GPR Application	Methodology			Processing		Results		Complementary Tests (NDT, coring, etc.)	Ref.
	Antennas & Acquisition parameters	Testing Set-up	Equipment	Filters & Algorithms	Software	Achievements	Inconveniences & Limits		
GPR travel time data were used to estimate the water content in each aggregate layer and the variations in water content with time, and GPR amplitude data were used to indicate areas of high-water content immediately beneath the asphalt layer	900 MHz and 1.2 GHz Trace-interval distance: 2 cm Data acquired in CO mode and CMP with the 900 MHz antenna Data acquired in CO mode with the 1.2 GHz antenna	Grid of profile lines Infiltration of water during 33 weeks and GPR data acquired periodically	PulseEkko1000 (Sensors and Software) Odometer	Stacking: 16 traces; low-cut filter; time-varying band-pass filter; automatic gain control (AGC)	NP	(i) The amplitude of the reflected radar-wave used to distinguish between wet and dry areas; (ii) low errors in the estimation of water content in sub-asphalt aggregates; (iii) the technique has potential to be used in routine pavement surveys; (iv) GPR travel time data used to estimate the spatial distribution of water inside the aggregate layer; (v) allows to determine the efficacy of sub-asphalt drainage layer	(i) In large scale surveys data collection must be simplified. The authors propose the use of a one frequency antenna although multi-frequency antennas; (ii) lower frequency is needed to analyse the layer. However, lower frequencies cannot accurately image reflections near the thin layers, producing errors; (iii) the reflection amplitudes may not be strongly correlated to the average dielectric permittivity of the underlying layer. This effect introduce errors in the thickness estimation; (iv) errors are also associated to inaccurate dielectric permittivity estimation as a consequence of pooled water in drained pavements	TDR Samples Gravimetric water content measurements after infiltration and monitoring	[34]
Analysis of the accuracy of pavement layer thickness estimation using different estimation approaches. Laboratory and field data	1 GHz air-coupled horn antenna	Nine pavement sections (between 0 and 5 years old) depending on homogeneity	NP GPR mounted at the front of a van with the antenna suspended 0.5 m and moved at 80 km/h	Band-pass filter (500 MHz - 2000 MHz) Horizontal low-pass filter of 5 scans Measurements of permittivity based on: i) field measurements; ii) using travel time core thickness; iii) laboratory measurements	NP	(i) The three approaches to obtain the dielectric permittivity have a satisfactory performance; (ii) the travel time core thickness provide the minimum error; (iii) direct estimation of dielectric permittivity in field surveys is an effective method	(i) The accuracy in the procedure based on travel time core thickness depends on the amount of cores obtained; (ii) direct estimation of dielectric permittivity in field surveys could not be enough precise for some pavement management purposes	Laboratory measurements in cores with percometer	[36]

A solution of the problem due to reflections in multiple pavement thin layers, that usually are difficult to identify. The solution consists of detecting the strong reflections and synthesizing a signal similar to the GPR strong reflections. The synthesized signal is subtracted from the field data, allowing the detection of the week and obscured signals	Ultra-wide band air-coupled antenna, mounted on a vehicle at 0.5 m above the pavement surface Horn 1 GHz bandwidth antenna	Data collected in a known experimental pavement site, with 12 different sections of about 100 m long each one of those sections	NP	Band-pass filters (large band-pass during data acquisition, and narrow band-pass during data processing)	NP	(i) Proposed and tested a technique to detect automatically all detectable reflections, including masked weak reflections; (ii) a matched filter detector (MF) is accurate if most of the pavement layers are thick; (iii) in pavements with multiple thin layers, a threshold detector should be used; (iv) the pavement layers are considered thick of thin compared with the GPR wave length; (v) the detector applied iteratively allows to detect all the layers of the pavement; (vi) the error in the measured thickness was 2.5%	(i) The error in the measured thickness analysis is 10.2% when only the strong reflections are considered for the interpretation	The 12 experimental sections were monitored with strain gages, pressure cells, thermocouples	[38]
Combining GPR with infrared thermography to detect cracks in the pavement and their possible origin. An experimental test is compared to field data	1 GHz antenna Time window: 30 ns	Data acquired in a prepared pavement, with cuts at different depths Trace-interval distance of 2 cm and 337 samples per trace	ProEx System from Mala Geosciences	Time-zero correction; Dewow; Gain function with linear and exponential components; Background removal; Band-pass (Butterworth) filter	ReflexW GprMax (for synthetic models) Mathlab (to export synthetic data)	(i) The amplitude is an indicator of the existence of cracks, but there is no correlation between amplitude and depth of the crack; (ii) the amplitude of the anomaly depends on the type of crack (geometry and angle of inclination); (iii) GPR allows to detect complex reflections under the superficial layers, associated to in-depth structural failure; (iv)	(i) The reflections produced at the bottom of the cracks are not distinguish in GPR images, and the procedure used in the experimental test to determine the depth of the crack produce inaccurate results in the field surveys; (ii) the reflection on the bottom is not detected because of: a) complex pattern of reflection of the surface layers due to the	Infrared thermography Computational models with GprMax	[40]

						reflections are better defined in the case of wetted cracks; (v) the difference in amplitude between dry and wet cracks is smaller in the case of field surveys than in the experimental test; (vi) GPR is effective detecting cracks due to amplitude variations, and thermography detects cracks based on different temperatures between cracks and pavement surface; (v) the error in the depth crack determination is 5.5%; (vi) GPR allows to determine cracks in-depth and other damage, while thermography determines differences between dry and wet cracks. This fact demonstrates the importance of combining methods	presence of voids and b) size of cracks less than 4 cm		
Analysis of cracks detection in rigid pavements by combining laboratory tests and numerical modeling. The cracks are simulated in the concrete layer covered by an asphalt layer	Shielded ground-coupled 2.3 GHz antenna Time window: 10 ns Sampling frequency: 20 GHz	Data acquired on samples simulating aligned and unaligned cracks at each layer. All data was acquired with the antenna dipoles oriented perpendicular and horizontal to the crack axis	Ramac (Mala Geosciences)	NP	GprMax for numerical modelling	(i) In laboratory cracks in the top asphalt layer are detected (until 10 mm wide); (ii) Laboratory and synthetic data allows to determine the bottom of the fracture	(i) Detection of fractures in the bottom layer are detected only in the case of non-aligned fractures; (ii) in field surveys, cracks in the concrete layer are more confuse; (iii) existence of rebar affects the detection of the bottom fractures in the concrete layer; (iv) thin fractures on the concrete layer are not detected	Numerical simulations Cores	[42]

Analysis and discussion about the use of GPR spectra in detecting layers and damage in pavements. The field study is carried out in a highway in two different stages of its service life (first survey in 2004 in a new pavement not open to the traffic, and second survey in 2013). The different pavement features are related to the frequencies and the shape of the spectrum	Ground-coupled shielded 800 MHz antenna	Antenna mounted on a vehicle 15 cm above the pavement surface One trace each 25 cm	Ramac (Mala Geosciences)	Processing: (i) Preliminary GPR and FWD used to divide the road in zones; (ii) each zone was divided in sections showing similar GPR images of about 5 m, and the average trace of each section was obtained; (iii) the A-scans in time domain were converted in frequency domain.	NP	(i) Changes in the frequency signature seems to be associated to the layers thickness; (ii) the peak of the spectrum is moved to lower frequencies, and the amplitude diminish in the case of thick layers; (iii) the spectrum presents two or more zones in the case of two or more pavement layers; (iv) changes in water content seem to be associated to changes in the bandwidth of the spectrum: the bandwidth diminishes as the water content increases; (v) some peaks of the spectrum seems to be related to debonding; (vi) comparing the spectrum between new and old pavement, differences in the spectrum can provide information about damages	(i) More studies and controlled tests are needed to determine the applicability of the frequency analysis in the assessment and monitoring of pavement	FWD Cores	[48]
The paper summarizes the use of GPR to estimate pavement layers thicknesses, validating the different methods with field tests, and proposing	Air-coupled antenna	NP	NP	Deconvolution Dielectric constant of each layer determined using the amplitudes Subtracted a synthesized signal containing only the strong reflections	NP	(i) In the studies of pavements composed by thick layers, GPR data provides accurate thickness results; (ii) the error in the thickness in the case of thick layers is 2.9%, approximately the same error when measuring directly from cores; (iii) results in the case of thin layers can be improved in the case of data	(i) In the case of pavements with one or more thin layers, the GPR accuracy degrades considerably; (ii) In the case of thin layers, the GPR data overestimates the average thickness in a 20% compared to the design thicknesses; (iii) lack of visibility of layers in the case of low dielectric permittivity contrast	Cores	[60]

alternative analysis techniques to increase the accuracy						acquisition with a bistatic air-coupled antenna and a monostatic ground-coupled antenna; (iv) in the case of GPR data obtained with a single antenna, the detection of thin layers can be improved by using deconvolution during processing. The error pass from 12% in the case of non-processed data to a 3% in the case of processed data			
Review and a analysis of different algorithms for time-delay estimation in order to determine the best techniques for estimating thin pavement layers thicknesses of approximately 2 cm thick, with special emphasis in those algorithms that provides superresolution and high-resolution	1.7 GHz bow-tie bistatic antennas (time window 10 ns)	1024 samples per trace Sampling frequency 102 GHz The antenna was moved slightly between various snapshots to generate independent spatial measurements	GSSI SIR-3000	Time filtering Data whitening Subband smoothing Hilbert transform Thickness estimation with the different tested algorithms: multiple signal classification (MUSIC), root-MUSIC (polynomial version of MUSIC), Min-Norm, root-Min-Norm, estimation of signal parameters via rotational invariance techniques (ESPRIT), least-square modified Yule-Walker (LSMYW)	NP	(i) All the tested processing techniques improve the time resolution of conventional GPR analysis; (ii) the resolution of each technique depends on the SNR; (iii) for the estimation of thin layers, a SNR higher than -7 dB is needed for a 2 GHz GPR bandwidth	(i) It is important to take into account the dispersion; (ii) further works are needed to determine the influence of pavement roughness on the correlation magnitude between echoes	Tests in laboratory Numerical modelling	[61]

Presents a method to determine layers thickness for flexible pavements, based on predicting the reflected frequency spectrum through a multiple reflection model. It is developed considering two layers: the hot-mix asphalt (HMA) and the base layers. It is based on comparing an spectrum modeled by using the reflected energy at each layer with the experimental data spectrum	NP	Tests in three sections of a secondary road	NP	FFT Model the spectrum and compare with the spectrum of the real data, computing the root-mean squared error The frequency of the spectrum is selected based on the minimum of the root-mean squared error Inverse Fourier Fast Transform	NP	(i) The proposed method resolves thin layers including dielectric permittivity and conductivity losses	(i) Validation is needed in the case of including more than two layers; (ii) high computational time to predict the thickness of the layers; (iii) multiple solutions can be found for the same pavement layout. In the work, the RMSE criterion (root-mean squared error) is used to select the best solution, but other criteria must be studied	NP	[62]
Use of an antenna array to determine the thickness and dielectric permittivity of the asphalt layer calibrating previously the antenna. Laboratory and	One Vivaldi antenna transmitter and five Vivaldi antennas receiver	Velocity and layer thickness are estimated after a conventional calibration and a phase center calibration	Own developed antennas	Band-pass filter (1 GHz to 4 GHz) Trace balancing	NP	(i) Thickness estimation of the asphalt pavement layer is less than 10% (approximately the same error than using cores); (ii) the method can be used without cores; (iii) the developed GPR antennas system is self-calibrating; (iv) dielectric permittivity is also accurately estimated, allowing the	(i) The equipment is only tested for asphalt pavements. In the case of concrete pavements, additional experiments are needed	Cores	[63]

field tests are presented. The GPR system is designed according to a reflection-to-coupling ration experiment in laboratory measuring gypsum plates with similar dielectric permittivity than the asphalt layers. The antennas were calibrated locating the antenna phase centers, which improves the accuracy of velocities and thicknesses estimation		Laboratory experiments using gypsum samples and field data acquisition in asphalt pavements				assessment of the materials; (v) the velocity in air is overestimated in a 3% with the conventional calibration, and it is reduced to a 1% after the phase center calibration; (vi) thickness is always overestimated after the conventional calibration (reducing the error 2.2% with respect measurements without calibration), but after the center phase calibration obtained errors are positive and negative being the error reduced 7.8%			
Description of the state-of-the-art of the GPR roads assessment in different European countries	Most common antennas in different countries: (i) Horn antennas mounted at 0.3-0.5 m above the	NP	NP	NP		(i) Determination of crack depth: a) Good results obtained with 50 mm depth cracks of higher and b) It is possible to detect cracks higher than 25 mm depth; (ii) Detection of excessive amount of water: a) comparative measurements are needed (period of minimum and	(i) Influence of data acquisition speed on GPR quality data; (ii) Position of the antenna during high speed data acquisition; (iii) data interpretation and automation of interpretation; (iv) autocalibration of layers and defects depth using multi-channels, WARR and CMP; (v)	NP	[64]

	surface pavement (Europe and USA) (ii) Dipole antennas (UK) (iii) Antennas arrays (allow autocalibration for thickness layers)					maximum rainfall) and b) several projects in progress. The effect in frequencies is being investigated; (iii) detection of voids under roadbase of joined unreinforced concrete pavements: voids higher than 30 mm thick and, in some cases, applying high resolution techniques, smaller voids can be identified; (vi) accuracy in roadbase layers depth: 5% in slow data acquisition; 10% in high speed data acquisition; (vii) accuracy in lower layers depth: 10% in slow data acquisition; 30% in high speed data acquisition	selection of the correct antenna for specific measurements; (vi) detection of water is affected by the type of bituminous layer		
Detection and characterization of vertical cracks. The work is based on field surveys and numerical simulation. Investigation of cracks visible in the surface and cracks that are not still visible in surface	Multi-channel SPIDAR system: two antennas (1 GHz and 250 MHz) Noggin SmartCart: single channel Ground-coupled multi-channel RoadMap system (1 GHz antennas at each lateral paths and 250	Ground-coupled multi-channel RoadMap system: antennas placed 0.01 m above the surface of the pavement; 0.05 m trace sampling interval with the 250 Hz antenna; trace sampling interval 0.03 m with the 1 GHz antenna	Sensors & Software	Dewow; Gain (exponential with a constant term, as a function of the distance to the source)	Field data NP GPRMax (numerical modeling) ADI-FDTD (subgriding before numerical modeling)	(i) Velocity obtained fitting hyperbolic anomalies and comparing TWT with cores; (ii) on some asphalt pavements, 250 GPR antenna often provides more distinctive response from vertical cracks than 1 GHz antenna, being more effective to detect cracks (probably due to crack roughness and waveguide effects), despite the small crack aperture; (iii) some cracks present high amplitude hyperbolas corresponding to the top and the bottom; (iv) sometimes the strongest	(i) High resolution GPR data can only be acquired with ground-coupled systems that cannot be used at highway speeds; (ii) comparing amplitudes of field data to synthetic models is only possible in the case of considering complete details of the antenna system in the model; (iii) field data present loss of high frequency content, that is not observed in the synthetic data; (iv) further studies are needed to investigate the waveguide effect that seem to be present in the 250 MHz field data	Cores 2D and 3D Numerical modeling (FDTD)	[65]

	MHz antenna in the central lane)	Position with odometer and GPS				response corresponds to the bottom of the crack when it corresponds to the contact between the asphalt and the underneath layer. This response is enhanced in the case of granular substrate; (v) for the 1 GHz antenna there is scattering from the interior of the asphalt layer and the underlying granular; (vi) Recommendation for pavements assessment: multi-frequency approach: high frequency for crack characterization and low frequency for crack detection			
Laboratory tests in acrylic specimens simulating pavements with cracks, and field surveys in three semi-rigid roads, to analyze the capability of GPR in pavement diagnosis. Several types of GPR response were classified and related to different type of cracks and processes associated to the	2.2 GHz air-coupled antenna	50 scans per meter Three parallel profile lines Position determined measuring the rotation of the vehicle wheel, and position of anchor points indicated manually	GSSI	NP	NP	(i) In lab tests the shape of the diffracted signal is a hyperbola with a peak corresponding to the crevice edge and point defect; (ii) in field tests, the shape of hyperbola presents correlation with the observed cracks; (iii) in asphalt pavements, the correlation of anomalies observed in adjacent traces is an indicator of the existence of cracks; (iv) the cracks having clear manifestations on echograms are generally large and developed structures, in some cases filled with foreign material	(i) The position of the anomalies along the profile line are not enough precise when determined with visible anchor points, mainly in the case of cracks that are not visible on surface, because decimeter of precision is needed, and this method allow a precision between 1 m and 10 m; (ii) the initial unopened cracks are not visible using GPR, and the use of higher frequencies shouldn't make them visible, because the signal is masked as a consequence of granular media (like asphalt mixture)	Cores	[66]

presence of cracks (crumbling, erosion and lithological alterations)						(v) Lower frequencies allows a better detection, and higher frequencies allows to outline details			
A method for automatic detection of road surface cracks with GPR, defining its limits regarding the size of the cracks. The method is tested in asphalt slabs cracked applying loads. The method consists of a processing using DVS: the first SVD eigenvalue corresponds to the reflection on the surface. The next eigenvalue of the image represents the reflection on cracks. All the remaining eigenvalues include the unimportant noises and	2 GHz antenna 4 GHz antenna	Position determined with and odometer	GroundVue 3 GPR (Utsi Electronics)	Clutter reduced with Singular Value Decomposition (DVS) Median filter to improve the peak-signal-to-noise ratio	NP	(i) The method provides a better visualization of cracks than the usual method; (ii) cracks are detected despite the conditions (covered with paper simulating leaves, filled with sand and other materials, etc.); (iii) the method can be used in a GPR system mounted on autonomous robotic systems, combined with other devices	(i) In 3.5 m long experimental section it was detected a false positive attributed to the effect of roughness; (ii) narrow cracks can be undetectable (1.1 to 1.3 mm wide); (iii) the post-processing used to improve the signals from cracks reduce the amplitude corresponding to small cracks. Therefore, further work can be devoted to diminish this effect	Modelling	[68]

reflection on other targets									
Report of the GPR highway applications in Scandinavia and USA	Ground-coupled antennas in a range of frequencies between 80 MHz to 1.5 GHz Air-launched antennas in a range of frequencies between 500 MHz and 2.5 GHz	Data collection up to 100 scans per second allows a survey velocities up to 100 km/h	GSSI Penetradar Pulse Radar Sensors & Software Mala Geosciences	Basic signal filtering; Background removal; Inversion techniques	GPR software integrated in road analysis and design software packages	(i) Application in subgrade soil evaluation: a) identify coarse gravel, sand and glacial till soils, b) GPR works well in organic peat soils and c) good penetration in silty soils; (ii) depth to bedrock: a) allows observe the bedrock stratification and the main fractures; (iii) soil moisture and frost susceptibility: a) estimation of water content and drainage characteristics of the subgrade, b) classification of subgrade soils in Finland depending on the dielectric permittivity and the conductivity and c) detection of frozen soils because the existence of frozen-not-frozen interface in the GPR images; (iv) Locating sinkholes under the road; (v) monitor grout injection into the voids; (vi) location of underground utilities; (vii) pavement structure evaluation: estimation of layer thicknesses (with TWT) and layers permittivity (with amplitudes). In new pavements the accuracy is about 3 to 5% without cores. In the base layer the accuracy is between 8 to 10%; (viii) detection	(i) Application in subgrade soil evaluation: a) problems in clay soils depending on the mineral content and b) soils with dielectric dispersion produce ringing in GPR images; (ii) depth to bedrock: a) bedrock difficult to observe depending on the penetration depth; b) weak signal in the case of small dielectric permittivity contrast between the bedrock and the subgrade soil and c) not always clear anomaly; (iii) pavement structure evaluation: for older pavements, validation is recommended; (iv) detection of defects: changes in moisture produce different patterns in GPR images	FWD Percometer Cores	[69]

						of defects; (ix) base course: GPR is more powerful combined with other geophysical surveys; (x) quality control: layers thicknesses and voids content			

Table S1. Roads: relevant on-site GPR surveys (NP = Not Provided; Ref. = Reference).