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Deliverable D9.2

Review of highway standards and manuals

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EXECUTIVE SUMMARY

The European Road Network (ERN) is undoubtedly one of the most important land infrastructures in the EU. Consisting of a wide variety of types of roads and motorways, it is and will remain for the foreseeable future a crucial artery for Europe. Transport infrastructure is fundamental for the smooth operation of the internal market, for the mobility of persons and goods and for the economic, social and territorial cohesion of the European Union. However, the most important factor for the quality of the ERN is maintenance and it is considered to be the most expensive function of a highway operating agency.

As a result, there is a real need for an early detection of deterioration mechanisms and of potential presence of defects through a more advanced road infrastructure inspection technology. Therefore, the ultimate goal of EU FP7 RPB HealTec project (Road Pavements & Bridge Deck Health Monitoring / Early Warning Using Advanced Inspection Technologies) is to develop an integrated solution that would be able to reduce the maintenance costs and improve the performance by means of accurate and fast road inspection

Deliverable D9.2 "Review of highway standards and manuals" covers the specifics of the pavement and bridge deck inspection as a problem domain including the basics of asphalt surfaced pavement structures, common types of distress and non-destructive testing (NDT) technologies commonly employed in the inspection processes. This review provides the basis for understanding defects and deteriorations, existing NDT inspection methods, EU end user requirements, and motivation for novel technological solution by fusion of multidimensional NDT technologies, namely Ground Penetrating Radar (GPR), IR Thermography (IRT) and Air Coupled Ultrasonic testing (ACU) in an integrated scanning system for the inspection surveys.

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ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
ACU	Air-Coupled Ultrasound
ATB	Asphalt Treated Base
CBR	California Bearing Ratio
CCU	Central Control Unit
COST	European Cooperation in Science and Technology
CPT	Cone Penetration Test
CRCP	Continuously Reinforced Concrete Pavement
CTB	Cement Treated Base
DB	Database
DTSS	Deck Top Scanning System
EUs	End Users
GMPC	Gas Matrix Piezoelectric Composites
GPR	Ground Penetrating Radar
GPS	Global Positioning System
GUI	Graphical User Interface
FEM	Finite Element Modelling
HDV	High Definition Video
HGV	Heavy Good Vehicle
HMA	Hot Mix Asphalt
HRA	Hot Rolled Asphalt
FWD	Falling Weight Deflectometer
IRI	International Roughness Index
IRT	Infrared Thermography

JPCP	Jointed Plain Concrete Pavement
NCU	Non-Contact Ultrasound
NDT	Non-Destructive Testing
PCC	Portland Cement Concrete
PCI	Pavement Condition Index
QC/QA	Quality Control and Acceptance
REA	Research Executive Agency
SHRP	Strategic Highway Research Program
SNR	Signal to Noise Ratio
SPA	Seismic Pavement Analyser
TCT	Technical Committee on Transport
TRACS	Traffic Speed Condition Surveys
TSD	Traffic Speed Deflectometer
UT	Ultrasonic Testing
VI	Visual Inspection
WP	Work Package

1 INTRODUCTION

The European Road Network, which is estimated at approximately 5,000,000 km for the EU 27, is undoubtedly one of the most important land infrastructures in the EU, both in economic terms and social terms. However, the most important factor for the quality of the ERN is maintenance and it is considered to be the most expensive function of a highway operating agency. The total cost of road construction and maintenance is measured in tens of billions of euros [41]. As a result, there is a real need for an early detection of pavement deterioration mechanisms and potential presence of defects through optimisation of the road infrastructure inspection technologies.

As shown in Figure 1.1, well-timed preventive maintenance actions such as crack sealing, surface coating, or patching extend the road pavement lifetime by deceleration of the deterioration processes before the required rehabilitation or reconstruction works as well as improving pavement serviceability [1]. Accordingly, the regular road condition surveys for detection of defects potentially causing pavement deterioration reduce the costs of maintenance, the costs due to impedance of goods travel during maintenance periods, and the costs related to traffic accidents. The pavement condition is characterised with respect to the functional and structural aspects. The structural condition determines the structural capacity of the pavement from the measured layer thickness, structural changes, and material properties, while the functional condition assesses the ride quality based on the measurement of surface texture parameters and the presence of surface defects.

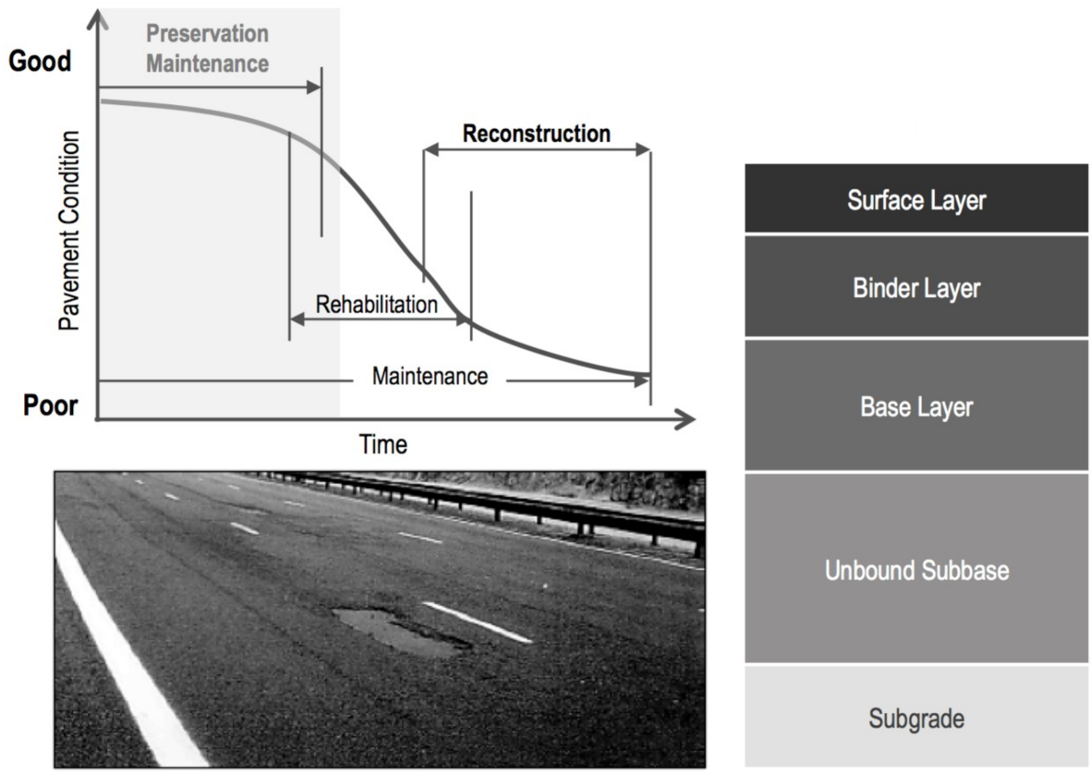


Figure 1.1 Flexible road pavement life cycle and general layer structure

Although the road infrastructure also includes bridge deck and tunnel pavements, hereafter, this report focuses on the road pavement condition surveys due to the specific requirement of this problem domain related to the large scale of the required data recording and information processing. In general, because of the varying and constantly changing international standards of pavement design and rehabilitation procedures (Figure 1.1) as well as the limitations related to the vast amounts of data, development of the universal survey guidelines or tools is a complex task. There are a number of commercial off-the-shelf survey equipment systems successfully utilized in the highway community, however there is a clear need for further optimisation and development of NDT sensor-based systems that cover both the functional and structural road pavement condition for efficient maintenance planning.

The majority of assessments and decisions in any pavement management process are based on the results of pavement inspection, i.e., identification of pavement condition, schedule of maintenance and construction works, prediction of pavement condition, analysis of traffic volumes, etc. As preventive maintenance is far less expensive than complete pavement repair, there is particular importance in the early detection of pavement deterioration sites and fast inspection methods. Moreover there are recognised needs of the industry for a more advanced road pavements inspection technology, which will be undertaken to:

- Detect the presence of defects,
- Determine the cause, extent and rate of deterioration,
- Provide information for assessing stability and serviceability,
- Provide information for evaluating the cost-effectiveness of various remedial measures, and
- Provide all of the aforementioned information in real time, not causing traffic disturbances.

At present, there are no existing solutions that can provide 100% coverage of road condition parameters. The end users of RPB HealTec, a leader in highways infrastructures BRENNERO and a public highway administrator CJ VRANCEA, are seeking an integrated solution that would be able to reduce their costs and improve their performance by means of accurate and fast road inspection. However, the current practice along the European infrastructure agencies varies, depending on their access to new technology and scientific advancements, their accuracy level requirements, their speed requirements, their countries of operation which are dictating the utilised standards.

The RPB HealTec system (Figure 1.2) proposes to provide a novel technological solution by fusion of multidimensional NDT technologies, Ground Penetrating Radar (GPR), IR Thermography (IRT) and Air Coupled Ultrasonic testing (ACU) in an integrated scanning system for the inspection of civil engineering structures (i.e., bridges, airport and road pavements). These NDT techniques can be successfully used in the detection of surface and subsurface detects such as cracks, delaminations and other deterioration mechanisms. Essentially, the aim of the project is to provide an integrated scanner system for prompt assessment and monitoring of pavement structures at traffic speeds (up to 60km/hr) and with the ability to detect surface and subsurface defects and deterioration sites as well as proving information on the layer structure profile.

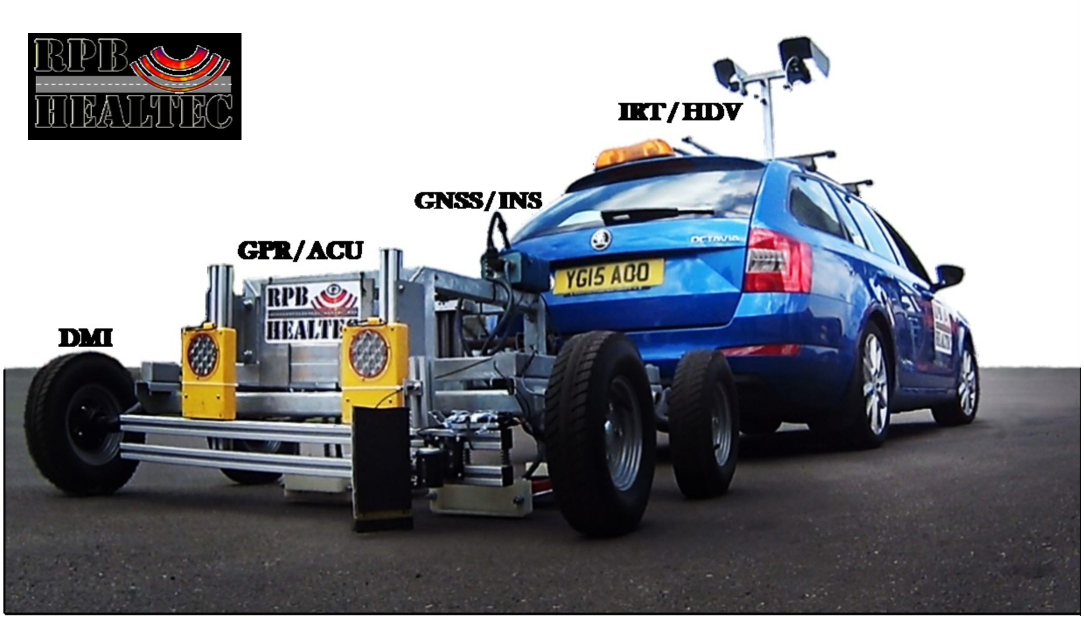


Figure 1.2 Integrated RPB HealTec system: fusion of GPR, ACU and IRT sensors

2 Road pavement structure and types of distress

The performance of road pavements is characterised by the following factors: traffic load support and distribution (structural capacity), surface smoothness and skid-resistance (ride quality and safety), and drainage. In addition, pavement construction has to be durable and resistant to environmental factors, e.g., water, oxidation, temperature extremes.

The main components of a pavement layered structure are the surface course, the base and sub-base layers, the subgrade, and the drainage system (Figure 2.1). The subgrade layer is the foundation upon which the pavement is constructed. It consists of naturally occurring or imported materials (soils) and is characterised by the strength to support the pavement without structural deformations. Its upper layer can be compacted (stabilised) to improve strength, stiffness, and/or stability [1]. The condition of subgrade strongly depends on the depth to the groundwater table, as high moisture content decreases its strength and thus affects pavement performance. The sub-base separates the base layer from the subgrade and provides additional strength. It is composed of graded granular material (usually hard rock). It also acts as part of the drainage system, sometimes in combination with additional filter layers. The subsurface drainage system is concerned with the rapid removal of infiltrated water from the pavement layers and the underlying subgrade before material and structure deterioration occurs. This free water is generally the result of a high water table or heavy rain. The base course (main load-bearing layer) supports the pavement by distributing load, providing drainage, and/or minimizing frost action. It is constructed with free-draining granular materials and can be bound or unbound. The base course has to be resistant to the structure deteriorations. The surface course accommodates the traffic load and has to provide smooth and uniform surface texture and skidding resistance. It also has to be resistant and durable against traffic loading and adverse environmental condition. The type of pavement surface material defines the pavement type (flexible, rigid, or composite) while the structure and material design determines the pavement quality. The surface course can consist of one or more layers. For instance, in flexible pavement, the binder layer provides load-carrying capacity and acts as the barriers to penetration of surface water to the underlying layer.

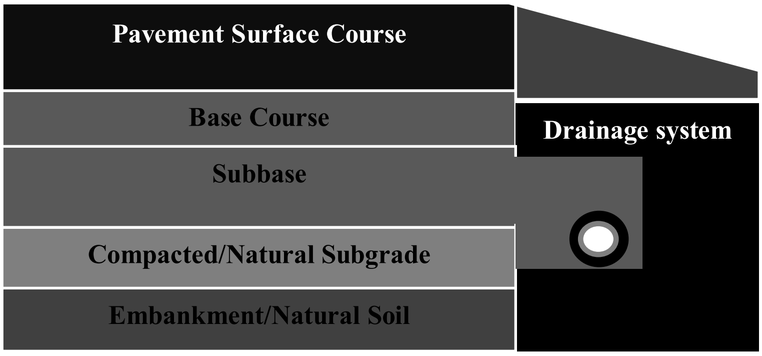
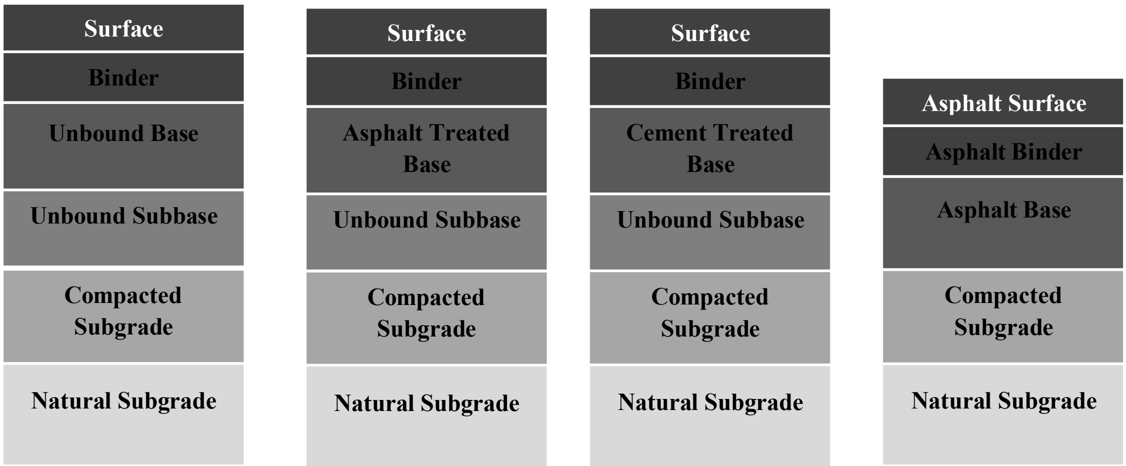


Figure 2.1 Cross-section of general road pavement structure

Flexible pavements, also known as asphalt concrete pavements, are constructed with bituminous mixture materials and distribute traffic load over subgrade through their multilayer structure. Rigid pavements use Portland cement concrete (PCC) with substantially higher modulus of elasticity that allows distribution of the traffic load over wider area of subgrade. Some types of rigid pavements contain steel mesh reinforcement. Advantages of flexible pavements include: less traffic noise, relatively low cost in comparison with other pavement construction methods, and easier maintenance. However, flexible pavements have lower durability (requiring resurfacing every 10-15 years) and tensile strength than compared to rigid pavements, require more layers and greater thickness, and are sensitive to deformation of subgrade and high temperatures. Generally, rigid pavements have 10-15 years longer lifetime (before rehabilitation is required) and high efficiency in terms of functionality, but require expansion joints and the force of friction is much higher. Composite pavements generally use asphalt concrete (or bituminous surface treatment) over PCC or rehabilitated flexible pavement. The choice of pavement type and materials mainly depends on the expected traffic volume, subgrade type (original surface), environmental condition, constraints on construction costs and long-term maintenance funding requirements. Pavements are also classified according to the construction type, i.e.: newly constructed, rehabilitated / overlaid (restoration or addition of new layers), and reconstructed (complete demolition of previous pavement).

2.1 Asphalt surfaced pavements

More than 90% of the European road network is surfaced with asphalt. Moreover, the majority of pavements in the road networks of the RPB HealTec end users, BRENNERO and CJ VRANCEA, are either flexible or composite. Therefore, the RPB HealTec system will be focused on the inspection of asphalt surfaced pavements, although the design of suitable calibration procedures for the sensors will also allow inspection of PCC pavements. The basic structure of flexible pavements consists of an asphalt-bound surface and binder courses, base and subbase layers (unbound/granular materials), and compacted subgrade. In some structures, the base course can be stabilised with cement or asphalt mixtures (asphalt stabilised and cement stabilised granular materials), while in other cases, the subbase layer may be excluded from the structure (e.g., full depth asphalt pavements). Sometimes additional layers can be included, for instance capping layer or bituminous membrane. Depending on the drainage system type, the surface provides either sealing or drainage of surface water.



a. Conventional flexible *b. Semi-rigid with ATB* *c. Semi-rigid with CTB* *d. Full depth asphalt*

Figure 2.2 Common types of flexible pavements

A bituminous mixture, also known as hot mix asphalt (HMA), is the result of blending graded aggregates with different amounts of bituminous materials (acting as binders) and additives. The optimal asphalt mixture has to have sufficient stiffness and deformation resistance and adequate flexural strength, while providing maximum durability. The quality of mixture composition is controlled by the requirements to the specific characteristics determined by the existing standards. These characteristics include particle size distribution, content of residual voids, stiffness module, sensitivity to water, resistance to permanent deformation, minimum stability, thickening level, etc. For instance, Figures 2.3.a-b shows the grain size distribution requirements for the asphalt concrete mixture for the binder course in the Brenner Motorway pavements.

GRAIN-SIZE DISTRIBUTION (MIXTURE FOR THE BINDER)

SIEVES OPENING (mm)	PASSING FRACTION (%)
20	100
16	90 - 100
12,5	70 - 90
8	55 - 75
4	36 - 58
2	25 - 42
1	18 - 33
0,5	12 - 23
0,063	4 - 7

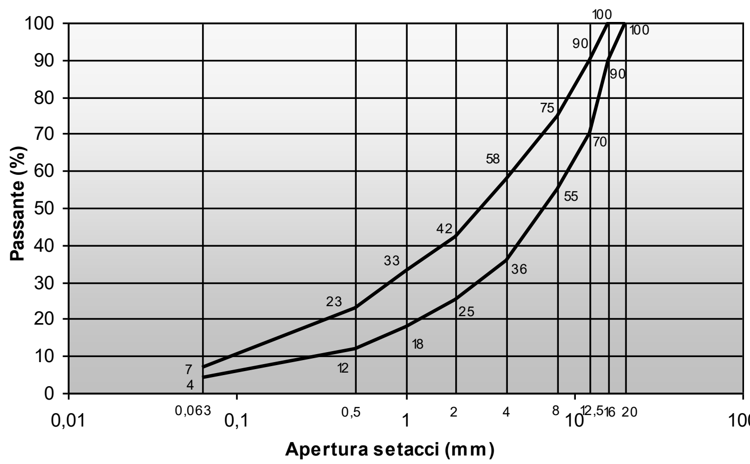
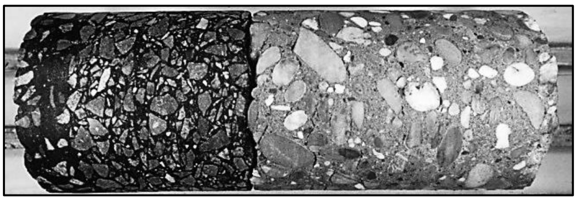


Figure 2.3.a Particle size distribution requirement to the binder in the Brenner Motorway pavements

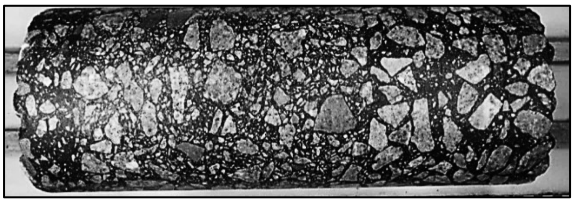
FEATURES OF THE MIXTURE FOR THE BINDER (*Volumetric method*)					
REQUIREMENT	TEST METHOD	SYMBOL	UNIT	THRESHOLD VALUE	CATEGORY (UNI EN 13108-1)
Voids 10 rotations	UNI EN 12697-5,6,8	$V10G_{min}$	%	>10	$V10G_{min9}$
		$V10G_{max}$	%	<14	-
Voids 100 rotations		V_{min}	%	>3	$V_{min3,0}$
		V_{max}	%	<6	V_{max6}
Voids 180 rotations		V_{min}	%	>2	$V_{min2,0}$
Stiffness module	UNI EN 12697-26	S_{min}	MPa	> 3 000	$S_{min2\ 800}$
Indirect tensile strength at 25 ° C	UNI EN 12697-23	ITS	N/mm^2	>1,0	-
Sensitivity to water	UNI EN 12697-12	ITSR	%	>75	$ITSR_{80}$

Figure 2.3.b Requirements to the binder AC mixture in the Brenner Motorway pavements

Some of the commonly used bituminous mixtures in road pavement construction and maintenance include: asphalt concrete (AC), hot rolled asphalt (HRA), porous asphalt, stone mastic asphalt, etc. Figure 2.4.a shows the core through flexible pavement with surface, binder, and upper base layers composed of hot rolled asphalt and cement bound material (CMB) lower base. In Figure 2.4.b pavement core, the surface course is composed of HRA, while asphalt concrete is used for binder and upper bases, and the lower layer of the base is HRA.



a. Surface, binder, upper base: HRA, lower base: CBM



b. surface: HRA, binder and upper base: AC, lower base: HRA

Figure 2.4 Examples of cores through flexible pavements of various design [10]

The choice of parameters of structural (layer thickness) and material (mixture type and composition) design is defined by the specified road pavement requirements, such as expected traffic volume, vehicle weight, environmental conditions, and subgrade type. It must comply with the existing pavement design and construction standards as they directly define the pavement serviceability and performance characteristic. The general characteristics of flexible pavement layers are given in Table 2.1.

Table 2.1 General characteristics of flexible pavement layers

Layer	**Average height**	**Examples of materials**	**Function and requirements**
Surface (or wearing)	2.5-5 cm	- HMA (e.g. HRA, AC)	- top layer of the pavement, - requirements: even surface (but not smooth), durable, high resistance to deformation and fatigue,

course			- depending on the type of drainage system it has to be impenetrable to the ingress of water or provide drainage, - very strong, durable, expensive
Binder course	5-10 cm	- HMA (e.g. HRA, AC)	- load spreading layer, - levels off the surface, - impermeable, strong, expensive
Base course	10-30 cm	- HMA (e.g. HRA, AC) - or CBM	- main load-bearing layers, - thickness depends on the expected traffic load, - type: unbound or asphalt- /cement- bound - strong, free-draining, less expensive
Sub-base (optional)	10-30 cm	- graded granular material (hard rock), - or cold recycled pavement	- protects base course, - load spreading layer, - improves drainage (part of the drainage system), - minimise frost action damage, - moderate strength, free-draining, inexpensive
Compacted Subgrade	15 cm	- granular low cost material	- improves strength, stiffness, and stability of the subgrade
Natural subgrade	-	- soil type: gravelly, sandy , clayey, etc.	- natural occurring material underneath the pavement, - weak and moisture sensitive

CJ VRANCEA has in its administration 107 bridges (with a length of more than 10 m each) and 731 km of county roads. For instance thickness requirements for pavement layers in road DJ 205D (a conventional flexible county road) in the CJ VRANCEA road network are as follows: subbase 25 cm, unbound base 15 cm, HMA binder 8 cm, HMA surface 5 cm, while the cross slope for carriageway is 2.5% and 4.00% for shoulders. The minimum pavement thickness requirement is 37 cm by law (AND 605 standard).

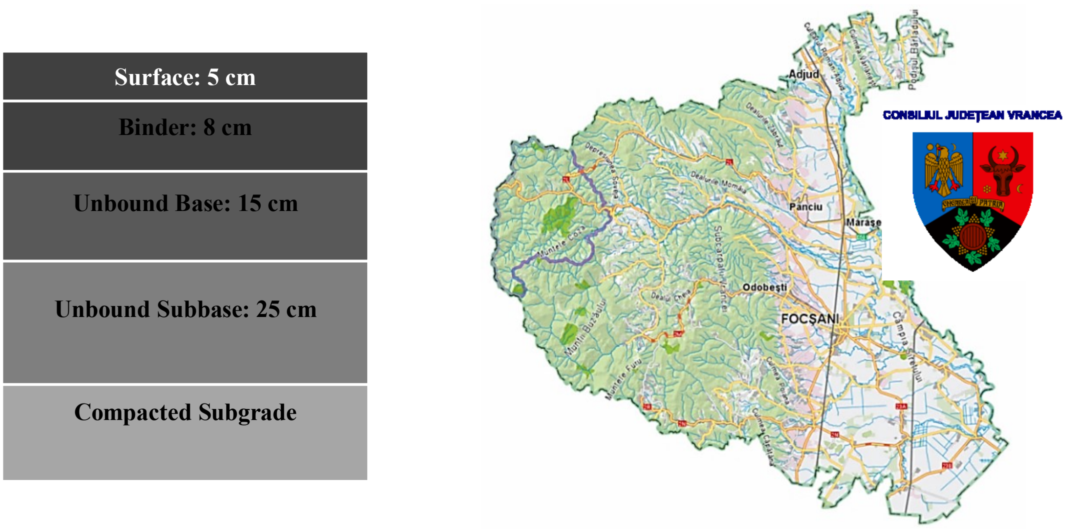
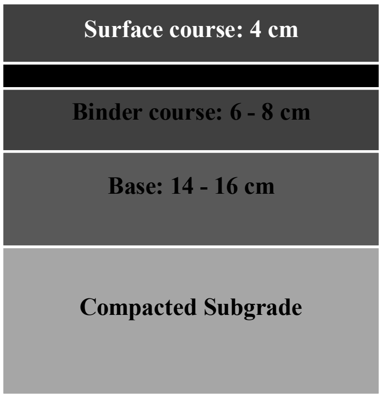


Figure 2.5 The Vrancea County Council road network: basic pavement structure

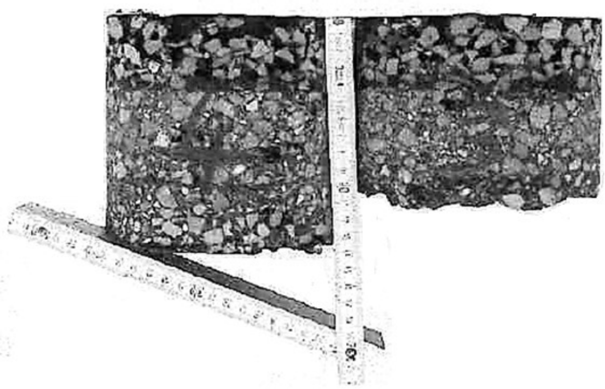
Most of the pavements along the Brenner Motorway are drainage sound-absorbing pavements, which are considered to be optimal in terms of safety as they reduce aquaplaning, spray and mirror effects. This full depth asphalt pavement type with surface drainage system is characterised by the absence of granular sub-base layer and water impenetrable binder course (Figure 2.6.d). In pavements of this type moisture contents do not build up in the subgrades.

a. BRENNERO road network: 626 km

b. Drainage sound-absorbing pavements in the Brenner-Motorway



c. Basic pavement structure in the Brenner Motorway (full depth asphalt)



d. Quality control: pavement core samples / surface and binder courses: AC

Figure 2.6 The Brenner-Motorway road network: drainage sound-absorbing pavements

Figure 2.5 shows a typical asphalt concrete pavement structure with drainage surface course (4 cm), binder (6-8 cm), and base (14-16 cm). The subgrade consists of non-bounded stabilised base material. A bituminous waterproofing membrane is laid between the drainage surface course and the binder layer. The base and binder asphalt concrete layers have similar physical features. The drainage sound-absorbing layer is made from a mixture of natural aggregates, additives and high-viscosity modified bitumen and is packaged at high temperature, after heating the aggregates and the binder. The drainage sound-absorbing bituminous conglomerate has a high content of intercommunicating voids which allow the passage of water and air for increasing permeability and decreasing the noise of vehicles circulating on the surface.

For bridges and viaducts two layer Antiskid pavements are used (Antiskid / Splittmastix surface course: 3-4 cm, binder course: 8-12 cm), while tunnel Antiskid pavements have three layers (Splittmastix surface course: 3-4, binder: 5 cm, base course: 10 cm). Splittmastix is a bituminous conglomerate characterized by the presence of a high amount of grit and a sort of "mastic" made from bitumen, filler, and stabilizing fibre (splitt-mastix asphalt). The particular granulometric (and lithologic) characteristics of the aggregates used in conjunction with a high content of binder modified with polymers allow this type of pavement to provide absolute level performances in terms of durability, stability and resistance to deformation, surface roughness and resistance to rutting. This conglomerate type is a HMA, dosed by weight or volume, consisting of stone aggregate, modified bitumen, additives and fibres. The Splittmastix conglomerate has the following characteristics: high resistance to deformation and rutting; less noise production; enhancement of the performance of adhesion of the road surface, even with wet surfaces; less aging of the binder due to the low voids content of the mixtures. It is particularly suitable for highways and high-intensity of traffic, changes in the road surface with longitudinal slope, dangerous bends and roads with risk of aquaplaning.

Figure 2.7 shows some typical structures of composite pavements, also known as HMA or AC overlays, commonly used as a rehabilitation option. It can consist only of the HMA course, or also include base layers: unbound, asphalt treated, cement treated. HMA overlays are also classified depending on the type of initial pavement: asphalt pavement, jointed plain concrete pavement (HMA/JPCP), continuously reinforced concrete pavement (HMA/CRCP), etc. However, because of reflection cracking caused by poor joints this type of construction requires inspection and treatment of the initial surface for cost-effective rehabilitation.

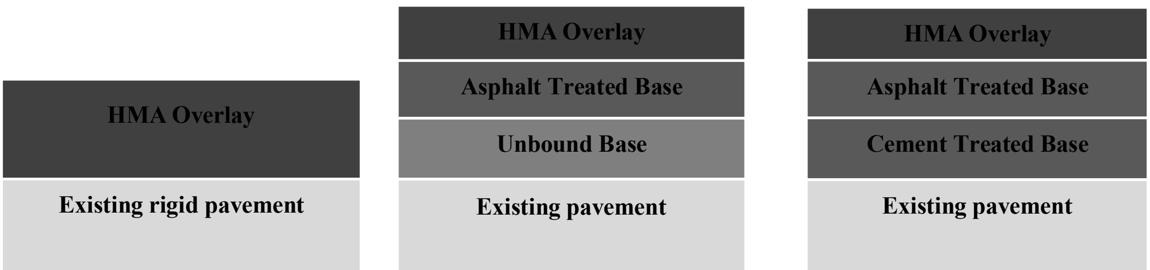


Figure 2.7 Common types of HMA surfaced composite pavements

Bituminous surface treatment can be considered as another form of composite pavement. It is used on lower traffic volume roads (generally less than 2,000 vehicles/ day) and asphalt concrete surfaces for higher traffic conditions. For instance, chipseal is a type surface treatment where a new wearing surface is applied to an existing pavement. Fog sealing is the application of asphalt emulsion to the surface.

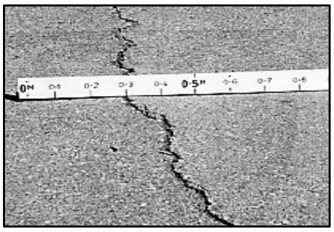
2.2 Common defects and deterioration mechanisms

The road conditions define its serviceability, riding quality, and traffic safety. Normally, new or newly overlaid pavements are in excellent condition. In its turn, the process of pavement deterioration (and failure) is associated with the defects in its surface and structure. Although different pavement types are associated with different defects, the main causes of defects are nearly always the same, specifically, fatigue due to heavy traffic loading / volume, poor drainage, composition of subgrade soils (e.g. between Mantova and Modena the subgrade has a high clay content), environmental conditions (e.g. frost heave, temperature extremes, heavy rainfalls and snowfalls), ageing processes, salt spread during the winter season, inadequate structural design, and the absence of appropriate maintenance treatment of existing defects. Heavy traffic loading beyond the structural capacity of the pavement (load rating of the initial construction) can lead to structure degradations. Surface cracking and texture deterioration reduce the structural capacity even more eventually leading to failure. For instance, regular passenger cars have no particular effect on a pavement structure but HGV's can produce 10,000 times greater damage. Traffic volumes along the Brenner Motorway are approximately 40,000 km per day, which is relevant to the pavement design. HGV's comprise ≈60% of all transits and they drive along the transit lane as there is a permanent overtaking ban. In flexible pavements, the natural processes of ageing result in hardening of asphalt and weathering of the surface course (e.g., loss of aggregates). When the "critical age and fatigue" point is reached, cracks appear on the pavement surface and, if no timely maintenance treatment (e.g., sealing) is performed, extensive crack patterns and potholes will form. Pavement condition is highly influenced by the environmental conditions and moisture and temperature especially. Modulus of asphalt materials varies with temperature, e.g., a range of 14,000-20,000 MPa. When the water in soil freezes the resilient modulus of unbound pavement materials can rise by 20 to 120 times, while the thawing can greatly reduce the strength of subgrade and other layers. Water can penetrate into the pavement structure through surface defects (e.g. cracks), as edge inflows, and from the underlying groundwater table (subgrade). High moisture content in combination with poor performance of the drainage system may weaken the subgrade and construction layers leading to loss of load spreading ability and structural deformations. Although bound materials are not directly affected by moisture, it can lead to stripping in asphalt materials (e.g., the binder course) due to pore water pressure or deterioration of the structural integrity of the CBM base [1]. In its turn, stripping in the pavement course may eventually result in delamination between the layers, which is not initially visible on the surface. If not timely treated, delamination progresses to severe surface cracks.

During a general visual pavement inspection, a surveyor reports every detected surface defect including specification of its type, location, measured area and depth, and estimated severity. The essentials of the pavement inspection process, existing methods, and road quality rating approaches are described in the following section.

The predominant surface defects in flexible pavements are: - cracking, - structural deformations, - surface texture deficiencies, - potholes, - and patching. In the Brenner Motorway, the most common defects are: ravelling, loss of surface aggregates, cracks, and potholes, while migration of mud to the surface is less common (these defects are typical of both types of pavements along the A22, but the loss of surface aggregates is more common for drainage sound-absorbing pavements). The metrics for the assessment of the severity rating and damage extent of defects in flexible pavements are based on the distress identification manuals [3, 4]. For example, the defect extent can be evaluated as: not significant, slight (less than 5% of pavement segment length/area is affected), moderate (5 - 20% affected), extensive (more than 20% is affected). Treatment of defects depends on the determined type, severity, and extent, and varies form sealing of cracks and patching of localised defects to complete overlay or reconstruction in the case of large damaged areas or severe structural defects. In the Brenner Motorway, severe defects are treated immediately by the internal staff or by specialised companies in case of extensive damage, while low to medium severity defects are treated within the routine framework of major interventions. In the Vrancea County Council road network, the goal is to eliminate the development or deterioration of defects and pavement degradation. This will be achieved by the optimal structural and material pavement design in accordance with the road class and expected traffic volume, and timely preventive maintenance measures performed in agreement with the prescribed regulations. This includes specific pavement design for HGVs and corresponding control in terms of tonnage, reinforcement of old road pavement constructions, prompt sealing/patching of surface defects, evaluation of the freeze-thaw action, etc.

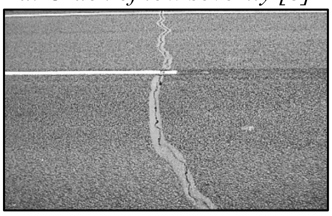
In HMA surfaced pavements, cracks generally develop as a result of fractures in the pavement layers. There are different types of cracks depending on the location in relation to the joint and wheelpath, pattern, and causes. They are characterised into: longitudinal, transverse, diagonal, slippage, joint reflective, edge, as shown in Figure 2.8. If not timely sealed, individual cracks eventually develop into patterns, e.g. alligator (fatigue) cracking or block cracking, as shown in Figures 2.8.e-f respectively. Factors leading to development of cracks include: fatigue due to heavy traffic loading, ageing processes, movement and fractures in underlying layers, hardening and shrinkage of surface layer, poor original construction, deformation, and severe weather conditions. For instance, longitudinal cracks can be caused by heavy traffic loading in the wheel path, while transverse cracks (also known as thermal cracks) are the results of extreme temperature changes and aging of binder. In composite HMA/PPC overlays, joint reflective cracking may occur in asphalt surface directly over the joints of underlying PCC slabs. Low severity localised fatigue cracking can potentially indicate a loss of subgrade support, while large area fatigue cracking is associated with general structural failure. In their turn, extensive surface cracks lead to loss of load spreading ability, riding quality, and the ingress of water to the underlying layers. In country road, further progression of edge cracking in combination with inadequate drainage system might lead to the edge failure. Water bleeding is seeping of water through the porous asphalt or cracks, while in mud pumping conditions it is the mixture of water and soil/concrete substances (Figure 2.8.k).



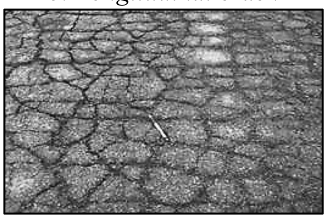
a. Crack of low severity [3]

b. Longitudinal crack

c. Joint reflection crack [5]

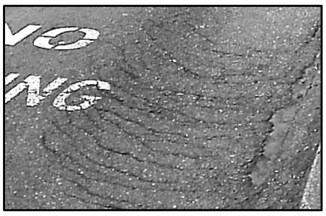


d. Sealed Transverse crack



e. Severe fatigue cracking

f. Block cracking



g. Slippage cracking

h. Cracks next to longitudinal joint

i. Edge cracking

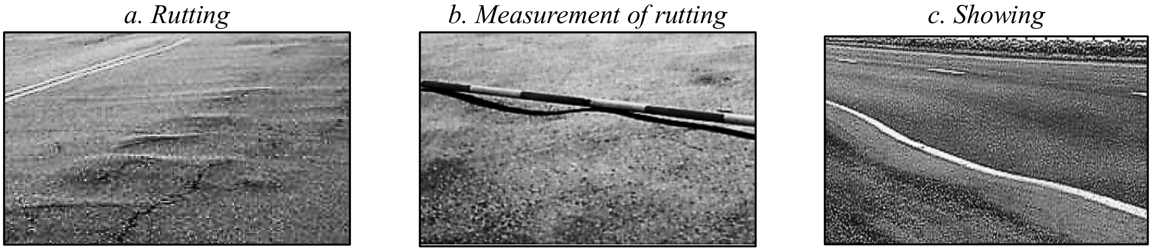
j. Edge failure *k. Multiple cracks and mud pumping* *l. Fatigue cracking*

Figure 2.8 Examples of cracking defects in HMA surfaced pavements

The severity of individual cracks is evaluated from the measured average width (low: < 6 mm, medium: 6-19 mm, high: > 19 mm), because when a crack is wide enough it permits water infiltration to the underlying layers that will lead to further degradation. The severity of alligator and block cracking is quantified by the affected area. Severe cracking is also associated with loss of material at the edges. The extent of damage is estimated from measured lengths, frequency of occurrence, or the covered area depending on the cracking type. Common treatment options include sealing, patching, or overlay. During the survey, crack seal condition is also investigated regarding the state of the bituminous sealant.

Figure 2.9 shows examples of the next group of defects related to structural deformations of the pavement surface. These include: rutting, corrugation, depression, bumps, and showing. Besides other factors these defects originate from poor quality aggregate or improper mixture design. Changes in the pavement structure significantly affect road serviceability and safety. Rutting is a surface depression can be caused by heavy vehicle loading and its severity is evaluated from the average rut depth along the inspected pavement segment (low: 6 - 12 mm, medium: 12 - 19 mm, high: > 19 mm). Showing and corrugation defects are longitudinal structural displacements of the surface material by an abrupt wave or rippling generally caused by braking or accelerating vehicle. Depression and bumps are localised areas that are lower / higher than the surrounding pavement and are generally caused by environmental conditions (e.g., frost heave or excessive moisture in the subgrade) or construction defects (e.g., wrong connection at the joints, uneven spreading of bituminous treatment).

a. Rutting *b. Measurement of rutting* *c. Showing*



d. Corrugation *e. Bumps [5]* *f. Surface depression*

Figure 2.9 Examples of structural deformation defects in flexible pavements

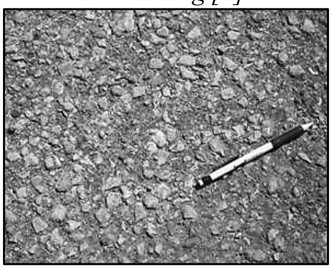
Pavement preservation maintenance works are generally used for low severity defect (cracking, texture deterioration); however they are not appropriate in the case of severe structural deformations that require specific rehabilitation design.

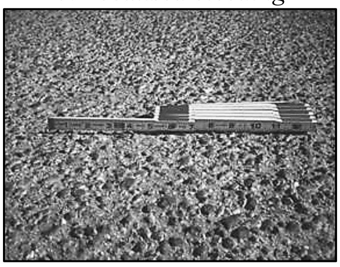
Pavement surface texture is a significant property affecting pavement functional condition: friction, skid resistance, noise, smoothness, etc. Texture deficiencies are characterised by the loss of surfacing materials and texture degradation processes. The so-called bleeding condition (Figure 2.10.a-b) is characterised by a film of bitumen binder on the pavement surface (black and shiny) usually caused by excessive asphalt binder in the mixture and hot weather conditions. Ravelling is the loss of coarse aggregate particles due to degradation of asphalt binder or mechanical dislodgement by certain vehicle types (Figures 2.10.c-d). Eventually, it results in rough and pitted surface texture. Surface weathering is the loss of asphalt binder due to oxygenation and natural ageing processes. On the other hand, the polishing defect is the loss of texture when the aggregate extending above the surface is polished or absent. It can occur in the areas of acceleration/breaking, which significantly worsens skidding resistance condition. These defects are generally caused by inadequate mixture quality, fatigue due to traffic loading, and old age. Estimation of the severity and extent of texture deterioration is based on visual examinations and specific measurements.


a. Bleeding [5]


b. Localised bleeding


c. Ravelling


d. Ravelling [8]

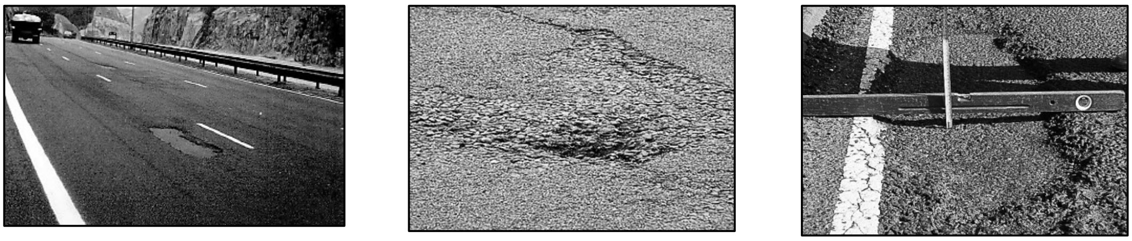

e. Weathering [8]


f. Polishing[8]

Figure 2.10 Examples of surface texture deficiency defects in flexible pavements

Pores or "porous surface" is another variation of surface degradation, which is characterised by the lighter colours and keeps moisture long time after rain. It is generally caused by the insufficient bitumen content in HMA, low quality natural subgrade, or inadequate weather conditions during construction (low temperatures, high humidity).

Potholes are bowl-shaped depressions with depth penetrating down to the base course. Potholes generally occur in pavements with thin surface layer and can originate from erosion of alligator cracking areas or "weak" areas in underlying layers due to poor drainage (e.g. stripping). The severity of potholes is quantified from the depth and size, while the extent is estimated from the number of occurrences and the size of the affected area (low: < 25 mm deep, medium: 25 - 50 mm deep, high: > 50 mm deep).



a. Pothole *b. Developing pothole* *c. Measuring height [9]*

Figure 2.11 Examples of pothole and patching defects in flexible pavements

The condition and extent of pavement patching are also investigated. Patches and surface treatment are considered as defects due to the origins of the initial distress and the fact that deterioration of the patches also can affect the surface smoothness. Patching materials are usually based on either hot mix or cold mix asphalt. Surface patching generally involves placing HMA over low severity cracks or potholes (asphalt filling the problem areas). Localised semi-permanent patching is used as a temporary/emergency repair option. Permanent patching can use either full-depth (from surface to subgrade) or partial-depth replacement of localised pavement area depending on the severity, extent, and cause of the defects. The severity of patches is estimated based on the initial defect and the type of patches (Figure 2.12) and is classified into: a) low: surface treatment and chipseal patching, covering low severity cracking or ravelling, b) medium: semi-permanent and part-depth patching, covering medium alligator cracking, potholes, rutting, c) high: full depth patching, replacing a portion of the pavement in case of severe alligator cracking. The percentage of the patched/treated area at each severity level ranges from: 1-9%, 10-24%, >25%, respectively.

a. Localised pothole patch *b. Fog seal surface treatment* *c. Permanent patching*

Figure 2.12 Examples of patching defects in flexible pavements

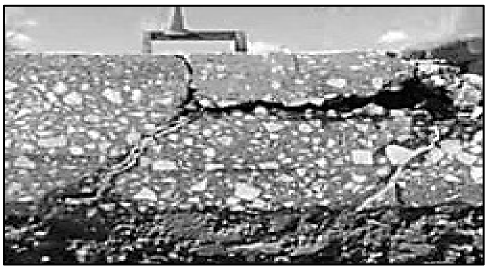
The majority of surface defects can be attributed to subsurface pavement deterioration. For instance, one of the causes of wheel path longitudinal cracking is delamination in the binder and base layers in flexible pavements and HMA overlays (Figures 2.13.a,b,e). In its turn, the primary cause of HMA delaminations is debonding or stripping. Reduced bond strength (tack coat) and eventual debonding result from construction issues causing poor tack coat between HMA layers or HMA/PPC overlay and water infiltration. Figure 2.13.e shows examples of cores with debonding, stripping, and cracking defects from study “De-Bonding of HMA Pavements in Washington State” [37]. Insufficient bond strength is also associated with fatigue cracking.

Stripping is the loss of binder-to-aggregate bond in HMA materials due to moisture damage (Figure 2.13.d). It is usually characterised by the following factors:

- presence of water in HMA course (poor drainage),
- inadequate moisture susceptibility of aggregate and binder,
- or insufficient preparation of the existing surface for overlay.

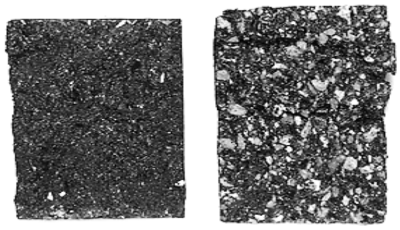
Besides delaminations, stripping also results in loss of bearing capacity, surface deformations (such as rutting, corrugations), or fatigue cracking. The summary list of initial design- and construction-related causes of delaminations include: inadequate mixture and tack coat, mixture and thermal segregation, use of water sensitive aggregates, etc. Slippage surface defect occurring in braking/accelerating areas is another visible indicator to poor bond between HMA layers.

a. Debonding in HMA layers [23]

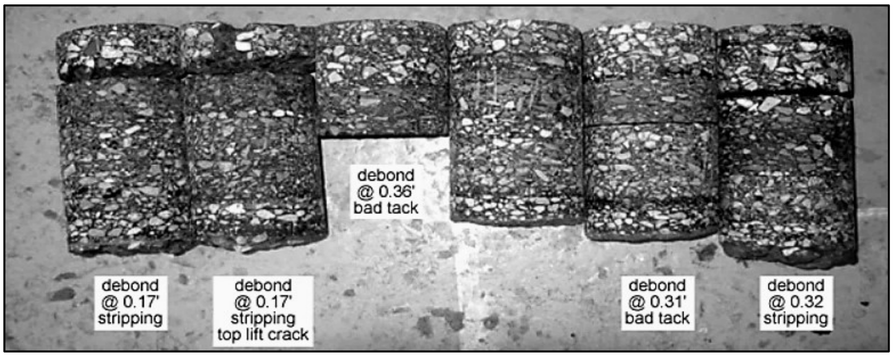


b. Severe cracking due do to debonding in HMA layers [23]

c. Severe slippage caused by debonding [38]



d. HMA samples with no damage (left) and stripping due to moisture damage (right) [40]



e. De-Bonding of HMA Pavements/Case Studies: SR 2 Tumwater Canyon Paving [37]

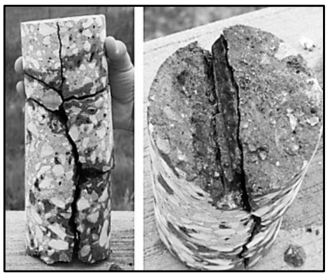
Figure 2.13 Examples of subsurface defects in flexible and composite pavements HMA layers

Being invisible until the severe stage of deterioration (surface defects), delamination and other discontinuities in HMA pavement and HMA/PPC overlays are difficult to detect. The existing NDT methods (e.g. GPR) use the following indirect indicators for detection of subsurface delaminations: - higher moisture level, - lower material density and stiffness, - increased amount of voids, - presence of surface deflections.

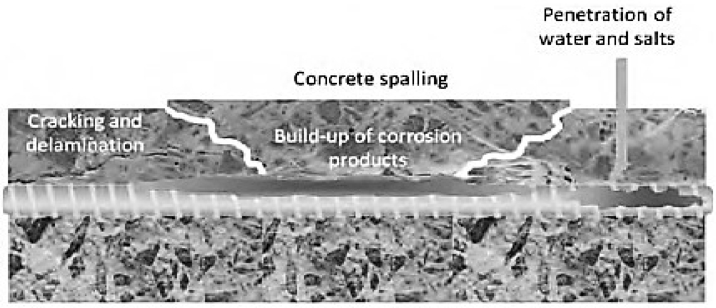
The most common subsurface deteriorations in concrete bridge deck are: rebar corrosion, delamination, concrete degradation, and cracking. Corrosion of rebars is caused by the influence of penetrated water. The resulting expansion of corroded reinforcing steel may cause subsurface fractures that finally develop into delamination (horizontal cracking) (Figures 2.14.a-d). In addition to progression of horizontal cracking, factors such as extreme temperatures, freeze-thaw cycles, construction constrains, traffic load, etc. cause concrete degradation (loss of strength) and further deteriorations in the form of vertical and load-related cracks. In the absence of timely repair delaminations develop into open cracks. Another subsurface defect type is debonding between the bridge deck and HMA overlay.

a. Deck delamination

b. Layer debonding



c. Vertical Cracking



d. Cracking caused by rebar corrosion

Figure 2.14 Examples of subsurface defects in concrete bridge deck [35,36]

These defects significantly affect the structural integrity and serviceability of the deck and consequently the efficiency and accuracy of the used NDT inspection methods is of a major importance in planning preventive maintenance and repair.

3 Road pavement and bridge deck inspection process

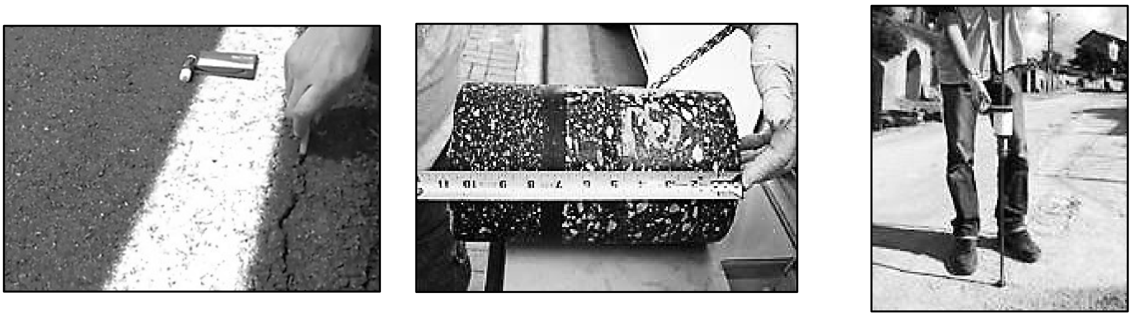
3.1 Common road pavement and bridge deck inspection methods

The pavement serviceability is directly related to the monitoring schedule and specified survey plan. Road and bridge deck inspection is conducted as a routine monitoring or planned maintenance procedure for assessment of functional and structural conditions of pavement section. The structural condition determines the structural capacity of the pavement from measured layer thickness, structural changes, and material properties, while the functional condition assesses the ride quality based on the measurement of surface texture parameters. The result of visual inspection (VI) is an overall evaluation of both functional and structural conditions. Examination of the pavement surface is performed by surveyors on slow moving vehicles or on foot. Thus, VI is characterised by low inspection speeds and high levels of dependency on the surveyor's level of expertise. During an inspection, surveyors measure parameters and evaluate the severity of the observed defects along with their location and weather conditions.

The general requirements for the inspection records are as follows [14]:

- location, severity, extent and type of all defects (detailed descriptions and photographs where appropriate);
- information on stability and integrity of the structural condition; - relevant headroom information for bridge structures;
- any significant changes or performed maintenance works since the last survey; - comments on possible maintenance strategy.

A list of common defects in flexible pavements is described in Section 2 including the summary guidelines on assessing of the defect severity rating and damage extent based on the pavement surface condition rating manuals [3,4].



a. Visual survey (cracking) *b. Asphalt Coring [9]* *c. DCP equipment [26]*

Figure 3.1 Visual pavement inspection process

The visual survey results are recorded in accordance with standard practices and next entered into a Pavement Management Information System database for further evaluation. Besides the basic tools for measurement of defects (e.g., crack width gauge, camera, ruler, etc.), surveyors can also use specific equipment for NDT or destructive testing (and further laboratory analysis). Coring is a static destructive testing that often used to evaluate type, severity, extent, and cause of defect after the surface deterioration becomes visible. Figure 3.1.c shows the application of Dynamic Cone Penetrometer (DCP) for in-situ measurements of the structural and material properties of unbound base course and subgrade pavement layers (layer thickness and relative stiffness) with approximately 1m required depth of penetration. DCP is a portable instrument and requires prior boring of a small pilot hole through the bound surface and base course. The subgrade measurements are used for CBR profiling and are compared with the conventional pavement design CBR specification (subgrade strength index). In the Brenner Motorway road network, visual and NDT surveys are carried out on an annual basis (in June), over all lines of the entire motorway from Brenner to Modena (626 km). The average carriageway width is about 10.5 - 11 m. Generally, the transit lane is the most vulnerable due to heavy truck traffic (middle lane between overtaking lane and emergency lane, 3.75 m width). The age of the pavement sections along the Brenner Motorway varies between 0 and 10 years.

In Romania, visual survey is the most common inspection method. It is based on national standards and regulations:

- Rules for construction technical expertise HG 925/1995,

- Standard for evaluating the degradation of the garment for rigid and semi-rigid road structures AND 540-2003,
- and Standard on determining the technical state of modern roads, indicative CD 155-2001.

The following aspects of the pavement construction and current condition are taken into account: the location / landscape and its geophysical characteristics, construction and previous inspection history information, road condition rating (bad/medium/good), maintenance works (e.g. strengthening of state slope), measurement and evaluation of IRI (International Roughness Index), water drainage system conditions, detected surface defects, and estimation and comparison of traffic volume.

However, visual inspection of the pavement surface does not provide sufficient information on the condition of the underlying pavement layers, which can be the root cause of surface failure. For instance, this could be due to cracking caused by deterioration and loss strength of base, sub-base or subgrade layers (resulting from poor drainage), cracks originating from fractures in lower layers, pavement structure deformation, etc. In summary, the underlying reasons of any inspection are [11]:

- To confirm that the structure is fit for purpose, and will remain so in the immediate future - that is, the rate of deterioration is acceptably low;
- To identify any obvious defects or instances of misuse, such as vehicle overloading, that may affect the safety of the public using the structure;
- To establish plans and estimates for undertaking remedial works.

Generally, NDT methods are used for evaluation of either functional or structural condition and, unlike visual surveys, require additional data processing and interpretation. NDT technologies commonly used in the quality control and acceptance (QC/QA) of HMA surface pavements include lasers, deflectometers, GPR (Ground Penetrating Radar), penetrometers, infrared, and seismic tools. Evaluation of the method efficiency is based on the speed of data acquisition, cost benefits, and resolution of the measurements (either surface texture or subsurface structure). It is common practice to use high speed inspection systems to minimise possible traffic disturbance and apply NDT methods for construction of a "structural map" of the entire highway network and the determination of the specific locations for destructive tests, i.e., targeted coring and sampling.

Evaluation of functional pavement condition is based on measurement of roughness, smoothness, skid resistance, friction, tire-pavement noise, etc. Roughness of pavement surface is characterised by the lack of smoothness in the longitudinal or transverse road profile usually resulting from high traffic volume and inadequate design. Severe roughness can significantly affect ride quality and safety. Laser profiling NDT methods use a profilometer (or profiler) survey vehicle (Figure 3.2.a) operating at highway speeds that measures longitudinal (and transverse) roughness statistics with 3D laser sensors. Parameters such as wheel path rut depths (transversal profile), macro texture of pavement surface, amount of surface cracking, as well as the International Roughness Index (IRI), Ride Number (RN), etc., are calculated from the processed measurements. IRI gives an indication of the longitudinal regularity of pavements and is commonly used worldwide in pavement management systems. Besides routine ride quality inspection, profilers are also employed for quality control and quality assurance (QC/QA) testing of new and rehabilitated road pavements.

a. Acuity® laser profiler [27]

b. GripTester skid resistance measurement equipment [28]

Figure 3.2 Examples of NDT equipment for evaluation of pavement functional condition

Skid resistance is defined by the surface micro and macro textures and its monitoring is of a particular concern due to the increased risk of accidents during wet weather conditions. A skid resistance survey is generally performed with either a locked-wheel skid trailer towed behind a vehicle (with a water tank), or a trunk mounted SCRIM (Sideway Force Coefficient Investigation Machine) system operating at speeds of up to 80 km/h. It measures the resultant resistance force to calculate surface frictional properties during simulated wet conditions (Figure 3.2.b). The results are represented as skid scores assigned along the inspected pavement segment (e.g., range 10-65, where greater values indicate higher skid resistance and high friction surface). The Brenner Motorway uses a SCRIM system (Figure 3.3), or equivalent, with reference to the CNR BU n. 147/92 "Standards for the measurement of surface features of pavements - Test method for measuring the grip coefficient with the SCRIM device" and/or similar European standards (CEN 15901-6 and 15901-8).

Figure 3.3 WDM® SCRIM system [30]

Another example of functional pavement condition measurement equipment is the TRACS (Traffic Speed Condition Surveys) system commonly used in the UK for trunk road network functional condition inspection. The pavement surface condition (texture profile, crack maps, transverse and longitudinal profiles) is measured with sensors and four view HDV cameras at speeds of up to 100 km/h. Defect detection is based on image processing and GPS location referencing (Figure 3.4.a). The Brenner Motorway uses a similar integrated system called ARAN (Automatic Road Analyser) that combines a laser profilometer, HDV, and GPS for data acquisition, and operates at traffic speeds (60 - 100 km/h) thus causing minimum traffic disruption. Tire-pavement noise is directly related to the surface macrotexture and is generally measured during phonometric surveys with fixed microphone located near the vehicle tire. In addition, phonometric surveys are also used for estimation of the acoustic pollution and potential draining capacity of pavements.

a. TRACS traffic speed pavement survey system [2]

b. ARAN system [23]

Figure 3.4 Examples of NDT equipment for evaluation of pavement functional condition

The characteristics of the functional condition of pavements are used for identification of the areas that require immediate maintenance actions and also provide quantitative information for planning and designing future interventions. According to the current provisions of the Italian Ministry for Infrastructure and Transport the status of pavements along the Brenner Motorway is defined by conditions related to grip/adherence (CAT parameter) and macro-roughness, i.e., the geometric texture (HS parameter), and finally through surveys related to the regularity of the longitudinal profile (IRI) [13]. In the Brenner Motorway, identification of maintenance requirements is based on evaluation of the following factors:

- pavement deterioration conditions (especially the transit lane);
- roughness (IRI);
- the grip features (CAT parameter);
- pavement surface defects (defects and deteriorations detected during visual inspection);
- historical data (pavement type, initial construction, and past maintenance works).

Some characteristics of data acquisition include: sampling step not exceeding 10 cm, survey of both wheelpaths, parameters are calculated for 20 m sections, while the macrotexture value TEX value is computed every 10 m. The system also measures the survey speed air and pavement temperatures and the progressive road mileage (GPS). Inspection weather conditions: air temperature 10 - 30 C°, pavement temperatures 10 - 35 C°.

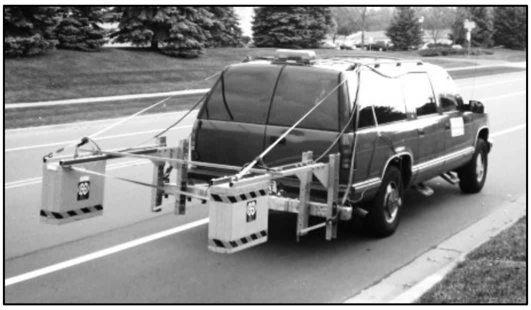
Assessment of structural pavement condition involves measurements of structural and material characteristics of pavement layers and indication of any changes that might affect pavement serviceability (e.g., structural changes defects). For instance, characteristics of HMA layers include dynamic modulus, density, voids, strength, while the condition of unbound layers is defined by density, water content, and strength. The structural capacity is generally evaluated by measurement of pavement deflection in specified locations by Falling Weight Deflectometer (FWD). FWD is a trailer or portable system (Figure 3.5.a) used for assessment of pavement load bearing capacity, layer thickness, and moduli. It measures surface deflection in the wheel path under dropped weights similar to the load produced by a vehicle. The testing intervals vary depending on the specified inspection plan. NDT inspection via FWD is commonly used to estimate pavement structural capacity for planned rehabilitation design or to determine if a pavement is being overloaded. Rolling Dynamic Deflectometer (RDD) measures load bearing capacity on the road network level. It applies heavy loads to the pavement and measures the induced deflection profiles that provide information on pavement fatigue and estimated residual life (Figure 3.5.b). RDD inspections are characterised by low speed (≈2.5 km/h). In the Vrancea County Council, FWD DYNATEST has been used for road inspection since 1996.

a. PaveTesting® FWD equipment [29]

b. WDM® Deflectograph [30]

Figure 3.5 Examples of NDT equipment for evaluation of pavement structural condition

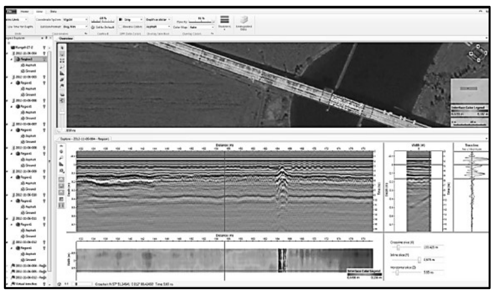
A novel and effective NDT pavement survey method, Ground Penetrating Radar (GPR) operates within the electromagnetic radiation spectrum and measures spatial dielectric characteristics of pavement layers. Air-coupled GPR is a vehicle-mounted device with one or more GPR antennas for the inspection of internal pavement structural parameters such as: layer thickness, material properties, moisture content, changes in construction, subsurface defects, embedded metals and reinforcement location (Figure 3.6.a). The measurements are obtained from the continuous profile of layer thicknesses and dielectric material variation. Penetration The penetration depth depends on the antenna characteristics, soil type, and environmental conditions. Estimation of material density and moisture content as well as detection of voids and stripping sites is based on the measured dielectric values (e.g., subgrade moisture content). Air-coupled GPR is the only traffic speed technology available for detailed evaluation of subsurface structure and composition.



a. Air-coupled GPR system [2]

b. Ground-coupled GPR system [24]

c. 3-D Radar® 3D GPR [21]



d. 3-D Radar® GPR data processing system [21]

Figure 3.6 Examples of NDT GPR systems (evaluation of pavement structural condition)

A ground-coupled GPR system consists of GPR antennas that are towed along the ground at walking speeds. It has better resolution and by operating at a lower frequencies it is able to penetrate much deeper into the pavement structure. Ground-coupled GPR is used for localisation of buried objects and estimation of deep water damage. GPR is mainly used on flexible pavements due to signal interference with the reinforcing steel joints in rigid pavements. New generation 3D GPR systems provide full lane width coverage with multi-channel antenna arrays, which allows reconstruction of 3D images of the subsurface objects (Figure 3.6.c-d). Portable GPR inspection systems are used for inspection of specific locations that require accurate subsurface measurement, e.g. bridge decks, concrete structures, utility mapping. Some of the inspection systems combine several NDT techniques. For instance, Figure 3.7 demonstrates an integrated pavement survey system with GPR providing information on pavement layer thicknesses for FWD measurements to achieve the correct interpretation of the corresponding layer stiffnesses.

Figure 3.7 GSSI® Integrated GRP and FWD system [25]

Emerging NDT pavement inspection technologies also include Traffic Speed Deflectometer (TSD), Infrared Thermography (IRT), Impact Echo, and other portable or vehicle-mounted sensors. Figure 3.8.a shows an example of Seismic Pavement Analyser (SPA) device, a seismic-based tool (based on impact hammers) for in-situ measurement of pavement layer material properties (stiffness) and thickness. Through analysis of the stress wave propagation speed, SPA is capable of detecting sites of material deterioration and the presence of discontinuities, such as voids, cracks, and delaminations. Unlike RDD, TSD (or Rolling Wheel Deflectometer) is a truck mounted system that measures pavement deflection from a large dynamic mechanical load at traffic speed although providing significantly lower resolution results. An example of a TSD system is shown in Figure 3.8.b.

a. Seismic Pavement Analyser [26]

b. Traffic Speed Deflectometer [22]

Figure 3.8 Examples of NDT equipment for evaluation of pavement structural condition

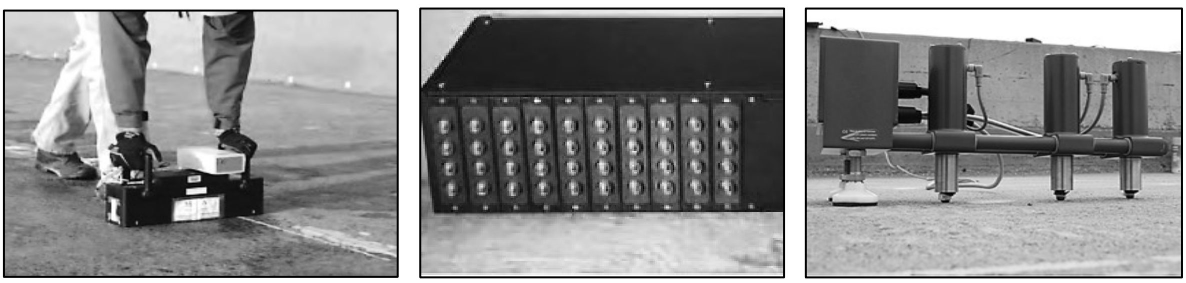
Infrared Thermography is employed for measuring segregation in pavement and concrete structures. IRT is used for detection of shallow delaminations, cracks, voids, and air gaps. Although IRT vehicle-mounted systems have been used routinely by highway agencies for detection of delaminations in concrete bridge decks, it is relatively new NDT method for pavement applications. IRT is highly effective in large area inspection but also has a number of limitations due to its sensitivity to environmental and surface conditions. Figures 3.9.a-b show bridge inspection Deck Top Scanning System (DTSS) with IR camera mounted on top of the specially designed vehicle and an example of an integrated GPR and IRT system for bridge deck inspection. Recently, Solla et al. showed successful application of combination of GPR and IRT for cracking detection and its severity evaluation in asphalt pavements [16]. IRT is also used for temperature measurement during HMA laydown to detect possible thermal segregation locations of the HMA course (Figure 3.9.c). The sites of segregation are characterised by lower density and higher susceptibility to ravelling and fatigue cracking.

a. NEXCO-West DTSS IR system [31] *b. Infrasense, Inc. integrated GPR and IRT system [33]* *c. IRT measurement of HMA overlay [32]*

Figure 3.9 Examples of NDT IRT systems for pavement inspection

Assessment of bridge deck condition is of critical importance for planning preventive maintenance, repair, or replacement. It requires the use of specific methods to monitor structure profiles (e.g. movements and deformations of bridge structures, and material deterioration). Currently, VI is the most common inspection method and the choice of used portable NDT equipment depends on the bridge type. Some of the NDT methods employed in concrete bridge deck inspection include mechanical sounding, acoustic rebound hammer, ultrasonics, electrical potential measurements, half-cell method, impact echo, IRT, and GPR [23]. The NDT inspection focuses on detection of the subsurface deteriorations: delamination, corrosion, cracking, and concrete degradation.

Based on the overall value in defect detection and characterisation, the most effective methods for concrete bridge deck inspection are impact echo, ultrasonics, GPR and IRT. Ultrasonic testing (UT) is widely used for bridge inspection for determining the integrity of structural concrete. This includes detection of voids, honeycomb, cracks, delaminations and assessment of density variations (relative strength). Figure 3.10 demonstrates application of pulse echo and surface wave UT equipment for bridge deck inspection.



a. MIRA dry-coupled UT pulse echo equipment [36] *b. MIRA dry-coupled UT transducer array[36]* *c. UT spectral analysis of surface waves equipment [23]*

Figure 3.10 Examples of NDT UT equipment for bridge inspection

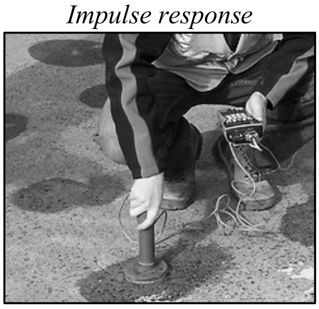
According to SHRP "Nondestructive Testing to Identify Concrete Bridge Deck Deterioration" project [35], amongst all NDT methods, impact echo and ultrasonic pulse echo/velocity have the highest accuracy and precision in detection of delaminations and cracking in concrete bridge deck. In addition, UT is the best option for of detection concrete deterioration sites and is successful in estimating shear modulus and identifying discontinuities in the pavement layers [39]. Cassidy et al. [17] showed successful combined application of GPR and dry-coupled ultrasound for void detection beneath reinforced concrete structures. However, portable dry- and water- coupled UT systems are generally characterised by low inspection speed. Air-coupled ultrasound is a promising method for NDT of bridge decks and pavements as it removes the coupling limitations of the traditional ultrasound inspection (Section 2.3). Recent studies showed that combined use of IRT and dry-coupled ultrasound [46, 47] is highly effective in identification of subsurface defects. In the system proposed by Aggelis et al., IRT provides information on position of a crack, while UT is used for measurement of its depth and proportions.

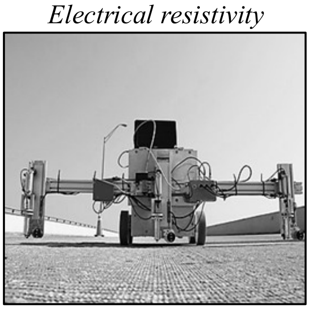
Figure 3.11 shows some examples of portable bridge deck NDT inspection tools. Currently, the thorough evaluation of bridge deck condition requires complementary application of multiple techniques. And most of them require high qualification surveyors and have limited inspection speed, which leads to traffic disruptions.


Impulse response


Electrical resistivity


Hammer sound


Galvanostatic pulse measurement


Impact echo


Chain drag

Figure 3.11 Examples of NDT techniques for concrete bridge deck inceptions [35].

At the same time, the severity of defects and the damage extent directly depend on timely detection and treatment. In the Brenner Motorway road network, it is the general practice to treat defects as soon as they are detected, thus ensuring high quality pavement condition by preventive maintenance. Two different types of construction methods can be used each time that maintenance interventions are required replacement of a 10 cm surface course (drainage course and binder), and reconstruction of all pavement layers of the transit lane (26 cm - drainage course + binder + base), which is undertaken in case of severe degradation in the pavement condition. Under more critical conditions, where the underlying structure is compromised, it is recommended that the superficial layers of the subgrade undergo regeneration. This has been the case in the southern part of the Brenner Motorway, between Mantova and Modena, for a road section of about 60 km.

3.2 Pavement management software and road condition rating

Pavement management software systems perform a number of functions for pavement monitoring and maintenance planning: from input, processing, and storage of raw inspection data to maintenance planning, budgeting, and analysis of repair history. For instance, the WDM® pavement management system has the following characteristics [30]:

- integrated multichannel mapping tools;
- HDV referenced to the maps;
- graphical full depth construction layers management;
- analysis of traffic statistics and modelling tools;
- GUI for graphical survey planning, road network editing, and construction management;
- automatic and manual input of inspection results (compatible with SCRIM system);
- advanced reporting tools (Strip Maps, business graphics, text reports);
- input and control of Maintenance Policies (structural, functional and safety requirements);
- asset management (history of maintenance costs and budget planning tools).

While maintenance software provides means for planning and control of both routine and targeted maintenance works. The figure below shows an example of pavement management system with visualised measurements of rutting severity along the city map.

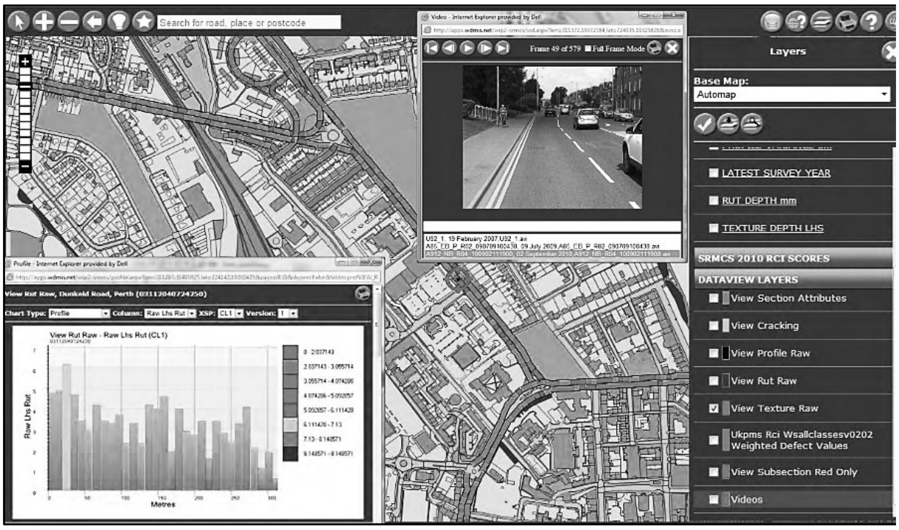


Figure 3.12 Example of pavement management software (WDM® pavement management system) [30]

Quantitative assessment of road condition (rating) is a product of the functional and structural conditions of the inspected road pavement segment, along with the detected surface defects (type, severity, extent). A number of pavement management systems use the AASHTO indices, specifically the Pavement Condition Index (PCI), the Road Condition

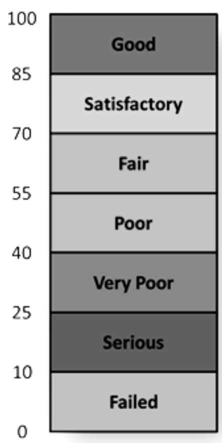


Figure 3.13 Pavement Condition Index (PCI) [8]

Index (RCI), and the Present Serviceability Index (PSI) for evaluation and numerical rating of general structural pavement condition and riding comfort.

For example, the FAA PAVEAIR [8] software uses PCI for assessment of airport pavement conditions based on the type, severity, and extent of the surface defects detected during visual inspection. A pavement condition rated by PCI is represented by a value between 0 (worst) and 100 (best condition). Pavement condition rating can be used for: - planning of required maintenance / rehabilitation works, - estimation of repair cost and extent, - and comparison of different pavements. While, the resent Serviceability Index is calculated as $I = 5.41 - 1.80\ lot(1 + SV) - 0.9\sqrt{C + P}$, where SV is the slope variance in the two wheelpaths, while C and P are measures of cracking and patching in the pavement surface, respectively [13].

COST Action 354 proposed the “Performance Indicators for Road Pavements” methodology [13] as a common maintenance tool to be used for management of the European road network (under the UN Road Safety Collaboration). The developed tool is based on the integrated system of performance indices (functional, structural, and environmental) used for evaluation of road condition with scores within 0 (very good condition) to 5 (very poor condition) range. The indices are calculated from pavement inspection results and technical characteristics such as surface macrotexture, longitudinal and transverse evenness, bearing capacity, cracking and surface defects, friction, noise, and air pollution.

According to [5], pavement condition can be rated in the range from 10 (excellent) to 1(fail), based on the visual survey results.

a. Rating10&9: Excellent / new or recently overlaid roads

b. Rating 8: Very good / recently sealcoated or overlaid roads

c. Rating 7&6: Good / signs of ageing, sealed cracks of low to medium severity, slight ravelling

d. Rating 5: Fair / extensive bleeding, medium ravelling, cracking of medium severity (but still in good structural condition)

e. Rating 4&3: Fair to Poor / severe ravelling, rutting, extensive cracking of medium to high severity, patching, potholes

f. Rating 2&1: Very poor to Failed / extensive severe cracking, rutting, potholes, severe patching and ravelling

Figure 3.14 Road condition rating from 10 to 1 [5]

Heavy traffic loading, changing weather conditions, original construction quality, and age are the main factors that cause deterioration of a new "excellent" pavement to lower grades. For example, Figure 3.15 gives a visual illustration of pavement condition vs. age [5].

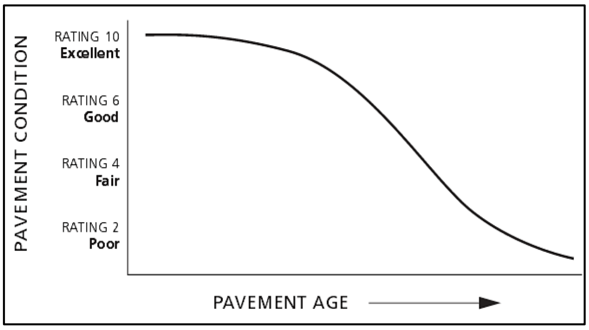


Figure 3.15 Pavement condition rating vs. age [5]

The pavement rating system can also be used for estimation of the optimal maintenance programme. For instance, in roads with a rating of 7 (good), routine crack sealing is recommended, while 4-3 rated roads must be strengthened with a structural overlay, because they have severe surface ravelling that cannot be sealed.

Although sometimes superficial, rating systems can visualise the general condition of a road network and can potentially provide convenient information for timely planning of maintenance works (e.g., to identify which roads require immediate maintenance).

4 RPB HealTec NDT system for road pavement inspection

There are many NDT techniques, each based on different theoretical principles, and producing as a result different sets of information regarding the physical properties of the structure. These properties, such as compressional and shear wave velocities, electrical resistivity and so on, have to be interpreted in terms of the fabric of the structure and its engineering properties. Inevitably, this interpretation involves some degree of assumption about the structure, and the use of calibration measurements is an essential feature of most non-destructive surveys. Furthermore, many structural problems will be best inspected by a particular NDT method, depending upon which physical properties of the construction materials offer the best chance of being reliably determined. The choice of the three NDT techniques was made after a careful consideration of the following factors:

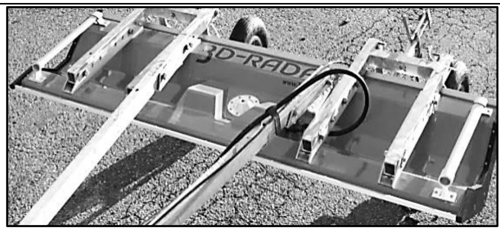
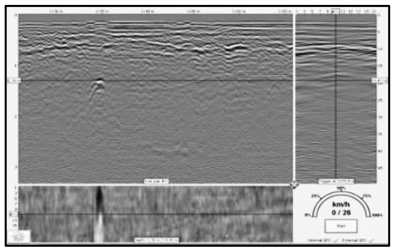
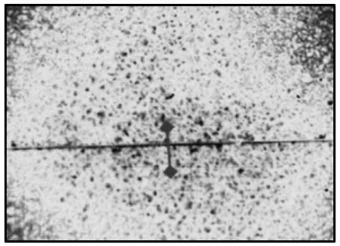
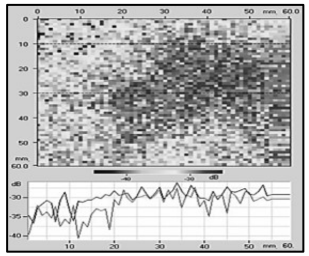
- Research on the latest developments in NDT, applicable to road inspection
- Analysis of these NDT technique developments regarding their eligibility to our ultimate goal (fast, accurate and low-cost road inspection)
- Evaluation and analysis of advantages / disadvantages
- Interrelation and interdependence of results to be expected from each method

The selected NDT assessment techniques GPR, IRT and ACU have the ability to inspect effectively substantial areas, such as pavements and concrete. These NDT techniques could be used successfully in the detection of cracks, voids and other imperfections appearing either from the ageing of the materials, heavy traffic load, adverse environmental condition, or due to poor maintenance. IRT directly senses the infrared radiation that a material or structure emits and detects surface temperature differences. Investigation of pavements by the means of IRT is achievable, in view of the fact that subsurface defects in a material affect the heat flow through that material, triggering surface temperature differences. So, the method is ideal for measuring segregation in pavements. GPR can provide information concerning the underlay structure of the examined pavements, layer thickness, as well as the depth and thickness of cracks, voids or other imperfections, such as moisture problems, appearing on the pavements. Furthermore, the use of ACU is mainly applied for sensitive inspections for defects such as voids, cracks and dis-bonds, for the identification of the thickness of pavements, the identification of complex modulus of elasticity of pavements, the non-destructive testing of bridge decks and the non-destructive testing of tunnels.

Table 4.1 provides summary characteristics on the NDT methods selected for RPB HealTec system regarding application areas, detection features, advantages and limitations.

Table 4.1 Comparison of the selected NDT methods

	Ground Penetrating Radar (GPR)	Infrared Thermography (IRT)	Air-Coupled Ultrasound (ACU)
Description and application areas	- Standard, widely employed technology for measurement of pavement structural and material characteristics. Application areas include inspection of concrete structures, bridge deck, pavement, railway, utility mapping, etc. - Electromagnetic echo sounding method that is used for mapping of structures and objects below the ground surface. - Processing, analysis, and reporting software is available. - For network-level survey 300 km or more can be scanned per day.	- By measuring IR energy from the surface, IRT cameras measure various levels of segregation. - Efficient in detection of segregation in concrete structures and bridge deck. - IRT is also employed in quality control of asphalt paving construction for measurement of density-related temperature differentials. - There are existing professional software and algorithms for image processing and algorithms for detection of defects.	- Novel efficient technology for non-contact ultrasound inspection of various materials (from wood and concrete to metals). - Unlike traditional UT, ACU does not require coupling. - Measurement the changes in ultrasound waves as they travel thought material. - Effective in detection of density variations and detects in structural concrete. - There are existing advanced algorithms and software for signal processing and algorithms for detection of defects.
Detection features	- Detection of variations in the pavement structure and material characteristics (surface, base, subbase), and variations of sub-base moisture content. - Assessment of depth and relative degree of severity of pavement discontinuities (defects). - Mapping of concrete reinforcement location and detection of buried objects.	- Detection of cracks with up to 1 mm width and their location, shallow delaminations (due to layer debonding), and voids/air gaps. - IRT provides an indication of the percentage of deteriorated area in a surveyed region. - Precision of temperature measurement is up to 20,000 points on a single image and 60 Hz image refresh time.	- Detection of shallow delaminations (stripping and debonding) and voids (air- and water- filled), measurement defect depth and changes in moduli. - Another application is analysis of surface texture characteristics based on the reflection wave measurements.
Advantages	- This is a standardized method for pavement structural inspection (layer thickness, subsurface defects and moisture content). Operates at traffic speeds. - HMA layer thickness detection accuracy is within 2-10% and the penetration depth of up to 1 m depending on the material type, age, and environmental conditions.	- IRT covers greater areas than other test methods. Easy to use equipment. - Detection of surface cracking and subsurface voids. - Existing vehicle mounted systems operate at traffic speeds up to 80 km/h. Modern IR cameras have 640x480 resolution.	- Structural measurements of surface course, detection of delaminations. - Effective resolution varies between 0.1 - 20 mm and penetration depth up to 30 cm depending on the system settings and the problem domain. - In theory ACU can operate at > 30 km/h speeds. Easy to use equipment.

	Ground Penetrating Radar (GPR)	Infrared Thermography (IRT)	Air-Coupled Ultrasound
Limitations	- Acquisition and interpretation of images requires training. - Sensitive to environmental (temperature, moisture level), surface texture (roughness), and subgrade (type of soil) conditions. - Cannot detect thin asphalt surfacing, adjacent layers of the same material of similar materials, debonding between asphalt layers (unless there is trapped moisture), and voids beneath reinforced concrete pavements. - Limited accuracy regarding measurements of surface crack depth.	- Highly sensitive to environmental conditions (time of testing, wind flow, sunlight, shadows). - Sensitive to surface texture and sub-surface conditions (moisture). - Anomalies are difficult to detect the deeper they are under the surface. - Trained operators are required for accurate data interpretation. - Higher speeds cause blurring and significantly lower detection quality.	- Low SNR due to the air-concrete impedance mismatch. Surface condition is critical for subsurface measurements. Limited depth of penetration. - Requires highly qualified interpreters. - ACU is a new technology and application specific systems have to be constructed from the commercially available components. - Concrete and asphalt concrete inspection is generally performed at 50 – 100 kHz frequencies and the low frequency transducers are more expensive.
Commercial equipment cost	- GPR systems are fairly expensive. Cost depends on the configuration: 50,000 – 200,000 €.	- High-resolution IR cameras cost around: 10,000-30,000 € for uncooled detectors and 30,000-100,000 € for cooled detector.	- Generally do not exceed 50,000 € depending on the required configuration.
Equipment examples	 *3D-Radar® GPR DX antenna array [21]*	 *FLIR® A655sc infrared camera [18]*	 *ULTRAN® ACU sensor arrays [20]*
Measurements examples	 *GPR: 3D view of inspected pavement [21]*	 *Thermogram of a crack (depth > 3cm) [16]*	 *ACU scan of uneven mixture HMA core [19]*

As the project outcomes demonstrated, fusion of GPR, IRT and ACU NDT techniques (Figure 4.1) provides multidimensional coverage for road pavement condition surveys and maintenance monitoring, i.e., identification of the pavement structure and possible deterioration sites, detection of surface and subsurface defects, assessment of pavement material condition, and detection of subgrade regions with moisture content. Besides the existing state-of-the-art NDT applications, major advantage of the RPB HealTec system is the traffic speed inspection that eliminates traffic disruptions associated with the commonly used pavement survey methods. The advanced data processing system was developed for efficient integration of the proposed NDT inspection approaches, while the sensor data analysis system provides reliable tool for detection of the pavement areas prone to deterioration and general assessment of the structural pavement condition.

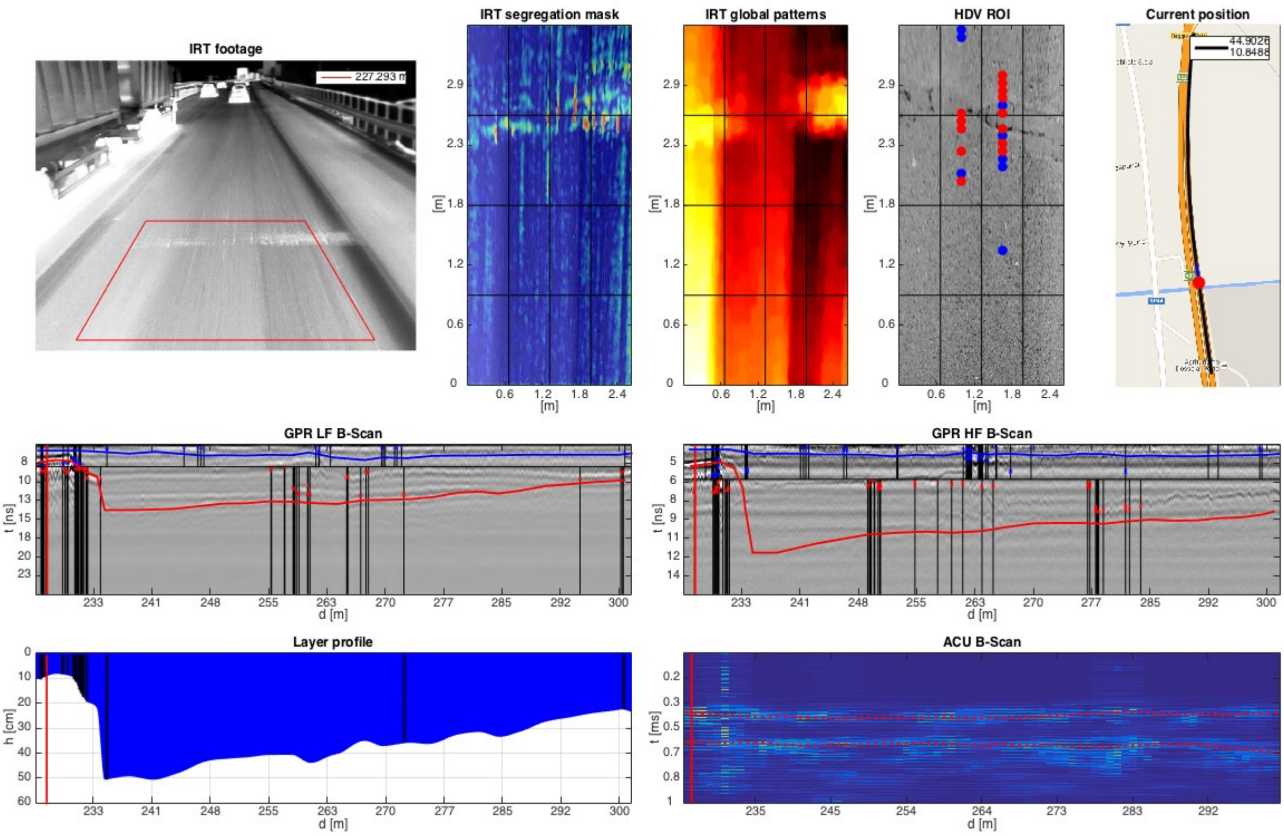


Figure 4.1 Fusion of GPR, ACU and IRT sensor datastreams

5 CONCLUSIONS

The present deliverable covered the essential aspects of pavement structure, commonly occurring defects and deteriorations, and existing NDT inspection methods for road and bridge deck inspection. Based on the EUs feedback, the list of general system requirements was formulated. HMA surfaced roads, and particularly flexible pavements, are predominant in the EUs' road networks. Correspondingly, common defect causes are related to the traffic load, pavement design and construction issues, ageing processes, and environmental conditions. A significant part of surface defects, such as cracking and deformations, is related to the subsurface distress, including stripping, debonding, and material degradation. Modern NDT vehicle mounted systems for functional pavement condition evaluation operate at traffic speeds but are limited to superficial surface information. And although a number of NDT technologies for structural pavement condition assessment have recently emerged and standardised (e.g., GPR, TSD), visual surveys remain the most common type of pavement inspection methods on a regular basis. Detection of subsurface defects and structure deteriorations is generally based on the analysis of surface defects as indicators, which however are not visible until a relatively severe level of damage. The cost of timely preventive maintenance measures is significantly lower than that of rehabilitation works.

At present, there are no existing solutions that can provide 100% coverage of road structural condition parameters. The end users of RPB HealTec, a leader in highways infrastructures BRENNERO and a public highway administrator CJ VRANCEA, are seeking an integrated solution that would be able to reduce their costs and improve their performance by means of accurate and fast road inspection. However, the current practice along the European infrastructure agencies varies, depending on their access to new technology and scientific advancements, their accuracy level requirements, their speed requirements, their countries of operation which are dictating the utilised standards.

The RPB HealTec system provides a novel technological solution by fusion of multidimensional NDT technologies, Ground Penetrating Radar (GPR), IR Thermography (IRT) and Air Coupled Ultrasonic testing (ACU) in an integrated scanning system for the inspection of civil engineering structures (i.e., bridges, airport and road pavements). Fusion of these NDT techniques can be successfully used in the assessment of the pavement structural condition including detection of surface and subsurface detects such as cracks, delaminations and other deterioration mechanisms. Essentially, the final aim of the project is to provide an integrated scanner system for prompt assessment and monitoring of pavement structures at traffic speeds (up to 60km/hr) and with the ability to detect surface and subsurface defects and deterioration sites as well as proving information on the layer structure profile.

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