagda motorvägar på vilka avgiften fastställs på grundval av vägens uppmätta standard, bl a innefattande vägtyekarakteristika. I princip kan man säga att fordonsföraren betalar för den standard han utnyttjar.

Sista delen av rapporten ägnas åt att spekulera om framtida användning och användningsmöjligheter för vägytetexturdata, inlagda i den nationella väg databanken (NVDB), samt hur pågående eller avslutad forskning kommer in i ett större sammanhang. Det konstateras att på sikt bör texturmätning kunna få en vidare användning, t ex bör tekniken kunna utvecklas så att separationer i belägningar kan identifieras. Redan idag bör man med enkla medel kunna kvantifiera förekomsten av blödningar, genom att jämföra textur mätt i olika sidolängan. Författarens framtidsvision presenteras i en ”Grand Model”; dvs hur mobil texturmätning över mikro-, makro- och megatexturområdena (av vilka mikrotexurmätning inte ännu är möjlig) kan användas för uppskattning av de viktigaste vägtyeroberoende effekterna. Detta kräver dock att modeller för effektsamband tas fram, även om några modeller redan finns eller åtminstone är av rudimentär form. Dessutom visas hur texturdata kommer att kunna användas för att kontrollera individuella beläggningsprojekt, kvalitetsklassificera äldre beläggningar samt för allmän tillståndsbeskrivning. Man kommer t ex att kunna ta fram årliga tillståndsskrivningar uttryckta i nationella eller regionala kvalitetsindex vad avser effekter på trafikbuller, friktion, rullmotstånd, etc, samt studera hur dessa förändras år från år som ett resultat av olika handlingslinjer eller resurstilldelningar.

Som exempel på redan förekommande omfattande nationell datainsamling redovisas franska data om friktionsnivåer och texturnamev på delar av franska vägnätet. Med de svenska RST-bilarna samlas texturdata in sedan flera år, men dessa data finns hos Vägverket endast latent på band och används i praktiken ej. Dessutom är måtten som används i RST-bilarna inte de som numera håller på att standardiseras.

En diskussion redovisas av i vilket steg i realiseringen av framtidsvisionen vi f n befinner oss samt författarens bedömning av vilka utvecklingsstider som kan behövas för de enskilda effekterna. Det uppskattas att en realisering av visionen som helhet kräver ca 15–20 års arbete men vissa delar kan realiseras inom några få år som följd av pågående eller planerad forskning. Det poängteras att genom att arbeta med målet för att på lång sikt realisera visionen kan man undan för undan ersätta alltmer av enskilda effektmätningar, typ friktions- och bullermätningar (vilka ofta är förknippade med höga kostnader och säkerhetsrisker), med prediktioner utgående från texturmätningar. I princip kommer det att vara möjligt att med t ex RST-bilar uppmåta en stor del av landets vägnät årligen och som resultat få omfattande statistik som beskriver vägnätets kondition i form av t ex nationella kvalitetsindex såsom ”friktionsindex”, ”bullerindex”, ”däckslitageindex”, ”bränsleförbrukningsindex” och ”luftföroreningindex” (här avses givetvis endast den del av dessa effekter som påverkas av vägtyans status). En del av dessa index skulle kunna användas i ett system med ”gröna nyckeltal” som på senare tid har rött stort miljöpolitiskt intresse.

En del av rapporten ägnas åt att presentera några väsentliga forskningsbehov som finns, t ex arbete som behövs för att följa upp PIARC-experimentet och för att undan för undan realisera
delar av framtidsvisionen ”Grand Model”. I avsnittet ”slutsatser” påpekas bl a vikten av att den internationella standardiseringen kan fortsätta på ett effektivt sätt. De senaste årens snabba utveckling visar hur sådant arbete utfört vid rätt tidpunkt kan medföra stora framsteg.

Det finns tre bilagor till rapporten; den första handlar om alstring av och mätmetoder för däck/vägbanebuller, den andra handlar om hur kvalitetsklasser för vägtyors bullerpåverkande egenskaper skulle kunna uppstållas och den tredje presenterar VTI:s delaktighet i vägtexturforskning under de senaste åren.
1. **INTRODUCTION**

Surface texture is the most important feature of the road surface and pavements in general, affecting tyre/road interaction processes such as friction, tyre wear, exterior noise emission, interior noise emission, and rolling resistance. It follows that the description of texture is very important when trying to quantify road surface condition and/or its potential effects on safety, economy and environment. Unfortunately, practical tools for describing this surface feature have become available only recently. This report attempts to describe the current state-of-the-art regarding the effects of road surface texture and attempts to outline near future activities which are recommended in order to make use of the latest developments, as well as how to encourage further development in the subject area.

2. **PURPOSE WITH THE STUDY**

The purpose with this study is to provide background information concerning the use of road surface texture data for condition surveys as well as for actions. Furthermore, near future research needs and other actions based on texture data shall be identified.

3. **TERMINOLOGY WITH REGARD TO PAVEMENT TEXTURE**

Based on physical relations between texture and friction/noise etc., PIARC, i.e. the World Road Association (previously the Permanent International Association of Road Congresses), defined ranges of micro-, macro- and megatexture ten years ago; see [PIARC, 1987]. Recently, these definitions were accepted and further refined within the International Standard ISO 13473-1 and the draft standard ISO/DIS 13473-2. Table 1 summarizes these definitions.

The ISO standards define texture as the deviation of a pavement surface from a true planar surface, within the texture wavelength ranges defined in Table 1. A profile of the surface is generated if a sensor, such as the tip of a needle or a laser spot, continuously touches or shines on the pavement surface while it is moved along the surface (see Figure 1). The profile is a two-dimensional sample of the surface texture.

The profile of the surface is described by two co-ordinates: one along the surface plane, called distance (the "x" co-ordinate), and the other in a direction normal to the surface plane, called amplitude (the "z" coordinate) as shown in Figure 1. The distance may be in a longitudinal or lateral (transverse) direction in relation to the travel direction on a pavement, or any direction between these.

The profile may be considered as a stationary, random function of the distance along the surface. By means of a Fourier analysis, such a function may be mathematically represented as an infinite series of sinusoidal components of various frequencies (and wavelengths), each having a given amplitude and initial phase. The texture wavelength (unit: m or mm) is defined as the inverse of the spatial frequency (unit: cycles/m or m\(^{-1}\)). The wavelengths may be represented physically as the various lengths of periodically repeated parts of the profile, see Figure 1. For typical and continuous surface profiles, a profile analysed by its Fourier components contains a continuous distribution of wavelengths.
Fig. 1 Illustration of some basic terms describing pavement surface texture. "Texture Wavelength" is an illustration of a component of the profile related to the wavelength concept but is not correct from a strictly mathematical point of view. It shall also be noted that the amplitude (height) has an arbitrary reference.

Table 1 The different ranges of road surface texture, as defined in ISO 13473-1 and in ISO/DIS 13473-2.

<table>
<thead>
<tr>
<th>Texture wavelength range</th>
<th>Typical peak-peak amplitudes</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microtexture</td>
<td>&lt; 0.5 mm</td>
<td>0.001–0.5 mm</td>
</tr>
<tr>
<td>Macrotecture</td>
<td>0.5 – 50 mm</td>
<td>0.1 – 20 mm</td>
</tr>
<tr>
<td>Megatecture</td>
<td>50 – 500 mm</td>
<td>0.1 – 50 mm</td>
</tr>
</tbody>
</table>
The following figure is an illustration of the various texture ranges.

**Fig. 2** Simplified illustration of the various texture ranges

**Fig. 3** Illustration of the long-wavelength end of the megatexture range. Photo by Mrs Merrie Bird, courtesy of Prof em J.C. Wambold, State College, PA, USA.
4. EFFECTS OF TEXTURE

4.1 Effects in general

The most important effects of road surface texture, for different texture wavelengths, are illustrated in Fig. 4. These are dealt with in more detail in the following.

As can be seen in Fig. 4, road surface texture is both a desirable and a not desirable feature – it depends on the viewpoint. Generally, one can say that megatexture is not desirable from any viewpoint, but both macro- and microtexture have favourable as well as unfavourable effects. Since safety characteristics, of which friction is one of the most essential parameters, traditionally have been considered as the most important performance features of road surfaces, it has not so much been questioned that one shall aim at high levels of micro- and macrotexture. With our current knowledge, however, it appears that one should aim at having a high level of macrotexture for texture wavelengths lower than approximately 10 mm, but a low level of macrotexture for the longer wavelengths. Thus there is an optimization problem here, both taking all effects into a balanced account and trying to amplify or reduce the proper parts of the texture spectrum.

![Figure 4](C:\eget\winword\others\texture_range.doc)

Fig. 4 Ranges in terms of texture wavelength and spatial frequency of texture and unevenness and their most significant, anticipated effects. A lighter shade means a favourable effect of texture over this range, while a darker shade means an unfavourable effect.
4.2 Friction

The following description is not claimed to be complete or scientifically correct in all details, but for the purpose of this report it is suitable.

Somewhat simplified, there are two major frictional mechanisms in the tyre/road interface:

**Adhesion**

Bonds between molecules of the tyre rubber and molecules of the road surface which are in close contact. These are quite sensitive to break-up by debris, dirt or water, separating rubber and road.

**Bulk hysteretic friction**

Energy is consumed as tyre rubber is locally displaced when it has to envelop road surface macrotexture. Part of this deflection or displacement is elastic and does not consume energy but another part is not retrieved (hysteretic).

Adhesion is highly sensitive to microtexture but rather insensitive to macrotexture, whereas the inverse is true for bulk hysteretic friction. Both micro- and macrotexture affects friction positively, i.e. higher texture means higher friction. On a dry road, the adhesion effect generally dominates which means that microtexture is the major determining surface feature. Bulk hysteretic friction reaches substantial levels only when the tyre slides on the road surface, in which case there is a lot of local dynamic rubber displacement. In such a case macrotexture has some importance; of course besides microtexture. This is illustrated in Fig. 5.

Megatexture has an effect similar to macrotexture, i.e. energy is consumed when the tyre rubber is forced to envelop and slide over this type of roughness. However, this takes place at a slower rate than for macrotexture (wavelengths are longer). There is an opposing and probably more substantial effect of megatexture also, and this is that a high level of megatexture will prevent the tyre from having an ideal contact with the road surface. The tyre might ”bounce” or ”bump” over part of the megatexture which means that adhesion is momentarily lost in parts of the tyre/road interface. Megatexture is thus essentially an unwanted feature of the surface, while micro- and macrotexture both are highly desirable.

On wet roads, there is another effect which highly influences friction, which is the separation of tyre rubber from the road surface, i.e. break-up of adhesion bonds, which is caused by water on the road surface.

When there is only little water on the road, the high pressure of the rubber on the road surface pushes water away from the contact points and friction is reduced only marginally. However, as soon as there is not enough space for the water to escape, or as soon as the time is not enough to push water away to a space where it makes no harm, friction will reduce significantly. As water level increases, and speed increases, water can no longer be displaced at sufficient rates and friction is reduced dramatically, as the water separates bigger and bigger areas of the tyre/road contact. The extreme case is hydroplaning, when there is no longer any tyre/road contact.

On a wet road, the relation between friction coefficient and driving speed looks typically like in Fig. 6. Microtexture again influences the entire range. Macrotexture has the effect of providing escape channels and spaces for water, where water can remain without being harmful to the adhesion. When speed is low, there will generally be ample time for water to be ejected from...
the tyre/road interface, irrespective of macrotexture, and in such cases macrotexture is not so important. At high speeds, however, time is not enough for water to escape from the tyre/road interface so there must be a "deep" macrotexture to take care of the excess water so that water does not separate the tyre rubber from the road surface. Consequently, the higher the speed, the higher is the importance of macrotexture.

As a general reference for this section, the reader is referred to [Henry & Marasteanu, 1992], [Wambold et al, 1995], [Nordström, 1996] and [Ohlsson, 1979].
It can be concluded that road surface texture affects friction dramatically. Microtexture might, in principle, affect friction over the range from almost zero up to maximum possible friction and is important at all sliding and driving speeds. Macrotexture might influence friction at low speeds to a much lesser extent, but at high speeds on wet roads macrotexture may affect friction over the entire range from maximum down to zero. The higher the texture, the better the friction ("positive influence"). Megatexture might have a rather marginal but not negligible influence and it may be both positive and negative; in general the negative influence dominates.

The mechanisms of microtexture influence, like abrasion and polishing, as well as studies of this range of texture, are dealt with in a comprehensive state-of-the-art report [Höbeda, 1997].

Fig. 6 Typical relation on a wet road between friction coefficient and driving speed (as opposed to the sliding speed in Fig. 5). Note that microtexture significantly affects the entire range, while macrotexture affects only at high speeds.
How can the relation between friction and texture be illustrated? In general terms it is often assumed that friction can be described with a basic model like this [Henry & Marasteanu, 1992]:

\[ F = F_0 \cdot e^{\frac{S}{S_p}} \]

where

- \( F \) = friction coefficient at a certain speed
- \( F_0 \) = a term which is determined by microtexture
- \( S \) = slip speed of the tyre, which is the product of slip ratio and driving speed
- \( S_p \) = a term which is determined by macrotexture, see Fig. 4 in [Sandberg, 1995]

The quotient \( S/S_p \) is the speed influence on the measurement. With this model, friction would be linearly increasing with microtexture, while it would be very unlinearly increasing with macrotexture. The macrotexture influence would also interact with speed to form a rather complicated relation. The PIARC experiment reported in [Wambold et al, 1995] refined the model somewhat but the basis was the same, see Table 4. On the other hand, [Sandberg, 1990-II] found that a linear model worked equally well as the exponential model, at least in his more limited experiment, which would mean a much simpler relationship.

Since we cannot quantify microtexture at the moment we cannot illustrate any quantitative relation here. However, for macrotexture, one could use the refined PIARC model and make some assumptions. Fig. 7 illustrates the relations for the special case when MPD is used as the texture measure (this is not exactly the same as the MPD later standardized by ISO, but rather close). Fig. 7 then shows the macrotexture influence in terms of how much friction may change from one speed to another, in this case from 70 to 140 km/h. Friction at 70 km/h is set at 0.70 in this figure. The macrotexture influence depends on the slip rate of the tyre during the braking. Two very different cases are illustrated, one is the case of 20 % slip ratio (close to optimum slip), which is typical of BV-11 and the other is 100 % slip ratio (blocked wheel), which is typical of several other friction measuring devices. The first case can be said to resemble the case in actual traffic when an ABS system is employed during an emergency situation and the second case when the wheels of the car are locked during braking. An MPD range of 0.3–4.0 mm is typical of Swedish roads; with dense asphalt concrete having an MPD of 0.5–1.0 mm.

Fig. 7  Relation between the friction at 140 km/h driving speed and macrotexture depth expressed as MPD. In this example friction at 70 km/h is set at 0.70 as a reference, and the vertical axis shows what friction will be at twice that speed. It is assumed that in one case the slip ratio is 20 % (—), in the other case it is 100 %, i.e. locked wheel (…………). Data processed by this author according to the model of PIARC [Wambold et al, 1995] and assuming that microtexture is constant. The relation is confirmed independently in [Lund, 1997].
A qualitatively similar relationship is presented in [Shimeno & Kawamura, 1997] for the limited case of SMA surfaces, but it has not yet been possible to check if it is numerically consistent with the PIARC data. The relation obtained by the Japanese was extremely sensitive to macrotexture.

Recently, a very interesting study of tyre/road friction and texture properties has been presented in [Roadware, 1997-II]. It is claimed that in the slip curves of Fig. 5, the part from zero until the peak is determined mainly by tyre properties and the part to the right of the peak mainly by road surface properties (texture). It follows, according to the paper, that fixed-slip devices like BV11 measure mainly tyre properties, while locked-wheel devices measure mainly road surface properties. An extension of the PIARC model mentioned above has been made by Dr. Zoltan Rado, which is called the Rado Unified Friction Model. This model in its simplified form, has three parameters: A is the maximum friction number, B is the critical slip speed (at which the peak friction occurs) and C is the shape factor, i.e. a texture-related factor which determines the speed gradient of friction (corresponds to the speed factor in the PIARC model).

\[ F(s) = A \cdot e^{-\left(\frac{\ln(s/B)}{C}\right)^2} \]

F is the friction coefficient and s is the slip speed. This Rado model is useful if one measures the entire friction-slip-speed curve, like a few friction meters are doing, and can then give a very extensive description of the friction process.

It is also discussed how the friction number at 60 km/h plotted as a function of the speed constant in the PIARC model, i.e. macrotexture, can be used for determining intervention levels of friction, depending on whether micro- or macrotexture needs improvement.

Furthermore, it is suggested by Rado that a fixed-slip device which measures friction only at a few speeds can give quite erroneous values, and to avoid this it is recommended that such devices always carry a texture meter in order to map friction characteristics of surfaces better.

Two recent papers, [Henry, 1998] and [Saito et al, 1998], discuss the use of the IFI (International Friction Index, see further below) for establishing intervention levels for friction and presents examples of application to the use of a combined friction and texture measuring system in pavement management.
4.3 Overview of texture effects on safety-related characteristics

Traffic safety is influenced by texture as follows.

**Friction:**
Microtexture should be as high as possible in order to increase adhesion
Macrotexture should be as high as possible in order to increase bulk hysteretic friction and to improve water drainage
Megatexture should be as low as possible, in order to avoid tyres losing contact with the road due to bumps

**Asym. tyre drag:**
Macrotexture, megatexture and rutting influence water depth on road surfaces. In cases with water in ruts and with highly non-uniform texture, tyre drag could become quite different on the two sides of the vehicle, potentially causing dangerous driver responses [Hight et al, 1993].

**Light reflection:**
Microtexture has little effect
Macrotexture should be as high as possible, in order to avoid specular reflection and to break up possible water levels in the wheel tracks and thus avoid glare, and to provide drainage to minimize water covering of the road surface. See e.g. [Kayser, 1985].
Megatexture should be as low as possible, in order to avoid water pools collecting in the wheel tracks

**Light retroreflection:**
Microtexture has little effect
Macrotexture should be as high as possible, in order to provide retroreflection on the aggregate slopes and to break up possible water levels in the wheel tracks, and to provide drainage to minimize water covering of the road surface
Megatexture should be as low as possible, in order to avoid water pools collecting in the wheel tracks

**Noise or sound:**
The driver shall be able to notice changes in surface texture and other surface conditions affecting sound or noise in the vehicle.
Rumble strips or profiled road edge markings are more and more used to alert drivers of potential dangers such as approaching hazardous situations (e.g. crossings) or drift-off from the driving lane resulting from drivers falling asleep. For this reason it is desirable to have a pronounced texture on the road or its shoulder which creates a maximum interior vehicle sound without creating too much exterior noise. Some dramatic road accident reductions have been recorded according to [Hickey, 1997].

**Vehicle wear:**
Micro- and macrotexture has negligible effect in this respect (i.e. safety aspects of vehicle wear)
Rough megatexture may result in increased vehicle wear, implying that some vehicles may operate in poorer condition than otherwise

A review of accident rates on roads with different textures is presented in [Wretling, 1996]. It is concluded there that accident rates increase with decreasing texture.
4.4 Rolling resistance: Effects on air pollution and economy

When tyres are rolling on a road surface without braking, bulk rubber hysteresis causes energy losses in the tyres when macro- and megatexture forces rubber to displace in relation to an ideal flat surface. This is noticed by the driver as an increase in the rolling resistance. It means that increase in texture results in increase in rolling resistance.

Furthermore, megatexture causes vibrations in the suspension system of the vehicle, some of which will result in hystereses losses in this system. This is contributing to the rolling resistance.

However, high macrotexture is not consistently undesirable. When there is standing water in wheel ruts, rolling resistance increases, because energy is consumed for removal of this water. High levels of macrotexture tend to reduce the amount of water in ruts as well as to reduce the energy needed to remove the water from the tyre/road interface. In such cases, high macrotexture reduces rolling resistance. Overall, however, texture should be low in order to give minimum rolling resistance.

A wheel rolling along a pavement produces a bow-wave effect as the pavement surface in front of and beside the wheel rises to relax the compression under the wheel. The magnitude and shape of this bow-wave is a function of vehicle weight, tyre characteristics, suspension system as well as pavement and subgrade stiffness. This bow-wave must result in some energy consumption which should be reflected in a certain contribution to rolling resistance [Transearch, 1996]. See further section 8.3 regarding research on this quite recently identified mechanism.

Increases in rolling resistance result in increases in fuel consumption (affecting economy), as well as increases in exhaust air pollution of various substances (affecting environment).

Effects of up to 11% of increased fuel consumption for a car driving on the roughest road compared to the smoothest road of a sample covering most "common" pavements in Sweden were recorded by [Sandberg, 1990]. Mega- and macrotexture were both responsible for this, particularly megatexture. Macrotecture was responsible for approximately 7% of fuel consumption increase (note that the effects of macro- and megatexture were not simply additive). Other investigations in which appropriate surface texture measures were included have arrived at similar conclusions, see Table 2. For trucks, however, relevant data are missing or are poor, mainly because few investigations have quantified texture appropriately. Apart from the values cited in Table 2 for trucks, one can mention a study by [Quinlin, 1989] in which a truck consumed 3% more fuel on a road with IRI = 3.1 than on a road with IRI = 1.4, when speed was 40 km/h. Corresponding fuel consumption increases were 8% at 60 km/h and 16% at 80 km/h. It was assumed that the only variable was unevenness. These values are remarkably high.
Table 2 Comparison of results from experimental studies of relation between texture and fuel consumption (or rolling resistance). Rolling resistance influence ($\Delta C_R$) has been converted to fuel consumption influence ($\Delta F_C$) by using the simplistic conversion $\Delta F_C = 0.25 \times \Delta C_R$. The data concerns car travelling at $50–70$ km/h, if nothing else is stated. The values indicate percent increased fuel consumption when the texture or the unevenness increases with a factor $10$ (20 dB) in relation to the smoothest and most even road surface. Such a range is reasonable with respect to a national road network.

<table>
<thead>
<tr>
<th>Data source</th>
<th>$\Delta F_C$ due to macrotexture</th>
<th>$\Delta F_C$ due to megatexture</th>
<th>$\Delta F_C$ due to unevenness</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>VTI, Sweden [Sandberg, 1990-I]</td>
<td>7 %</td>
<td>8 %</td>
<td>16 %</td>
<td>Fuel consumption measurements using a Volvo car on 20 sites</td>
</tr>
<tr>
<td>CRR, Belgium [Descornet, 1990]</td>
<td>17 %(^1)</td>
<td>13 %</td>
<td>7 %(^2)</td>
<td>Trailer method. (^1) Tyre without pattern. Value probably lower for a patterned tyre.   (^2) All losses were not measured. True value may be considerably higher.</td>
</tr>
<tr>
<td>LCPC, France [Laganier &amp; Lucas, 1990]</td>
<td>7–10 %</td>
<td>–</td>
<td>5–7 %(^3)</td>
<td>Value probably underestimated due to co-variation with macrotexture</td>
</tr>
<tr>
<td>Works, New Zealand [Cenek &amp; Shaw, 1989]</td>
<td>7 %</td>
<td>–</td>
<td>–</td>
<td>Rolling resistance measurements using an instrumented car</td>
</tr>
<tr>
<td>Dunlop, U.K. [Williams, 1981]</td>
<td>10 %</td>
<td>14 %</td>
<td></td>
<td>Values are $= 6$ % resp. 6 % if an extreme, smooth steel drum is included in the test sample</td>
</tr>
<tr>
<td>CSIR, South Africa [du Plessis et al, 1990]</td>
<td>2 %</td>
<td>–</td>
<td>6 %</td>
<td>Coast-down technique used. Corresponding values for trucks are 0 %, resp. 10 %</td>
</tr>
<tr>
<td>BAS, Germany [Ullrich et al, 1996]</td>
<td>10 %</td>
<td>12 %</td>
<td></td>
<td>Measurements made on internal drum facility. Also noise and friction meas.</td>
</tr>
<tr>
<td>VTT, Finland [Sistonen et al, 1983]</td>
<td>7 %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Works, New Zealand [Transearch, 1994]</td>
<td>20 %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GM, USA [deRaad, 1978]</td>
<td>21 %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRL, United Kingdom [Ramshaw, 1981]</td>
<td>4 %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRL, United Kingdom [Young, 1988]</td>
<td></td>
<td>10 %</td>
<td></td>
<td>Corresponding value for trucks is 25 %</td>
</tr>
<tr>
<td>Data from Brazil [Watanatada et al, 1987]</td>
<td></td>
<td></td>
<td>8 %</td>
<td></td>
</tr>
<tr>
<td>Wisconsin DoT, USA [Ross, 1982]</td>
<td></td>
<td>2 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pretoria, South Africa [Bester, 1984]</td>
<td></td>
<td></td>
<td>12 %</td>
<td></td>
</tr>
<tr>
<td><strong>Summary of above:</strong></td>
<td><strong>Range</strong></td>
<td><strong>Average</strong></td>
<td><strong>Range</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2–21 %</td>
<td>10 %</td>
<td>8–14 %</td>
<td>2–16 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12 %</td>
<td>8 %</td>
<td></td>
</tr>
</tbody>
</table>
The author has collected data from various sources in literature in Table 2. From the table it can be concluded (tentatively) that the average influence is 10\% for macrotexture, 12\% for megatexture, and 8\% for unevenness. These values represent the influence on fuel consumption when comparing the smoothest road surfaces with the roughest on the normal public road network (in industrialized countries). Within the same type of road, but in different ”normal” conditions or with different ”normal” pavements for that type of road considered, it is more realistic to use approximately half of the values in the table as representative of potential influences. Nevertheless, it can be concluded that road surface texture affects air pollution and economy very significantly. See further section 8.2 about a potential effect of pavement stiffness.

An effect which is mostly forgotten in studies of texture influence on fuel consumption is the tyre drag effect on surfaces partly covered with water. The water level in ruts and pools (the latter is often an effect of megatexture) will be partly influenced by the macrotexture. Non-uniform water depth may cause vehicle instability [Hight et al, 1993] but also increased fuel consumption. The water depth influences fuel consumption by at least about 10\% according to [Sävenhed, 1986].

Is rolling resistance influenced by microtexture? Yes, two things indicate that this should be the case:

1. It is widely accepted that tyre wear is influenced by microtexture and wear should mean a loss of energy.

2. A laboratory investigation by [de Raad, 1978] showed that 10 tyres had an average of as much as 5\% more rolling resistance on a sandpaper-like surface than on a smooth steel surface. This is more likely to be a microtexture rather than a macrotexture effect.

For a more extensive literature review of the relation between rolling resistance/fuel consumption on the one hand and texture/unevenness on the other, please refer to a working draft at VTI [Henriksson, 1997].

If, as indicated above, macro- and megatexture influences fuel consumption over a range max-min of 10\%, assuming that road authorities in practice are able to influence fuel consumption by one-third of this by consideration of texture, it is indisputable that this effect of texture represents substantial effects (say 3\%) on both fuel costs and exhaust emissions.

4.5 Tyre wear

The title of a major paper on tyre wear is ”The Most Complex Tire-Pavement Interaction: Tire Wear” [Veith, 1985]. Possibly with the exception of the extremely complex tyre/road noise generation, it may well be true that tyre wear is the most complex tyre/road interaction. The exceptional complexity of tyre wear, including the influence of road surface texture, has prevented this problem from being thoroughly investigated, although it is widely recognized that tyre wear is largely influenced by surface texture and that this has substantial economical and environmental implications.

Tyre wear has two major components:
**Carcass wear:** This is mostly a fatigue process that causes carcass defects and/or tread separation from the carcass. When such defects occur the tyres may perform worse or even become useless, and it may even cause the tyres to be useless for retreading. The carcass fatigue life depends on a number of parameters, among them vehicle suspension quality, road unevenness and road megatexture, which may cause higher vibration and/or very transient severe loads.

**Tread wear:** This type of wear has three mechanisms, abrasion, fatigue and wave formation [Nordström & Andersson, 1996], and is caused by the sliding action between the tyre tread elements and the road texture, influenced by road-related factors such as microtexture, macrotexture, water, ice and contaminations on the road surface. It is in direct conflict with friction requirements.

The economical influence of tyre wear is obvious. The worldwide rubber consumption is around 17 million tons per year. For the rather limited Swedish market, more than 4 million car tyres and 0.5 million truck and bus tyres are manufactured per year. This represents an economic value of approximately SEK 6 000 000 000 per year only in Sweden. The environmental influence may be less obvious, but considering the fact that approximately 10 000 tons of tyre particles are worn off tyres on Swedish roads annually, and that approximately 2000 tons of this are considered to be harmful carcinogenic substances, mainly high aromatic oils, the environmental problem of tyre wear must be considered as serious [Anon., 1997]. For example, the annual emission of polyaromatic hydrocarbons (PAC) due to tyre wear amounts to 14 tons, which is more than emitted from the vehicle exhaust systems [Ahlbom & Duus, 1994]. Fortunately, this problem is expected to be reduced by and by since the tyre manufacturers will switch to less harmful oils in the next few years.

Another illustration of the potential environmental problem is that it has been calculated that along "main roads" in Germany, about 550 kg tyre debris is worn-off per km and year [Fehrle, 1996]. This seems to be quite a lot....

From the following, it should be obvious that road surface texture plays a significant role in this problem. From a state-of-the-art review in [Cenek, 1987] the following text has been adapted.

Based on the assumption proposed by a number of investigators that wear is directly proportional to the amount of frictional work, the simplest equation that relates tread wear and frictional work is:

$$ R_W = A \cdot E_F $$

where

- $R_W$ = rate of wear, amount of rubber lost from a unit surface per tyre revolution
- $A$ = abradability, i.e. the amount of rubber lost per unit area per unit frictional work, under specified interface conditions
- $E_F$ = the frictional work per unit area, per revolution, for a typical tread element

The factors that contribute to abradability include macro- and microtexture.

Other than occasional references in the literature to the fact that newly prepared pavements are abrasive and give high rates of tread wear, the scientific literature on tread wear versus pavement texture is sparse. The main contribution is a paper by [Lowne, 1971].
Lowne’s investigations showed that the microtexture was the dominant factor in determining tread wear. Macrotexture played a minor role, with increased macrotexture giving increased wear. Lowne also showed that tread wear \( W \) was given by a multiple regression equation of the form:

\[
W = -9.2 + 90\cdot(S_{50}) + 18\cdot\text{MTD}
\]

where \( S_{50} \) is the wet cornering traction coefficient at 50 km/h for a smooth patternless tyre, and MTD is the macrotexture depth (probably measured with the patch method), normalised to a reference surface. The parameter \( S_{50} \) is an indirect measure of microtexture.

Tests carried out in USA showed that differences in tyre wear rates could be as high as 100% between different US public roads. Unfortunately, no description of the road surface types was given.

So far, the review in [Cenek, 1987]. This can be supplemented by mentioning that [Le Maitre and Stüssner, 1995] of Michelin claim that surface characteristics influence tyre wear by a factor 2–3. They also present data indicating that on a wet road tyre wear was around 30% lower than on a corresponding dry road. In a more recent paper by Cenek [Cenek et al, 1997], experiments show that dry surface characteristics influence tread wear rates by a factor of 3 for 13 tested sites and even by a factor of 7 if a 14th site (an outlier) is included.

A state-of-the-art review on tyre wear mechanisms was recently presented in a paper by [Nordström & Andersson, 1996]. However, with regard to the texture influence problem studied here, most of the items covered in Nordström’s document are already mentioned above. Perhaps it should be emphasized from this study that climatic effects such as temperature and percentage of wet road are important parameters which have been too much neglected so far. The wet road case is related to the texture, so this is an effect which must be considered here.

Finally, an experimental study made at VTI and reported in [Backman, 1978] shall be mentioned:

Tyre wear was measured on two newly laid road surfaces. The surfaces were:

- Surface No. 1: A single-layer surface dressing, 12 – 20 mm crushed chippings
- Surface No. 2: An asphalt concrete (maximum chipping size 8 mm)

On each of these surfaces, two cars were driven 6000 km each. The tyres, cars and drivers were shifted at certain intervals in a way to eliminate systematic errors caused by differences in cars and driver behaviour. One set of four tyres was run on surface No. 1 and the other set of four tyres was run on surface No. 2. The tyres were Gislaved steel radial tyres, dimension 175SR14.

Tyre wear was measured by tread depth measurement (resolution 0.1 mm) as well as by weighing each tyre.
After 6000 km the tyre tread depth had decreased 84% more on the surface dressing than on the asphalt concrete. At the same time the tyre weight had decreased 51% more on the surface dressing than on the asphalt concrete.

In that study, the rough surface had a much higher macrotexture than the smooth one; in particular the texture included sharp edges on the exposed aggregate. Microtexture was probably also higher, but it is not clear to what extent. It is thus not possible to distinguish between macro- and microtexture effects on wear from that experiment.

A follow-up study reported in [Kihlgren, 1980] for the same type of surfaces but in a medium-worn condition, confirmed these results except that the wear influence was less for these worn surfaces than for the new ones.

Measurements with test tyres on a trailer gave results inconsistent with those reported above, see [Ohlsson, 1986-I]. Later, some doubt was raised as to the method of all these studies [Ohlsson, 1986-II]. The main problem was that tyre wear may have been largely influenced by how the test vehicles were turned around after each 10 km.

Nevertheless, it can be concluded that both macrotexture and microtexture influences tyre wear; macrotexture quite significantly and microtexture dramatically.

4.6 Other vehicle wear

Over the speed range 50–100 km/h, megatexture induces vibrations over the frequency range 25–600 Hz. The lower of these frequencies will cause vibration amplitudes on surfaces with high megatexture which are likely to contribute to wear of vehicle components (other than tyres) through these vibrations. Such wear will generally not be as bad as that from road unevenness, but it is probably significant. See further [Magnusson, 1998] regarding this topic.

4.7 Road wear

Does road wear depend on road surface texture? This is an interesting question which cannot be answered at the moment. Of course, road wear depends very much on the design of the road surface, such as choice and proportioning of aggregate, etc., but whether texture has a unique influence has not been investigated, as far as this author is informed. However, it could well be so.
4.8 Exterior noise

In a co-operative Belgian/Swedish program, a study was made to find which parameters of the road surface that influence exterior noise generation [Sandberg and Descornet, 1980]. Parameters such as macrotexture, megatexture, friction (microtexture), water drainage, sound absorption and mechanical stiffness of the roads were considered. The outcome was that there was no influence by friction or water drainage on noise that could not equally well or better be attributed to the mega- or macrotexture. Sound absorption influenced the noise, but only for porous surfaces. Mechanical stiffness could perhaps influence the noise, but to a minor extent only.

Due to the finding that the noise level failed to show any good correlation with the commonly measured sand-patch texture depth, it was preferred to replace this measure by a measurement of the profile curve of the road surface. This profile curve was analyzed either by filtering it using an analogue technique or by calculating its spectral content with a digital technique to obtain a third-octave band texture spectrum.

Again, the overall noise levels did not show any strong relation with texture depth. However, over the range of road surfaces tested, the noise levels at each acoustic frequency were correlated against the road texture levels at each texture wavelength. The best correlation between noise and road texture was obtained for certain frequencies of the noise and certain spatial frequencies or wavelengths of the macrotexture. Fig. 8a illustrates the correlation of the noise at low frequencies with the texture at long wavelengths and Fig. 8b illustrates the same relation between high frequencies of the noise and short wavelengths of the texture. The relation appears to be reverse in these two cases!

![Fig. 8 Illustration of how noise and texture are related for the two most pronounced cases:](a) a. Noise at a low frequency (≈400 Hz) versus texture at a long wavelength (≈80 mm)  
(b) b. Noise at a high frequency (≈3 kHz) versus texture at a short wavelength (≈2–3 mm)
These facts explain why there is no simple and general relation between the overall noise level and texture. Rather, the overall noise level is composed of the sum of these two effects which may favour any of them depending on the exact circumstances.

Back again to the correlation between noise and texture for all noise frequencies and all texture wavelengths as mentioned above. It was concluded in this study that there are (at least) two major generation mechanisms which are uncorrelated with each other; one acting in the low-frequency range (below 1000 Hz) with a positive correlation with road mega- and macrotexture and another acting in the high-frequency range (above 1000 Hz) with a negative correlation with macrotexture. These results have been confirmed by several other studies later.

If one considers the range of surfaces used on the national road network, the magnitude of the influence of texture is around 15 dB at specific frequencies. Since effects at low and high frequencies often cancel each other when describing overall noise as an A-weighted noise level, the influence is reduced to half that at individual frequencies when considering overall tyre/road noise. For example, the road surface correction now included in the Nordic Traffic Noise Prediction Model covers a range of up to 7 dB(A) for different pavement types and conditions (paving stones and concrete blocks excluded), see further [Sandberg, 1993] and [TemaNord, 1996]. A difference of 10 dB is equal to a 10-fold increase/decrease in acoustic power. In fact, the road surface influence on traffic noise on a highway is about equally big as the influence of different vehicles, see Fig. 9.

The bars show the spread in vehicle noise from the "most silent" to the "noisiest" case (the 5- and 95-percentiles) for the case that the vehicles are different but the road surface is the same (the two bars to the left), as well as the case that the vehicle composition is constant but the road surface varies (the two bars to the right). Consequently, the left two bars show how much the noise from different vehicles vary (mainly due to tyres) and the right two bars how much the noise varies when driving on different road surfaces. Thus the result is that the road surface influences the overall noise about as much as the individual vehicle.

The figure refers to free-flowing traffic at about 70 km/h, but is valid also for higher speeds. At lower speeds, or for interrupted-flow traffic, the right two bars will decrease, i.e. the effect of the road surface will be reduced. The left two bars may then increase instead and power unit noise becomes the major factor. However, wet or extreme surfaces have not been included in the figure. If wet surfaces, cement concrete or paving-stone surfaces had been included, the effect of the road surface would have increased further.

A summary of the generation mechanisms for tyre/road noise is presented in Annex A.
4.9 Interior vehicle noise

Noise inside vehicles—interior noise—is related to exterior noise, but is coloured by the transfer of vibrations from the tyre through the axle, suspension system and body of the vehicle, so-called "structure-borne sound", to the air pressure fluctuations in the vehicle cabin, i.e. "airborne sound". This transfer favours low frequencies and rejects high frequencies. It implies that interior noise is influenced by road texture mainly through the low-frequency mechanism mentioned above. This is influenced by macrotexture (increased macrotexture increases noise) but even more by megatexture (similar but bigger influence), since the low frequencies and thus long wavelengths are favoured.

One should keep in mind that for the driver texture-induced noise is not only noise (i.e. unwanted sound) but also information-carrying sound. This tyre/road sound is influenced by the surface condition and may alert the driver. This is sometimes utilized in the form of rumble strips or other sound-alerting profiles on/in the road or road shoulder. In the US, dramatic increases in road safety with such devices have recently been obtained, see [Hickey, 1997] and the section about safety.
5. PREVIOUS AND CURRENT STANDARDIZATION ACTIVITIES

5.1 ISO – the International Standardization Organization

5.1.1 ISO 10844 – Reference surface for noise measurements / Volumetric Patch method

In the years 1987–1992, a group within the ISO developed a standard for a reference surface for vehicle noise measurement (ISO/TC 43/SC 1/WG 27, convened by this author). The result was an ISO standard – ISO 10844 – which contained a specification for a reference surface intended for vehicle noise measurement. It also included an appendix specifying a method for measuring texture with a volumetric patch technique (see further chapter 6 on history).

The ISO 10844 surface, popularly referred to as "the ISO surface", is widely used today. Practically all vehicle and tyre manufacturers and a lot of test centres and research organizations have such "ISO surfaces". This author knows of 5 such surfaces laid according to the ISO standard only in Sweden.

5.1.2 ISO 11819-1 – The Statistical Pass-By method for comparison of road surfaces

ISO/TC 43/SC 1/WG 33 "Measuring method for comparing noise on different road surfaces" recently worked out a procedure with which one can quantify the influence on traffic noise of various road surfaces in an internationally standardized way. The new standard, ISO 11819-1 printed in September 1997, has the title "Acoustics – Method for measuring the influence of road surfaces on traffic noise – Part 1: The Statistical Pass-By method". The popular name of the method is the SPB method.

In the SPB method, one measures vehicle speed and the maximum pass-by noise levels of normal cars and heavy vehicles in the ordinary traffic passing-by the microphone at the roadside. The noise levels are regressed on speed and a type of statistical average noise level for the surface is calculated for light and heavy vehicles. Normalizations are made to speeds of 50, 80 or 110 km/h and the light and heavy vehicle levels are weighted together to form a final single-value noise index, called the SPBI (the Statistical Pass-By Index).

By using this standard it is possible, after some follow-up work (see below), to introduce a "type testing" of surfaces with respect to noise.

The method has been used in non-standardized versions since the late 70’s, in Sweden since the early 80’s. In its standardized version, an example of its use is presented in [Sandberg, 1997-I].
5.1.3 ISO/CD 11819-2 – The Close-Proximity method for comparison of road surfaces

The above-mentioned group continues its work to develop a supplementary measuring method that can be used on a wider selection of road sites, making possible for example more general surveys and noise approval tests of resurfacing works. Such tests have been widely requested. A very practical method is the so-called Close-Proximity method (the CPX method), formerly referred to as the Trailer method. In this case, test tyres are mounted (usually one by one) on a test trailer towed by a car or van and two microphones are positioned in close proximity to the tyre. Provided a lot of precautions are observed, instead of having a trailer one can put the test tyre in the position of one of the ordinary tyres of a vehicle, or as a fifth wheel. In such a case the name Trailer Method is obviously not appropriate and "CPX method" was chosen instead.

With this method, one measures the average noise level over a test section of (almost) arbitrary length for four reference tyres at reference speeds of 50, 80 or 110 km/h. These noise levels are combined into a final single-value noise index, called the CPXI (the Close-Proximity Index). It is assumed to correlate well with the SPBI, although its absolute values are higher.

Very recently, a first proposal from this group was submitted as a first Committee Draft. In a review process within ISO, some member countries was of the opinion that this draft should not be issued as a draft international standard until it had been supplemented with a method that more appropriately measures the noise reduction of porous surfaces, something which the working group suggested as part of a third standard within the series. Therefore, it will take a few years more until the Committee Draft can reach a higher status within ISO.

Furthermore, in 1998, an international validation experiment will take place in mid-western Europe with the purpose to study the performance of the method, its relation to the SPB method and how well the various equipment will correspond to each other.

5.1.4 Reference tyres

For comparison of noise characteristics of road surfaces, using the CPX method mentioned above, it is necessary to employ reference tyres which are the same irrespective of time and place. Four such tyres are suggested within the ISO/CD 11819-2 and these are subject to production in a first batch, for validation in mid-1998. Reference tyres are very important for studying road surface characteristics, equally important as reference surfaces when studying tyres.

The four tyres are intended for use in the CPX method, i.e. for noise classification of road surfaces. However, it is expected by many that once they are available they will be used also in other noise studies. Since there is a similar need also in studies of rolling resistance and friction, it might be that they are also applied in such studies later on. At least they will be potentially very interesting for use in such applications. It is recommended that when new studies are made in which tyres are essential measuring tools, these reference tyres be included as part of the experiment. It will give much better possibilities to relate studies to each other in the future.

For practical reasons, all the tyres are car tyres. However, the fourth tyre, although it is also a car tyre, has been selected in order to be able to represent the effect of a truck tyre on noise.

The chosen tyres are presented here:
- **Tyre A: Tread pattern “Summer A“**

This is a tyre intended for use mainly in temperatures above 0 °C. It is a tread pattern type introduced on cars at the time when this standard is produced. The tread pattern features attributes of the currently most popular car tyre designs. It is not yet possible to show a picture of it, since it is currently being developed and the tread pattern is still confidential.

- **Tyre B: Tread pattern “Summer B“**

This is a tyre intended for similar use as Tyre A, but it has a different tread pattern. See Fig. 10 (left part). It is a type commonly used on cars in the time period 1990–97. Tyres A and B together are intended to give a road surface noise characteristics classification which is representative of that obtained with cars in the SPB method, during climate conditions above 0 °C.

- **Tyre C: Tread pattern “Winter“**

This is a tyre intended for use mainly in temperatures around and below 0 °C, i.e. in conditions that may include snow and ice on the road. See Fig. 10 (middle part). In such climate applications, it is a type introduced on cars at the time when this standard is produced. The tread pattern features attributes of the currently most popular car tyre designs for winter climates. Tyre C is intended to give a road surface noise characteristics classification which is representative of that obtained with cars in the SPB method, during climate conditions around or below 0 °C. However, such classification is not very different from that obtained with tyres A and B.

Tyre C is also possible to equip with studs, in case it is desirable to supplement the set of reference tyres with an extra tyre having studs.

![Fig. 10 The proposed reference tyres B (left), C (middle) and D (right).](image)
Tyre D: Tread pattern “Block“

This is a tyre originally intended for winter use. Through its ”aggressive” block pattern, the dimensions of which are somewhat resembling those of many truck tyre designs, it has appeared that classification of noise characteristics of road surfaces using this tyre is fairly similar to that obtained with heavy vehicles in the SPB method [Sandberg, 1997-III]. See Fig. 10 (right part).

5.1.5 Sound absorption measuring method for comparison of porous road surfaces

Porous road surfaces are often applied world-wide for noise reduction purposes. A special feature of such surfaces which is not fully accounted for in the CPX method is the sound absorption properties; or rather the complex acoustical impedance which affects sound propagation from the tyre source to the recipient at the roadside. In order to supply a supplementary value of such effects, most notably for the CPX method, but also to provide means of studying this feature in research, design and project stages, two special methods for measuring sound absorption of road surfaces in-situ are being developed. This is done in the group ISO/TC 43/SC 1/WG 38, convened by Dr. van Blokland, the Netherlands.

5.1.6 ISO 13473-1 — Measurement of Mean Profile Depth

ISO/TC 43/SC 1/WG 39 ”Measurement of pavement surface macrotexture depth using a profiling method” recently worked out a procedure with which one can measure a single value ("MPD – Mean Profile Depth") representing the macrotexture of various road surfaces in an internationally standardized way. The new standard, ISO 13473-1 printed in September 1997, has the title ”Characterization of pavement texture utilizing surface profiles – Part 1: Determination of Mean Profile Depth”. The MPD, which was originally meant just to replace, as a mobile and improved variant, the volumetric patch value specified in ISO 10844, has proved to be a very good descriptor for the speed effect in wet friction. Furthermore, by means of this measure and the results of the International PIARC Experiment [Wambold et al, 1995], different friction measuring devices can be related to each other. See further the section about CEN activities.

Figure 11 illustrates the basic values Baseline, Profile Depth (PD), Mean Profile Depth (MPD) and Estimated Texture Depth (ETD) in the ISO 13473-1 standard. The reference (bottom) line is arbitrary and just for illustration purposes here. The baseline is either 100 or 50 mm long. The ETD value is the value which is intended to directly replace the (sand) patch measured texture, thereby providing a link to traditionally measured texture depths, while the MPD is intended to be the value to be used in all future applications.

The MPD measure has the following advantages:

1. MPD may be determined continuously along a surface with mobile methods at normal traffic speeds, unlike the patch method which is only a spot method needing temporary road closure to traffic

2. From the MPD it is possible to estimate the old volumetric patch value ”Mean texture depth”, thus giving a bridge for comparison with old data or with current low-tech studies
3. The MPD is a good general quantitative illustration of road surface texture; however, it does not describe how the texture is composed.

4. The MPD is a good description of the speed-depending term of wet friction.

5. The MPD enables harmonization of friction values measured with highly different equipment, see chapter 5.2.2.

\[
\text{Mean Profile Depth (MPD)} = \frac{\text{Peak level (1st)} + \text{Peak level (2nd)} - \text{Average level}}{2}
\]

*Fig. 11* Illustration of the terms Baseline, Average Level, Peak Level, Profile Depth (*PD*), Mean Profile Depth (*MPD*) and Estimated Texture Depth (*ETD*).

5.1.7 Future parts of ISO 13473 – Terminology and Specifications of Profilometers

The previously mentioned group continues its work with defining the terminology and basic measures within this subject. This is important because many studies and research projects in this area are ongoing or planned and their quality will be much enhanced if relevant and appropriate measures can be used consistently. More progress will result if they can record what are agreed as scientifically appropriate measures in common units and if results can be compared internationally as a result of standardization. The draft standards will also make it possible to agree on methods for performance specification in road surfacing projects and check that these specifications were actually met after laying the surfaces.

Consequently, the ISO group has proposed in a first Committee Draft, which was recently lifted by ISO to the Draft International Standard (DIS) level, a standardized terminology which includes specifications of a lot of useful measures for pavement texture (ISO/DIS 13473-2).
Furthermore, in a first Committee Draft, a proposal for specifications of profilometers for texture studies has recently been made (ISO/CD 13473-3). This is useful since many profilometers are currently being constructed (see e.g. [Cenek, 1996]) and many have recently been constructed, while there is a lot of uncertainty of how to do this in a proper way. Many of the profilometers in-use today may not be suitable in certain respects, unless they are tested or revised to comply with the proposed specifications. The standard is also needed in order to prepare for future unified procurement specifications and checking of road surfacing construction projects.

Both the mentioned drafts will be subject to a joint ISO and CEN review during 1998.

5.1.8 ISO draft on "Measurement of road surface friction"

The draft ISO/DIS 8349 "Road vehicles – Measurement of road surface friction" is not a standard dealing directly with texture. It specifies methods for comparing friction properties of different test tracks and road surfaces. However, since it deals with road surface properties highly determined by texture, for the sake of completeness this draft is mentioned here.

5.2 CEN

5.2.1 Texture measuring methods

The European Committee for Standardization (CEN) has a technical committee for Road Materials (TC 227) which has a working group for Road Surface Characteristics (WG 5). CEN/TC 227/WG 5 has in the latest year produced the following draft European standards (prEN) with regard to pavement texture (note that final CEN numbering will be different, based on the series EN 13036-x, where x will probably equal the last digit in the numbers below):

- prEN 00227-111: "Measurement of Pavement Surface Macrotextrue Depth Using a Volumetric Technique". This method was approved by TC 227 in 1997 and is identical to that in ISO 10844, Annex A.

- prEN 00227-112: "Characterization of pavement texture utilizing surface profiles – Part 1: Determination of Mean Profile Depth". This is the CEN version of ISO 13473-1; hopefully it will be editorially revised by CEN to be identical to the ISO version before printing. It has been submitted to TC 227 but no response has yet been received. It is likely to be approved in 1998.

- prEN 00227-113: "Pavement Surface Horizontal Drainability Test Method". This specifies a method which is commonly known as "the outflow method". It has been submitted to TC 227 but no response is yet received. It is likely to be approved in 1998.

Of these, the Swedish delegates have considered the one about drainage measurements as not very useful. There is no need for it now that mobile laser texture measurements on smooth as well as on rough surfaces are easy to perform. In fact, neither the Volumetric method is needed now that the MPD measure is specified. CEN/TC 227/WG 5 has expressed the relations between the methods as follows (intended to be stated in the beginning of each standard):
Table 3  Application areas for texture measuring methods. The three methods can be used in different applications, depending on availability of equipment, measuring speed requirement and surface texture, as follows:

<table>
<thead>
<tr>
<th>Method</th>
<th>Smooth textures</th>
<th>Medium textures</th>
<th>Rough textures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainability method</td>
<td>prEN 00227-113</td>
<td>Low-tech methods</td>
<td>suitable</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(only slow speed*)</td>
<td>suitable</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>not suitable</td>
</tr>
<tr>
<td>Volumetric patch method</td>
<td>prEN 00227-111</td>
<td>not suitable</td>
<td>suitable</td>
</tr>
<tr>
<td>or Annex A of ISO 10844</td>
<td></td>
<td></td>
<td>suitable</td>
</tr>
<tr>
<td>Profilometry method</td>
<td>prEN 00227-112</td>
<td>High-tech method</td>
<td>suitable</td>
</tr>
<tr>
<td>or ISO 13473-1</td>
<td></td>
<td>(slow and high speeds**)</td>
<td>suitable</td>
</tr>
</tbody>
</table>

* Slow speed means that the measuring device is stationary (but portable)
** High speed means that the measuring device can be used on a travelling vehicle (mobile)

In 1998 WG 5 submitted ISO 11819-1 to TC 227 proposed as a prEN, i.e. as a CEN standard.

Much of the work in the mentioned ISO and CEN groups have been related. Therefore, the working documents of ISO have frequently been circulated also among the CEN delegates and the latter have been invited to several ISO meetings. In many cases, CEN members have responded to proposals from the ISO groups, resulting in improved documents and bigger possibilities of approval not only by ISO but also by CEN.

5.2.2 Friction measuring and harmonization methods

Friction, or skid resistance, is measured with highly different equipment in different countries; even within some countries. There is a great need to have possibilities to relate such friction values with each other, or translate from one method to another. But this has been a great problem and no generally valid principles for doing so have been known until very recently.

The friction coefficient depends, among other things, on the following:

- Surface texture
- Driving speed of the measuring vehicle
- The slip speed (the relative speed between the contact surface of the tyre and the road surface, in other words how much the tyre is braked in relation to full locking)
- Eventual sideways forces, i.e. if the measuring wheel rolls in an angle $\neq 0$ towards the direction of driving
- The dimensions of the test tyre, rubber mix, tread pattern, inflation, load, etc.
- Water depth


- Contamination of the surface (such as oil, loose debris, etc.)
- Temperatures of air, tyre and water

In most cases, what one wants to measure is the surface effect on friction, i.e. the first-mentioned point. The next five points, which are all equipment-related parameters, normally influence the friction coefficient to a very significant degree. As there are friction measuring devices based on different measuring principles where the above-mentioned parameters are often totally different for different devices, consequently the values obtained are not easily comparable. In reality it is almost meaningless to compare friction coefficients which are not measured with measuring devices from the same family and with the same test parameters according to the above.

The great variations depending on equipment and test parameters can be illustrated with some measurements from the International PIARC Experiment in Belgium and Spain some years ago where at one and the same speed (60 km/h) on one and the same 75 m long test section, a friction coefficient was obtained as high as 0.90 for one measuring device and as low as 0.33 for another. On another 75 m test section, a value of 0.90 for one measuring device was obtained and 0.44 for another. One of the measuring devices measured a friction coefficient of 0.90 on test surface No. 1 and 0.53 on test surface No. 6, i.e. surface No. 6 was considerably worse than No. 1, while for another measuring device surface No. 1 measured 0.83 and surface No. 6 measured 0.90, i.e. surface No. 6 should with the latter device be somewhat better.

One can thus obtain almost any results, depending on the measuring device and measuring parameters, and comparisons between measurements and possible friction limits will be meaningless unless methods, equipment and test parameters are the same. This was really the main reason for the International PIARC Experiment conducted in 1992-95, namely to provide means of harmonizing such methods and equipment. The aim with this experiment was partly to explain relations between measuring devices and reasons for variations between them, partly to try to obtain some sort of normalization of the friction devices/methods to a uniform standard.

For Swedish conditions it can be said that BV11, Saab Friction Tester and BV14 belong to the same family of measuring devices where the same measuring principle and to a great extent the same equipment are used. Measurements with these devices are comparable and ought (ideally) to give identical results, at least in tests with the same water sprinkling rate and at the same speed. However, when comparing with measuring equipment such as the SCRIM or any of the many locked-wheel devices one will really be "skating on thin ice".

The mentioned PIARC experiment, in which VTI participated with a BV11 and a laser profilometer, resulted in the development of a normalized, universal measure of friction, namely IFI — the International Friction Index. The IFI contains two values, defining a curve — friction versus slip speed — which can be considered as a kind of average friction curve (called "the Golden Curve") that will be obtained if (almost) all friction devices in the world would be used for measuring on a particular site. By means of a normalization procedure utilizing equipment-related constants determined in the measurements made for the devices participating in the above mentioned experiment, the friction values obtained with any of these devices can be converted to IFI. However, not only a friction measurement but also a measurement of the macrotexture is needed for the normalization. In the latter case the Mean Profile Depth is used in accordance with ISO 13473-1.
The above-mentioned experiment is a great and important step to attain an acceptable equivalence between different friction measuring devices, but the normalization will still not give sufficiently small errors when a high precision is desirable. A further development of the normalizing principles is therefore going on in separate projects but with CEN/TC 227/WG 5 as a potential user.

With regard to pavement friction, CEN currently works with the following draft:

- prEN 00227-114: "Method for Measurement of Skid Resistance of a Surface: The Pendulum Test". This is a more elaborate version of the one described by the Road Research Laboratory (now TRL) in a "road note" from the 60’s. This has been submitted to TC 227, but the problem is that there are several versions of this method submitted to TC 227 and to other committees, and a harmonization is sought. It is not likely to be approved in 1998.

Furthermore, on the work programme there is a draft called "Dynamic measurement of friction". The draft is intended to be a generic specification outlining the framework and common requirements for all European friction measuring devices. The various devices will still be possible to use but there will be requirements, as to their calibration as well as to specifications, in some national standard or in a similar, publicly available document.

The draft will also provide a basis for harmonization of friction values measured with these devices, ending up with a European Friction Index (EFI). This will largely but not entirely rely on the method for calculation of an International Friction Index (IFI), mentioned above and presented in the PIARC report about the international experiment, see [Wambold et al, 1995]. The normalization means that the steps according to Table 4 must be applied.

In the PIARC report it is assumed that IFI is a variable composed of two components:

- The friction coefficient at a reference slip speed of 60 km/h ("the golden value", $F_{60}$)
- The friction speed constant, $S_p$ (which depends on macrotexture and is thus not really "constant")

Very simplified, one can say that the $F_{60}$ is the “level” of the friction versus slip speed curve, at a reference slip speed of 60 km/h, while $S_p$ is the (exponential) “slope” of the same curve. When these two values are reported, the complete friction/speed relation for a certain surface can be described by an exponential equation, from which one can determine friction at any slip speed, see Table 4.

The procedure is probably at first understood as somewhat complicated, but after having applied it the first times, it is really quite simple. IFI can be calculated by a computer directly after measurements have been conducted, and it can in fact be presented equally fast as the normally presented friction coefficient, i.e. in parallel; provided driving speed, friction coefficient and texture are all measured and that the equipment-related coefficients have been determined in advance, e.g. in the PIARC experiment.

Pending the results of ongoing discussions in CEN, EFI would be calculated in the same way as IFI, but replacing the number 60 (i.e. the reference slip speed) with 30 everywhere. The various constants would also be determined based on a slightly different database (only European devices).
Table 4  Brief description of the PIARC and planned CEN procedures for harmonizing measurements of friction on wet surfaces made with different methods and equipment.

**Measurements:**
- Measure the friction coefficient, \( F_m \), of a surface with the friction measuring device at a normal measuring speed, say 80 km/h. It is enough with measurement at one speed!

- Also measure the texture of the surface, more precisely the MPD according to ISO 13473-1 or prEN 00227-112, although *provisionally* also some other texture parameters may be allowed (still a matter of discussion).

**Calculations:**
- Calculate the slip speed, \( S_m \), of the friction measuring device. It is equal to the driving speed, \( V_m \), times the slip ratio or (for sideway force measuring devices like the SCRIM) the product of driving speed, \( V_m \), and the sine of the slip angle. This is normally a constant for each device and is easily calculated once for all.

- Calculate the texture-depending friction speed constant \( S_p \), to obtain the first of the final two values constituting the IFI. \( S_p \) depends on texture as follows (so it is not really a "constant"): 
  \[
  S_p = a + b \cdot T_m
  \]
  - where \( a \) and \( b \) are constants related to the texture measuring device, as determined in the PIARC experiment. When using the MPD, the \( a \) and \( b \) constants should be possible to determine once for all (work is underway).
  - \( T_m \) is the measured texture value, normally the MPD, but provisionally also some other measures may be allowed (still a matter of discussion).

- Normalize the friction coefficient from the actual driving speed to a reference slip speed of 60 km/h (still a matter of discussion, the proposal for EFI is currently 30 km/h) to obtain the second of the final two values, the \( F_{60} \), by applying the equation:
  \[
  F_{60} = A + B \cdot F_m \cdot e^{(S_m-30)/S_p} + C \cdot T_m
  \]
  - where \( A \), \( B \) and \( C \) are constants related to the friction measuring device, as determined in the PIARC experiment or some later, similar experiment (\( C = 0 \) for certain tyres)
  - \( F_m \) is the measured friction coefficient
  - \( S_m \) is the slip speed during measurement (see above)
  - \( T_m \) is the measured texture, normally the MPD (see above)
  - \( S_p \) is the friction speed constant, which is based on \( T_m \) (see above)

- The IFI is then composed of \( F_{60} \) and \( S_p \), i.e. two values representing, respectively, the *level* of the friction at 60 km/h of slip speed and the *slope* of the friction versus slip speed.

- Finally, the friction \( F(S) \) can be calculated for any slip speed \( S \), using the following formula:
  \[
  F_{60} = A + B \cdot F_m \cdot e^{(S_m-30)/S_p}
  \]
The equipment-related constants a, b, A and B (they should be re-named to avoid confusion) are already determined for those devices that participated in the PIARC experiment. In view of this, it appears as very important that VTI and Sweden really participated in this experiment with its major friction and texture measuring devices, having in mind the financing difficulties encountered for that project. In fact, at hindsight, it appears quite unlucky that Sweden did not participate with more devices, for example the Portable Friction Tester (PFT or "Fido" as it is sometimes called) or the BV12, for which funding was insufficient.

However, the constants are not constants forever. Equipment may change with time and wear. Therefore, WG 5 currently works not only with the harmonization procedure above, but also with a periodic calibration method for such devices. In the current very preliminary proposal it is suggested that some devices shall meet each year and go through a specified calibration procedure on some selected test sites. This shall give new, adjusted constants for the devices. Most devices would meet, a few at each place, at various places in the world and each time new and adjusted constants are produced. This is repeated at regular intervals (say annually) but each new time the same devices shall not meet again, instead new combinations of devices shall always be sought. With time, the constants will then be adjusted to come close to the true value of the constants, in fact the errors should not be big.

This calibration procedure will mean extra costs. The advantage will be the possibility to compare friction measurements as EFI values universally, or at least in Europe. This is not at all possible at the moment. The delicate task will now be to develop the calibration procedure so that it minimizes costs and time consumption while still maintaining good accuracy.

The position of the Swedish delegates in the CEN working group has been that it is important to develop this harmonized procedure into a standard, but that it is preferable that it is an international (using IFI) rather than European standard (using EFI). The reasons are that (1) utilizing all available data rather than only European should give better accuracy or at least general validity – it is unwise and scientifically wrong to disregard a significant portion of all data collected in the PIARC experiment, (2) road measuring equipment is no longer used only in one part of the world but the trend is increased exchange of equipment world-wide (for example cars, buses and trucks are no longer confined only to a certain continent), and (3) the non-European major equipment operators or scientists will probably be fully willing to take part in the discussions to arrive at a compromise which is acceptable.

It has been suggested by [Descornet, 1997] that repeatability and reproducibility of the EFI will be 0.14 (95 % confidence) when all wet road surfaces are considered. If extreme road surfaces (outliers in the PIARC experiment and some supplementing measurements) are disregarded these inaccuracies will reduce. They include also errors in the model for the harmonization. It is possible that future development can improve these inaccuracies.

Finally, it should be emphasized that the IFI and EFI concepts have been worked out for friction on wet pavements. Wet pavement friction is considered to be the most common friction problem in the world. No measurements on dry or icy surfaces have been included when working out the IFI or EFI. For Nordic circumstances, however, one may want to try to extend the validity to icy surfaces in the future, since this is one of our major friction problems. But this requires extensive experiments.
5.2.3 Quality classes and normative values

CEN goes a little further than ISO. The ISO never deals with limiting values or regulations, but CEN has decided to propose classes of performance of road surfaces, which can be used for limiting the use of surfaces to certain classes in certain situations. Such a quality class system might for example look like that in Annex B, suggested by this author for noise characteristics of road surfaces.

5.2.4 Overview of standards

Fig. 12 provides an overview of the international standards or drafts being considered at the moment, and their relations. An arrow between them means that one of them is based on the other. For example, the ISO standards have normally been taken over by other organizations. Note that only the ISO standards 10844, 11819-1 and 13473-1, as well as the EU and ECE regulations are currently official (frames indicated with shadow). None of the CEN standards have yet reached the final editing process.

5.3 Others

American Society for Testing and Materials (ASTM) also deals with standardization of surface characteristics (Committee E17). For example, ASTM has basically adopted the ISO 13473-1 standard as ASTM Standard E1845 and is currently working on the IFI concept. VTI has sometimes taken part in such work by correspondence. It is important to make sure that all the standards are harmonized as much as possible in order to prevent double work or collection of incommensurable values caused by differing standards.

It should also be mentioned that the European Commission (EU / EEC) and the United Nations Economic Commission for Europe (ECE) are using ISO 10844 as mandatory references in their regulations on vehicle noise.
Overview of the international standards related to pavement texture, including drafts currently considered. The high-tech-based standards are indicated in bold letters, the others are based on low-tech methods. Note that the final numbering of the CEN standards will be different; they will be numbered in a series of EN 13036-x.
6. THE MEASUREMENT AND USE OF ROAD SURFACE TEXTURE DATA – HISTORY AND CURRENT TRENDS

6.1 Historical remarks

In the past, the dominating texture measuring method has been the so-called sand patch method, or more general the 'volumetric patch' method. It was developed in the late 60’s at the Road Research Laboratory (now the Transport Research Laboratory – TRL) in the U.K. This method has been used world-wide for many years to give a single and very simple measure describing surface texture. It relies on a given volume of sand or glass spheres which is spread out on a surface. The material is distributed to form a circular patch, the diameter of which is measured. By dividing the volume of material spread out with the area covered, a value is obtained which represents the average depth of the sand or glass sphere layer, i.e. a 'mean texture depth' (MTD). The method has been standardized in ISO 10844 in order to put limits with regard to surface texture for a reference surface used during vehicle noise testing. Actually, the ISO 10844 appendix with the volumetric patch procedure seems to have been the first international standard on road surface texture!

Another patch method have used grease as the material to be spread out on the surface. In addition, a so-called "Outflow Method" has been frequently used. In this case the time of water outflow between a rubber ring placed on the surface and the texture has been taken as the texture measure. This method can distinguish very well between various smooth textures, but is not useful for rough textures.

The volumetric patch method is very crude, depends on the operator and can be used only on surfaces which are partly or fully closed to traffic. It is not very useful on smooth surfaces, unless grease is used as the material, something which is impractical. Therefore, the patch method is not useful in network surveys of roads, for example. Recognizing the need for a mobile method, the TRL in the UK developed a laser sensor that took laser spot samples of the surface texture and calculated the standard deviation of the samples, which could be used to calculate a "sensor-measured texture depth (SMTD)" intended to replace the patch-measured MTD. This was developed as various mobile devices, as well as a portable "Mini Texture Meter (MTM)". The TRL devices did not record continuous profiles, but along with developments in contactless surface profiling techniques, it became possible to replace the volumetric patch measurement with measures derived from real profile recordings in the 80’s. The use of the profile enables a more advanced texture analysis to be made, for example one in which the effect of the patch method can be simulated. A most important step was taken in the early 70’s, when [Lawther and Henry, 1974] pioneered in using (contact) profiling methods to analyze texture profiles in frequency spectra.

Over the years, several and very different techniques have been used to calculate a predicted mean texture depth like the mentioned SMTD; many of them quite successful. The values they have given are not always comparable, although individually they have generally offered good correlation coefficients with texture depth measured with the volumetric patch method. Therefore, it has been found important to offer a standardized method for measuring texture depth by a more modern, safe and economical technique than the traditional volumetric patch method, resulting in values which are directly compatible both with the patch-measured values and between different equipment. The profiling techniques, which generally are contactless and mobile and have a potential for advanced texture analyses, meet such demands and have been developed or are under development for adoption as international standards, as mentioned above.
6.2 Use of texture data in some other countries

Since the late 60's, texture measurements have been used throughout the world for documentation of investigations and for research whenever texture has been considered an interesting factor. Countries like France have also collected texture data from the national road network for survey and documentation purposes. This makes it possible to study how the network changes over time and differences between regions, etc.

Texture measures have been used for legal purposes or for putting up requirements for roadworks since a few years ago; for example:

- In the U.K. where texture depth must meet certain limits for certain classes of roads. Texture depth is to be measured by sand patch or laser techniques, in the latter case the laser-measured values (SMTD) must be calibrated against the patch-measured ones. The requirements are as follows according to [Phillips, 1998]:

<table>
<thead>
<tr>
<th>Table 5</th>
<th>British requirements with regard to macrotexture (EACC = Exposed aggregate cement concrete).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of project</td>
<td>Pavement type</td>
</tr>
<tr>
<td>Specifications for new types of road surfaces</td>
<td>Bituminous, and EACC</td>
</tr>
<tr>
<td></td>
<td>Cement concrete except EACC</td>
</tr>
<tr>
<td>Specifications for newly laid road surfaces</td>
<td>Bituminous, and EACC</td>
</tr>
<tr>
<td></td>
<td>Cement concrete except EACC</td>
</tr>
<tr>
<td>Guidelines for road surfaces in service</td>
<td>Bituminous, and EACC</td>
</tr>
<tr>
<td></td>
<td>Cement concrete except EACC</td>
</tr>
</tbody>
</table>

All new types of road surfacing are currently approved under a Highways Agency five stage performance assessment procedure, of which the last one is a field trial. One of the criteria is then that texture depth (sand-patch) must be higher than 1.5 mm and shall still be higher than 1.0 mm after one year of operation. Proposals are currently being worked out to develop a new type approval procedure called HAPAS to be operated by the British Board of Agrément, but this system will adopt the same texture criteria [Phillips, 1998].

Newly laid bituminous surfaces are required to have a texture depth greater than 1.5 mm as detailed in Clause 921 of the Specification for Highway Works. This also applies to exposed aggregate cement concrete surfaces, although other cement concrete surfaces are required to have a texture depth between 0.75 and 1.25 mm when new, as detailed by Clause 1026 of the same act. The upper limit is introduced to avoid excessive tyre/road noise.

For in-service roads, there are no firm rules governing macrotexture, although guidelines are given for interpreting the results from High-speed Road Monitor (HRM) measurements, the
latter of which are taken at least once every two years. Volume 7 of the Design Manual for Roads and Bridges (DMRB), says that if macrotexture measured as SMTD is less than 0.5 mm on bituminous surfaces or 0.25 mm on cement concrete surfaces, immediate action is required (or recommended?) to ensure that proper skidding resistance is maintained. In addition, if the SMTD readings are reduced by more than 0.5 mm in two years this may be a sign that fretting is occurring and immediate action is recommended [Phillips, 1998].

- In France there are recommendations from SETRA pertaining to new surface constructions (albeit they are often unofficially referred to also for older road surfaces) where there are requirements of minimum texture depth for the purpose of obtaining acceptable friction. There are no requirements regarding friction values here. Texture depth shall normally be measured by laser techniques, by which patch-equivalent texture depth is calculated, using a laser device (“Rugolaser”) mounted on modified SCRIM friction measuring trucks. The French recommendation for new construction is as follows [Gothié, 1997]:

Table 6 French recommendations with regard to macrotexture.

<table>
<thead>
<tr>
<th>Site</th>
<th>Road type</th>
<th>Posted speed km/h</th>
<th>Texture depth in mm (measured with vol. patch method)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>&quot;Easy&quot; sections Pot. hazard spots &quot;Difficult&quot; sections</td>
</tr>
<tr>
<td>Urban sites</td>
<td>Transit</td>
<td>60</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>High speed</td>
<td>110</td>
<td>0.4</td>
</tr>
<tr>
<td>Other sites</td>
<td>Bi-directional</td>
<td>90</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Separat. directions</td>
<td>≥110</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Note: "Easy" section could mean that the road is straight and level, while "difficult" may be a road with sharp curves and high grades. "Potentially hazardous spots" may be for example a light-controlled intersection.

A special “Skid Resistance Sub-group” within a national French group “Pavement Surface Characteristics — GNCDS” is working on a new recommendation document and continues its efforts to “define macrotexture specifications and ‘potential’ microtexture recommendations that will reconcile aspirations and possibilities”, according to [GNCDS, 1998].

- In Germany, texture measurements are made as a supplement to friction measurements with the pendulum [Huschek, 1997]. The method they have chosen for macrotexture measurements is the outflow method, mainly because it is more sensitive on smooth textures than the patch method. There is a requirement in Germany to measure friction on new constructed surfacings with either the Stuttgarter Reibungsmesser (SRM), the SCRIM or the "Combined method" and to meet certain limits. The "Combined method" is the Pendulum method together with macrotexture measurements as mentioned above. The limits with the "Combined method" are rather complicated. For in-service surfaces a requirement has been worked out which at the moment is subject of a juridical review, before formal acceptance. This proposal also requires measurements with either one of the three mentioned methods.

- Italy has defined five classes of macrotexture ranging from 0.2 to 1.2 mm. It is not known whether they are used in requirements, although the fact that Italian SCRIMs are equipped with texture-measuring devices suggests that it may be the case. The macrotexture value is a patch-measured texture depth, but it may probably be estimated from laser measurements.
Portugal requires minimum macrotexture values, determined with the patch method, on roads according to the following table (the last three pavement types are probably erroneously translated from Portuguese):

Table 7   Portuguese requirements (7) with regard to macrotexture.

<table>
<thead>
<tr>
<th>Type of pavement</th>
<th>Macrotexture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement concrete (&quot;Rigid pavements&quot;)</td>
<td>&gt; 0.6 mm</td>
</tr>
<tr>
<td>Dense asphalt concrete</td>
<td>&gt; 0.6 mm</td>
</tr>
<tr>
<td>Porous asphalt concrete</td>
<td>&gt; 1.2 mm</td>
</tr>
<tr>
<td>&quot;Rough micro concrete&quot; (bituminous)</td>
<td>&gt; 1.0 mm</td>
</tr>
<tr>
<td>&quot;Asphalt construction concrete&quot;</td>
<td>&gt; 0.4 mm</td>
</tr>
<tr>
<td>&quot;Mixed bitumen with high modulus&quot;</td>
<td>&gt; 0.4 mm</td>
</tr>
</tbody>
</table>

In the Australian states of New South Wales and Victoria it is currently considered to supplement their SCRIM devices with texture-measuring equipment, as a result of the PIARC Experiment.

In Spain, the SCRIM is also equipped with a texture measuring device, like in France and Italy. It might mean that also Spain has requirements or recommendations with regard to macrotexture, but this is not yet clear to the author.

As is evident from this list, road surface macrotexture measurement is applied in many countries and the use of such measures seems to be increasing. The results of the PIARC Experiment will most probably accelerate this development. This emphasizes the need for international standardization before methods are becoming too disperse and before standardization will be politically difficult due to locked positions.
7. MEASURES, METHODS AND INSTRUMENTS

7.1 Measures and methods

Several measures and methods have been explained already in Chapter 5 regarding standardization activities. The reader may want to refer back to Fig. 12 for an overview, to Fig. 11 for illustration of calculation of the Mean Profile Depth (MPD) and to Table 4 for an explanation of how the EFI (or IFI) index is calculated.

Measures and methods for characterizing pavement texture are listed and commented in Table 8. Apart from the measures and methods listed in Table 8, it should be mentioned that normal (mono) photographs of the surface are very often produced as means of documenting the surface and sometimes for making partly subjective estimations from the photographs. This cannot be considered an objective method, however.

Microtexture-measuring methods and equipment are not listed in Tables 8–9, other than the pendulum method, since they are not used today. However, it can be mentioned that already some 30 years ago, a microtexture measuring needle profilometer was tested [Gallaway & Tomita, 1970]. As a later method, it can be mentioned that microtexture profiles have been analyzed by means of electron microscopes [Forster, 1981].

For curiosity, it can be mentioned that in the 70’s trials were made in USA to calculate texture and speed influence on friction from tyre/road noise measurements by means of the acoustic signal from an onboard microphone and establishing a relation between noise and texture [Bronsdon, 1977][Veres et al, 1975]. The trials were partly successful but were not followed-up.

In these years, tests were also conducted to see if light depolarization of polarized light reflected on a road surface could be a reasonable measure of texture [Spring III & King Jr, 1981]. The tests indicated that correlation coefficients between the degree of depolarization and texture of up to 0.80 were possible, but it was impossible to distinguish between micro- and macrotexture effects in this investigation and the equipment was not adapted for permanent field use.

The ISO and CEN methods for measuring surface influence on traffic noise are not mentioned in the table, because they are measuring directly the effects of the texture rather than the texture itself. It is discussed, however, that a texture measure might be included in a future standard for the Close-Proximity method (refer to Fig. 12) for describing special effects of porous surfaces. Macrotexture measurement is also required in ISO 10844, ISO 11819-1 and ISO/CD 11819-2 for specification of a reference surface.

The imprint and stereophotograph methods, see e.g. the Schonfeld method in [Howerter & Rudd, 1976], which are listed in the table are, as far as this author is aware, not currently used to any significant extent. However, they have been included since these hold a certain potential for development now that video cameras and automatic picture analysis are gaining popularity in automated road surface survey systems. The imprint method will be tried in an ongoing project, see the special chapter about ongoing research and development projects.

Image processing has been applied to surface texture analysis also, see [Wigan & Cullinan, 1987] and [Ljungström, 1998]; however, the methods need further refinement. See also further about [Rado, 1996] below. Ljungström concluded in his Lic Thesis that provided the aggregate is not covered with bitumen and the surface is dry, it is possible to analyze aggregate shape, etc.
Table 8 Measures and methods for characterizing pavement texture. Only such methods that have had or have other than very limited use are listed.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Method of measurement</th>
<th>Origin</th>
<th>Present use</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean texture depth (MTD)</td>
<td>Volumetric patch (or sand patch) (ISO10844 Annex A prEN 00227-111)</td>
<td>TRL, UK 1960</td>
<td>World-wide</td>
<td>Manual and stationary method that needs closure of the lane while measuring. See Fig. 15. Not very good on smooth surfaces</td>
</tr>
<tr>
<td>Mean texture depth (MTD)</td>
<td>Volumetric patch: Silicone putty or grease smear</td>
<td>1960's</td>
<td>Occasionally on airfields in USA (?)</td>
<td>A variant of the first item in this list. Manual methods that need closure of the lane while measuring</td>
</tr>
<tr>
<td>Outflow time</td>
<td>Outflow method (prEN 00227-113)</td>
<td>Kummer, PTI, USA, 1960's</td>
<td>Starting world-wide</td>
<td>Mobile method. Intended to describe primarily speed dependence of friction, and be a better alternative to MTD</td>
</tr>
<tr>
<td>Mean Profile Depth (MPD)</td>
<td>Profilometry (ISO 13473-1, and prEN 00227-112)</td>
<td>CRR Belgium 1980's</td>
<td>Starting world-wide</td>
<td>Mobile method. Intended to provide a measure numerically corresponding to MTD above, in transition period</td>
</tr>
<tr>
<td>Estimated Texture Depth (ETD)</td>
<td>Profilometry (ISO 13473-1, and prEN 00227-112)</td>
<td>CRR Belgium 1980's</td>
<td>Starting world-wide</td>
<td>Mobile method. Intended to provide a measure numerically corresponding to MTD above, in transition period</td>
</tr>
<tr>
<td>Sensor Measured Texture Depth (SMTD)</td>
<td>Profilometry</td>
<td>TRL, UK 1970's. Based on RMS below UK, France, Spain, Italy (&quot;Scrimtex&quot;, &quot;Rugolaser&quot;, &quot;Mini Texture Meter&quot;, etc.)</td>
<td>This is similar to ETD above, but non-standardized, and adapted mainly for use with SCRIM friction measuring systems and with UK equip. like HRM</td>
<td></td>
</tr>
<tr>
<td>Root Mean Square (RMS) of texture</td>
<td>Profilometry (ISO/CD 13473-2)</td>
<td>TRL, UK 1970's. Basis for SMTD above</td>
<td>Rather frequently, e.g. by the RST vehicle</td>
<td>Mobile method. Often filtered with bandpass filter to let through only certain parts of the texture spectrum</td>
</tr>
<tr>
<td>Profile spectrum</td>
<td>Profilometry (ISO/CD 13473-2)</td>
<td>PTI, USA 1970's</td>
<td>For research in S, B, D, NL. See Fig. 14</td>
<td>Holds a potential for providing a lot of useful texture information, e.g. for predicting various influences of texture</td>
</tr>
<tr>
<td>Texture Level in 80 &amp; 5 mm octave bands</td>
<td>Profilometry (ISO/CD 13473-2)</td>
<td>CRR Belgium 1980's</td>
<td>For research in S, B, UK</td>
<td>For predicting noise characteristics, the octave bands at texture wavelengths of 80 and 5 mm have been found useful</td>
</tr>
<tr>
<td>Profile curve</td>
<td>Profilometry (ISO/CD 13473-2)</td>
<td>Old method, used in 60's and before Only for illustration purposes. See e.g. [Wambold et al, 1995]</td>
<td>Could be a good illustration of a certain surface, as a supplement to or replacing a photo. See Fig. 13</td>
<td></td>
</tr>
<tr>
<td>Profile amplitude distribution</td>
<td>Profilometry (ISO/CD 13473-2)</td>
<td>TUB Berlin, Profilometry (ISO/CD 13473)</td>
<td>Research in S and D. See Fig. 13</td>
<td>Can illustrate asymmetric profiles, is often a good supplement to a profile curve (a sort of quantification)</td>
</tr>
<tr>
<td>Number and area of tyre/road contact points</td>
<td>Imprint in tyre/road pavement interface</td>
<td>Kraemer? 1962? Occasionally, for research only</td>
<td>Imprints can be analyzed with image processing methods. Needs closure of the lane while measuring</td>
<td></td>
</tr>
<tr>
<td>3D Surface topography</td>
<td>Schoenfeld method of stereo photography</td>
<td>TRL, UK 1960's</td>
<td>None?</td>
<td>Traditionally relies on partly subjective estimations of topography features, but potential for image processing, etc.</td>
</tr>
<tr>
<td>Enlarged surface 2D photograph</td>
<td>Electron microscopy</td>
<td>Unknown</td>
<td>World-wide</td>
<td>Mostly used only for illustration purposes, see (Höbeda, 1997), sometimes also scales are presented</td>
</tr>
<tr>
<td>British Pendulum Number (BPN)</td>
<td>Pendulum test (measuring friction) (prEN 00227-114)</td>
<td>TRL, UK 1960</td>
<td>World-wide, for testing roads, airfields, side-walks, edge markings, floor coverings, etc.</td>
<td>Indirect and approximate measure of microtexture. Manual and stationary method that needs closure of the lane while measuring. See Fig. 19</td>
</tr>
<tr>
<td>EFI European Friction Index</td>
<td>Friction + macrotex- ture measurements, see ISO13473-1 and prEN 00227-115</td>
<td>Adapted from the PIARC Experiment, see [Wambold et al, 1995] PILOT studies are being made, future European requirements to report it or EFI may come</td>
<td>See Table 4 for description. The EFI uses MPD as an input parameter for equipment harmonization and describing speed influence on friction</td>
<td></td>
</tr>
<tr>
<td>IFI International Friction Index</td>
<td>Friction + macrotex- ture measurements, see ISO13473-1 and prEN 00227-115</td>
<td>The PIARC Experiment, see [Wambold et al, 1995] PILOT studies are being made, future European requirements to report it or EFI may come</td>
<td>See Table 4 for description. The IFI uses MPD as an input parameter for equipment harmonization and describing speed influence on friction</td>
<td></td>
</tr>
</tbody>
</table>
Two types of results from profile measurements and subsequent analyses are shown in Figs. 13-14. Both are part of the presentation currently implemented by VTI. Firstly, Fig. 13 shows a profile curve, with a profile amplitude distribution to the right, vertical scales being the same. It is evident from the profile curve that the profile is asymmetrical. The distribution to the right quantifies this asymmetry in an objective way and also shows that there is a concentration of profile at the level around +2.5 mm and at around -4 mm. The normal case for dense bituminous surfaces is a distribution which is approximately Gaussian. The distribution curve to the right can summarize an arbitrarily long profile in a very useful way which is not practical in other ways and which is easy to treat mathematically. Such distribution curves are useful to evaluate for example if the texture has its peaks directed upwards or downwards. SMA and porous surfaces are examples of pavements which have their texture peaks directed downwards.

Secondly, Fig. 14 shows a typical profile spectrum with third-octave band resolution. Whereas Fig. 13 analyzes the profile in the space (time) domain, Fig. 14 does it in the spatial frequency domain. Very simplified one can say that such a spectrum shows the distribution of the "energy" at various horizontal spacings between surface elements. For example, the peak in the spectrum appears at the texture wavelength of 16 mm. It means that this is "the most commonly observed periodicity" in the profile curve. For example, if 12 mm round chippings were placed on a flat surface 4 mm apart (i.e. 4 mm spacing between their edges) the profile would be repeated at an interval of 12 + 4 = 16 mm. It would then be recorded as a pronounced peak in the texture spectrum at 16 mm wavelength. In the example, the peak at 16 mm therefore suggests that the most common chipping size is less than 16 mm and that there is some spacing between these chippings. All the largest chippings are not placed absolutely edge-to-edge but are generally separated a few mm by some mortar or by smaller chippings. According to our experience, the example would be typical of a dense asphalt concrete with 12 mm maximum chipping size. The peak in the example is very flat, almost non-existing, which indicates that the (possible) 12 mm dominating chipping size may be the most common size but the content of other, smaller sizes is almost as big.

See also the next section in which a number of the methods have been illustrated by photographs.

Finally, a totally new approach to describing texture will be mentioned. Based on a PhD work, including data collected within the PIARC Experiment utilizing the texture data collected by VTI, a Hungarian PhD student developed a fractal texture model. It is shown there that texture in the wavelength range of 0.01–25 mm can be described as fractals according to the fractal geometry founded by B.B. Mandelbrot [Rado, 1996]. From the VTI profiles collected in the PIARC experiment, Dr. Rado was able to calculate a couple of fractal parameters (named G and D) which describe the roughness and are input parameters for calculating "real area of (tyre/road) contact" and which is part of a new "Fractal contact model" to describe the relation between friction and texture. The fractals may be derived from gray-scale pictures of the surface by image-processing using a Markov theory, which means that profilometry would be exchanged with photography or video recordings followed by advanced image processing.

The work by Rado is extremely interesting but the available documentation so far is incomplete and not easy to understand. The thesis is not yet available. It could well be that the new technique would hold and release potential advantages over "conventional" profilometry which would be important features in future research.
Fig. 13  Sample profile of an actual grooved cement concrete pavement, and its profile amplitude distribution shown to the right.

Fig. 14  Sample profile spectrum. The example is a dense asphalt concrete surface.
7.2 Instruments and equipment

For the purpose of measuring texture for characterizing its influence on various parameters, equipment listed in Table 9 is available. A more complete and extensive description of each one, including photographs, can be found in [Wambold et al, 1995]. Some of the equipment is illustrated in the following figures.

First, Fig. 15 illustrates measurement of MTD with the patch method, using glass spheres as spread-out material. The operator is just measuring the diameter of the circular patch he has obtained after distributing the material with the tool at the left (an ice-hockey puck with handle). This is often a problem outdoors due to wind which may blow away part of the material.

Then Fig. 16 illustrates an outflow meter. The water level in the glass tube has decreased almost down to the level where a stop-watch is stopped (in this case manually) to read the outflow time of 1 dm$^3$ of water.

Fig. 15 The volumetric patch method.  
Fig. 16 The water outflow meter of VTI.

Fig. 17 shows the British "Mini Texture Meter (MTM)", which is pushed by the operator down the test section at a normal walking speed. The texture depth is then printed out on a paper roll and presented on a digital display.

Fig. 18 shows the version of ROSAN from FHWA in USA that was used in the PIARC Experiment. It contains a laser sensor measuring macrotexture depth and a rubber slider measuring dry friction, the latter assumed to be a microtexture property. By combining the two values it was intended to get a value which could represent friction. It did not work well in practice; one reason being a too poor laser device.

Fig. 19 shows the British Pendulum in use for measuring friction with a rubber slider touching the surface during part of its pendulum swing. Normally the surface is wetted before testing.
The patch and the pendulum methods are low-tech methods which are used very frequently. However, the most widely used mobile system seems to be the ARAN. Currently there are 64 ARAN vehicles operating in 13 countries, most of them in the USA. The ARAN system relies on measuring an RMS value.

Several vehicles also operate worldwide with the RST system. A total of 21 vehicles have been built of which about half are in current operation. It is also probable that there are quite a number of SCRIMTEX vehicles, or corresponding, not listed in the table.

The system which is currently being developed more intensively than any other system (as far as this author is aware) is the ROSAN series of profilometers, developed first by the Federal Highway Administration (FHWA) in USA, but recently taken over for development and deployment by Surfan Engineering and Software, Inc. This series of new devices are able to measure ETD (see 5.1.6) and a US version of the MPD [ASTM E1845] as well as some other profile features. There is also a special ROSAN algorithm simulating the movement of a rubber pad (puck) for calculating the MPD, which is denoted RMPD. Outputs of ROSANvnm are for example claimed to include "macrotexture, faulting, grooving, rutting and slope". See [FHWA, 1998].

Table 9 indicates that currently there are more than 100 texture profiling devices in the world, most of them mobile.

It should also be mentioned that it is claimed in [Roadware, 1997-III] that the so-called Norsemeter, which is a Norwegian-developed device which is part of the ARAN system, measures IFI as well as macrotexture and microtexture in one pass. This seems to this author to be a little exaggerated, since it seems to measure friction (and not texture), and it is assumed that macrotexture and microtexture can be predicted from these friction measurements. This is an interesting and unusual approach, reminding of the trials in the 70’s to "measure" macrotexture by measuring tyre/road noise and establishing a relation between noise and texture in order to calculate texture (see 7.1). It is not clear from the information whether "macro- and microtexture" values actually are presented by the Norsemeter; this is probably not the case.

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Origin</th>
<th>Type</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>FHWA Texture Measuring System</td>
<td>USA</td>
<td>Profilometer system. Light sectioning device</td>
<td>Measures texture depth (lateral profile curve) utilizing video system. Mobile. Light slit =100 mm</td>
</tr>
<tr>
<td>A12</td>
<td>ROSAN, old version (Belongs to FHWA)</td>
<td>USA</td>
<td>Profilometer system. Laser spot, linear sensor</td>
<td>Measures texture depth, at walking speed. Includes also friction measurement (by slider). Not in oper?</td>
</tr>
<tr>
<td>ROSANbp (Belongs to FHWA)</td>
<td>USA</td>
<td>Profilometer system. Laser spot, linear sensor</td>
<td>Measures longitudinal profile curve Stationary but portable</td>
<td></td>
</tr>
<tr>
<td>ROSANv (Belongs to FHWA)</td>
<td>USA</td>
<td>Profilometer system. Laser spot, linear sensor</td>
<td>Measures longitudinal profile curve Mobile. Unit possible to mount on any bumper</td>
<td></td>
</tr>
<tr>
<td>ROSANvm (Belongs to FHWA)</td>
<td>USA</td>
<td>Profilometer system. Laser spot, linear sensor</td>
<td>Measures longitudinal profile curve. Mobile. Like ROSANv, but unit also moved transversely</td>
<td></td>
</tr>
<tr>
<td>ROSANvm(P) (Belongs to FHWA)</td>
<td>USA</td>
<td>Profilometer system. Laser spot, linear sensor</td>
<td>Measures longitudinal profile curve. Mobile. Like ROSANvm, but also measures IRI</td>
<td></td>
</tr>
</tbody>
</table>

Table 9  Texture measuring equipment currently available. The "No." refers to the designation of this equipment in the International PIARC Experiment [Wambold et al, 1995]. There is no particular order in the table. The table continues on the next page.

(continues on the next page)
Table 9 (continued) Texture measuring equipment currently available.

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Origin</th>
<th>Type</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2</td>
<td>VTI Mobile Laser Profilometer</td>
<td>S</td>
<td>Profilometer system. Laser spot, linear sensor</td>
<td>Measures longitudinal profile curve + spectrum. Mobile. See Figs. 21–23</td>
</tr>
<tr>
<td></td>
<td>VTI Stationary Laser Profilometer</td>
<td>S</td>
<td>Profilometer system. Laser spot, linear sensor</td>
<td>Measures longitudinal profile curve + spectrum. Stationary but portable. See Fig. 20</td>
</tr>
<tr>
<td></td>
<td>TU Berlin Stationary Laser Profilometer</td>
<td>D</td>
<td>Profilometer system. Laser spot, linear sensor</td>
<td>Measures longitudinal profile curve + spectrum. Stationary but portable</td>
</tr>
<tr>
<td></td>
<td>FIGE Stationary Laser Profilometer</td>
<td>D</td>
<td>Profilometer system. Laser spot, linear sensor</td>
<td>Measures longitudinal profile curve + spectrum. Stationary but portable</td>
</tr>
<tr>
<td></td>
<td>Geocisa Stationary Laser Profilometer</td>
<td>E</td>
<td>Profilometer system. Laser spot, linear sensor</td>
<td>Measures longitudinal profile curve + spectrum. Stationary but portable</td>
</tr>
<tr>
<td></td>
<td>A3B ARAN (&quot;Smart Texture&quot;)</td>
<td>CDN</td>
<td>Profilometer system. Laser spot, linear sensor</td>
<td>Measures texture depth. Mobile. Part of bigger system. Now 64 ARAN vehicles in 13 countries</td>
</tr>
<tr>
<td></td>
<td>A3E RST</td>
<td>S</td>
<td>Profilometer system. Laser spot, linear sensor</td>
<td>Measures texture depth and IRI in both wheel tracks. Mobile. Part of bigger system. Several vans</td>
</tr>
<tr>
<td>A4</td>
<td>CRR Mobile Laser Profilometer</td>
<td>B</td>
<td>Profilometer system. Laser spot, linear sensor</td>
<td>Measures longitudinal profile curve + spectrum. Mobile</td>
</tr>
<tr>
<td></td>
<td>CRR Static Profilometer</td>
<td>B</td>
<td>Profilometer system. Laser spot, linear sensor</td>
<td>Measures profile curve + spectrum. Stationary, but easy to move, can be towed by or put into van</td>
</tr>
<tr>
<td>A8</td>
<td>Pendulum tester</td>
<td>many countries</td>
<td>Rubber slider sweeps over wetted surface patch</td>
<td>To so-called British Pendulum. Stationary. See Fig. 19. Is assumed to measure mainly microtexture</td>
</tr>
<tr>
<td>B8</td>
<td>Outflow meter</td>
<td>many countries</td>
<td>Time for water outflow of 1 dm³</td>
<td>Measures surface drainage. Stationary method. See Fig. 16</td>
</tr>
</tbody>
</table>
Fig. 17 The British "Mini Texture Meter".

Fig. 18 The ROSAN device from FHWA, USA.

Fig. 19 Friction measurement with the British Pendulum device. When the rubber slider at the pendulum end touches the surface, it is decelerated an amount proportional to friction and the pendulum swings to the upper right an angle depending on the friction.
Fig. 20 shows the Stationary Laser Profilometer at VTI. It was the first real laser profilometer and is still used today. The electro-optical device in the black "box" is moved along the surface approximately 1 m with a "carriage" powered via a chain by an electrical motor on the tripod. The output signals (vertical displacement, laser spot brightness and longitudinal position) are fed to signal-processing equipment in the car.

Fig. 20 (above)
The VTI stationary Laser Profilometer.

Fig. 21 (right)
The calibration device for the VTI Mobile Laser Profilometer in Fig. 23. It makes use of a triangular profile on a disc which is rotating below the laser at a speed similar to the driving speed of the car. The equipment above the profiled disc is the electro-optical sensor of the profilometer mounted in a vibration-damping unit.
Fig. 23 shows the VTI Mobile Laser Profilometer, the most visible part of which is the electro-optical sensor ("the laser") at the rear of the car. A view inside the car is presented in Fig. 22, showing the spectrum analyzer at the bottom and at the top the laptop computer that handles the data processing and presentation. One person can operate the entire measurement and drive the car, but it is more convenient and safe to have one operator and one driver. The spectrum analyzer can, in principle, be integrated into the computer.

Fig. 22 The data processing equipment inside the car, a part of the VTI Mobile Laser Profilometer. There is also a power unit (12VDC/230VAC converter) and a box with data processing components for the profilometer output signals at the rear of the car.

Fig. 23 The VTI Mobile Laser Profilometer system, contained in a Volvo 245 car, nowadays replaced with a Volvo 850 car. The sensor is mounted on a bar at the rear of the car, possible to move laterally to other positions.
The texture meter that seems to be applied in practical measurements more than other equipment, and the results of which are also actually used, is the "Rugolaser" used in France, with corresponding versions used also in Spain and Italy. It uses the same type of laser probe like the VTI profilometer shown above. An excellent description of this device appears in [Gothié, 1994]. Normally, this equipment is used only to calculate a patch-equivalent texture depth, similar to the ETD.

Most profilometers nowadays use the triangulation principle, measuring with an electro-optical device in which a laser creates the light (laser) spot on the surface, the image of which is projected on a sensor in the receiver ("the camera"). See Fig. 24. These devices are usually named "laser profilometer", just "laser" or something similar. In fact, the laser is only a small part of such a system. Fig. 25 shows how a rather typical "laser profilometer" system (the VTI Mobile Laser Profilometer) is constructed. Note that this block diagram is a little outdated now, since both spectrum analyzer and computer have been exchanged since the diagram was produced.

\[ d = \frac{0.5 \cdot h \cdot K_1}{K_2 - h \cdot 0.87} \]

\( d \) = The detector output signal  
\( K_1 \) and \( K_2 \) are constants referring to the lens system  
\( h \) = Displacement in the road profile

Fig. 24 The dominating principle of the "laser profilometer" – the triangulation principle. The laser light spot on the pavement is projected on a light – sensitive displacement sensor. In the formula, it is assumed that the "average" angle between transmitted and received laser light beams is 30° (the angle indicated in the figure is then 60°).
An alternative profilometer method is the light sectioning method. A narrow strip of light or a very sharp light-dark transition edge is projected onto the surface. By means of a video camera directed at an angle towards the light section, a profile of the surface can be projected on the camera sensor. This method was specified already in [Cantor, 1976] and [Hinch et al, 1980] but applied in practical, working operation by the first device listed in Table 9 at the end of the 80's.

A couple of systems claim that they can measure microtexture: The Yandell-Mee Texture Friction Meter and the Dagmar/Petra system. In the latter, a texture meter using the laser triangulation principle is claimed to measure at wavelengths and amplitudes lower than 100 μm, i.e. in the microtexture range. From its values, combined with sensor data for wetness and temperature, friction is predicted for most road surfaces and conditions, with good accuracy [Bachmann et al, 1994]. However, this author believes that the laser triangulation principle is inadequate to measure microtexture. Regarding the Yandell-Mee meter, see comments in 8.1.
8. MAJOR ON-GOING OR PLANNED INTERNATIONAL AND NATIONAL RESEARCH OR DEVELOPMENT PROJECTS

8.1 Friction

As explained in earlier sections of this report, the International PIARC Experiment on Friction and Texture was finished and finally reported in [Wambold et al, 1995]. Some follow-up studies are underway. The probably most important is conducted at CRR in Belgium [Descornet, 1997]. It investigates the results of PIARC in more detail, trying to find better ways of analyzing data and a somewhat improved model for relation between measuring devices and between friction and macrotexture. Texture values are recalculated in order to meet the new ISO 13473-1 standard for MPD, since this was developed directly after the PIARC experiment was conducted. It also includes supplementing measurements on pavement types that were not sufficiently well covered in the main experiment. So far, the project has indeed made some progress in the data analyses procedures making it possible to improve the procedures, and it has shown that the conclusions in the PIARC experiment are also valid when including more uncommon surfaces. Something which is, however, disliked by this author is that it also has limited the analysis to European friction measuring devices. The project will probably be finished in 1998.

A project run jointly between road research institutes in Netherlands (DWW), Germany (BASt) and Denmark (Road Research Lab) is also conducted at the moment, as a follow-up study to the PIARC experiment. Results could be expected in 1998.

Follow-up studies in France have already been reported, but are probably continuing. A most interesting result so far is a trial to use the PIARC model to translate friction values measured on 17 test road sections by two highly different measuring devices to IFI values. These two devices were the SCRIM, measuring sideway force coefficient with a motorcycle tyre, and the ADHERA, measuring with a locked wheel with normal but smooth tyre. Normally these two devices give very different friction values which cannot be directly compared. However, when applying the PIARC model (Table 4), the IFI values measured and calculated by these two devices were very close to each other [Gothié, 1997-II]. This can be seen as a first (and successful) validation of the PIARC experiment. Another confirmation of the harmonizing capability of the IFI is presented in [Lund, 1997].

A Norwegian company offers a new friction measuring device, the "Norsemeter ROAR", which is also part of the ARAN system. Based mainly on measurements made within the PIARC experiment, it is claimed that this device eliminates the need for making macrotexture measurements together with friction measurements. Instead, more extensive friction data are collected. ROAR makes a measurement of the entire friction-slip curve illustrated in Fig. 5 in one run, when the test tyre starts in free-rolling condition and is gradually braked until a full lock-up occurs. The process can also be reversed. The fall-off slope of the friction-slip curve after passing the maximum point is used as a measure from which macrotexture can be calculated (although it does not seem to be made). See [Roadware, 1997-I].

The main problem with this device, as this author sees it, is that for each part of the friction-slip curve (in Fig 5), only a very short track on the road is measured. It is estimated that normally each significant part of the slip curve is based on less than 1 m of pavement length. Normally, macrotexture of pavements vary quite much between 1 m sections. This means that pavements which are not very homogeneous will have to be measured with a lot of runs in order to have representative average values, and this can also be made with this device.
It is believed that the ROAR device is being tested at some locations at the moment. One recent test was made in New Zealand, for example [Transearch, 1996-II].

Most other users of friction measuring devices prefer to minimize the need for friction measurements, for example by making use of the PIARC results, since friction measurements are expensive, require lots of water, consume test tyres and often create hazards in traffic. It is interesting to note that the promoters of the ROAR device are going in the reverse direction.

Already since the early eighties, it has been claimed by some Australian researchers that tyre/road friction can be predicted from texture measurements. In later years these researchers have presented a measuring instrument, the "Yandell-Mee texture friction meter", which samples a 0.6 m long texture profile by a laser device and from this predicts side force and locked-wheel wet friction for three speeds in seconds. This meter has even been incorporated in the "Australian Road Evaluation Vehicle". The result is claimed to vary only with texture changes. This model and device are still subject to refinement. See e.g. [Yandell and Sawyer, 1994].

This author holds the view that the Australian instrument cannot do what it is claimed to do. The reason is that to predict friction one must have both macro- and microtexture values. The Yandell-Mee meter cannot reasonably measure microtexture, as little as any other field-adapted device today. The reason that the Australian researchers have concluded that their friction-texture relations are proved, is that they have used rather limited operation conditions and a too limited amount of data, and not understood that for a relatively small sample of test surfaces where macro- and microtexture co-varies, it is sufficient to measure only macrotexture. This has little to do with reality, however, and their model and meter is unlikely to work for surfaces in general.

Another interesting on-going development trend is the increased use of re-texturing machines. Cement concrete surfaces, and sometimes also asphalt surfaces, have for a couple of decades been subject to re-texturing by longitudinal or, most frequently, transversal grooving. Longitudinal grooving has had the disadvantage of sometimes causing side forces on motorcycles and transversal grooving mostly increases traffic noise emission. A newer technique is the longitudinal grinding technique, in which a huge "grinder" removes ridges and other unevenness features and leaves a track of longitudinal fine grooves on a very even surface. This technique has been tried in e.g. Sweden, and has been found to decrease noise considerably see [Sandberg, 1997-II].

Another technique is to knock away part of the surface layer, as is done by the Dutch "Klaruw" machine [Klaruw, 1993], which uses bush hammers that virtually chisel the surface. This operation removes relatively "soft" parts of the surface and exposes the more durable "stony" parts of the texture. It is to some extent similar to the anti-polishing effect of studs during winter, although it is more powerful. There is also a smaller variant called "Minitex" which uses only nine hammers and which is man-moved.

Related to the Klaruw technique is the shot-peening technique employed by the "Skidabrader" in USA, refer to [NASA, 1996] and [Billiard, 1998]. See Fig. 26. The Skidabrader is a machine which hurls steel abrasive media at high velocity to abrade the surface and thus creates a rougher texture.
According to [Cenek, 1998], simple high-pressure water blasting can also increase friction significantly, in particular on chip seal surfaces. Retexturing techniques utilised on airport pavements are subject to an on-going research project at VTI sponsored by FortV [Ihs, 1997]. An extensive review of retexturing techniques is presented in [Dravitzki, 1997].

![Fig. 26](image)

The Skidabrader retexturing machine. Courtesy of [Billiard, 1998].

### 8.2 Other safety-related projects

The trials with driver-alerting road shoulder rumble strips in the USA, mentioned earlier, are continuing. A related field project is on-going at VTI in Sweden and noise measurements have been conducted in the autumn of 1997 [Anund, 1997].

### 8.3 Rolling resistance and fuel consumption

As mentioned in an earlier section, the bow-wave in the pavement substructure in front of a rolling tyre must result in some energy consumption which should be reflected in a certain contribution to rolling resistance. So far, such effects have just been speculations and have always been neglected. However, a recent pilot study in New Zealand [Transearch, 1996-I], has pioneered in trying to quantify such potential effects. Their results showed that fuel consumption for heavy vehicles operating at maximum legal axle weights ranged 13% between the most and the least rigid pavements. Apart from the implications this has on cost-benefit analyses of pavements of different stiffnesses, this means that it is possible that some of the effects on fuel consumption interpreted as texture or unevenness effects in the past, may in fact have been attributable to pavement rigidity, at least for heavy vehicles. A preliminary check of data concerning cars from [Sandberg, 1990-I], however, have not indicated that this effect might have been very big in that particular study. In these data there are two outliers in the regression of fuel consumption on texture, which are pavements likely to have a much lower rigidity than the others, but if one would "correct" them for low rigidity or even remove them, the final conclusions do not seem to be significantly affected.
Nevertheless, the New Zealand results are most exciting and should lead to further studies also in other countries. Fortunately, these experiments will continue in New Zealand in order to better quantify the effects of stiffness modulus of the top surface layer.

8.4 Exterior Noise

A large project called TINO sponsored within the EU Brite program was started recently, in which prototypes for more quiet tyres and road surfaces are to be constructed and models be developed [Domenichini, 1996]. The participants are:

- University of Rome, Dept. of Hydraulic, Transportation and Roads
- Techn. University of Darmstadt (Automotive Dept.), Germany
- University of Helsinki
- Technical University of Budapest
- Pirelli Tyres, Italy
- Nokia Tyres, Finland

The company Numerical Integration Technologies is also involved. As far as this author is aware, none of the participating organizations have any previous record of widely published tyre/road noise research, although Pirelli of course must have a very good (unpublished) experience in the subject. VTI was asked to assist with road surface texture measurements, and these were actually conducted on-site in Italy in June 1997.

Another large project is a German-Dutch co-operation to investigate tyre/road noise-texture relations [Beckenbauer, 1998]. On an earlier Soviet airfield in eastern Germany, a lot of special surfaces have been laid on which tyre/road and texture measurements have been made in 1997 and will continue to be made in 1998. Several tyre types are tested there. Relations noise-texture will be established with the aim of developing a model. The Technical University of Berlin is engaged to measure the texture with a laser profilometer and will also, very interestingly, make tyre/surface footprints from which contact points and areas will be analyzed by image processing. This will be studied both in transversal and longitudinal direction to see the effects of directional textures [Huschek, 1997].

A research project in Texas (by TxDoT) studies the relation between noise measured with the CPX method and pavement texture. The latter will be measured with a Selcom Optocator mounted on a friction measuring vehicle. The objective is "to correlate texture readings with noise readings to come up with some quantitative basis for making judgements" [Selcom, 1997].

From the Public Works Research Institute (PWRI) in Japan, VTI has recently received a request for co-operation concerning a project to develop the poroelastic road surface for traffic noise reduction. The proposal is very interesting and VTI is currently working for a project plan (sponsored by Vägverket).

An ongoing project in the Netherlands, [Gerretsen et al, 1997] and [de Roo et al, 1998], aims at constructing a complete computational model for prediction of the contribution of tyre/road noise to vehicle pass-by noise, with surface texture as one of the primary input parameters.
There is an ongoing European BRITE EURAM project named SIRUUS = "Silent Roads for Urban and extra-Urban Use" with a budget of 3.2 MECU over four years. The objective is to study new solutions for low-noise road surfaces and to reduce low frequency noise. It is coordinated by the company Autostrade SpA in Italy, with partners Belgian Road Research Center, INRETS in France, LNEC in Portugal, Pavimenta in Italy, IPSE in Italy, SACER in France och ARGEX in Belgium. They will study a new type of surface called the Euphonic Pavement for extraurban use and another one for urban use. Both utilize very interesting ideas of acoustic resonators within the wearing course structure.

8.5 Tyre wear

An advanced finite element model describing the tyre wear process was recently presented [Becker & Seifert, 1997]. With this tool, a-priori predictions of tyre wear properties are now possible. A future coupling of this model to vehicle simulation is foreseen. It does not seem to this author that surface texture is a variable in that model, but it must be possible to introduce it, once more knowledge can be gained on this.

8.6 Texture in general

The Swedish Road Administration is periodically ordering road surveys for data collection covering the national road network. With regard to texture, it was considered the latest time to require the collection of data for:

<table>
<thead>
<tr>
<th>Macrotexture</th>
<th>measured as Mean Profile Depth (MPD) in accordance with ISO 13473-1.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Megatexture</td>
<td>measured as Root Mean Square value (RMS) of the longitudinal road surface profile signal within the megatexture range; the latter as defined in Sub-clause 3.3.3 in ISO 13473-1. By using third-octave band filters, or equivalent bandpass filter, this includes texture wavelengths between 56 and 560 mm. (This is now better defined in ISO/CD 13473-2).</td>
</tr>
</tbody>
</table>

The above is estimated to be adequate for characterising speed-related friction properties, and could tentatively serve also for rolling resistance, until a better measure has been established. However, noise properties absolutely need other measures, still to be developed. The megatexture values are not yet standardised, but draft measures are specified in ISO/CD 13473-2.

Development of microtexture measurement methods is going on at CRR in Belgium by a PhD student, using an electron microscope in which profiles of laboratory core samples are studied in great detail. The method and instrumentation worked-out there could be an interesting reference in future studies of field-measuring methods. Some other institutions are also interested in development of microtexture measuring devices, for example at the University of Aachen, but so far there is no significant progress known by this author.
Interesting ideas of application of surface texture data: Quality-based systems

Two interesting applications of surface texture data will be mentioned here. At present, both make use of friction values rather than directly measured texture, but it is not surprising if they are supplemented with texture measurements in the future, especially with the results of the PIARC Experiment and EFI and IFI values in mind.

- The first case is an example from France [Gothié, 1997]. There are toll motorways between Paris and Lyon, operated by private companies. The first three years a pavement must have a friction coefficient of > 0.18 measured at 120 km/h with the ADHERA device (locked wheel, smooth PIARC tyre). If friction goes below this limit, the company has to repave the road or in other ways restore friction. Some other motorways have similar requirements, although the limit is then 0.16.

- The other case is an example from Italy, also for toll motorways operated by private companies [Gorsky, 1997]. They have requirements for measuring friction (by SCRIM) and unevenness (as IRI). There are also some limits [La Torre, 1997]. The measured values are input to a formula, which finally gives an overall evaluation of the motorway quality. This quality index is used as a basis for direct determination of the toll that the company may charge the drivers on this motorway. Consequently, the income from the motorway is determined by its measured quality. It lies in the interest of the company to optimize the quality and expenditures in order to maximize benefit. The drivers are paying in relation to what they get – a certain road quality.

This Italian example may seem like a brand new idea, but in fact something similar existed already long ago. According to [Schulze, 1939], in the famous ”Mainzer Landfrieden” document issued in 1235 by the emperor Frederick II, it was required that those charging toll for the use of a road were obliged to maintain the road quality in such a state as not to cause hazard or damage to the goods or travellers. It is not known to what extent road surface texture was considered then, however, but at least the megatexture should have been an issue....

Sweden does not yet have toll roads, but in the near future it is possible that such will be established, in particular some major bridges. In principle, the quality-based system could probably be used also for allocation of central funds to regional road maintenance in the interest of optimizing road surface maintenance towards a balance between road-user benefits and expenditures, if desired.

In such quality-based systems, which are likely to be more and more common internationally, surface characteristics data are essential, and texture will be needed as a measure in itself, or for reduction of necessary friction measurements.
9. **VISION FOR THE FUTURE**

The author’s vision for the medium- and long-term future with regard to road surface texture and its effects encompasses the following items:

1. Most of the Swedish road and street network is surveyed annually by (for example) RST vehicles measuring macrotexture, as Mean Profile Depth (MPD) according to ISO 13473-1, and megatexture derived from ISO 13473-2.

2. These data are used in the National Road Data Base (NVDB, with state and communal coverage) with a sub-base on pavements, from which one can obtain the texture information specified for various types of roads and pavement types.

3. The development over time of some national or regional macro- and megatexture index is presented regularly, for example in annual reports. At the beginning this would give information relevant as to:

   - friction speed coefficient, where one would like to have as high macrotexture (MPD) as possible, at least on high-speed roads
   - tentative rolling resistance influence, where one would like to have as low macro- and megatexture as possible, in particular on roads where most of the traffic work is done
   - tentative comfort index, where one would like to have as low megatexture as possible. It would also have some relevance with respect to vehicle operating costs (although not quantified)

4. A significant part of the Swedish road and street network is surveyed annually by (for example) BV11/BV14 vehicles measuring friction at one speed only. Say that representative parts of the entire road network shall be measured each five years. These data are also fed into the National Road Data Base (NVDB) where they are co-ordinated with corresponding macrotexture data, and EFI or IFI are calculated (see below). This for example can be used to calculate friction at any speed, say the maximum posted speed, although it has actually been measured only at one speed which is safe and practical. Note: This normalization and speed extrapolation applies only to wet conditions (not icy) so far.

5. The development over time of some national or regional friction index, based on the European Friction Index (EFI), or International Friction Index (IFI), whichever is adopted in Europe, is presented regularly, for example in annual reports. This would give a very interesting overall quantification of the safety standard, as represented by friction, of Swedish (and/or regional) road surfaces. It will also be possible to compare with other countries.

6. Using yet-to-be-developed models for relation of texture with exterior noise, interior noise, tyre wear, light reflection, water runoff, splash and spray and rolling resistance, the macro- and megatexture data are used to predict the influence of road surfaces on these parameters from the mobile measurements. Direct measurements of such variables, which are both expensive and difficult to make, would then be needed only for validation purposes and in some cases where the highest accuracy is required.
7. The predicted values for the mentioned parameters, presented perhaps as some kind of national or regional index (for each parameter) are calculated from the road data bank and presented regularly, for example in annual reports. This will give a unique possibility to quantify and to follow over time the status of the national and/or regional road surface network, or say for each European highway, in terms of quality indices expressed individually for all these parameters or weighted together into "overall quality" or as "safety quality", "environmental quality" or "economic quality".

8. When microtexture is possible to measure with mobile devices, such measurements can replace also the regular friction measurements for survey purposes, and friction need to be measured only on snow-covered roads and in special cases where problems are encountered or expected, and probably also for validation purposes. The procedure according to 6–7 above can then be conducted essentially based only on texture measurements.

Fig. 27 shows how a futuristic and (almost) complete "Grand Model" can be built up in order to collect and utilize the relevant data. Parts of such a model can be worked-out rather soon, making use of the present knowledge and expected knowledge from ongoing or near-future-projects. See also Fig. 31 regarding the estimated current status of such model work.

Fig. 28 illustrates another and in the short time perspective perhaps more important use of the data, namely how data can be used for evaluating pavement quality in relation to some specified requirements for new paving work, for checking of old pavements, as well as for general surveys.

Following are some comments with respect to the ideas presented in the visionary list above.

First, it can be pointed out that already today it is in principle possible to realize points 1–3 above; it is mostly an economical question, and a matter of interest. Points 4–5 will be possible within 1–2 years when the EFI or IFI and calibration of friction measuring devices have finally been decided on.

Secondly, research is needed to realize points 6–8. Limited parts of points 6–7 can, however, be realized within a few years, following ongoing or suggested research. Point 8 will be a difficult one, but this author is convinced that it can be solved within a 10–year period.

However, everything is not that easy in practice. For example, since there are also some other characteristics of road surfaces that influence the mentioned variables, e.g. sound absorption influencing noise on porous surfaces, porosity influencing splash and spray, as well as surface contamination influencing friction, texture measurements will never be able to entirely predict surface influences. However, it is likely to come pretty close; enough to warrant its widespread use. In some cases, one would like to have supplementary methods, however. Light reflection might be an exception where direct measurements must always be required, but where macrotexture is a useful complement.
Fig. 27 "Grand Model" for collection of texture data, for describing the influence on relevant parameters, and (optionally) for making comparisons with specifications or requirements.
Nytt beläggningsarbete
New paving work

Kontroll av äldre beläggningsarbete
Checking of old pavement

Tillståndsbeskrivning / Condition survey

Fig. 28 Illustration of procedure for utilizing texture data in three different applications.
Some countries are more advanced in their data collection than Sweden, in this respect. A couple of examples of collection of national data will be given here. In France, data on friction and texture have been collected for several years. Fig. 29 below shows an example of distribution of friction levels measured with the SCRIM on 40000 km of French roads in 1989-1994. The ordinate shows the relative frequency in percent of the friction numbers collected. The friction numbers in 5 unit classes are shown on the abscissa. The average friction coefficient is 0.64. Approximately 11 % of the values are below 0.50.

Fig. 30 shows the same distribution for texture measured as sand-patch-equivalent texture depth "HSC" (approximately what is called Estimated Texture Depth, ETD, in ISO 13473-1). The abscissa shows the texture depth in mm in 0.2 mm wide classes. The average depth is 1.01 mm.
Fig. 29  Distribution of friction values measured on 40000 km of French roads with the SCRIM equipment. Figure based on data from [Gothié, 1997].

Fig. 30  Distribution of texture values measured on 40000 km of French roads with the Selcom laser sensor on the SCRIM equipment. Figure based on data from the same source as the previous figure [Gothié, 1997].
In a long-term perspective, the vision also includes a uniform European system of minimum requirements with regard to pavement influence on variables like friction, rolling resistance, tyre wear and noise, based on (solely) texture measurements. If desirable, all or several European countries might have identical requirements, based on international standards. For limits expressed in micro-, macro- and megatexture terms, all mentioned performance variables can be addressed at the same time and with only one (?) mobile measurement. This might take 15 years or more, with limited parts possibly implemented within 5–10 years, but it is worth aiming at and planning for already now. The two following, speculative tables could illustrate how such a vision could appear when it is realized.

Table 10 Speculative vision of future European requirements or recommendations on pavement texture (an example).

<table>
<thead>
<tr>
<th>Performance variable</th>
<th>Road surface characteristic addressed</th>
<th>Limit for Type 1 roads</th>
<th>Limit for Type 2 roads</th>
<th>Limit for Type 3 roads</th>
<th>Measuring method</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction</td>
<td>Macrotexture</td>
<td>&gt; 0.60 mm &lt; 1.80 mm</td>
<td>&gt; 0.80 mm &lt; 1.60 mm</td>
<td>&gt; 1.00 mm &lt; 1.40 mm</td>
<td>ISO 13473-1</td>
<td>Possible rather soon</td>
</tr>
<tr>
<td></td>
<td>Megatexture</td>
<td>&gt; 0.25 mm &lt; 2.00 mm</td>
<td>&gt; 0.30 mm &lt; 2.00 mm</td>
<td>&gt; 0.40 mm &lt; 1.80 mm</td>
<td>ISO 13473-3</td>
<td>Futuristic</td>
</tr>
<tr>
<td></td>
<td>Microtexture</td>
<td></td>
<td></td>
<td></td>
<td>ISO 1XXXX</td>
<td>-</td>
</tr>
<tr>
<td>Rolling resistance</td>
<td>Macrotexture</td>
<td>&lt; 2.00 mm &lt; 2.20 mm</td>
<td>&lt; 1.50 mm &lt; 1.80 mm</td>
<td></td>
<td>ISO 13473-4</td>
<td>Not yet possible</td>
</tr>
<tr>
<td>(+ fuel consumption</td>
<td>Megatexture</td>
<td>&lt; 2.00 mm &lt; 2.20 mm</td>
<td>&lt; 1.50 mm &lt; 1.80 mm</td>
<td></td>
<td>ISO 13473-3</td>
<td>-</td>
</tr>
<tr>
<td>and air pollution)</td>
<td>Unevenness</td>
<td>&lt; 3.5 IRI &lt; 3.5 IRI</td>
<td>&lt; 2.5 IRI &lt; 2.5 IRI</td>
<td></td>
<td>CEN 111YY</td>
<td>-</td>
</tr>
<tr>
<td>Tyre wear</td>
<td>Macrotexture</td>
<td>&lt; 2.00 mm &lt; 2.00 mm</td>
<td>&lt; 1.50 mm &lt; 1.40 mm</td>
<td></td>
<td>ISO 13473-4</td>
<td>Futuristic</td>
</tr>
<tr>
<td></td>
<td>Microtexture</td>
<td>&lt; 0.90 mm &lt; 0.90 mm</td>
<td>&lt; 0.80 mm &lt; 1.00 mm</td>
<td></td>
<td>ISO 13473-3</td>
<td>-</td>
</tr>
<tr>
<td>Exterior noise</td>
<td>Macrotexture</td>
<td>&gt; 0.70 mm &gt; 2.10 mm</td>
<td>&gt; 1.00 mm &gt; 1.80 mm</td>
<td></td>
<td>ISO 13473-4</td>
<td>Not yet possible</td>
</tr>
<tr>
<td></td>
<td>Megatexture</td>
<td></td>
<td></td>
<td></td>
<td>ISO 13473-4</td>
<td>-</td>
</tr>
<tr>
<td>Light reflection</td>
<td>Macrotexture</td>
<td>&gt; 1.00 mm &gt; 1.00 mm</td>
<td>&gt; 1.20 mm &gt; 1.20 mm</td>
<td></td>
<td>ISO 13473-4</td>
<td>Not yet possible</td>
</tr>
</tbody>
</table>

Table 11 The requirements/recommendations according to Table 10, if they are all combined into one.

<table>
<thead>
<tr>
<th>Type of roughness</th>
<th>Limits for Type 1 road</th>
<th>Limits for Type 2 road</th>
<th>Limits for Type 3 road</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microtexture (MiTx)</td>
<td>0.25 &lt; MiTx &lt; 0.90</td>
<td>0.30 &lt; MiTx &lt; 0.80</td>
<td>0.40 &lt; MiTx &lt; 0.70</td>
<td></td>
</tr>
<tr>
<td>Macrotexture (MaTx)</td>
<td>1.00 &lt; MaTx &lt; 2.00</td>
<td>1.20 &lt; MaTx &lt; 1.80</td>
<td>1.40 &lt; MaTx &lt; 1.50</td>
<td></td>
</tr>
<tr>
<td>Megatexture (MeTx)</td>
<td>MeTx &lt; 1.80</td>
<td>MeTx &lt; 1.60</td>
<td>MeTx &lt; 1.40</td>
<td></td>
</tr>
<tr>
<td>Unevenness (IRI)</td>
<td>IRI &lt; 3.5</td>
<td>IRI &lt; 3.0</td>
<td>IRI &lt; 2.5</td>
<td></td>
</tr>
</tbody>
</table>
10. RESEARCH AND DEVELOPMENT NEEDS

10.1 Relation between texture and friction

It is believed that friction, in principle, can be measured and modelled indirectly as a combination of macro- and microtexture (possibly also including some megatexture term). Recent research has made possible the use of macrotexture as a replacement for part of the friction measurements, but lacking a practical method to measure microtexture, a full realization of the dream to predict friction from only texture measurements is not yet possible.

The research and development needs with emphasis on Swedish conditions are:

1. Determine how MPD measurements according to ISO 13473-1 can be practically applied to measurements with BV-11 and Saab Friction Tester in order to normalize these results to the International Friction Index (IFI), or its European equivalent (EFI), and supply these devices with procedures for automatically calculating IFI or EFI values as a supplement to the friction coefficient normally reported. The PIARC Experiment supplemented with the expected report of [Descornet, 1997] give the framework and most details needed for this.

2. Determine how MPD measurements according to ISO 13473-1 can be practically applied to measurements with BV-11 and Saab Friction Tester in order to calculate the friction coefficient at any speed from a measurement at one speed in the range 50–70 km/h. This would eliminate the need for doing measurements at more than one speed, provided that macrotexture is also measured. The PIARC Experiment supplemented with the expected report of [Descornet, 1997] give the framework and most details needed for this.

3. Develop a more practical and better texture measuring device than today’s devices, for use in connection with BV-11 and Saab Friction Tester as well as on the RST vehicles. Today’s devices seem to have compromized resolution too much at the expense of measuring range.

4. Introduce the MPD calculation and recording in the RST vehicles.

5. The results of the PIARC Experiment should be followed-up by:
   - taking part with the Swedish devices in regular international calibrations of friction measuring devices
   - taking part in international test programs to further assess how accurately the IFI/EFI values can be determined
   - taking part in assumed international projects conducted in order to further improve the IFI/EFI concept

6. Refine and check the general friction-texture-speed model. This is needed in order to more and more replace friction measurements with much easier, safer and economical texture measurements. One should look further at the PIARC data and those of [Descornet, 1997], look at how the earlier data of VTI [Sandberg, 1990-II] can supplement the PIARC data, the same with the data of [Shimeno & Kawamura, 1997], and for example check if a simpler linear model instead of an exponential model could work equally well as the latter.

7. Develop a contactless microtexture measuring device (using laser beam).
8. Once this is available, determine the quantitative relation friction-microtexture. This should probably be made in international co-operation since it is a difficult and extensive task.

Points 1–4 can be made rather soon. Points 5–6 are something which should start soon (1999) but should go on for a number of years. Points 7–8 are long-term needs. For other measuring devices of importance here, refer to 10.10 below.

10.2 Optimization of rumble strips and other driver-alerting texture measures

Ongoing research at VTI regarding depressed rumble strips on road shoulders should continue and possibly be extended, pending the results of the project. For example, one might consider putting inexpensive accelerometers on a vehicle axle and by proper tuning of the megatexture of such rumble strips and an appropriate analysis of the accelerometer signal one might be able to detect a drift-off from the road lane at an early stage and with acceptable accuracy, in order to warn the driver. The same thing can in principle be made with electro-optical devices reacting on reflections from edge markings, but the latter will be much more susceptible to problems caused by dirt, splash and spray.

Rumble strips having a positive profile, i.e. strips laid on existing surfaces, are frequently used to alert drivers when approaching roundabouts or other road sections where dangers are higher than elsewhere. These are rather quickly worn away. For this reason, it should be considered to try the same principle with a negative and tuned profile instead, i.e. appropriately spaced strips are cut down into the surface.

10.3 Relation between texture and rolling resistance

The economic and environmental consequences on Swedish roads of different textures, especially megatextures, are potentially very big. This warrants more studies of the problem:

- To investigate the mechanisms of rolling resistance (e.g. how can unevenness influence on trucks be as big as indicated in Chapter 4.4?)

- To get more precise data with regard to the influence (the present estimates deviate too much from each other)

- To develop better or improved existing methods of measurement of rolling resistance and fuel consumption on the road

- To estimate influence on rolling resistance and fuel consumption by using only road surface profile measurements, i.e. to develop a model for this influence

- To investigate further the influence of pavement stiffness on rolling resistance (the bow-wave effect, see chapter 8.3). Follow the continuing efforts in New Zealand to determine this effect. Supplementing work may be needed, for example to study the effect for car tyres. Use
the RDT Truck under development at VTI for such studies, see [Arnberg et al, 1992]. Perhaps a co-operation project is feasible.

The data would be very valuable for revision of VOC (Vehicle Operating Cost) models like the World Bank's HDM and VETO, and whenever cost-benefit ratios of traffic or road objects are calculated. Another important use of the data would be in models calculating the environmental effects (air pollution) of road traffic and roads.

10.4 Relation between texture and tyre wear

Appropriate methods to reliably measure the effect of texture on tyre wear are still missing. One may want to consider using a test vehicle driving in a controlled way over long test sections (10 km or more), for the purpose of which it is necessary to build a turning device (for turning the test vehicle around 180° when it has made one run and shall return for another run) as suggested in [Ohlsson, 1986-II]. One might also want to consider the Grip Tester as used in [Cenek et al, 1997] or the Portable Friction Tester (PFT) at VTI.

One should also consider building a test trailer for measuring tyre wear, alternatively something like the Saab Friction Tester principle instead of a test trailer, i.e. having an extra test tyre inside a host vehicle, the tyre of which can be lifted up during turning manoeuvres.

Introducing surface texture effects in a tyre wear model such as the one of [Becker & Seifert, 1997] seems to be a good example of needed fundamental research in this area. In [Cenek et al, 1997] it is suggested to improve and validate the HDM III micro-tread wear model, which seems to be a good idea.

It is also suggested in [Cenek et al, 1997] that there is an “overrange” of microtexture which is “unnecessary” high for friction but which will absolutely cause a lot of tyre tread wear. In [Transearch, 1998] it is claimed that “overseas experiments involving artificial surfaces have shown that at slip speeds occurring on roads the removal of a certain range of microtexture can reduce tyre abrasion by 40 percent, but reduce wet friction by only 5 percent”. It is worth investigating this matter further because it would mean that tread wear could be reduced without sacrificing friction.

It seems that the effects of wet surface on tread wear is not sufficiently covered in today’s models. Wetness on the surface may reduce the effect of microtexture to such an extent that tread wear may decrease by some 20–30 % in relation to a similar dry surface. Consequently this should be an item to study.

Finally, research into the effect of surface type on tyre wear appears highly warranted with variations in tyre wear rates on different surfaces differing by a factor of up to 7 reported in the literature. First, however, the methodology and instrumentation above shall be worked out.

The data would be very valuable for revision of VOC (Vehicle Operating Cost) models like the World Bank’s HDM and VETO, and whenever cost-benefit ratios of traffic or road objects are calculated. Another use of the data would be in models calculating the environmental effects (ground and water pollution) of road traffic, since the wear products of tyres amount to significant quantities annually.
10.5 Relation between texture and exterior noise

A very good research programme is listed in the R&D programme worked-out 1995 by Vägverket by request from the Government [Vägverket, 1995]. This included projects listed here in Table 12. All these are still interesting. Apart from the projects listed in Table 12, the following new or modified projects are suggested.

Table 12 The research and development programme with regard to road surfaces suggested in [Vägverket, 1995] by request from the Government. The information in ( ) or [ ] refer to ongoing or already conducted projects.

<table>
<thead>
<tr>
<th>Project name (prelim. short form)</th>
<th>Brief description</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porous asphalt concrete</td>
<td>Increase lifetime by optimum selection of binder and aggregate (example of project, see [Sandberg, 1997-II])</td>
<td>1</td>
</tr>
<tr>
<td>Poroelastic road surface</td>
<td>Improve adhesion to the base course, initial friction and fire resistance, etc., and make field trials (pilot study 1997)</td>
<td>1</td>
</tr>
<tr>
<td>Porous cement concrete</td>
<td>Apply this technique in Sweden, making use of experience gained abroad, with some own improvements</td>
<td>2</td>
</tr>
<tr>
<td>Equipment for cleaning of porous surfaces</td>
<td>Trials with cleaning by ejection of high-pressure water and vacuuming should be made, using earlier experience</td>
<td>1</td>
</tr>
<tr>
<td>Surfaces with self- or easy-cleaning properties</td>
<td>Try e.g. Twin-lay surface in Sweden. The poroelastic surface mentioned above is an example of self-cleaning</td>
<td>2</td>
</tr>
<tr>
<td>Methods to measure noise reduction properties of pavements</td>
<td>Develop and standardize methods for field and lab use (example: Work with ISO 11819-1 and ISO/CD 11819-2) Develop methods using texture to predict noise properties Study temperature influence on the noise emission</td>
<td>2</td>
</tr>
<tr>
<td>Survey of noise reduction properties of surfaces with optimum aggregate size</td>
<td>SMA and normal AC with improved texture Cement concrete with exposed aggregate 8-10 mm (example of the latter, see [Sandberg, 1997-II])</td>
<td>2</td>
</tr>
<tr>
<td>Noise emission from different types of vehicles</td>
<td>Study noise emission from diff. types of vehicles running on different surface types (see [Sandberg, 1997-III]). Influence of size and mounting of truck tyres, e.g. super single versus twin-mounted duals + influence of surface</td>
<td>3</td>
</tr>
<tr>
<td>C-weighted noise levels</td>
<td>Study surface influence using not only A-weighted levels but also C-weighted ones to improve interior noise predic.</td>
<td>3</td>
</tr>
<tr>
<td>Noise emission from the road surface itself</td>
<td>To which extent can the road surface emit noise?</td>
<td>3</td>
</tr>
<tr>
<td>Properties of noise-reducing surfaces with respect to costs, safety and general environment</td>
<td>Try to obtain an overall view on the efficiency of noise-reducing road surfaces</td>
<td>2</td>
</tr>
<tr>
<td>Use of noise-reducing surfaces on other areas than in driving lanes</td>
<td>Study possibilities to use such surfaces also on parking areas and sidewalks in order to reduce noise propagation</td>
<td>3</td>
</tr>
<tr>
<td>Combination of noise-reducing surfaces with other types of reduction</td>
<td>Study the combined effect of porous road surfaces and screens</td>
<td>3</td>
</tr>
<tr>
<td>Use of porous road surfaces in tunnels</td>
<td>Study noise reduction inside tunnels as well as emission from openings when road surface is exchanged to porous</td>
<td>3</td>
</tr>
<tr>
<td>Subjective evaluation of noise-reducing surfaces</td>
<td>How are the reactions of those living close to a road when surface is exchanged to a &quot;noise-reducing&quot; one?</td>
<td>2</td>
</tr>
<tr>
<td>Maintenance of noise-reducing surfaces</td>
<td>Study possibilities to recycle noise-reducing pavements with attention to potential pollution in clogged material</td>
<td>2</td>
</tr>
</tbody>
</table>

VTI notat SBA—1997 65
The Skidabrader and Klaruw techniques for restoring or developing a certain texture on existing old surfaces would be interesting to try in Sweden, for the purpose of reducing traffic noise emission by texture modification. Another potential effect could be a safety improvement.

A road surface using expanded shale should be tested in southern Sweden or in Denmark (where studded tyres are not extensively used). Such material seems to have a porous-like fine texture on the aggregate. Tests in southern Europe with such material seem to have been successful with regard to noise. There has been an interest in such tests also in Texas, but it is not known whether tests really were conducted.

Sweden should co-operate with PWRI and others in Japan in development of the poroelastic surface. A pilot VTI-VV project is underway (this project is already mentioned in Table 12).

An other project which would be interesting is to study the possibilities to use porous pavements on bridges. Special care must then be observed regarding salt penetration to the bridge structure. Noise from bridges in urban areas often propagates over long distances, due to the elevated structure as well as little screening by buildings and rocks. Elevated roads on bridges are becoming more and more common, especially in Japan. It is also not very desirable to screen the noise since this may obstruct the view from the bridge and constitute an ugly view towards the bridge. In this case, it is recommended to try a combination of low screens, not obstructing any view for the travellers, and a porous surface. A poroelastic surface would perhaps be the ideal if the current problems with this surface can be solved.

In connection with such an experiment, it would also appear interesting to check how much of the tyre/road noise that is emitted from the bridge itself. See the 10th project on the previous list. Similar studies have been made in Japan already, the results of which are not giving the full answer. A poroelastic surface has the potential of reducing the vibration transfer from the tyre/road interaction to the bridge road sub-base, so it would be interesting also in this respect to compare such a surface with a normal dense asphalt surface on a bridge.

The list in Table 12 includes "Methods to measure noise reduction properties of pavements" with priority "2". It has appeared in the later few years that there is an increased pressure in Europe from those requiring noise reduction in society to work out such methods as soon as possible, to make possible performance requirements on road surfaces from the noise point of view, like there are similar requirements on vehicles and plans for introducing them shortly on tyres. It is therefore essential that the efforts to develop ISO/CD 11819-2 be continued at as high speed as possible with respect to available knowledge. In a long-term perspective, however, one may want to work for replacing such measurements with indirect texture measurements.
In order to achieve the goals above, it is necessary to develop and agree internationally on reference tyres which may be used as measurement tools. Such tyres are also needed for other purposes, like for rolling resistance measurements and for friction measurements. The presently used friction test tyres are in fact obsolete and their current relevance can be questioned.

It is also important to develop reference surfaces for testing tyres and vehicles. ISO 10844 specifies such a surface but in the near future there is a need for a supplementing rough-textured surface and for refinement of the one in ISO 10844 following the development in the latest years, not the least some other ISO standards that have been developed or are underway, see [Sandberg, 1997-IV].

10.6 Relation between texture and interior noise

Interior noise reduction is taken well care of by the vehicle and tyre industry and in general no new work in this area appears acute or should have high priority. It is also questionable whether more noise reduction is needed here. An exception is work to utilize surface texture – primarily megatexture – to alert drivers of potential dangers. See the section about rumble strips above.

10.7 Relation between texture and water runoff

The relation between texture, expressed as sand-patch-measured MTD, and water runoff rate is rather well established since many years. See e.g. [Lewis, 1994] and [Kayser, 1985]. This together with lateral road slope may be used for calculating water depth on the pavement. What should be done here is to compile these findings, convert the possible model to use MPD rather than MTD, and apply this model to, for example, the RST vehicles for survey purposes and for use in a model such as suggested in Fig. 27. Such a possible model most likely will need validation studies. The MPD measure should be particularly well suited to determine water runoff properties.

Water runoff rate, or hydraulic resistance expressed as "Manning’s n" value, should need a description of macrotexture not only in the wheel tracks but also between and outside the wheel tracks.

10.8 Relation between texture and splash and spray

How splash and spray depends on texture depth is, as far as this author is aware, not studied. There should be a significant influence of texture, however. Research on this is motivated, but is extremely difficult due to the measuring methods for splash and spray being complicated and requiring good resources. Such research in Sweden would therefore be difficult and expensive to conduct. The best resources with respect to splash and spray measurement seem to be available in the U.K., primarily at the Transport Research Laboratories (TRL).
10.9 Relation between texture and light reflection properties

There is little previous research on the relation between road surface texture and light reflection. Some 15–20 years ago, research in USA tried to utilize depolarization of light by texture as a method of measuring texture depth, but this has limited application here. VTI noted several years ago (unpublished own data) that there seemed to be a statistical significant relation between retroreflection and a simple macrotexture value. Even better relations could be possible to obtain now, using some of the measures defined in ISO/DIS 13473-2, like skewness. More research in this area could result in some progress making it possible to predict some aspects of light reflection from texture measurements, as was indicated in Fig. 27. See also [Kayser, 1985].

Like for water runoff rate, a description of macrotexture not only in the wheel tracks but also between and outside the wheel tracks would be desirable.

10.10 Texture measurement, models and general utilization

Current and planned ISO and CEN work for developing standardised measuring methods need to be continued, since they are an important pre-requisite for most of the other work. In fact, this is crucial for the progress in the other areas where effects of texture are studied.

There is a need to study the general relation between road surface condition (state of wear, etc.) and values representing macrotexture and megatexture. For example, on a surface dressing, the relation between macroscale in the wheel tracks and between the wheel tracks should be a measure of either the bleeding or of the accumulated wear. By looking at also colour differences, which should be latent information from current road laser devices, it should be possible to distinguish between the mentioned effects. Homogeneity should be a measure related to surface wear and can be studied by looking at macrotexture variations.

Some 10–15 years ago, VTI studied the possibilities to detect and quantify aggregate segregation effects by laser profilometry. These trials were not successful. It was believed that a three-dimensional rather than two-dimensional measurement was necessary to achieve the goal. With more modern lasers, one can now achieve something like a three-dimensional measurement, but it could also be tried if the any of the new measures defined in ISO/DIS 13473-2, such as the profile distribution (see Fig. 13, right part), may be better descriptors of segregation. There is some potential for it.

Very recently, FHWA has issued a leaflet in which it is suggested that aggregate segregation has been detected when using the new ROSAN texture measuring device with a normal two-dimensional profile and an MPD-related measure [FHWA, 1998]. It seems like this (possible) detection has been achieved on an extremely segregated section, but it would nevertheless be worthwhile testing this further.

Present laser profilometers work fine at texture wavelengths above about 2.5 mm, but not so well below this value. It is desirable to develop present technology in order to get improved operation at the short macrotexture wavelengths. These are important mostly for tyre wear, but also for friction and exterior noise. It should be possible to do so in co-operation with laser sensor manufacturers.
A microtexture measuring device is very important to develop. Most investigations made so far on the effects of texture have been hampered by the lack of quantitative measures of surface microtexture.

There is an urgent need to develop a simple portable device for measuring MPD. It should be a relatively inexpensive device that can be owned by major road contractors and administrations, useful for checking the compliance of road surfacing projects with specifications. Another use of it would be to make spot-checks of suspected safety hazard locations.

There is also a need to develop a relatively simple profilometer system which can be carried as luggage on an airlight and then assembled into a full system in a van or car available at the destination. Very often, there are requests for carrying out profilometer texture measurements in research projects in other countries, but the need today of moving an entire system mounted in a car, like the VTI Mobile Laser Profilometer, makes such operations too expensive and cumbersome.

Based on the present practice of the Swedish Road Administration and the most recent information, procedures for collecting data about road texture on the Swedish road network should be reviewed annually. There should be no unnecessary delay in applying the best available measuring technique or measure.

How shall such data be used? The texture values as such will not give any direct information of desirable characteristics. However, a step further, which would be easier to implement, would be the creation of:

- National index for surface texture influence on friction, preferably based on a parameter contained in the IFI or EFI
- National index for surface texture influence on rolling resistance, the latter of which influences fuel consumption and, finally, air pollution
- National index for surface texture influence on traffic noise

Each of these indices could give a quality index describing the state of the national road network, for each parameter, comparable year by year. It could also be used to compare different regions with each other, or different classes of roads. The latter two indices would be useful in a system with annual reporting of "Environmental indicators" ("gröna nyckeltal") which at the moment are receiving growing interest [Miljövårdsberedningen, 1998]. Refer further to Chapter 9.
11. CONCLUSIONS

11.1 Current knowledge about effects, variables and measuring methods

A summary of conclusions with regard to current knowledge about texture influences on various variables is presented in Table 13.

Note that on the first line in the table, i.e. the one dealing with friction — macrotexture, macrotexture is also important from a methodological standpoint, namely for harmonization of friction values measured with different devices.

A summary of conclusions with regard to the status of current knowledge about texture relations with various variables and the availability/status of measuring methods is presented in Table 14.

It follows from the above that:

- Road surface texture is of high importance for traffic variables such as friction, rolling resistance (from which follows fuel consumption and air pollution), tyre wear, noise emission, water runoff rate and water depth, splash and spray, as well as light reflection.

- Increased texture is sometimes desirable, sometimes not desirable. From an overall point of view, optimization of texture with regard to its amplitude, shape and wavelength appears important, and requires considerations of many different and sometimes conflicting effects.

- If texture can be measured appropriately, and if quantitative relations between texture and the influenced variables can be established, it would be possible to control these variables mainly by measuring texture (in certain cases, some supplementary measures might be necessary). Based on texture, one can treat virtually all the surface effects in a unified way.

- It is only with regard to texture influence on the friction-speed relation that any model is currently available which can be more or less directly applied. It is desirable to work systematically in order to develop supplementing models in the coming 10–20 years. Some aspects may be modelled rather soon without too much efforts.

- The development in later years has opened up possibilities of measuring macrotexture fairly inexpensively and on a large scale.

- All the three ranges of texture as defined by PIARC and ISO are important to measure: Micro-, macro- and megatexture.

A vision of how texture can be utilized in a future "Grand Model" for describing influence of texture on all relevant parameters, and to make comparison with requirements in order to make decisions, was presented in Chapter 9 and summarized in Fig. 27. How close are we to realizing the vision expressed in Fig. 27? Fig. 31 attempts to illustrate what has been achieved already and how much that remains. The darker the shade, the closer we are to realizing the vision. It can be seen in the figure that the left parts, i.e. data collection and primary calculations are quite advanced, thanks to the work with the ISO standards. The reason for not colouring those parts darker is that microtexture measurement is still not possible. Some parts of the "model" block
are also fairly advanced, so that the Grand Model can already shortly be partly realized. Some parts are completely white, implying that many years of research are still needed here.

Table 13 Status of current knowledge about the influence of texture on the most important variables.

<table>
<thead>
<tr>
<th>Effect on vehicle, driver or environment</th>
<th>Road surface characteristic of importance</th>
<th>Magnitude of the influence</th>
<th>Estimated importance to society</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction</td>
<td>Macrotexture</td>
<td>High</td>
<td>High safety effect</td>
<td>Also import. for harmonization</td>
</tr>
<tr>
<td></td>
<td>Megatexture</td>
<td>Moderate</td>
<td>Moderate safety effect</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Microtexture</td>
<td>Very high</td>
<td>Very high safety effect</td>
<td></td>
</tr>
<tr>
<td>Rolling resistance/ Fuel consumption/ Air pollution</td>
<td>Macrotexture</td>
<td>High</td>
<td>High (economy + environm.)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Megatexture</td>
<td>Very high</td>
<td>Very high (econ. + environ.)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unevenness</td>
<td>High</td>
<td>High (economy + environm.)</td>
<td></td>
</tr>
<tr>
<td>Tyre wear</td>
<td>Macrotexture</td>
<td>Moderate</td>
<td>Moderate economic effect</td>
<td>Also low environmental effect</td>
</tr>
<tr>
<td></td>
<td>Megatexture</td>
<td>Very high</td>
<td>High economic effect</td>
<td>Also moderate environm. effect</td>
</tr>
<tr>
<td>Exterior noise</td>
<td>Macrotexture</td>
<td>Very high</td>
<td>Very high environm. effect</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Megatexture</td>
<td>Very high</td>
<td>Very high environm. effect</td>
<td></td>
</tr>
<tr>
<td>Water runoff</td>
<td>Macrotexture</td>
<td>High</td>
<td>High safety effect</td>
<td></td>
</tr>
<tr>
<td>Splash and spray</td>
<td>Macrotexture</td>
<td>High ??</td>
<td>High safety effect and</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>high environmental effect</td>
<td></td>
</tr>
<tr>
<td>Light reflection</td>
<td>Macrotexture</td>
<td>High</td>
<td>High safety effect</td>
<td>Depolarization effect?</td>
</tr>
<tr>
<td></td>
<td>Microtexture</td>
<td>Little known</td>
<td>High safety effect</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>High safety effect</td>
<td></td>
</tr>
<tr>
<td>Interior noise</td>
<td>Macrotexture</td>
<td>High</td>
<td>High comfort effect</td>
<td>Possibly some safety effect??</td>
</tr>
<tr>
<td>(Is this important?)</td>
<td>Megatexture</td>
<td>Very high</td>
<td>Very high comfort effect</td>
<td>Possibly some safety effect??</td>
</tr>
<tr>
<td></td>
<td>Unevenness</td>
<td>High</td>
<td>High comfort effect</td>
<td>Possibly some safety effect??</td>
</tr>
</tbody>
</table>

Table 14 Status of current knowledge about relations between texture and the most prominent variables, as well as the availability or status of measuring methods.

<table>
<thead>
<tr>
<th>Effect on vehicle, driver or environ.</th>
<th>Road surface characteristic</th>
<th>Status of current knowledge re. relation?</th>
<th>Status re. available measur. method?</th>
<th>Notes regarding meas. methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction</td>
<td>Macrotexture</td>
<td>Rather good, due to PIARC</td>
<td>ISO 13473-1 available</td>
<td>Finalized in 1996 Work till 1998? Very difficult</td>
</tr>
<tr>
<td></td>
<td>Megatexture</td>
<td>More inform. desirable*</td>
<td>ISO/DIS 13473-2 importnt</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Microtexture</td>
<td>Still insuffic. knowledge*</td>
<td>Nothing (only indir. BPN)</td>
<td></td>
</tr>
<tr>
<td>Rolling resistance/ Fuel consumption/ Air pollution</td>
<td>Macrotexture</td>
<td>Still insuffic. knowledge*</td>
<td>ISO/DIS 13473-2 importnt</td>
<td>Work till 1998?</td>
</tr>
<tr>
<td></td>
<td>Megatexture</td>
<td>Still insuffic. knowledge*</td>
<td>ISO/DIS 13473-2 importnt</td>
<td>Work till 1998?</td>
</tr>
<tr>
<td></td>
<td>Unevenness</td>
<td>Still insuffic. knowledge*</td>
<td>ISO8608 +inform IRI spec</td>
<td>Work till 1998?</td>
</tr>
<tr>
<td></td>
<td>Microtexture</td>
<td>Very little knowledge*</td>
<td>Nothing (only indir. BPN)</td>
<td></td>
</tr>
<tr>
<td>Exterior noise</td>
<td>Macrotexture</td>
<td>Good basic knowledge*</td>
<td>ISO/DIS 13473-2 importnt</td>
<td>Work till 1998?</td>
</tr>
<tr>
<td></td>
<td>Megatexture</td>
<td>Good basic knowledge*</td>
<td>ISO/DIS 13473-2 importnt</td>
<td>Work till 1998?</td>
</tr>
<tr>
<td>Water runoff</td>
<td>Macrotexture</td>
<td>Good basic knowledge*</td>
<td>ISO/DIS 13473-2 importnt</td>
<td>Work till 1998?</td>
</tr>
<tr>
<td>Splash and spray</td>
<td>Macrotexture</td>
<td>Very little knowledge*</td>
<td>ISO/DIS 13473-2 importnt</td>
<td>Work till 1998?</td>
</tr>
<tr>
<td>Light reflection</td>
<td>Macrotexture</td>
<td>Not very good*</td>
<td>Nothing</td>
<td></td>
</tr>
<tr>
<td>Interior noise</td>
<td>Macrotexture</td>
<td>Good basic knowledge*</td>
<td>ISO/DIS 13473-2 importnt</td>
<td></td>
</tr>
<tr>
<td>(Is this important?)</td>
<td>Megatexture</td>
<td>Good basic knowledge*</td>
<td>ISO/DIS 13473-2 importnt</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unevenness</td>
<td>Good basic knowledge*</td>
<td>ISO8608 +inform IRI spec</td>
<td></td>
</tr>
</tbody>
</table>

*model must be developed
Fig. 31 Block diagram showing how far or close we are on the way to realizing the vision expressed in Fig. 27. The darkness of each block indicates the level of knowledge and possibilities of implication. The darkest shade indicates that we are already close to realizing it, while no shade at all indicates that many more years of research are needed.
11.2 The role of international standardization

This paper includes a chapter in which the author outlines future possibilities of utilizing road surface texture measurements for mapping, documenting year-by-year, controlling and checking the effects of surface characteristics on a number of parameters important for determination of economical, safety and environmental effects of traffic. This takes the form of a vision of a future overall model for describing the mentioned effects, composed of partial models for each interesting parameter. This visionary model can and should be developed by and by over the next 10–20 years. For some of the parameters the model can be developed within the near future making use of existing knowledge. The model, or parts of it, can also be used for establishment of performance requirements, rather than design requirements, on road surfaces.

In realizing the vision expressed above, development of measuring instruments and international standardization play key roles. The example of microtexture shows how much research is hampered when there are no good methods for measurement of a certain characteristic. The effects of microtexture on friction and tyre wear have not yet been possible to quantify due to the lack of measuring method. It is then very difficult to establish requirements with regard to e.g. tyre wear – and we do not even know if such are feasible in view of a potential conflict between friction and tyre wear.

The multitude of different friction measuring methods and instruments in use worldwide, and even within each country, is another illustration of the problems created when there is no standardization activity in due time. It is very important that standardization takes place when basic knowledge of the underlying phenomena has been obtained, but no earlier, and before national practice or standardization has advanced to a level at which prestige and investments in equipment inhibit international agreements and compromises.

The initiatives within PIARC, CEN and ISO to establish common criteria and international standards within the subject of surface characteristics are therefore very positive and must be continued. These initiatives can be seen as manifestations of a consensus of the international community in recognizing the future needs. The International PIARC Experiment to Compare and Harmonize Texture and Skid Resistance Measurements has shown that there is indeed a very successful way of utilizing texture measures in practical road engineering, in particular if international co-operation can take place.

It would be useful to have a technical committee within ISO dealing with road surfaces. Currently, although ISO has more than 200 technical committees, it has no committee whatsoever regarding roads. CEN has such a committee and its is very strange and illogical that practically all other technical subjects are internationally standardized by ISO except road-related topics. In the future, road-related work will know no boundaries. There is no reason why one should have different methods and measures in Europe, Australia, Japan and USA, for example. It is proposed that Sweden acts in order to establish such an ISO Road Surface or Road Committee.

It is shown in the paper how important it is to have an overall view on the subject and how the current research projects fit into the picture of work towards a future stepwise realization of the model according to available resources and speed of work. The ongoing projects are important components to this end, logically designed to achieve the future goal.
11.3 Vision for the future – general recommendation

It is recommended that in a near and long-term perspective work aims in the direction of gradually replacing as much of friction, rolling resistance, tyre wear and noise measurements by mobile texture measurements as possible. Provided appropriate actions are taken now, this can probably be realized gradually over a time period of from one to ten years according to this rough estimation:

1 year Speed influence on friction
1–2 years Water runoff rate and (combined with lateral slope) water depth
3 years Exterior noise for light vehicles
5 years Exterior noise for heavy vehicles
6 years Rolling resistance (but preliminary model could perhaps be used rather soon)
7 years Friction, as influenced by microtexture, but measured by stationary profilometer or other microtexture meter
10 years Tyre wear
10+ years Friction, as influenced by microtexture, mobile profilometer measurement

Performance requirements on pavements will more and more replace or supplement design requirements in the future. Improved texture measurements will significantly amplify this movement. It is recommended that when setting performance requirements internationally (for example in Europe) for road surfaces in a 10–15 years future perspective, one should aim at primarily using texture measurements for this. Such measurements will be much easier, safer and less expensive to perform in a standardized way than any direct friction, rolling resistance, tyre wear or noise measurements. It will require development and refinement of prediction models, however, but the economy in such an international system would be superior to any alternative using direct measurement of the variables.
REFERENCES


Anund, Anna (1997): Personal communication with the project manager. Swedish National Road and Transport Research Institute, Linköping, Sweden.


Billiard, Gary (1998): Personal communication with Mr. Gary Billiard, Skidabrader, Norwalk, Ohio, USA.


Descornet, Guy (1997): Personal communication, verbal report given at CEN/TC 227/WG 5 meeting 1997-11-20 in Brussels. Dr. Descornet works at the Belgian Road Research Center (CRR) in Charleroi, Belgium.

Descornet, Guy; Sandberg, Ulf (1980): "Road Surface Influence on Tire/Road Noise -Part II". Proceedings of Inter-Noise 80, Miami. Noise Control Foundation, New York, USA.


GNCDS (1998): "French example of consultation between the administration and the road industry". Information memo from Groupe National des Caractéristiques de Surface (GNCDS), whose secretary is Mr. P. Dupont, SETRA, Gagneaux, France.

Gorsky, M. (1997): Personal communication. Mr. Gorsky works at the Belgian Road Research Center (CRR) in Sterrebeek, Belgium.


Gothié, Michel (1997): Personal communication. Mr. Gothié works at the LRPC (Ceté) of Lyon, France.


Huschek, Siegfried (1997): Personal communication. Prof. Huschek works at the Technical University of Berlin, Berlin, Germany.


Kihlgren, Bo (1980): "Slitage av bildäck vid körning på äldre ytbehandling och asfaltbetong". VTI Meddelande No. 236, National Swedish Road & Traffic Research Institute, Linköping.

Klaruw (1993?): "Videobrochure describing the Klaruw anti-skid re-texturing machine". Video film from Signal Vision, Knutsford, Cheshire, UK.


La Torre, Francesca (1997): Personal communication, letter to Mr. G. Magnusson, VTI. Ms. La Torre works at "La Sapienza", Rome University, Rome, Italy.


Lund, B. (1997): "Friction Test – Comparative testing with 3 different equipments carried out during the summer 1996". Report No. 82, Danish Road Institute, Roskilde, Denmark.


Nordström, Olle; Andersson, Olle (1996): Chapter 11 in "International study of highway development and management (ISOHDM) – Supplementary technical relationship (STR) study – Addendum to draft final report 1995". Swedish National Road Administration, Borlänge, Sweden.


Ohlsson, Evert (1979): "Friktionsmätning på rullbanor och vägar". VTI Rapport No. 177, National Swedish Road & Traffic Research Institute, Linköping (pp. 8–14, in Swedish).

Ohlsson, Evert (1986-I): "Däckslitagemätningar inom VETO-projektet". VTI Meddelande No. 481, National Swedish Road & Traffic Research Institute, Linköping.

Ohlsson, Evert (1986-II): "Däckslitagesstudier vid Väg- och trafikinstitutet". VTI Meddelande No. 492, Swedish Road & Traffic Research Institute, Linköping.


Phillips, Steve (1997): Personal communication. Mr. Phillips works at the Transport Research Laboratory, Crowthorne, United Kingdom.


Wretling, Peter (1996): "Relationship between the functional properties of road surface and traffic safety". VTI Notat No. 32A–1996, Swedish National Road and Transport Research Institute (VTI), Linköping (in English).


ANNEX A: TYRE/ROAD NOISE GENERATION MECHANISMS AND MEASURING METHODS

A1. Mechanisms and related phenomena

Research on tyre/road noise generation mechanisms has been conducted since the mid 70’s and has resulted in an extremely complicated menu of mechanisms and related phenomena, all of which have been demonstrated to have some influence. Figs. A1 and A2 illustrate these in a comprehensive way. Firstly, Figure A1 shows the mechanisms mostly based on structure-borne vibrations in the tyre; secondly, Fig. A2 shows the mechanisms mostly based on air movement and/or airborne sound.

However, the most influential mechanism are not that many and can be picked out and described a little more. The table below includes a brief summary of the mechanisms considered to be the most significant:

Table A1: Summary of the most important generation mechanisms.

<table>
<thead>
<tr>
<th></th>
<th>Mechanism</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Radial vibration mechanism</td>
<td>1A Impact of tyre tread blocks or other pattern elements on road surfaces</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1B Impact of road surface texture on the tyre tread</td>
</tr>
<tr>
<td>2</td>
<td>Air resonant mechanism</td>
<td>2A Pipe resonance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2B Helmholtz resonance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2C Pocket air-pumping (this may also be a special case of 2B)</td>
</tr>
<tr>
<td>3</td>
<td>Adhesion mechanism</td>
<td>3A Stick/slip motions causing tangential tyre vibrations (might give excitation to 2A and/or 2B)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3B Rubber-to-road stick/release (adhesive effect)</td>
</tr>
</tbody>
</table>

In addition to this, there are some phenomena very much related to the mechanisms and influencing the amplitude, but which are not really "generation mechanisms". These are:

I. The horn effect
II. Sound absorption in the road surface
III. The mechanical impedance effect
Figure A1  Mechanisms mostly based on structure-borne vibrations in the tyre
Fig. A2  Mechanisms mostly based on air movement and/or airborne sound.
A2. Further explanations and comments

Tread radial vibrations are caused by small deflections in the tyre tread due to the impact and release forces, and radiate as sound after low-pass filtering in the tyre.

The pipe resonance is due to standing waves in the "air tube" in the grooves of the tyre tread. Concerning the Helmholz resonance, the volume of air in a cavity will act as a spring resonating with the mass of air in the "throat" between the cavity and the external air. In a tyre-axle-fixed co-ordinate system, a cavity in the tread travels out of the road contact area and up the tyre circumference. The resonance frequency and probably also the amplification then change with the tyre revolution.

Air pumping occurs when a cavity is closed and opened and the air is compressed/expanded with such a speed as to cause great air turbulence and thus noise. The Helmholz resonance may amplify this noise.

At the leading and trailing edges of the tyre, between the curved tyre tread fore and aft of the tyre/road interface and the road surface, there is a space forming an acoustical horn which increases the radiation efficiency backwards and forwards. This may be largely ineffective if one side of the "throat", e.g. the road surface, is porous.

The stiffness of the road surface, or the matching of mechanical impedance tyre-to-road, influences the tread block or road texture impact so that it may be amplified (stiff road) or attenuated (soft road), i.e. it influences mechanism No. 1.

Mechanism No. 1 is limited to rather low frequencies (generally below 1 kHz) while mechanisms No. 2 and 3 seldom occur below 1 kHz. Mechanisms No. 2B, 2C and 3 should be most important at the trailing edge, accentuated also by the horn effect.

Thus, the generating mechanisms encompass many interesting acoustical phenomena of a fundamental nature, but altogether form a very complicated pattern.

A3. Fundamental influence of road surface texture on noise

In a co-operative Belgian/Swedish program, a study was made to find which parameters of the road surface that influence exterior noise generation [Sandberg and Descornet, 1980]. Parameters such as macrotexture, megatexture, friction (microtexture), water drainage, sound absorption and mechanical stiffness of the roads were considered. The outcome was that there was no influence by friction or water drainage on noise that could not equally well or better be attributed to the mega- or macrotexture. Sound absorption influenced the noise, but only for porous surfaces. Mechanical stiffness could perhaps influence the noise, but to a minor extent only.

Due to the finding that the noise level failed to show any good correlation with the commonly measured sand-patch texture depth, it was preferred to replace this measure by a measurement of the profile curve of the road surface. This profile curve was analyzed either by filtering it using an analogue technique or by calculating its spectral content with a digital technique to obtain a third-octave band texture spectrum.
Again, the overall noise levels did not show any strong relation with texture depth. However, over the range of road surfaces tested, the noise levels at each acoustic frequency were correlated against the road texture levels at each texture wavelength. The best correlation between noise and road texture was obtained for certain frequencies of the noise and certain spatial frequencies or wavelengths of the macrotexture. Fig. A3a illustrates the correlation of the noise at low frequencies with the texture at long wavelengths and Fig. A3b illustrates the same relation between high frequencies of the noise and short wavelengths of the texture. The relation appears to be reverse in these two cases!

![Fig. A3](image)

**Fig. A3** Illustration of how noise and texture are related for the two most pronounced cases:

a. Noise at a low frequency (≈400 Hz) versus texture at a long wavelength (≈80 mm)
b. Noise at a high frequency (≈3 kHz) versus texture at a short wavelength (≈2–3 mm)

These facts explain why there is no simple and general relation between the overall noise level and texture. Rather, the overall noise level is composed of the sum of these two effects which may favour any of them depending on the exact circumstances.

Back again to the correlation between noise and texture for all noise frequencies and all texture wavelengths as mentioned above. It was concluded in this study that there are (at least) two major generation mechanisms which are uncorrelated with each other; one acting in the low-frequency range (below 1 000 Hz) with a positive correlation with road mega- and macrotexture and another acting in the high-frequency range (above 1 000 Hz) with a negative correlation with macrotexture. These results have been confirmed by several other studies later.

The low frequency mechanism is No. 1 and the high frequency mechanism No. 2 and/or No. 3 (see Table A1).
A4. An overview of measurement techniques

An overview of the major measurement methods is given in Table A2. Note that the microphones generally are positioned as follows:

**CB, SPB, TCB, CPB methods:** Microphone 7.5 m from the centre of the test lane, 1.2 m above surface. The CB and TCB methods generally utilize microphones symmetrically on both sides of the test lane.

**CPX, DR methods:** Microphone(s) 0.2 or 0.4 m outside undeflected tyre sidewall, one at 45° and the other at 135° relative to the rolling direction. In non-standard cases 0.2-0.8 m outside tyre sidewall and sometimes microphones also aft and fore of tyre. Microphone height over surface 0.1–0.2 m.

Table A2  The most important measuring methods for tyre/road noise. Full reference to the ISO methods is given in Chapter 12, "References"

<table>
<thead>
<tr>
<th>Name of method</th>
<th>Principle of method</th>
<th>Application areas</th>
<th>Standards or other documentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coast-by (CB)</td>
<td>Vehicle with test tyres coast-by a microphone on the road shoulder or test track, engine switched-off. Test speeds spread out over a range. Usually, the max sound level is read, regression may be used to calculate sound level at ref speeds, 80 for cars, 70 for heavies</td>
<td>Type testing of tyres, General testing of tyres, Detailed studies of tyres, Detailed studies of road surfaces</td>
<td>ISO/CD 13325 Draft EU Directive Draft ECE Regul.</td>
</tr>
<tr>
<td>Controlled Pass-by (CPB)</td>
<td>Two selected cars (one small and one large) with selected tyres (4 tyre sets, 2 per car, are specified) pass-by a road-side microphone with engine on. Max sound level is read. Average value at specified speeds is calculated.</td>
<td>Detailed studies of road surfaces</td>
<td>French standard S 31 119 German standard GesrO‘92</td>
</tr>
<tr>
<td>Statistical Pass-by (SPB)</td>
<td>Normal vehicles in traffic (accepted only if not disturbed by others) pass-by a roadside microphone. Type of vehicle, speed and max sound level are read. Normalised sound level at ref speeds 50, 80, 110 km/h is calculated by regression using &gt;100 cars and &gt;80 heavies</td>
<td>Type testing of road surfaces, General studies of road surfaces</td>
<td>ISO 11819-1</td>
</tr>
<tr>
<td>Close-Proximity (CPX)</td>
<td>A test tyre on trailer or attached to normal vehicle (or one of its normal tyres) is run over the test area, microphones mounted close to the test tyre. Average sound level over the test site is read. Ref speeds 50, 80, 110 km/h</td>
<td>Detailed studies of road surfaces, Check of road surfacing work, Detailed studies of tyres</td>
<td>ISO/CD 11819-2</td>
</tr>
<tr>
<td>Trailer Coast-by (TCB)</td>
<td>Trailer with two test tyres is towed over the test area by truck/van. Long tow-bar separates tow vehicle and test axle time histories. Max level for test axle pass-by is read, correction for tow vehicle pass-by (alone) is made</td>
<td>General testing of tyres, Detailed studies of tyres</td>
<td>ISO/CD 13325</td>
</tr>
<tr>
<td>Laboratory Drum (DR)</td>
<td>Test tyre rolling against drum in laboratory. Microphone(s) close to tyre, average sound level is read. Drum must be equipped with replica road surface(s). Closely controlled conditions, e.g. temperature and surface</td>
<td>General testing of tyres, Detailed studies of tyres</td>
<td>ECE/WP29/GRB, doc R.100</td>
</tr>
</tbody>
</table>
ANNEX B: QUALITY CLASSES FOR PAVEMENTS WITH RESPECT TO EXTERIOR NOISE CHARACTERISTICS

B.1 Quality classes

The following list is a possible classification scheme for road surfaces with respect to their influence on exterior road traffic noise (working paper submitted to CEN/TC 227/WG 5). It is included here as an example for discussion.

Type 0: "Excessive noise road surfaces". Surfaces which result in more noise than the reference surface

*Informal comment: This type would normally include surfaces like hot rolled asphalt (HRA), bituminous chip seal (BCS), rough-textured surface dressings (in unworn condition), transversely grooved cement concrete, several other types of cement concrete, paving blocks, etc. This would represent the type of surfaces which should be avoided where traffic noise is a problem.*

Type I: "Normal noise road surfaces". Surfaces which correspond to the reference surface ± 1 dB. See further below for explanation of "reference surface"

*Informal comment: This type would normally include surfaces like dense asphalt concrete and SIWA with max chipping size 11–16 mm, exposed-aggregate concrete with max. chipping size 11–16 mm. This would represent the most commonly used surfaces on high-traffic streets/roads in urban areas today.*

Type II: "Improved noise road surfaces". Surfaces that result in 2–3 dB in noise reduction relative to the reference surface

*Informal comment: This type would normally include surfaces like dense asphalt concrete and SMA with max chipping size < 9 mm, open-textured surfaces with 10–15 % voids, exposed-aggregate concrete with max. chipping size < 9 mm, longitudinally ground cement concrete, surface dressings or similar with max. chipping size < 7 mm. Some innovative block pavements might also fall into this category. This type would represent what is possible today in terms of noise reduction without using "real" sound-absorbing surfaces.*

Type III: "Low noise road surfaces". Surfaces that result in 4–6 dB in noise reduction relative to the reference surface

*Informal comment: This type would normally include surfaces like pervious asphalt or cement concrete with max chipping size < 16 mm and >20 % voids. This type would represent what is state-of-the-art today in terms of noise reduction when using effective sound-absorbing surfaces.*

Type IV: "Extra low noise road surfaces". Surfaces that result in at least 7 dB in noise reduction relative to the reference surface

*Informal comment: This type does not yet exist as a fully developed surface. However, the poroelastic surface, when sufficiently developed for field use, would fall into this category. Probably, it will also be possible to develop conventional pervious surfaces to meet this*
criterion in the future, when applying special techniques to increase voids content. In summary: this type would represent what will be possible tomorrow in terms of noise reduction when using extremely efficient sound-absorbing surfaces.

Note: All noise levels are expressed as A-weighted overall noise levels

B.2 Reference surface

(In accordance with ISO 11819-1, Clause 10, Option 1:)

The reference surface is a dense, smooth-textured, asphaltic concrete surface with a maximum chipping size of 11–16 mm. From the acoustical point of view, this is approximately equivalent to a stone-mastic asphalt pavement (SMA) with the same maximum chipping sizes. The surface shall have been trafficked for at least one year when used as a reference here. Macrotecture depth as measured according to ISO 10844 or ISO 13473-1 shall be within 0.50 and 1.00 mm. To ascertain that the surface is acoustically non-absorbing, air voids content or the sound absorption coefficient shall meet the requirements specified in Subclauses 4.1 and 4.2 of ISO 10844.
ANNEX C: VTI INVOLVEMENT IN TEXTURE-RELATED RESEARCH IN THE LATEST TWO DECADES

Following is a list of projects in which VTI has made significant contributions and which hopefully have advanced the knowledge about texture influence on various road performance parameters or the practical use of texture-related measures.

VTI developed the first contactless profilometer in the world useful for measuring a complete texture profile of a road surface. The first device (stationary) came in 1979, the second (mobile) in 1981. Later development phases were partly sponsored by Vägverket (the first by STU). The first device was modified to fit the Saab RST to create the Laser RST in the early 80’s. After that, for many years, VTI was probably leading in the development of contactless road surface survey instruments. Many other devices worldwide had the RST vehicle as a model in their development.

In the late 70’s and early 80’s, VTI studied the influence of road surface on tyre wear, as well as on rolling resistance. The results gave some new insight into this problem, but pointed at the necessity of more investigations.

In co-operation with CRR in Belgium, VTI has investigated the relations between road surface texture and tyre/road noise emission (sponsored by the former STU, now NUTEK). The first major paper was presented already in 1980, a paper which has been and is still after 17 years frequently referenced in numerous papers by international authors.

In a pilot study in 1982 (sponsored by VTI) and reported in [Sandberg, 1990-I], VTI investigated the relations between car fuel consumption and road surface texture. The experiment showed which texture wavelengths that are most important for creating a low or high rolling resistance, i.e. how texture shall be created for best economy and environment by using different surfacing techniques and compositions. This study has been rather frequently referenced.

Based on texture profile analysis, in 1982 this author proposed two standard road surfaces for measurement of exterior tyre/road noise. This was later (1982–86) used in work within the ECE, convened by VTI and partly sponsored by Vägverket, which resulted in a proposal for three standard methods for measurement of tyre/road noise, including specification of two reference surfaces. Parts of this work has been utilized in recent standardization work.

VTI convened the working group (sponsored by Vägverket) which developed the international standard specifying a reference road surface for vehicle noise measurement: ISO 10844. This is now part of a EU Directive currently in force and is also referenced in an ECE regulation. Such reference surfaces are now laid on test tracks all over the world.

VTI convened the working group (sponsored by Vägverket) which developed the second international standard on road surface texture measurement: Annex A of ISO 10844. This has also resulted in a corresponding CEN draft standard.

VTI convened the working group (sponsored by Vägverket) which developed the second international standard on road surface texture measurement: ISO 13473-1. This is also a CEN draft standard.
VTI convened the working group (sponsored by Vägverket) which developed the international standard for measurement of the noise characteristics of road surfaces: ISO 11819-1. This is intended to become also a CEN draft standard.

VTI developed a common Nordic correction for road surfaces in the traffic noise prediction model (sponsored by the Nordic Council).

This author initiated and made most of the preparations for the International Tire/Road Noise Conference 1990 and was also the editor of the book of proceedings from this conference. A significant part of the conference dealt with surface influence on tyre/road noise. The conference was a great success and its book of proceedings is still a major source of reference in the specialized tyre/road noise literature.

In an international project (partly sponsored by Vägverket) conducted by VTI with assistance by PTI in USA, ARRB in Australia and Transit New Zealand in 1987–88, VTI investigated the relations between friction and road surface texture. The experiment showed which texture wavelengths that are most important for creating a good friction, i.e. how texture shall be created by using different surfacing techniques and compositions [Sandberg, 1990-II].

In 1990–95 an "International Experiment to Compare and Harmonize Texture and Skid Resistance Measurements" was conducted (Swedish part sponsored partly by Vägverket). VTI took active part in all its phases, as part of the organizing committee, conducting most of the texture measurements in a pilot study to select test pavements, participating with two devices in the texture and friction measurements in the main programme, taking part in the analyses and finally taking part in the reporting of the experiment [Wambold et al, 1995].

This experiment turned out to be extremely successful, in fact it is probably the most important project ever performed in the subject. It resulted in these major achievements:

- The relations between most texture measuring devices in the world was determined
- The relations between most friction measuring devices in the world was determined
- A formula to normalize friction measurements to an international friction index (IFI) was established. For the first time, this enables most friction measurements in the world to be compared. Texture values are required for this normalization.
- The relations between texture and friction were investigated and good correlations were found between texture and the speed influence on friction
- From now on, friction measurements need to be made only at one speed, if macrotexture has also been measured. If a texture measurement is available, friction at any other speed can be calculated from this
- The experiment gave a good basic knowledge on which development of ISO 13473-1 could be based
This author wrote the state-of-the-art report about tyre/road noise for the extensive Swedish "Action Plan Against Noise" ("Handlingsplan mot buller") SoU 1993:65. Furthermore, state-of-the-art reports about design and maintenance of low-noise road surfacings have been published, the most recent one in 1996. Texture is an important issue in these.
Statens väg- och transportforskningsinstitut (VTI) har kompetens och laboratorier för kvalificerade forskningsuppdrag inom transporter och samhällsekonomi, trafiksäkerhet, fordon, miljö samt för byggande, drift och underhåll av vägar och järnvägar.

The Swedish National Road and Transport Research Institute (VTI) has laboratories and know-how for advanced research commissions in transport and welfare economics, road safety, vehicles and the environment. It also has research capabilities for the construction, operation and maintenance of roads and railways.

<table>
<thead>
<tr>
<th>Adress</th>
<th>Telefon</th>
<th>Fax</th>
<th>E-post</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE-581 95 Linköping, Sweden</td>
<td>Nat 013-20 40 00</td>
<td>Nat 013-14 14 36</td>
<td><a href="mailto:vti@vti.se">vti@vti.se</a></td>
</tr>
<tr>
<td>Postal address</td>
<td>Telephone</td>
<td>Fax</td>
<td>E-mail</td>
</tr>
<tr>
<td></td>
<td>Nat 013-20 40 00</td>
<td>Nat 013-14 14 36</td>
<td></td>
</tr>
</tbody>
</table>