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1 **GPR Monitoring for Road Transport Infrastructure: A Systematic**
2 **Review and Machine Learning Insights**

3 Mezgeen A. Rasol ¹, Jorge C. Pais ², Vega Pérez-Gracia ³, Mercedes Solla ⁴,
4 Francisco M. Fernandes ⁵, Simona Fontul ⁶, David Ayala-Cabrera⁷, Franziska
5 Schmidt¹, Hossein Assadollahi⁸

6
7 ¹ Université Gustave Eiffel, MAST/EMGCU, 5 Boulevard Descartes, 77454
8 Marne-la-Vallée cedex 2, France

9 mezgeen.rasol@univ-eiffel.fr ; franziska.schmidt@univ-eiffel.fr

10 ² University of Minho, ISISE, Department of Civil Engineering, Guimarães,
11 Portugal

12 jpais@civil.uminho.pt

13 ³ Universidad Politécnica de Cataluña, EEBE School, RMEE Department,
14 Barcelona, Spain

15 vega.perez@upc.edu

16 ⁴ CINTECX, GeoTECH research group, Universidade de Vigo, Vigo, Spain

17 merchisolla@uvigo.es

18 ⁵ University Lusíada – Norte, Largo Tinoco de Sousa, Vila Nova de Famalicão,
19 Portugal

20 francisco.fernandes@fam.ulusiada.pt

21 ⁶ National Laboratory for Civil Engineering (LNEC), Transportation Department,
22 Lisbon, Portugal

23 simona@lnec.pt

24 ⁷ CWRR - School of Civil Engineering, University College Dublin, Belfield,
25 Dublin 4

26 david.ayala-cabrera@ucd.ie

27 ⁸Setec Group, Structural and Geotechnical Health Monitoring Department, LERM,
28 Paris, France

29 assadollahi.hossein70@gmail.com;

1 GPR Monitoring for Road Transport Infrastructure: A Systematic Review and Machine 2 Learning Insights

3 Mezgeen A. Rasol¹, Jorge C. Pais², Vega Pérez-Gracia³, Mercedes Solla⁴, Francisco M. Fernandes⁵,
4 Simona Fontul⁶, David Ayala-Cabrera⁷, Franziska Schmidt¹, Hossein Assadollahi⁸

5
6 ¹ Université Gustave Eiffel, MAST/EMGCU, 5 Boulevard Descartes, 77454 Marne-la-Vallée cedex 2,
7 France

8 mezgeen.rasol@univ-eiffel.fr ; franziska.schmidt@univ-eiffel.fr

9 ² University of Minho, ISISE, Department of Civil Engineering, Guimarães, Portugal

10 jpais@civil.uminho.pt

11 ³ Universidad Politécnica de Cataluña, EEBE School, RMEE Department, Barcelona, Spain

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14 merchisolla@uvigo.es

15 ⁵ University Lusíada – Norte, Largo Tinoco de Sousa, Vila Nova de Famalicão, Portugal

16 francisco.fernandes@fam.ulusiada.pt

17 ⁶ National Laboratory for Civil Engineering (LNEC), Transportation Department, Lisbon, Portugal

18 simona@lnec.pt

19 ⁷ CWRR - School of Civil Engineering, University College Dublin, Belfield, Dublin 4

20 david.ayala-cabrera@ucd.ie

21 ⁸ Setec Group, Structural and Geotechnical Health Monitoring Department, LERM, Paris, France

22 assadollahi.hossein70@gmail.com;

23 Abstract

24 Suitable road pavements assessment becomes essential to provide safe traffic movements of people
25 and goods. Moreover, a reliable transportation network is a crucial aspect of economic growth.
26 Road pavements are subjected to various factors that influence overall performance (e.g., traffic
27 load, temperature, moisture, delamination of the pavement layers, subsurface condition, etc.).
28 These factors can reduce the infrastructure's life and decrease the circulation comfort of the
29 vehicles in the transportation network. Early inspection of pavements optimizes maintenance and
30 repairing methodologies, decreasing the maintenance cost and increasing the lifespan of the road
31 pavements. Non-destructive techniques are strongly recommended to achieve accurate and
32 valuable information from the subsurface condition. Ground Penetrating Radar (GPR) is a non-
33 destructive geophysical method widely used on infrastructure assessment, particularly in road
34 pavements, due to its low operation cost, time-saving, non-invasive, and less workforce. This paper
35 presents a critical state of the art of applying GPR to diagnose road pavement and detect inner
36 damages such as debonding, sinkholes, moisture, etc. The incorporation of the GPR with other
37 complementary techniques in pavement inspection is also discussed. Through the review, the GPR
38 capabilities for road inspection and evaluation of subsurface identification have been successfully
39 demonstrated and validated in numerous studies and case studies. Finally, the application of more

40 recent processing techniques to support decision-making owners/operators, such as machine
41 learning and intelligent data analysis methods, and the future challenges on the GPR application
42 in road pavements are introduced.

43 **Keywords:** GPR, road pavements, NDT, damages, intelligent data analysis, machine learning,
44 inspection, deep learning, decision-making

45 **1. Introduction**

46 1.1 Distresses in road pavement

47 Throughout the years, highways have been primordial for the mobility of people and goods, despite
48 the increase of different transportation modes, such as transportation by water, rail, and air. The
49 quality and safety of highways transportation depend on their surface regularity and strength
50 offered by road pavements designed to support a given traffic spectrum under certain climatic
51 conditions [1]. Depending on traffic volume and based on a life cycle analysis, pavements can be
52 constructed using asphalt or cement concrete on their surface, which leads to flexible or rigid
53 pavements.

54 Flexible pavements are composed of granular layers over the pavement foundation and asphalt
55 concrete layers on their top. In contrast, rigid layers are formed by cement concrete layer over a
56 cemented treated base. It is possible to have composite pavements that mix asphalt and cement-
57 based layers providing improved strength due to the cement-based layers and comfort due to the
58 asphalt layers.

59 Pavement design defines the pavement layers' thickness, which is controlled during and after
60 pavement construction. During construction, spreading equipment and the compaction process
61 ensure that thickness. However, the layer thickness is controlled by probes. After construction,
62 thickness is controlled by holes where it is possible to measure the layer's thickness or extract
63 cores for further measurement. These verifications only control the pavement thickness punctually.
64 However, continuous control is mandatory to ensure pavement quality. This control can be done
65 using Ground Penetrating Radar (GPR) with good precision after calibration for the layer material.
66 Depending on the layer thickness, different types of equipment should be used, and suitable results
67 have been obtained for very thin asphalt layers [2].

68 The quality of road materials is related mainly to their density obtained during compaction. Except
69 for certain types of materials, increasing material density increases material quality and extends
70 pavement life. This density can be controlled during and after pavement construction using

71 equipment for punctual measurement, but a continuous assessment is recommended. This
72 continuous assessment has been made using GPR equipment with exciting results.

73 The design periods of flexible and rigid pavements are entirely different, but the cracking level
74 characterizes their end-of-life period. Cracking is not the only distress on road pavements. Still, it
75 is the primary indicator for the lack of bearing capacity and thus requires a pavement rehabilitation
76 that, in most cases, is carried out by a pavement overlay. Typically, cracking propagates from the
77 bottom of pavement layers to the top, but in thick pavements, it is often to see cracking that
78 propagates from top to bottom. Cracks are very thin in flexible pavements, but their width increases
79 and can reach 1 or 2 cm due to the traffic and temperature variation. In rigid pavement, cracks are
80 always very thin, but these pavements have joints 1 to 2 cm wide. Even after pavement
81 rehabilitation or reinforcement, existing cracks in the old layers propagate to the new pavement
82 layers. This phenomenon is frequent and is due to the discontinuities in the old pavement layers,
83 and the cracking pattern of the old pavement is reflected in the new layers. In terms of crack width
84 and depth, the cracking condition can be assessed using GPR despite the difficulties inherent to
85 the signal propagation and the crack faces directions. These directions, using ground-coupled
86 antennas, are almost coincident, and measurements are not accessible.

87 Soils and granular layers have a behaviour influenced by moisture. These materials are compacted
88 for optimum moisture content, and the values above produce a decrease in their bearing capacity.
89 Because bound pavement layers (asphalt or cement-treated layers) are supported by foundation
90 (soil) and granular layer, the missing bearing capacity of these materials (due to the excess of
91 moisture or water) allows the pavement to bend, and the consequent cracking in asphalt and
92 cement-treated layer. Thus, moisture control and its assessment are vital for pavement integrity
93 and have been made using GPR equipment.

94 The pavement rehabilitation design requires two types of information from the old pavement: the
95 thickness of all layers and their stiffness. The accuracy for stiffness evaluation depends on the
96 exact pavement thickness on the bearing capacity assessment location. Because it is necessary to
97 assess the pavement thickness in all locations where bearing capacity tests are carried out, a
98 continuous evaluation of pavement layers thickness is essential and can be made using GPR
99 measurement. So, a combination of bearing capacity tests and GPR for thickness evaluation is
100 paramount for the correct analysis and design of road pavement and for its rehabilitation.

101 There are many utilities associated with highways, and the main are the utilities for underground
102 drainage, which must be in good shape for perfect water flow [3]. The main problem of these
103 utilities, when constructed with plastics, is their breaking due to the weight above them. Earth

104 obstruction is also frequent and avoids proper water flow. The identification and quality state
105 assessment of these utilities is primordial for good underground drainage. Other utilities under
106 highways include electric cables and water pipes, which must be located and identified mainly
107 during highway construction because they are not always well documented. Decision-makers in
108 both transportation agencies and utility companies need timely access to accurate utilities location
109 information to minimize the risk of disruption during highway renewal activities [4].

110 1.2 GPR background in road pavements

111 Proper monitoring of road pavement is a challenging task during the lifecycle of road pavements.
112 An appropriate inspection could lead to a better understanding of the current needs and the
113 structural performance status of the road pavements. On the other hand, a comprehensive
114 assessment of road damages provides reliable information to avoid unnecessary economic losses
115 and makes convenient transportation of people and goods available. Road pavement assessment is
116 divided into three main categories: visual inspection, destructive and non-destructive techniques.
117 Visual inspection is usually used when the damage is visible. Road inspection aims to provide
118 valuable but ultimately qualitative information during the initiation stage of damages in road
119 pavements to avoid unnecessary maintenance. Data is obtained from destructive and non-
120 destructive tests. Destructive methods are affected by some aspects: operation time window, cost,
121 professional labour, damage in the pavement's structural elements, and insufficient knowledge of
122 the pavement structure.

123 For this reason, researchers and road engineers in both academia and industry have strongly
124 recommended the use of non-destructive methods [5], [6]. GPR is a non-destructive geophysical
125 method widely used in the last decades for road pavement subsurface inspection [7]. Thus, GPR
126 has been used in various civil engineering applications, including road pavement assessment and
127 evaluation for repair and maintenance purposes [8]–[15]. The GPR method is based on the
128 propagation of electromagnetic (EM) waves through subsurface media. A transmitter antenna
129 emits pulsed EM signals towards a target medium with a specific wave velocity that depends on
130 the dielectric constant corresponding to each layer. The EM signal is partly reflected at the
131 interface between two different media and returns to the receiver antenna, and partly transmitted
132 into deeper layers until it reaches the time window established in setting parameters (Figure 1)
133 [16], [17]. The reflected wave is based on the amplitude strength, proportionally dependent on the
134 dielectric constant for each subsurface layer. The larger the dielectric contrast, the higher the
135 reflection amplitude is. EM wave velocity depends on the centre frequency of the GPR antenna
136 and subsurface conditions. For instance, higher wave velocity is achieved in dry than wet
137 conditions [18].

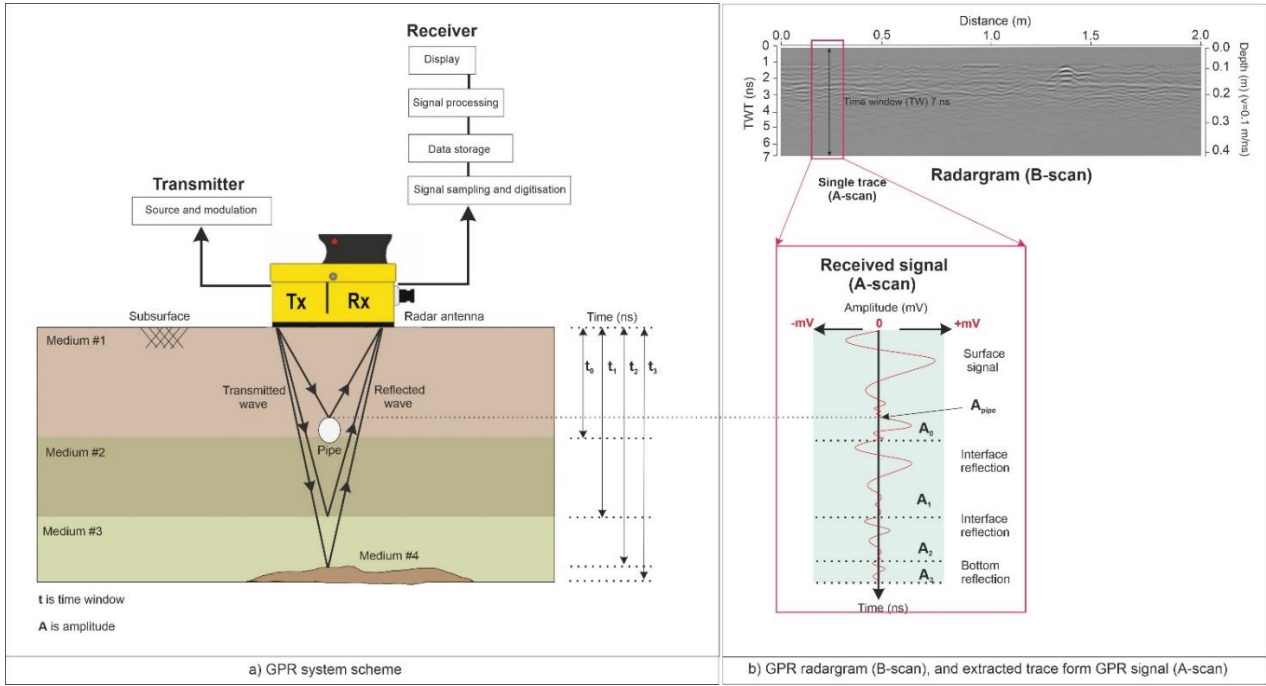


Figure 1 a) Scheme of a GPR system, b) visualization of an A-scan and a B-scan (adapted from [16]).

1.3 Advantages and limitations of current GPR technique

The GPR method is considered one of the most flexible and versatile non-invasive geophysical techniques, which has many advantages for road pavement inspection work and civil engineering applications [7], [16] Alongside the main strengths of the GPR method, various limitations are observed in previous studies and research works. Table 1 presents a list of advantages and limitations of the current GPR technique for road pavements inspection.

Table 1 List of possible advantages and limitations of the current GPR technique.

No.	Advantages	Limitations
1	High speed of inspection operation	High conductivity of materials such as clay and saturated clay
2	Mobile data acquisition or clouding sources	Signal attenuation in heterogeneous subsurface conditions
3	Low cost of the inspection operation	Scattering and backscattering of GPR signal
4	Less labour professional	Expert knowledge to process/interprets radar images
5	In-service road transports during the inspection	Depth of penetration highly dependent on the centre frequency of antenna and ground material condition

1.4 Objectives

This paper presents a critical review and progress of road transport monitoring opportunities by using GPR equipments, including the main applications related to road pavements. One of the main sections of this paper address current challenges, methodologies of the complex data analysis based on machine learning and other possible complex data analysis approaches. An advanced intelligent data analysis leads to a better understanding of road pavements and potential damages, which can be valuable information for repairing and maintenance processes. This analysis can be

156 an efficient approach to provide a helpful tool for owners/operators to monitor road pavements,
 157 obtain a green sustainable transport infrastructure, and overcome the current challenges and
 158 constraints in road pavement inspection. Moreover, through the literature review of this paper,
 159 some current methodologies are presented in terms of best practices of machine learning,
 160 intelligent data analysis of complex radar images, and recent advances in the field aiming to
 161 improve the application of GPR and avoid misinterpretation of radar images. Besides, a few
 162 European projects are presented in the area of advanced robotic platforms for road transports. The
 163 framework for systematic review of our research study is illustrated in Figure 2. This review study
 164 upgrades the current knowledge, literature by comprehensively reviewing the main distresses and
 165 features are occurs as a real damages over time on-site, and the possibility of the use of machine
 166 learning apparoaches to enhance the radar images, and this work is dedicated to present different
 167 ML approaches which can be efficient for the road pavement monitoring as a complementary
 168 approaches in order to provide better interoperability of radar images.

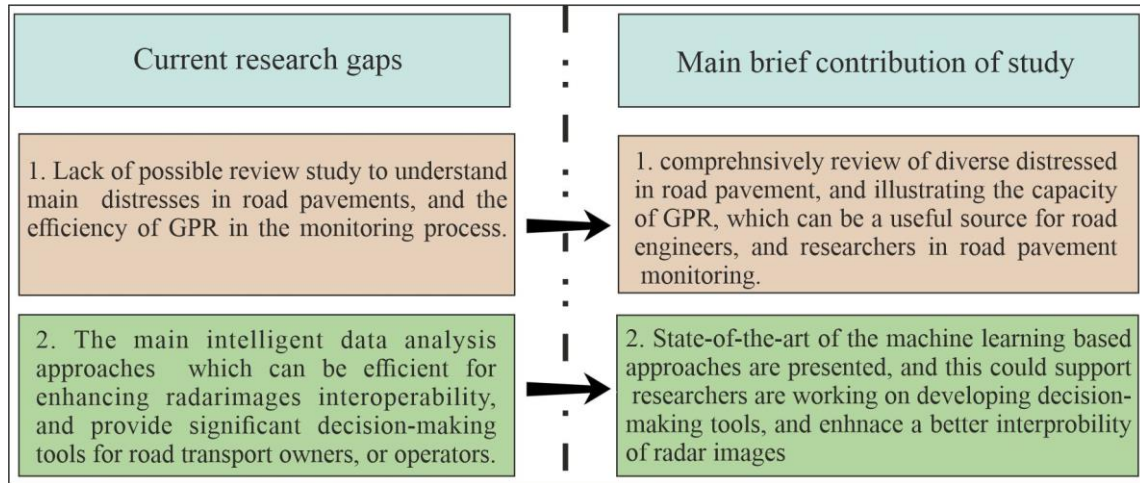


Figure 2 Existing research gaps vs main brief contribution of this review study.

1.5 Review Methodology

This paper highlights the main current progress and monitoring opportunities for road pavement inspection. The information considered in this review includes the main challenges addressed by the industry and researchers during the last two decades. The analysis is divided into three parts:

- i) those studies corresponding to the road pavement structure (i.e., layer thickness, thin-layer thickness, delamination and compaction of pavement layers, and conductivity properties of materials);
- ii) those studies dealing with the subsurface conditions of road pavement such as inner damages and deteriorations that occur along the road pavement lifecycle (i.e., cracking, delamination/debonding of pavement layers, subsidence and sinkholes, moisture content of granular and subgrade layer, etc.);
- iii) underground utilities in the subsurface of road pavements.

183 The following criteria were considered in this review:

- 184 • More than 100 studies over 20 years in GPR application on road pavements;
- 185 • Two main categories of the road pavements are considered, i.e., flexible and rigid
186 pavements;
- 187 • Pavement surface and subsurface distresses and real scale damages;
- 188 • Intelligent data analysis approaches based on machine learning and deep learning are
189 presented;
- 190 • New trends, research projects and future directions are also presented.

191 **2. GPR application on road pavement structure**

192 Road pavements use several types of equipment for assessment during construction, in service,
193 and after rehabilitation. Physical properties are obtained with these equipments to support the
194 design, maintenance, and rehabilitation of road pavements. GPR application on road pavements
195 dates back to the 1990s [19], [20], when a GPR was developed and used in various civil
196 engineering applications, in this case for inspection of the pavement condition to provide a
197 preventive maintenance plan. Significant applications have been made to measure pavement layer
198 thickness and density, which are supported by assessing the dielectric permittivity of road
199 materials. This chapter focuses on these applications.

200 **2.1 Layer thickness measurement**

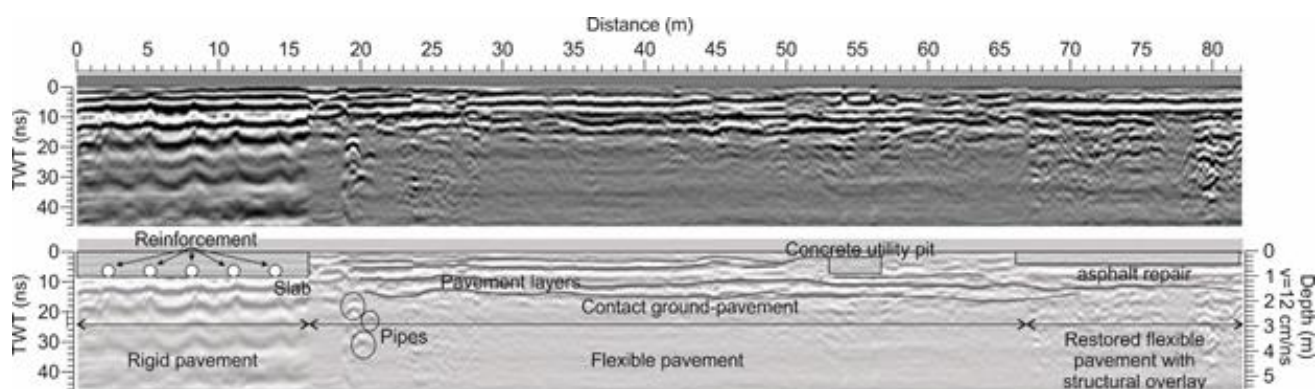
201
202 Assessment and management of roads require layer thickness control. This information is crucial
203 in quality control and for the evaluation of their remaining service life. Non-destructive tests
204 (NDT) with GPR have been proved a helpful procedure that provides precise information for
205 pavement maintenance and rehabilitation design. Therefore, this technique is nowadays fully
206 applied as the primary or complimentary test method in regular road inspections, which is usually
207 combined with Falling Weight Deflectometer (FWD) and coring. NDT applications reduce the
208 number of invasive tests, the conventional approach that consisted of extracting pavement cores.

209 Many authors have described the methodology applied in GPR assessments, demonstrating the
210 accuracy for:

- 211 • pavements composed of thick layers [2];
- 212 • acquiring data with a common offset and with common midpoint procedure [21];
- 213 • developing methods to detect automatically multiple layers, arriving at errors of about
214 2.5% [22].

215 The method has been included in guides for pavement evaluation in several countries. For
 216 example, the guide [23] contains the procedures recommended in the GPR inspection of
 217 bituminous and concrete pavements to assess thicknesses of layers. The standard alert about two
 218 problematic scenarios at which assessment can be difficult or even impossible: saturated
 219 pavements and extreme iron content in the aggregates. In these two cases, penetration depth could
 220 be insufficient to evaluate the state of the pavement because of the high signal attenuation. The
 221 use of GPR in roads evaluation has also been included in recommendations developed in different
 222 countries. This is the case of the Belgian [24] and British [25] regulations and the Mara Nord
 223 Project [26], a project developed in cooperation between the Nordic road administrations.

224 In most cases, thickness data is obtained from common offset measurements with impulse radar
 225 systems, usually with air-coupled antennas [27]. Those antennas are placed on a vehicle,
 226 suspended at a height of about 50 cm from the pavement surface. Data is acquired at a regular
 227 traffic speed, without impact on the use of the road, and pulses are emitted each 20 to 50 cm.
 228 Despite their low penetration and the distance between measurement points, their speed in data
 229 acquisition makes them ideal for the study of pavement layer thicknesses. However, in the case of
 230 more detailed studies of higher penetration depth required, the analysis is usually carried out with
 231 ground-coupled antennas. In this case, the antennas are in contact with the ground, being the data
 232 acquisition speed lower than in the case of air-coupled antennas, but reaching greater depths of
 233 study, which allows the analysis of the contact between the pavement and the ground, or the
 234 detection of anomalous targets under the pavement. Figure 3 presents an example of the image
 235 obtained with a 500 MHz centre frequency ground-coupled antenna during the study of the
 236 pavement of a main street in a dense city.



237
 238 Figure 3. Radar image of pavement layers. The discontinuities are associated with the contacts between layers. The
 239 presence of other targets is also detected.

240 In Figure 3 it is possible to distinguish between three different parts of the road: a concrete
 241 pavement (at the beginning of the profile), a flexible pavement (in the central part of the image)
 242 and, at the end of the profile, a flexible repaired pavement. In the three parts, the layers are

243 detected, combined with other anomalies corresponding to reinforcement or utilities. However, the
 244 images obtained in the flexible pavement are more detailed than those obtained in the other parts
 245 of the road. The contact between the subbase and the ground is clearly identified only in this part.
 246 The analysis of thickness layers is more difficult in the case of deteriorated material, older
 247 pavements or repaired roads.

248 The use of antennas arrays has also been evaluated and tested in different sites and laboratories,
 249 obtaining errors under 10% in the thickness estimation [28]. Many authors recommend using
 250 higher frequency antennas combined with lower frequency antennas to obtain an effective balance
 251 between resolution of the shallowest layers and penetration depth to detect the contact with the
 252 ground of anomalies placed under the pavement [29]. However, the conclusion of many analyses
 253 indicates that the thickness estimation accuracy in the case of non-uniform thickness layers is less
 254 than in the case of uniform layers. The precision depends on the calibration of the antennas [30]
 255 and on the approaches to assign dielectric constants to each pavement layer. The analysis presented
 256 by [31] compares three approaches that allow determining the dielectric constant of the layers: a
 257 direct estimation from GPR data, comparing GPR data with cores and, finally, using laboratory
 258 tests. The first method, which is using direct estimation from GPR data is the most imprecise, but it
 259 is as effective as a quick and rough procedure, compared with cores, this is one of the most
 260 effective methods, and non-invasive to detect the thickness layer then compared with core samples.
 261 The inconvenient is that in order to increase the accuracy requires a large number of cores, or in
 262 some cases an advance data analysis is a key to increase a better accuracy for the purpose of the
 263 decision-making assessment.

264 The detection of layer thickness (h) based on the estimated dielectric permittivity (ϵ_r) of each layer
 265 starts with the detection of the echoes time (t) and the analysis of the wave velocity (v) or dielectric
 266 permittivity at each layer, as indicated in Equation 1:

$$h = \frac{vt}{2} = \frac{ct}{2\sqrt{\epsilon_r}} \quad \text{Equation 1}$$

268 The direct estimation of the wave velocity from the GPR data usually is based on comparing the
 269 amplitudes of the different echoes, being the dielectric permittivity of the layer n , ϵ_m :

$$\epsilon_{rn} = \epsilon_{r(n-1)} \left\{ \frac{1 - \left(\frac{A_0}{A_{inc}}\right)^2 - \sum_{i=1}^{n-2} Ri \left(\frac{A_i}{A_{inc}}\right) - \left(\frac{A_{n-1}}{A_{inc}}\right)}{1 - \left(\frac{A_0}{A_{inc}}\right)^2 - \sum_{i=1}^{n-2} Ri \left(\frac{A_i}{A_{inc}}\right) + \left(\frac{A_{n-1}}{A_{inc}}\right)} \right\}^2 \quad \text{Equation 2}$$

271 Being ϵ_{rn} , $\epsilon_{r(n-1)}$ the dielectric permittivity at layers n and $n-1$, A_0 the amplitude of the echo from the
 272 first discontinuity, A_{inc} is the amplitude of the incident signal, A_i is the amplitude of the echo from
 273 the $i+1$ discontinuity, and R_i is the reflection coefficient from the i discontinuity. On the other hand,

274 several factors are affecting the detection of pavement thickness layer results, mainly, subsurface
275 condition, antenna frequency, noisy data, lack of information, combination of GPR signal between
276 different layers and ground size distribution of the media properties. Beside that the use of an
277 appropriate data processing is essential, for example using full-wave inversion, or using straight
278 ray methods for layer thickness or thin layer thickness [32]. In the following section more details
279 are presented for the thin-layer thickness assessment.

280 2.2 Thin-layer thickness assessment

281 Although layer thickness identification is one of the most typical GPR applications in pavements,
282 the depth and thick resolution are lower in thinner layers, having the highest difficulty in detecting
283 and separating the first echoes. Thin layers are those layers whose thickness is about the
284 wavelength of the incident wave. The echoes from both surfaces of a thin layer are detected as
285 overlapped anomalies in the GPR data, being difficult to distinguish the time of the arrivals.
286 Therefore, the usual evaluation of the images, using raw data or simple processing, is useless to
287 determine the layer thickness. The identification of close reflective surfaces depends on the GPR
288 vertical resolution, which theoretically is considered.

289 However, in field surveys, the vertical resolution is approximately the wavelength [33]. Although
290 this limit, GPR is sensitive to the existence of those thin layers. The resultant waveform of the
291 signal reflected on the top and bottom surfaces includes the coupling effects of both reflections,
292 and the shape and length differ from the source pulse. Based on those reflective properties, [34]
293 defined a thin layer as the layer whose thickness is less or equal to the predominant wavelength
294 divided by 8, obtaining the wavelength from the frequencies of the wave and the propagation
295 velocity in the layer material.

296 Thin layers are those layers with a thickness similar or smaller to the wavelength. Distinguishing
297 between the reflections on the top and the bottom of the layer is difficult or even impossible.

298 The accurate estimation of layer thickness requires a precise determination of the two-way travel
299 time of each reflection, which is not possible in the case of layers with thin thickness compared
300 with the electromagnetic incident wave length. The superposition of different reflections makes it
301 difficult or even impossible to determine those times. Consequently, noticeable errors affect the
302 estimation of the dielectric permittivities, leading to an inaccurate estimation of the thickness.

303 The problem of thin layers analysis has been evaluated by different authors. [35] analysed the
304 thickness estimation using GPR based on the vertical resolution of each antenna and distinguished
305 between rigid and flexible pavements. The work observes the difficulty in separate reflections due
306 to the overlap of waves. It also concluded that, in most cases, the estimated thickness is an average

307 value that combines several layers, detected as a single one. The different dielectric permittivity
308 from thin layers produces an overestimation of the total thickness. Determining the correct average
309 wave velocity inside the layers group and deconvolution in the data processing could produce more
310 accurate results. [36] proposed the regularized deconvolution to increase the thin layer detection
311 accuracy. They concluded that the error is less than the construction tolerance but only in the case
312 of a previous calibration. The analysis carried out by [35] compared the errors without calibration
313 for thick layers (more than 50 mm thick) with intermediate layers (between 30 mm and 40 mm
314 thick) and thin layers (between 25 mm and 19 mm thick), obtaining errors lesser than 8%. Still,
315 for thin layers, the errors present a wide variation, about 55%. The work demonstrates that the
316 error reduces dramatically when a core is used to calibrate the dielectric constant of each layer.

317 [37] analysed thin layer asphalt concrete (thickness between 19 and 50 mm) during compaction,
318 obtaining similar errors in the thickness estimation. Errors between 8% and 10% are obtained in
319 field surveys, while errors of about 9% and 1% affect the simulation results. The thickness of this
320 asphalt concrete layer is also analysed by [38] using a nonlinear gradient descent method. This
321 method produces accurate results but requires knowledge of the pavement structure.

322 High-frequency antennas between 1 and 2 GHz are recommended to improve the vertical
323 resolution and processing techniques to improve the time resolution [39], combined with
324 numerical models [37]. The technic and results depend highly on the signal-to-noise ratio in the
325 radargrams. Studies in sediments demonstrated that the data spectrum is sensible to the existence
326 of thin layers. These elements produce a shift towards high frequencies [40]. Applications of
327 spectra analysis in pavement assessment demonstrates the sensibility of spectrum in layers of about
328 12 cm, using a 900 MHz centre frequency antenna [41] , presenting changes in the amplitude
329 corresponding to the different layers' materials. In addition, the amplitude of the spectrum is
330 reduced, and the peaks move to lower frequencies when thickness increases [42].

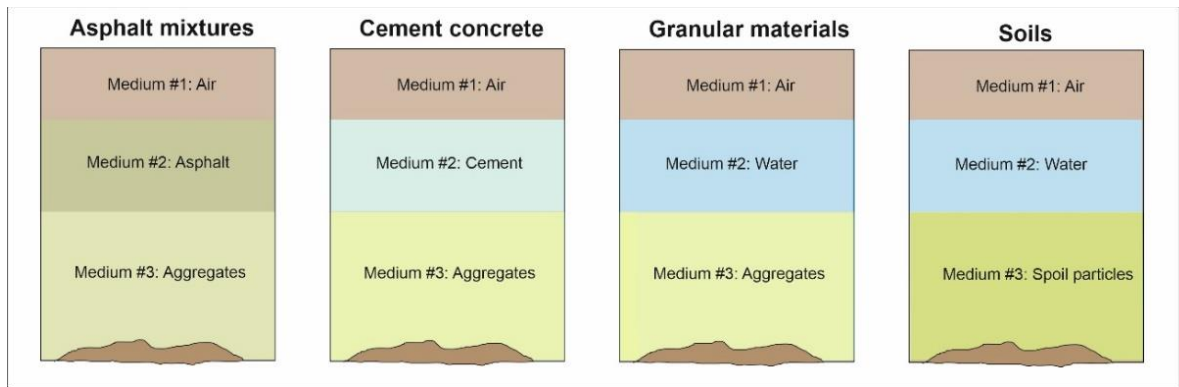
331 However, [22] concluded that the thickness estimation of thin layers is still a complex problem
332 due to the vertical resolution of the antennas; although accurate results have been obtained in the
333 case of the thin top layer thickness, using high pass filter and trace correlations [27]; or using a
334 regularized deconvolution algorithm that allows to distinguish between overlapped signals,
335 improving the vertical resolution in the radargrams [35] . Another proposed solution refers to the
336 design of new equipment and antennas. An example is the proposal described by [43], a step-
337 frequency radar operating in a range of 500 MHz to 6 GHz, specially designed for pavement
338 assessment. The tests in controlled areas indicate that this equipment can detect shallow layers of
339 about 2.5 cm.

340 2.3 Dielectric permittivity of road materials

341
 342 The dielectric permittivity (ϵ) is an essential quantity for GPR measurements. The terms relative
 343 permittivity (k) or dielectric constant are often used and defined in Equation 3, where ϵ_0 is the
 344 permittivity of vacuum, 8.89×10^{-12} F/m.

$$k = \frac{\epsilon}{\epsilon_0} \quad \text{Equation 3}$$

347 Road pavements have four materials, namely asphalt mixtures, cement concrete, granular
 348 materials, and soils. These materials are composed of elementary components such as asphalt,
 349 aggregates, air, cement, water, and solid particles, as represented in Figure . The dielectric
 350 permittivity of the bulk material is function of the percentage and dielectric permittivity of their
 351 components. Road materials typically have a dielectric permittivity in the range of 3-8.



352
 353 Figure 4. Schematic representation of road pavement materials showing their components (not to scale).

354 Based on the CRIM, the dielectric constant can be estimated by Equation 4 [44] for the case of
 355 an asphalt mixture,

$$(\epsilon_{am})^{\frac{1}{\alpha}} = \theta_{ag}(\epsilon_{ag})^{\frac{1}{\alpha}} + \theta_{ap}(\epsilon_{ap})^{\frac{1}{\alpha}} + \theta_v(\epsilon_v)^{\frac{1}{\alpha}} \quad \text{Equation 43}$$

357 where:

358 ϵ_{am} = dielectric constant of the asphalt mix;

359 α = parameter dependent on the mix composition (usually assumed to be 2);

360 θ_{ag} , θ_{ap} , θ_v = volumetric concentrations of aggregate, asphalt and air-voids, respectively;

361 ϵ_{ag} , ϵ_{ap} , ϵ_v = dielectric constants of the aggregate (typically 4 to 8), asphalt (typically 2 to 4) and
 362 air (1), respectively.

363 Considering the dielectric constants of the air and $\alpha = 2$, Equation 4 can therefore be simplified
 364 as expressed in Equation 5.

$$\sqrt{\epsilon_{am}} = \theta_{ag}\sqrt{\epsilon_{ag}} + \theta_{ap}\sqrt{\epsilon_{ap}} + \theta_v \quad \text{Equation 5}$$

367 This model can be used for the other road materials with suitable changes due to different
 368 components, mainly water for granular materials and soils.

369 A correct calculation of the dielectric permittivity is essential for GPR data processing as it is
 370 necessary for all measurements in road pavements. Usually, dielectric permittivity is calculated by
 371 a back-calculation procedure by reference materials when using ground-coupled systems.
 372 However, for air-coupled antenna systems, the surface reflection method is the most used. It is
 373 based on comparing the reflection amplitude from the pavement and the metal plate reflection.

374 Equation 6 presents the model for the dielectric permittivity of the asphalt layer of road pavements,

$$\varepsilon_1 = \left(\frac{1 + \frac{A_1}{A_m}}{1 - \frac{A_1}{A_m}} \right)^2 \quad \text{Equation 6}$$

376 where

377 ε_1 = dielectric permittivity of the asphalt layer;

378 A_1 = amplitude of the reflection from the top of the pavement;

379 A_m = amplitude of the reflection from a metal plate.

380 For the granular layer (second layer) of asphalt pavements, dielectric permittivity is calculated as
 381 indicated in Equation 7,

$$\sqrt{\varepsilon_2} = \sqrt{\varepsilon_1} \left[\frac{1 - \left(\frac{A_1}{A_m}\right)^2 + \left(\frac{A_2}{A_m}\right)}{1 - \left(\frac{A_1}{A_m}\right) - \left(\frac{A_2}{A_m}\right)} \right] \quad \text{Equation 7}$$

383 where

384 ε_2 = dielectric permittivity of the granular layer (second layer);

385 A_2 = amplitude of the reflection from the top of the granular layer.

386 Recently [45] developed an innovative method for measuring pavement dielectric constant using
 387 the extended common mid-point method with two air-coupled GPR systems. This method works
 388 better for pavements with non-uniform thickness than the classic method based on surface
 389 reflection. Also, the technique dispenses the use of a ground-coupled antenna. Therefore, the time
 390 delays of the two GPR systems can be estimated at a higher level of accuracy, and the GPR survey
 391 can be conducted at a higher speed. They obtained dielectric constants for the asphalt layer ranging
 392 between 5.3 and 8.4 in a trial section with four different thicknesses.

393 An attempt was made by [28] to measure dielectric permittivity using an antenna array GPR. The
394 antenna was calibrated considering the phase centre and the antenna offset, which improved the
395 velocity and thickness estimations accuracy compared with the conventional method.

396 [46] proposed a methodology for determining the dielectric permittivity of soils using the Born
397 Approximation and demonstrated that the electrical field scattered by a spot-like buried object
398 permits accurate estimation of the soil permittivity even when no information of the soil
399 conductivity is available. In above-mentioned previous studies it is strongly recommended to
400 calibrate GPR antenna before using in the experimental campaign to avoid or minimize errors of
401 calculating dielectric constant. Besides, there are several factors can influence of the clarity of the
402 dielectric constant, mainly are vertical and horizontal resolution based on antenna frequency and
403 subsurface conditions, wet or moisture condition, external signals which mislead the gpr signal,
404 attenuation of GPR signal, and during the postprocessing it is also essential to select an appropriate
405 set of filters in order to maintain the correct dielectric constant.

406 2.4 Density/compaction of asphalt layers

407
408 The density of bituminous concrete layers is highly dependent on its constituents, especially the
409 percentage of bitumen and the compaction energy. The density can be assessed by calculating the
410 dielectric constant of the bituminous layers and using the Complex Refractive Index Model
411 (CRIM) theory [44]. CRIM is used to estimate the permittivity of heterogeneous mixtures based
412 on their single components and pavement geometry. This equation has been used to calculate the
413 density of the asphalt mixes by knowing the volumetric characteristics of the asphalt mixes, in
414 terms of asphalt and air-void content, as a function of the dielectric constant of the aggregates and
415 asphalt. Due to its simplicity, it is widely applied for GPR applications because GPR allows the
416 assessment of the parameters necessary to use CRIM, such as dielectric constants and geometry.

417 Considering the data obtained from GPR, it is possible to use the CRIM model to get information
418 about the bulk specific gravity (or apparent density) of asphalt mixtures. The correlation between
419 asphalt mixtures apparent density (G_{mb}), dielectric values of the individual components (binder,
420 ϵ_{mb} , and aggregates, ϵ_s), specific gravity (relative density) of binder (G_b) and asphalt mixtures
421 (G_{mm}), the apparent density of aggregate (G_{sb}) and binder content (P_b) is given by Equation 8.

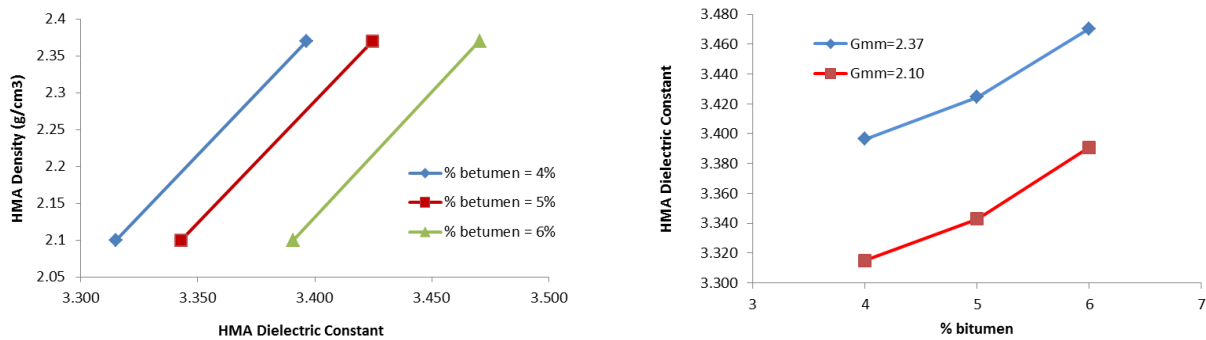
$$422 \quad G_{mb} = \frac{\sqrt{\epsilon_{HMA}} - 1}{\frac{P_b}{G_b} \sqrt{\epsilon_b} + \frac{(1-P_b)}{G_{sb}} \sqrt{\epsilon_s} - \frac{1}{G_{mm}}} \quad \text{Equation 8}$$

423 Other authors produce other models, namely the Rayleigh and the Böttcher Mixing Models. Both
 424 allow estimating the asphalt mixtures density from known or measured values with GPR. The
 425 respective Equations 9 and 10 are as follows:

$$G_{mb} = \frac{\frac{\varepsilon_{HMA} - \varepsilon_b}{\varepsilon_{HMA} + 2\varepsilon_b} \frac{1 - \varepsilon_b}{1 + 2\varepsilon_b}}{\left(\frac{\varepsilon_s - \varepsilon_b}{\varepsilon_s + 2\varepsilon_b}\right) \left(\frac{1 - P_b}{G_{sb}}\right) - \left(\frac{1 - \varepsilon_b}{1 + 2\varepsilon_b}\right) \left(\frac{1}{G_{mm}}\right)} \quad \text{Rayleigh Mixing Model} \quad \text{Equation 9}$$

$$G_{mb} = \frac{\frac{\varepsilon_{HMA} - \varepsilon_b}{3\varepsilon_{HMA}} \frac{1 - \varepsilon_b}{1 + 2\varepsilon_b}}{\left(\frac{\varepsilon_s - \varepsilon_b}{\varepsilon_s + 2\varepsilon_b}\right) \left(\frac{1 - P_b}{G_{sb}}\right) - \left(\frac{1 - \varepsilon_b}{1 + 2\varepsilon_b}\right) \left(\frac{1}{G_{mm}}\right)} \quad \text{Böttcher Mixing Model} \quad \text{Equation 10}$$

428
 429 These models produce similar results in predicting the density of asphalt mixtures based on the
 430 dielectric constant and percentages of constituents. Based on this model, the density of the asphalt
 431 layer increases with dielectric values. It was found that dielectric values also correlate with the
 432 percentage of bitumen, which results in the density increasing with the percentage of bitumen. In
 433 a recent study by Fernandes and Pais [5], a laboratory program was established to check the GPR's
 434 capability in detecting the value of the asphalt mixtures apparent density in pavements with
 435 different densities and different water saturation levels. In this study, six small slabs were produced
 436 varying air-void content and bitumen content. GPR measurements using a high-frequency antenna
 437 (1.6 GHz) were performed on all slabs without water, and the dielectric constant of the asphalt
 438 mixtures layer was obtained. In Figure 5 (left), the asphalt mixtures apparent density using the
 439 CRIM increases with the increase in dielectrics, increasing the bitumen percentage. This fact is
 440 expected considering that more binder, less voids, thus, slightly higher dielectric value.
 441 Figure 5(right) shows an increase in the dielectric value with the percentage of bitumen and the
 442 maximum specific gravity of asphalt mixtures.



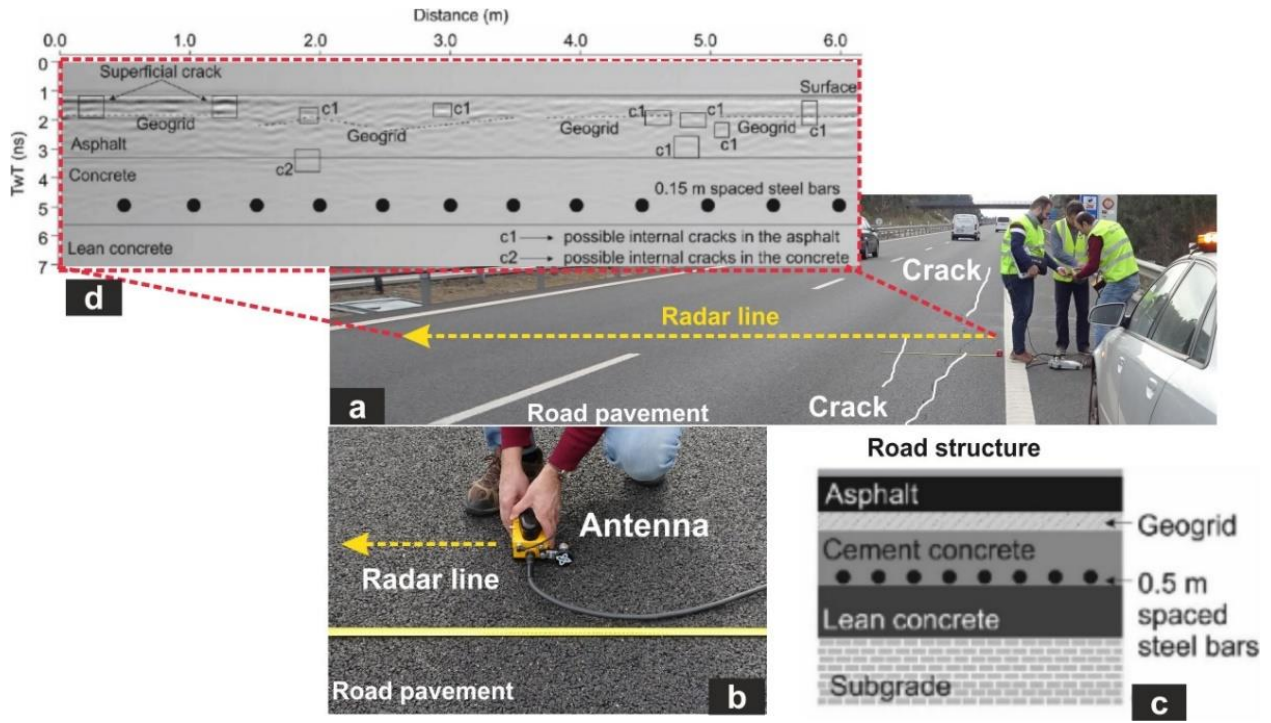
443
 444 Figure 5. Correlation between density, dielectric constant, percentage of bitumen and maximum specific gravity of
 445 asphalt mixtures.

446 3. GPR Application of Road Pavement Subsurface conditions

1 447 GPR has also been used for assessing subsurface pavement conditions and all utilities below the
2 448 pavement. Thus, this chapter focus on the characterization of cracks existing in rehabilitated
3 449 concrete pavements, the evaluation of the delamination/debonding of asphalt layers, the detection
4 450 of subsidence and sinkholes, the assessment of moisture in granular and subgrade layers, and
5 451 finally on the identification of utilities, mainly drainage pipes. Some examples of these
6 452 applications and the relevant studies will be presented.

11 12 13 453 3.1 Cracking identification

14 454
15 455 Cracking is one of the most common problems in the road pavement, which occurs due to the
16 456 severe deformation and deterioration in road pavements. Cracks are caused by some factors,
17 457 namely, the passage of heavy load trucks, pavement ageing, pavement mixture materials (e.g.,
18 458 shrinkage and expansion of the pavement materials), natural hazards and subgrade properties (e.g.,
19 459 landslides, liquefactions, and settlements), weather conditions and climacteric agents (e.g.,
20 460 temperature, icing, water film thickness, snow and rain) [6], [13], [47], [48]. Crack dimension
21 461 (width and depth) generates different effects on road pavement serviceability. Cracks are usually
22 462 one of the leading causes that could significantly influence the structural performance of the road
23 463 pavement. Crack inspection is essential in road pavements. Regular repairs and maintenance can
24 464 prevent any uncontrolled hazards to increase the life cycle of road pavement. These repairs are
25 465 supported by an appropriate observation strategy in road conditions. Non-invasive techniques such
26 466 as GPR are widely recommended to provide valuable information about road pavement conditions
27 467 [16]. A high-resolution 2300 MHz GPR shielded antenna has been applied to identify cracking
28 468 patterns and early cracks in composite road pavements composed of two layers (asphalt layer over
29 469 a concrete layer) [49]. Figure 6 shows a GPR survey conducted in a composite pavement to identify
30 470 surface cracks and internal cracks before propagating to the pavement surface. The processed radar
31 471 image shows the road structure and various features (e.g., steel rebars, cracks in the asphalt and
32 472 concrete layer, superficial cracks, and geogrid).



473
 474 Figure 6 GPR survey on an asphalt pavement adapted from [13]: (a) view of the highway, (b) 2.3 GHz GPR antenna
 475 applied on the road section, (c) road structure composed in different layers, (d) processed radar image.

476 GPR has been extensively underlined in many road pavements research studies in academia and
 477 industry during the last 30 years. Cracking is commonly studied in critical road infrastructures,
 478 and different features and causes have been investigated. Table 2 presents detailed information,
 479 crack dimensions, GPR antenna and supplementary analysis of road pavement studies in previous
 480 works.

481

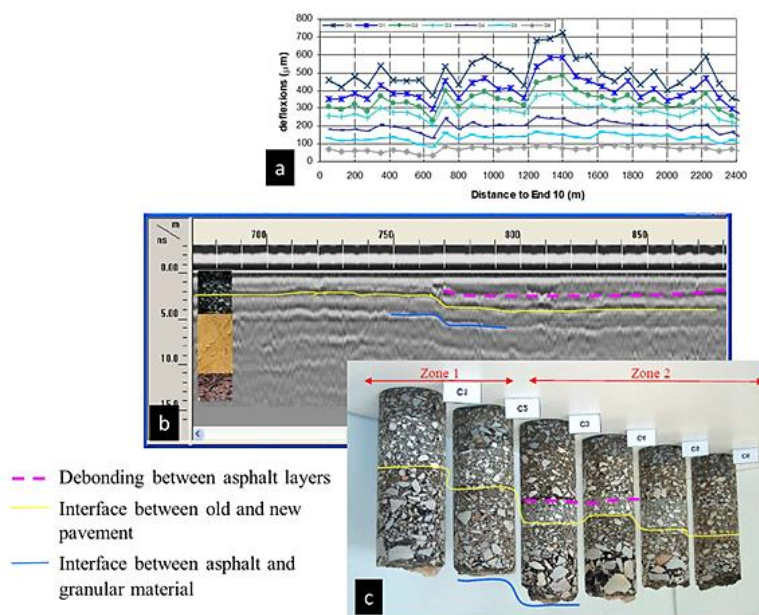
482 Table 2 Cracking inspection previous studies and methodologies considered during these works, and each study is referred to its original references.

N o.	Cracking condition	Antenna (MHz)	Antenna dipole orientation	Depth (mm)	Width (mm)	Extra features	Pavement type	Crack observation	GPR signal analysis	Numerical modelling	References
1	Vertical cracks	250 and 1000	Perpendicular to the crack line	(45-350)	(1-5)	-Granular layer	Asphalt	Detected	Amplitude	2D and 3D FDTD ¹	[47]
2	Early cracking	2300	Perpendicular and parallel to the crack line	(100-200)	(10-20)	-Steel rebars -Settlement in steel rebars -Lean concrete layer	Concrete layer covered by asphalt layer	Detected	Amplitude	2D FDTD ¹	[6]
3	Cracks	1600	Perpendicular and parallel to the crack line	150	(2-30)	Dielectric constant	Cement concrete	Detected	Amplitude	2D FDTD ¹	[49]
4	Cracks	1600	Perpendicular and parallel to the crack line	150	(2-30)	-Dielectric constant -Weather condition and filled cracks with air, sand, water, saturated sand and bitumen -Early cracks - Surface cracks -steel rebars	Cement concrete	Detected	Amplitude	2D FDTD ¹	[13]
5	Cracks	1000	Perpendicular to the crack line	10-28	3	- temperature -water content	Asphalt	Detected	-Amplitude analysis considering width of cracks - Thermograms	2D FDTD ¹	[50]
6	Layer thickness and cracks	800 and 950	-	-	30	- porosity -moisture -layer thickness	Asphalt	-	-Amplitude -Frequency	None	[51]
7	Transversal cracks	2200	Perpendicular and parallel to the crack line	-	Small size	Pavement structure	Asphalt	Detected	-Amplitude -Core samples	None	[52]
8	Vertical and horizontal cracks	250 and 800	Perpendicular to the crack line (simulated data)	5	5	Rock in pavement	Concrete	Detected	-F-K Migration -2D wavelet analysis	None	[53]

483 FDTD¹ Finite-difference time-domain method is a common numerical analysis of computational electromagnetic waves (<http://www.gprmax.com/>).

484 3.2 Delamination/debonding of pavement layers

485 Debonding of pavement layers affects the bearing capacity of the pavement. The bounding
1 486 condition between asphalt layers is a significant feature to be considered during the pavement
2 structural evaluation. The significance is because the commonly used numerical models for
3 487 flexible pavement are linear elastic, and erroneous results can be obtained for layer moduli if the
4 debonding condition between layers is not considered [54]. In addition, water can infiltrate
5 488 between layers and accelerate the deterioration of the asphalt interface. Debonding can appear
6 during the construction stage due to dirty surfaces, inadequate tack coating, or pavement operation.
7 489 Antireflective cracking solutions, such as geosynthetics, geotextiles or geogrids, applied for
8 pavement reinforcement, can also cause debonding. Detection of the debonding between layers is
9 490 a challenge considering only traditional techniques. In the past, coring samples (pits) were
10 considered the most efficient method to diagnose the debonding condition. Nevertheless, layers
11 491 can debond even more during the extraction of coring samples, which is considered a limitation of
12 the coring tests, and results can be erroneous. Detection of the debonding condition is essential to
13 492 adequately provide comprehensive information related to the layers for rehabilitation purposes.
14 This detection will support a proper plan for overlaying solutions that mitigate the debonding, such
15 493 as milling and overlaying. On the other hand, a few different techniques can also be used to observe
16 494 the bonding condition, such as FWD. A case study of using FWD for debonding condition
17 inspection is presented in Figure 7 in which, between 800 m and 1400 m the difference between
18 495 the highest deflection (D0) and the second-highest (D1) is observed, which is the detection area of
19 the debonding compared to the rest layers of the pavement [54].
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506 Figure 7 NDT combined survey of an airfield pavement with the identification of asphalt layer interfaces and
507 debonding section - adapted from [54] (a) FWD spectrum, (b) GPR B-scan at the transition between zone 1 and 2
508 (using 1.0 GHz air-coupled horn antenna) and (c) cores extracted along the pavement.

509 A research program was dedicated to the study of delamination detection using NDT. Each NDT
510 technology measurement is based on scientific principles related to the measured response from
511 the material properties. Theoretical modelling is commonly used to predict the response for
512 debonding and stripping in the asphalt pavements. The main aim of the modelling is to demonstrate
513 the theory response of each test and the main aspects of the key measurements of the road
514 pavement. For example, the FWD model is also used for back-calculation for FWD test data.
515 Results show that the amount of deflection in pavement changes as the depth of delamination
516 changes considering the non-linear relationship [55]. In the mentioned study, various NDT
517 methods were studied, such as GPR (antenna array, frequency sweep), mechanical wave
518 technology (impact echo (IE) and spectral analysis of surface waves (SASW)). GPR technology
519 has proven to be the most efficient NDT technology capable of testing full lane width at a moderate
520 testing speed (60 km/h).

521 On the other hand, other NDT methods such as the mechanical wave technique significantly have
522 less testing operation time but are limited at a speed of less than (8 km/h). The main conclusions
523 from this work prove that the GPR can identify variations in the pavement, isolate the depth of a
524 discontinuity in the pavement, and provide a relative degree of severity. Detecting debonding
525 between asphalt layers is possible with the current analysis methodology, and only when moisture
526 is trapped in the debonded area between the layers. None of the NDT technologies can identify
527 partial debonding due to inadequate tack coat during construction. It is highlighted that GPR, IE,
528 and SASW can be valuable project-level tools. A specific data analysis is required to allow NDT
529 into a network-level tool for detecting delamination in asphalt pavements.

530 Several studies were carried out in the Nantes Accelerated Pavement Testing facility to thoroughly
531 study the behaviour of debonding pavements and the possibility of GPR detecting debonding [56]–
532 [58]. In these researches, advanced post-processing methods were also implemented for data
533 interpretation, such as support vector machines (SVM) [56]. The main tasks were the detection of
534 the horizontal debonding occurring between the first two pavement layers from Stepped-frequency
535 Radar (SFR) [56] data and air-coupled ultra-wideband GPR antennas (SF-GPR), two wideband
536 2D ground-coupled GPRs (a SIR-4000 with a 1.5 GHz antenna and a 2.6 GHz-Structurescan from
537 GSSI manufacturer), and a wideband 3D GPR (from 3D-radar manufacturer). Radargrams are
538 processed with refined signal analysis to detect constructive interference between overlapping
539 echoes. It was performed from timely data by a supervised machine learning method, namely
540 support vector machines (SVM) [56], and the result is compared to the conventional reference
541 method and the Amplitude Ratio Test (ART). In this latter, debonding detection requires
542 computing the conventional ART as the ratio between the reflected wave (RW) and the direct wave

543 (DW), namely, $ART = RW/DW$ for each A-scan [56], [57]. Data processing automatically picks
544 the maximum (or minimum) amplitude of the two latter echoes with some existing commercial
545 radar processing software. In terms of pavement monitoring related to any debonding provides
546 additional echoes which mostly interact constructively with each other. Consequently, the
547 amplitude of the GPR signal of the reflected signal (RW) compared to one of the healthy zones
548 [57].

549 Based on the GPR signal, a novel methodology was developed to detect the delamination of thin
550 air-gap caused by delamination, which usually is less than 2 cm thick [27]. A vehicle-mounted
551 GPR system, consisting of two air-coupled antennas of 1 GHz and 2 GHz, respectively, and four
552 300 MHz ground-coupled antennas were used in this work. Obtained results have a good
553 agreement with the core samples extracted from the same location. GPR can also be combined
554 with other NDT methods for delamination detection on concrete bridges [59]. Other delamination
555 detection studies using NDT, including GPR, are illustrated in the work of [7].

556 3.3 Subsidence and sinkholes detection

557 Subsidence seriously affects the structural stability and safety of pavements. Many causes can
558 generate this type of problem, such as poor soil compaction, non-homogeneous consolidation and
559 weak load-bearing capacity of soils, which seriously affect the conditions and mechanical
560 behaviours of the foundation soils. When subsidence occurs, cracks, fractures, and potholes can
561 appear on the pavement surface. Most seriously, in heavily loaded pavements, there is a risk of
562 pavement sinking that can lead to collapse.

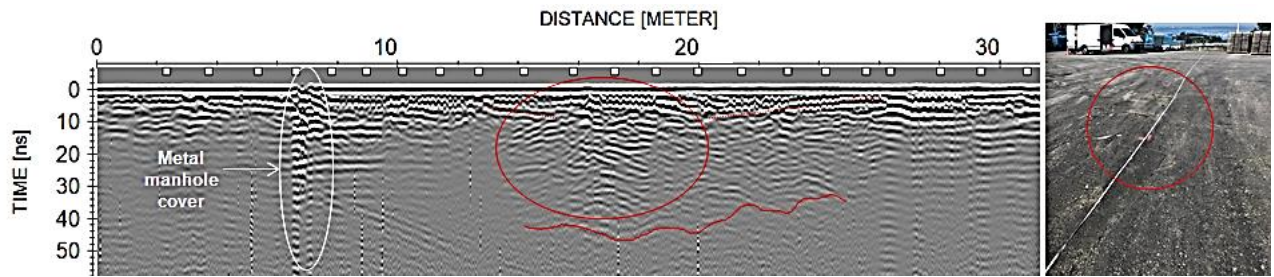
563 The solution to maintain both the integrity and stability of the pavement and foundation soils is
564 the early detection of subsidence so that preventive actions can be carried out. In this context, the
565 GPR provides an ideal solution to map sinkholes and settlements due to its high-resolution imaging
566 without altering the soil structure while covering a vast area in a relatively short time with a
567 reduced effort. One of the most followed guidelines, such as the ASTM-D6429 standard guideline
568 [60], has also mentioned and included three primary geophysical methods for the investigation of
569 sinkholes and voids: GPR, Frequency Domain Electromagnetic and Gravity.

570 [61] showed several GPR case studies on subsidence and sinkholes detection in urban areas
571 affected by karstic processes. The GPR surveys were conducted using 500 MHz, 250 MHz, and
572 100 MHz shielded antennas. The GPR data produced allowed the identification of zones with
573 subsidence processes and collapse geometry affecting different anthropic levels that were
574 progressively accommodated (revealing continuous aggradation). One of the cases studies were
575 carried out in a motorway with a shallow water table. In this case, anomalous asphalt thickness

576 was identified and considered as subsidence. [62] performed a GPR study with a 250 MHz shielded
577 antenna to locate depressions and sinkholes in an area of old mine workings. From the GPR data
1 578 produced, it was found that a sinkhole (which appeared at the surface a few months after
2
3 579 measurements) was most certainly caused by the existence of an underground water channel and
4
5 580 subsequently weakened strata. [63] showed a 400 MHz GPR survey used for air-void detection
6
7 581 under a road. A subsurface void approximately 4 m long and 1.5 m deep was detected and
8
9 582 confirmed by drilling boreholes. [64] presented a GPR study to characterise the ground conditions
10
11 583 in an urban area, where subsidence occurred and was repaired. A shielded antenna with a frequency
12
13 584 of 400 MHz was used for data acquisition, and the GPR data produced allowed to differentiate
14
15 585 between loose and dense layers successfully. [65] used GPR shielded antennas with frequencies
16
17 586 of 800 MHz and 500 MHz to map loose filling and subsidence in a port area consisting of stone
18
19 587 paving blocks and “all-one” filling. 3D methodologies were used to provide reliable information
20
21 588 about the actual extent of the anomalies. [66] presented a 3D GPR study using a 200 MHz shielded
22
23 589 antenna focusing on detecting sinkholes in a collapsed urban area. It was possible to identify loose
24
25 590 soil and cavities along a stretch of the road that could be affected by leakage and the water pouring
26
27 591 into the layers. [67] included a 3D GPR study to detect sinkholes in a parking area where a sinkhole
28
29 592 formation has collapsed in the past. For the survey, a 100 MHz shielded antenna was used, and the
30
31 593 results revealed a large subsurface cavity that collapsed several months after measurements. [68]
32
33 594 presented two different GPR case studies using a 400 MHz shielded antenna, (i) to investigate the
34
35 595 area outside a warehouse and (ii) to investigate an adjacent area to a bus garage, which aimed to
36
37 596 evaluate the buildings foundations and possible causes of the decay of their structural elements.
38
39 597 For the first case study, poorly-compacted or eroded zones were detected in the shallow layers of
40
41 598 the soil that suggests a settlement phenomenon at the shallow foundations; whereas for the second
42
43 599 case study, it was possible to identify a soil area with greater water content; hence, this irregular
44
45 600 distribution of water, and the absence of drainage systems, could be the cause of the settlement
46
47 601 observed in the adjacent building. [69] carried out a GPR study to monitor an active sinkhole in
48
49 602 an urban area. The survey was performed with both 100 MHz and 200 MHz shielded antennas.
50
51 603 The results produced have revealed the internal structures of the sinkhole and approximate extent,
52
53 604 while identifying boundaries of subsidence areas and deformation structures (collapse faults,
54
55 605 fissures, etc.).

56
57 606 Figure 8 presents an example of subsidence detection with 500 MHz ground-coupled antennas.
58
59 607 The GPR profile line was conducted along an area supporting trucks circulation and maneuvering.
60
61 608 This area consists of a 20 cm reinforced concrete slab, followed just underneath by an anthropic
62
63 609 filling. From the interpretation of the GPR data, it was possible to identify reinforcement
64
65

610 settlement (highlighted in dotted red lines), as well as a large subsidence in the middle of the B-
611 scan (highlighted in the red ellipse) that compromises the stability of the soil system and, more
612 importantly, could lead to collapse under heavy load conditions.



613
614 Figure 8. 500 MHz GPR data showing reinforcement settlement and filling subsidence (highlighted in red ellipse).

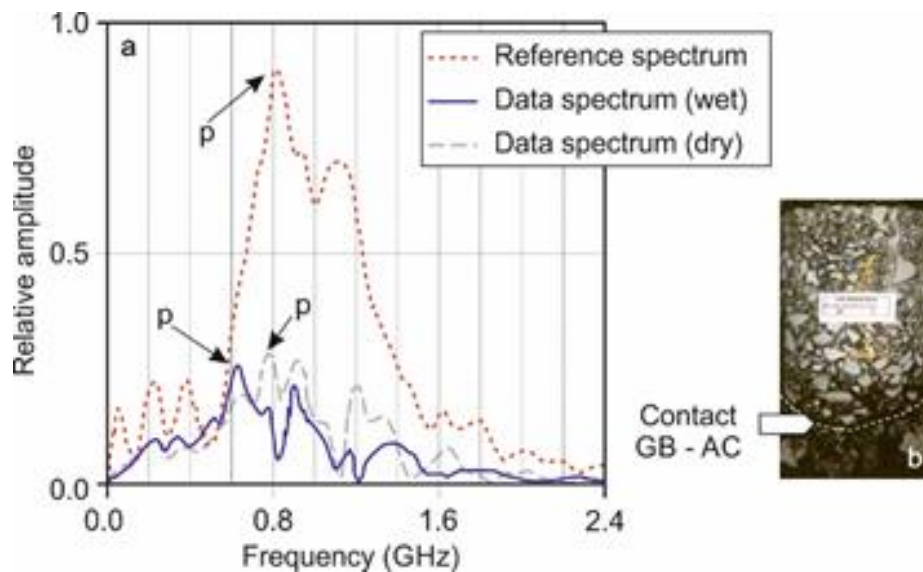
615 3.4 Moisture of granular and subgrade layers

616
617 One of the main causes of damage in pavements is the humidity in the asphalt and subgrade layers.
618 The subgrade is the deepest layer of the pavement and supports the base and the asphalt layers.
619 The water content in the subgrade may come from surface filtration through the cracks in the upper
620 layers, from the subsoil water, or due to filtrations from the road's gutters. In all cases, incorrect
621 drainage could damage the pavement because the subgrade reduces the bearing capacity when
622 water accumulation saturates the soil.

623 The study of the subgrade layer is crucial to assure the proper conditions for the service life of the
624 infrastructures. The analysis in railways to detect moisture in the subgrade demonstrates the
625 technique's feasibility [70]. This work obtained the wave velocity in the subgrade from common
626 mid-point data acquisition, determining the velocity curves and gradients. The humidity is
627 estimated from those velocities using the Topp relationship [71]. The dielectric permittivity from
628 aggregate sub-bases was also determined by comparing amplitudes of the reflected waves [72].
629 The gravimetric water content was estimated from a relation between the moisture content,
630 densities and dielectric permittivity of aggregates and base materials [73]. In other cases, the
631 identification of reflections allowed to determine the wave velocity used to analyse the water
632 content comparing the two-way travel time in radargrams to the layers observed in cores. The
633 accuracy of this method is higher as more samples are obtained [31]. However, due to the noise,
634 humidity in the pavement layers is difficult to determine only using GPR, and complementary
635 methodologies are recommended [74], being GPR mainly used to determine the water content in
636 the soil under the pavement. In general, GPR is recommended to determine the water content and
637 soil substructure under roads because the permittivity estimated with GPR is sensitive enough to
638 detect differences in soil materials, moisture content, and the presence of frost in soils used to
639 construct roads [75]. The surveys with high-frequency antennas (higher than 2 GHz) allows a more

640 accurate analysis of the pavement layers, being in some cases possible to develop algorithms for
641 rapid pattern recognition, detecting automatically damaged zones [76].

642 Changes in the frequency of the reflected signals can also highlight the existence of moisture in
643 the base of pavements [42] because an increase in the gravimetric water content produces a
644 displacement of the maximum amplitude peaks of the spectrum to lower frequencies. Figure
645 compares the spectrum from a dry sector with the spectrum obtained in a road with significant
646 damage due to water content in the subbase and a reference spectrum. The study was performed
647 with an 800 MHz centre frequency antenna, analysing the granular subbase of the pavement.



648 Figure 9. Spectrum of dry and wet pavement base. a) Reference spectrum compared to the spectra from data obtained
649 in dry and wet sections. b) Sample showing the contact between the asphalt concrete (AC) and the granular subbase
650 (GB) (modified from [42])

651
652 The peak corresponding to the maximum amplitude in the reference spectrum is placed around
653 800 MHz. In the dry granular subbase, the peak is slightly moved to a lower frequency but the
654 peak has a significant move to the lower frequency for wet granular subbase.

655 Based on frequency analysis and dielectric permittivity estimation, the development of automatic
656 detection of humidity is a challenge. [77] carried out deep learning approaches with promising
657 results.

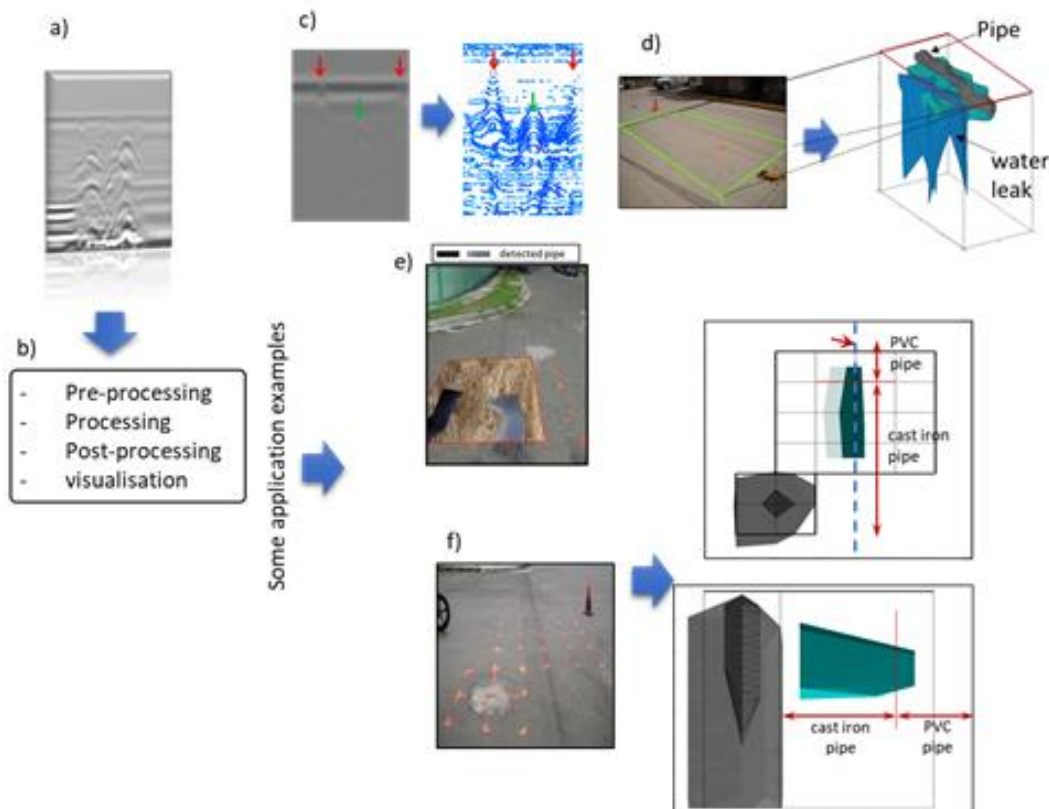
658 3.5 Underground utilities assessment

659 Critical infrastructures such as transportation networks, water, electricity, among others, are
660 essential systems for the development of cities. The proper operation of these critical
661 infrastructures depends not only on the components of the system itself but also on the adequate
662 functioning of the components of their interconnected systems. For example, failures of pipes in
663 either water collection systems or water distribution networks can lead to prolonged disruptions

664 (or also collapse) in parts of the city for the services in both the water and road infrastructure [78],
 665 [79]. Thus, in road pavement inspection and given its close relationship with buried assets of buried
 666 infrastructures i.e., drinking water pipes, drainage pipes/water collection (e.g., rainwater and
 667 sewage pipes), gas pipelines [80], among others., the development of reliable
 668 assessment/monitoring mechanisms for the health of buried assets (i.e. in particular for utility
 669 pipes) is gaining a main interest in cities. This development prevents/mitigates failures that can
 670 lead to potential economic, social, and environmental impacts in transportation and utility systems
 671 [81]. One of the most common methods used for health assessment and characterisation of buried
 672 pipes is the GPR [80], [82]. In this sense, this section explores the use of GPR in buried pipes for
 673 both characterisation and health assessment, focusing on drainage pipes in the context of urban
 674 roads.

675 In general, GPR applications for pipes (some examples of these applications are presented in
 676 Figure .10):

- 677 • the utility mapping (e.g. detection of pipe layouts, pipe size, pipe depth);
- 678 • pipe wall thickness estimation;
- 679 • identification of the state condition of the pipe by detecting each anomaly/defect within
 680 pipe wall (e.g. pipe wall fractures, corrosion in case of metallics pipes, pipe-bursting) [83];
- 681 • identification of water leakage and mapping cavities in surrounding pipe areas [80].



682 Figure10 A few GPR application examples for pipes assessment. a) Raw GPR images, b) treatment and interpretation,
 683 and c-f) applications. c) Characterisation of plastic pipes, d) water leakage detection and characterisation of the leak
 684 phenomena, e) visualisation - augmented reality, and f) 3D retrieval. (Adapted from [[84]–[87]]..
 685

686 Due to the dielectric differences between the material and the areas surrounding it, a contrast is
687 generated, mainly in the relative dielectric permittivity, facilitating the pipes' identification
688 (detection) in images captured using GPR [88]. Numerous authors take advantage of this principle
689 in order to map the water-related pipes. Thus, [89] reported some GPR studies to detect buried
690 utilities, among which stands out the use of a frequency antenna ranging from 100MHz to
691 1500MHz (in particular 100, 200, 250, 270, 300, 400, 500, 700, 800, 900, and 1500 MHz) for asset
692 depths between 8cm-163cm in real urban environments. [89] uses a kinematic GPR (with central
693 frequency of the antenna of 400MHz) and self-tracking (robotic terrestrial positioning systems -
694 TPS) for identifying the layouts and also the characteristics (material, diameter, depth, position)
695 in urban environments. Evaluated assets include pipelines (drinking water, plumbing water,
696 industrial water, sewage, heating - culvert), gas, electrical and signal cables, with different pipe
697 materials (polyethene, concrete, ductile iron, ductile cast iron, glass reinforced polyester), for
698 diameter of 31mm-400mm and depth ranges of 80cm-350cm. The layers of the real urban sites
699 include materials such as asphalt concrete and granular base.

700 Similarly, [90] used a multi-channel GPR unit (34 transmitter-receiver with a frequency of
701 600MHz), combined with a Global Navigation Satellite System (GNSS) with the support of pulse
702 per second (PPS) and total station to identify the location of the utilities in urban settings. Pre-
703 location of pipe layout for the sewage system was conducted by identifying visible components
704 (e.g., drainage grille, metal tape) and then GPR confirmation was performed. Although the authors
705 highlight the uses of GPR in layout detection for sewage pipes, they also noted the reduction in
706 detection efficiency for pipes with large diameters located at depths for the frequency of the
707 antennas used.

708 In order to characterise pipes (i.e., estimation of depth, diameter, content and eventually the pipe
709 layout) for drainage systems embedded in concrete pavement, [82] coupled simulated GPR images
710 (i.e., using the finite-difference time-domain (FDTD) method) and migration reconstruction
711 method. Internal pipe condition is another topic of particular interest in water-related pipes. Thus,
712 there are some studies based on amplitude analysis, as in [91] developed in water sewage systems
713 with GPR (with a central frequency of the antenna of 2.6 GHz) in asbestos cement pipes (out of
714 service pipes) of different ages, diameters (from 300mm to 525mm) and thicknesses (from
715 24.1mm to 40.6mm) for pipe health assessment (estimation of wall thickness and pipe state). [92]
716 estimated the corrosion rates in cast iron pipes using GPR through numerical simulations and based
717 on hyperbolic reflection analysis. The formation of underground voids in surrounding pipe areas
718 was studied in [93] and [94] to preserve the structural integrity of sewerage pipes. The first uses
719 FDTD in its studies, while the second performs a cavity mapping using a 400MHz in a real urban

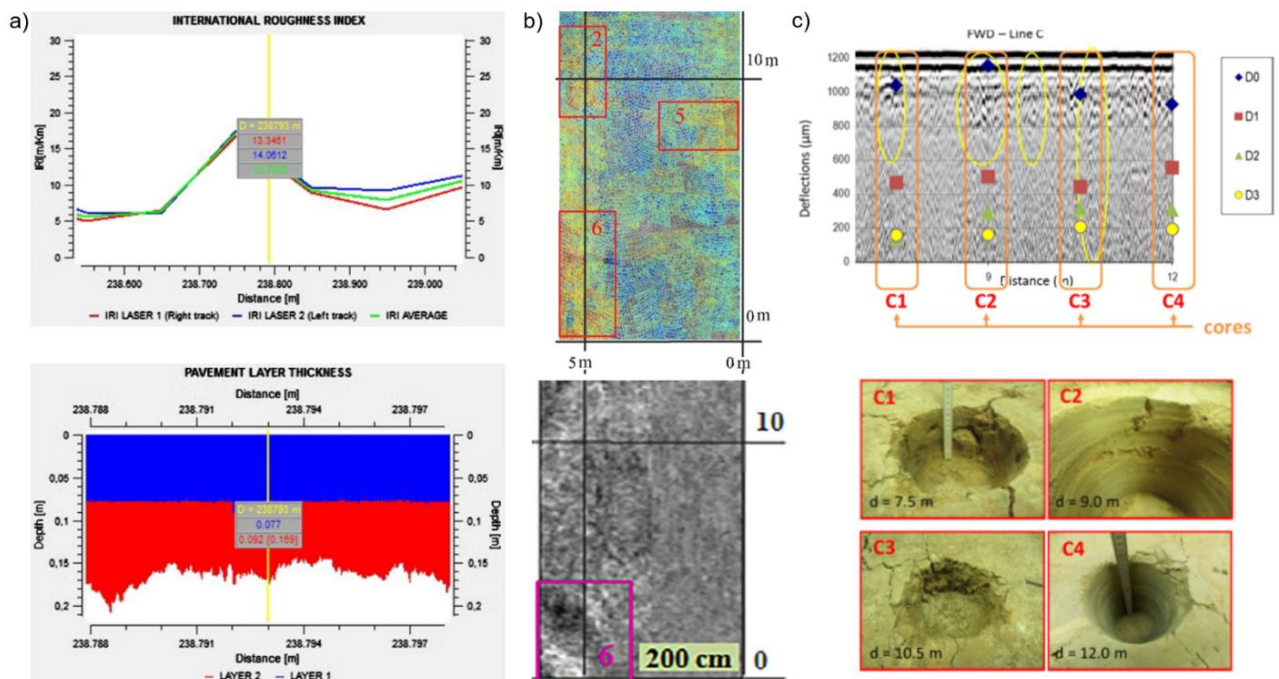
720 environment. To evaluate pipes within themselves, [95] coupled a GPR (antenna frequency used:
721 unknown) with the digital scanning and evaluation technology (DSET) to detect both geometric
722 anomalies and property changes (potential pipe defects) for the assessment of underground sewage
723 pipe condition. The GPR system in this case is used to facilitate the detection of anomalies that
724 are difficult to appreciate by the human eye through the DSET system. Similarly, [83], [96]
725 addressed the pipe assessment of voids within and outside, as well as the defect in pipes by using
726 a GPR system (antennas with frequency of 1.6 GHz to 2.3 GHz were used) incorporated in a robot
727 that performs the inspection inside the pipe. In addition, the detection of the deep underground
728 small size pipe positions, and localise them is a challenge task in the assessment of critical
729 infrastructures. The detection of such pipes depends on the GPR antenna frequency, and subsurface
730 conditions, mainly wet, dry, contaminated. Use of intelligent data analysis, such as machine
731 learning or deep learning could be efficient in order to increase the accuracy of the radar images
732 [97], or combination of GPR with other possible non-destructive evaluations (NDE) [98].

733 **4. Incorporation of GPR with other methods for pavement assessment**

734 As addressed in the previous sections, the GPR method represents an essential non-destructive
735 pavement structural assessment tool. It allows for the continuous detection of layer thicknesses
736 and locating defects and inner damages such as cracking, delamination or subsidence. In addition
737 to the GPR for providing layer thickness information, other complementary devices such as
738 accelerometers and laser scanning profilometers are generally used to measure the road texture
739 and roughness for quality control and quality assurance [99]. GPR was combined with infrared
740 thermography to detect cracking and shallower delamination in asphalt pavements [50] and inner
741 defects (lack of filling and subsidence) in paving blocks roads [65].

742 Another NDT technique commonly used together with the GPR for the structural evaluation of
743 pavements is the FWD, which allows evaluating the bearing capacity of pavements based on
744 loading tests. The FWD simulates the pavement responses under traffic loading by applying an
745 impulse load and then measuring the pavement deflection bowl. The standard procedure is to
746 measure the deflections in a considerable number of points located along several lines parallel to
747 the pavement axis (the same test lines as the GPR) and spaced in 50 to 200 m [54]. Thus, layer
748 modulus (strength of each layer) can be estimated throughout back-calculation using the deflection
749 values measured by FWD and the layer thickness obtained from GPR. Examples of published
750 articles combining GPR with FWD are [11], [100]–[102]. New loading tests devices were
751 developed for monitoring at high traffic speed, such as Traffic Speed Deflectometer (TSD) [103],
752 [104].

753 Figure 11 shows three examples on the combination of different NDT data for pavement
 754 assessment. First, **Erreur ! Source du renvoi introuvable.** 11-a) presents two graphics showing
 755 both the International Roughness Index (IRI) profile and the GPR layer thicknesses profile
 756 produced for the same profile line. Next, **Erreur ! Source du renvoi introuvable.** 11b) displays
 757 the orthothermogram produced in the shallower subsurface (2-5 cm depth) of a paving blocks road
 758 and the 3D GPR time-slice obtained at 2 m depth in the grid. The IRT image shows the
 759 interpretation of some areas having higher temperature (highlighted into red boxes) At the same
 760 time, the GPR data allows to detect an inner subsidence (lack of filling or cavity) that extends from
 761 0.5 to 2.0 m depth, coinciding with one of the anomalies interpreted by the Infrared Thermography
 762 (IRT) method (box n. 6). Finally, **Erreur ! Source du renvoi introuvable.** 11-c) illustrates a
 763 comparison and integration of both FWD deflections (D0 to D3) and GPR B-scan (2.3 GHz
 764 ground-coupled antenna) for the same profile line (the yellow ellipses indicate anomalies in the
 765 GPR data). The discontinuity observed between deflections D2 and D3 at 7.5 m (C1) was
 766 interpreted as cracking or debonding of the subgrade layers. In comparison the higher difference
 767 between deflections D0 and D1 at 9.0 m (C2) was associated with cracking on the top layer.



768
 769 Figure 11 Examples of the combination of different NDT techniques for pavement evaluation: a) IRI- roughness
 770 profile and layer thicknesses profile obtained by GPR; b) IRT and 500 MHz GPR data (time-slice at 2 m depth)
 771 highlighting a subsidence (box n. 6); and c) FWD and 2.3 GHz GPR data to detect cracking and debonding. Adapted
 772 from [11], [65], [105].

773 Concerning the stability of the pavement structure, the Electrical Resistivity Tomography (ERT)
 774 is combined with GPR aiming to assess the soil compaction, cavities and the depth and condition
 775 of the bedrock [106], [107]. Another geophysical technique widely used together with GPR in
 776 pavement assessment and geotechnical road stability is the Seismic Refraction Tomography (SRT)

777 [108], [109]. The seismic method allows for deeper investigations than GPR to assess geological
778 hazards (subsidence phenomena, cavities, fractures in rocks, etc.).

1
2 779 The use of a multi-temporal Interferometric Synthetic Aperture Radar (InSAR) for pavement
3
4 780 assessment has also been significantly increased during the last few years [110]. In this regard,
5
6 781 some works in the literature [111], [112] show the potential of the applicability of the InSAR
7
8 782 technique to monitor differential settlements as well as, together with GPR, to outline subsidence
9
10 783 areas.

11 784 Regarding concrete pavements, especially in bridge decks, most of the published literature focuses
12
13 785 on delamination. Thus, it was possible to find some articles dealing with the combination of GPR
14
15 786 with acoustic surveys. [113] revealed that the acoustic method detects near-surface delamination,
16
17 787 while GPR can penetrate concrete thus proving deterioration in depth. Another NDT technique
18
19 788 used in conjunction with GPR on delamination assessment is the IRT method. Once again, the
20
21 789 orthothermograms detect near-surface delamination under convenient weather conditions, while
22
23 790 GPR allows for deeper investigation [114] Both impact-echo and pulse-echo techniques are widely
24
25 791 used to detect delamination and other defects such as voids and cracks [115], [116]. Other methods
26
27 792 such as half-cell potential (HCP), electrical resistivity (ER) and hammer sounding resistivity, are
28
29 793 used in combination with GPR and/or ultrasonic surveys to analyze corrosion and its spatial
30
31 794 distribution in areas affected by delamination [117], [118].

32 33 795 **5. GPR-based Machine Learning and Intelligent Data Analysis approaches**

34
35 796 Numerous efforts have been made to increase the interpretability of GPR data to make this
36
37 797 information more accessible, less dependent on interpretation skills for the persons responsible to
38
39 798 conduct assessment on transport systems, and ultimately to facilitate the decision-making process.
40
41 799 GPR appears to be an efficient method capable of providing road transportation systems with
42
43 800 reliable information on the infrastructures' health and surroundings using non-destructive
44
45 801 equipment. GPR data analysis requires expert experience in the treatment of this type of data. This
46
47 802 treatment requires methods that automate the interpretation process, making it feasible and
48
49 803 applicable to large-scale systems [119]. Therefore, advances in data analysis reduce analysis times
50
51 804 and minimise the human errors involved in this process [120]. This section explores machine
52
53 805 learning (ML), deep learning (DL) and the intelligent data analysis (IDA) methods applied to GPR
54
55 806 data for road transport infrastructure inspection.

56 807 The main objective of the use of ML approaches is an alternative approach to more traditional,
57
58 808 but computationally more expensive, algorithms, trained models which can usually be applied only
59
60 809 to a post-processing radar data. Certainly, in literature ML has already been proved as an effective

810 approach to GPR various civil engineering applications in both aspects; detection and
811 classification of the buried objects [121], [122]. The main approaches were used from different
1 812 researcher (i.e., pre-processing, segmentation approaches, and feature extraction). In this paper
2
3 813 mainly, modern deep learning approaches are considered and indicated based on literature. On the
4
5 814 other hand, dealing with GPR images is a challenged task, and using various approaches beside
6
7 815 deep learning is crucial to increase the interoperability of the radar images, and increase the
8
9 816 probability detection of the embedded target considering reliability of the data-driven from the field,
10
11 817 controlled laboratory or numerical models. Table 3 shows some examples of the efforts conducted
12
13 818 to incorporate IDA methods to increase the interpretability of the GPR data and transform this data
14
15 819 into valuable information [123]. Aspects addressed through IDA approaches related to road
16
17 820 inspection include object detection, cavity detection, pavement distress detection, grade
18
19 821 classification of loose damage, pavement cracks, moisture damages, and thickness estimation. In
20
21 822 addition, other relevant aspects should be considered in the GPR data analysis, such as data
22
23 823 acquisition/generation, clutter removal reduction [37], [124] and reduction of medium
24
25 824 inhomogeneity [125] that have been addressed in IDA methods.

26 825 The interpretation of GPR images typically comprises the development/adaptation of ad-hoc filters
27
28 826 that get understandable the information collected. In this sense, the application of deep-learning
29
30 827 methods, particularly convolutional neural networks (CNN), stands out. In these systems, data is
31
32 828 synthesized through several filters (kernels) within different layers in a feature map that condense
33
34 829 the relevant information gathered from the initial inputs. The feature maps obtained are the basis
35
36 830 for other processes such as classification, detection and prediction. Pre-trained network
37
38 831 architectures such as AlexNet is considered in order to facilitate the CNN training process [37],
39
40 832 [125]–[127], Darknet53 [120], Cifar-10 (on grayscale) [128] and ResNet50 [129], which have
41
42 833 been adapted by using transfer learning methods for the feature extraction of GPR images. A part
43
44 834 or entire pre-trained network's architecture (including the weights) is adapted either for automatic
45
46 835 characterisation or target detection. For example, [123] a coupled CNN with Long Short-Term
47
48 836 Memory (LSTM) is used, which is a model of Recurrent Neural network (RNN) for the automatic
49
50 837 identification of the diameter of buried cylindrical object. An equivalent method to the CNN which
51
52 838 is based on wavelet transformation with the rotation and translation of invariant operators, called
53
54 839 wavelet scattering network, is also used to extract GPR images [130] .

54 840 Following the feature extraction methods, there is the detection/classification process. Detection
55
56 841 algorithms such as Soft-max in [120], [127] and You Only Look Once (YOLO) in [119], [129],
57
58 842 [131], where a multi-label classification is used for GPR imagery purposes. Furthermore, Faster-
59
60 843 region convolutional neural network (Faster-RCNN) for buried objects detection with a few

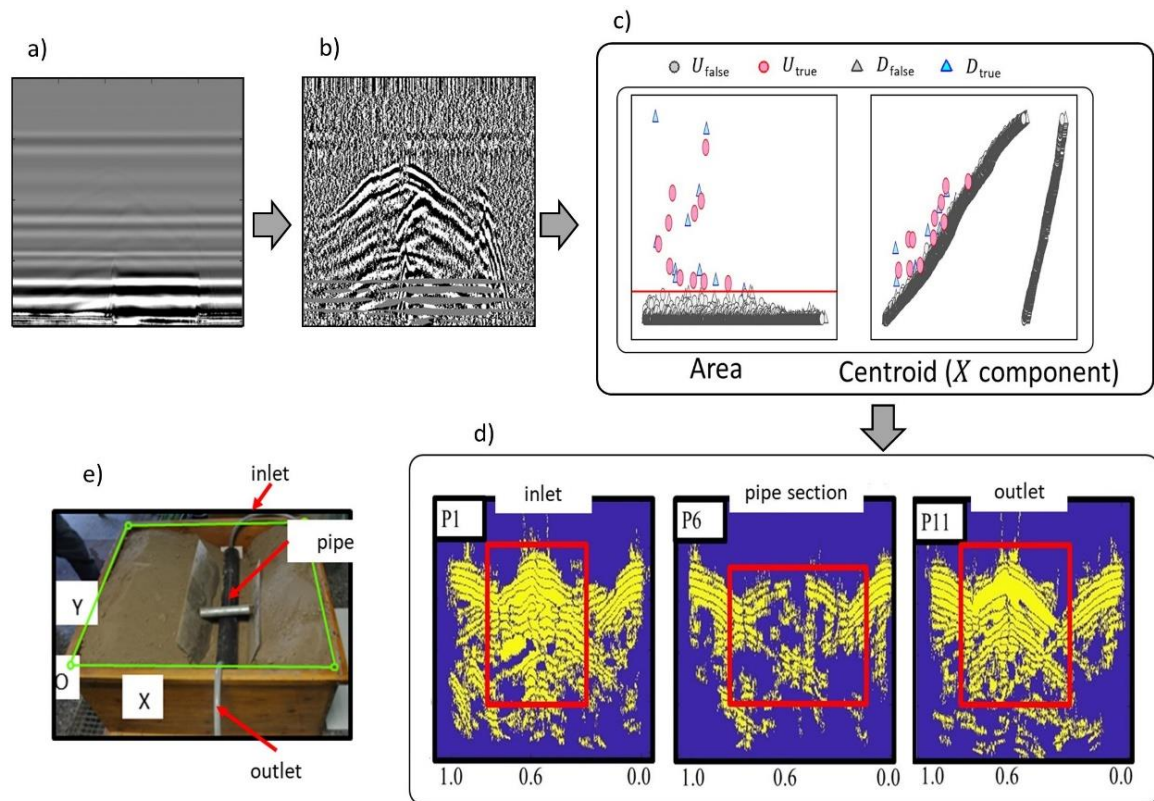
844 training samples is proposed [128] and for pavement distress detection in [132]. Inspired in YOLO
845 algorithm in [18] which is proposed as a single-stage object detector. A Support Vector Machine
1 846 (SVM) with the uses of radial basis function is used for classification in [130] and [133].
2
3 847 Alternative method using the traditional three-point circle method (denoted as "three-point
4
5 848 rounding") for automatic identification of buried pipes (e.g., diameter and position) is proposed in
6
7 849 [134]. A procedure to increase the cavity detectability on roads that includes the CNN, super-
8
9 850 resolution (SR) generation and automated classification phase is also proposed in [126] and [135],
10
11 851 [136] used back-propagation (BP) neural network for the automatic classification and recognition
12
13 852 of looseness in base.

14
15 853 The process of gathering adequate data sets that enable the training, fine-tuned, and validation of
16
17 854 the above-mentioned intelligent system is a challenge task. In this sense, the most common
18
19 855 strategies involve the field surveys, experimental samples, and artificial generation of GPR data
20
21 856 based on simulation or combination of various data sets. Field data collection of GPR images (e.g.,
22
23 857 see [77], [128], [136]), in some cases, data acquired by a vehicle-mounted GPR system (e.g., [119],
24
25 858 [120], [126], [127], [131], [137]) which has been used as a strategy for GPR dataset preparation
26
27 859 for inspection of roads in urban environment. Similarly, the use of experimental samples to collect
28
29 860 the GPR images is highlighted (e.g., tank configuration [123], [136]). laboratory experiments of
30
31 861 GPR dataset are conducted in order to maintenance or re-install buried objects in urban areas. For
32
33 862 instance, the GPR information is used for the detection algorithms (e.g., see open database of
34
35 863 radargrams in [138] as used in [130] , or in [139] as used in [136]). The use of FDTD method is a
36
37 864 complementary approach to validate GPR dataset driven from field or/and laboratory in a
38
39 865 simulated form. This can also feed the pattern extraction systems; e.g., in [136] a FDTD code is
40
41 866 usually generated in MATLAB to obtain simulated GPR images of embedded features in
42
43 867 pavements. Several research studies have been investigated on the similar topics such as [53],
44
45 868 [76], [123], [128], [130], [134] , use the gprMax software [140], [141] which is based on FDTD
46
47 869 to solve maxwell's equations in order to obtain simulated GPR images of buried objects e.g., pipes,
48
49 870 rebars, and complement/develop their datasets.

50
51 871 Several researches support their own IDA process in a pre-treatment of the information to facilitate
52
53 872 the feature extraction process. Among this, a technique of the signal amplitude thresholding
54
55 873 (determination of upper and lower signal to separate targets from the background) is investigated
56
57 874 [120]. Similarly, in order to delimit the regions of the GPR image where the target object is
58
59 875 embedded in [123], the use of an adaptive target region detection (ATRD) algorithm is proposed.
60
61 876 By removing the linear features from GPR images, i.e., consequently increasing the visibility of
62
63 877 buried objects in them, in [127] an algorithm denoted by the authors as "basis pursuit-based
64
65

878 background filtering" was developed. In [130], two pre-processing methodologies "dewow" and
 879 "amplitude gain" are used. The first "dewow" is applied to remove the effects of the occurrence
 880 of low-frequency noise components within each GPR image. The second filter (amplitude gain) is
 881 to improve the signal for the attenuation in particular for the latter arrived signals. To extract the
 882 signal attributes from GPR images which have a correlation with the loose damage, in [136] a
 883 signal eigenvalue extraction method is used. A series of pre-processing treatments is included
 884 among others, inverse Discrete Fourier Transform, and background removal are applied in [77],
 885 [131].

886 Also multi-agent systems supported by game theory have been proposed in [142] with the so-
 887 called "race agent" algorithm. This algorithm has the premise of seeking data reduction, while
 888 preserving the characteristics of the elements embedded into the GPR images. With the use of this
 889 pre-processing method both classification and visualisation processes are facilitated. Figure 12
 890 presents an example for the extraction of water leakage patterns by the uses of both the "race-
 891 agent" algorithm and classification by means of perceptron neural network. Some examples of the
 892 uses of this algorithm are, for example, the automatic detection of plastic pipes [143], the
 893 characterization of water leaks [84], and the extraction of patterns that allow understanding and
 894 anticipating the water leak phenomenon in urban water infrastructures [97].



895
 896 Figure 12 An example of pre-processing and extracting water leak patterns from GPR images. a) Raw GPR image, b)
 897 pre-processed matrix using agent-race algorithm, c) data families and data labelling, d) families classified by
 898 perceptron neural network, and e) setup for water leak capture. (Adapted from [97]).

899 Data augmentation is proposed in order to increase the quality, diversity and size of the GPR
900 datasets[119]; This technique preserve the input target labels considering the input transformation.
901 Shifting an original GPR image has been used in [125], [127] in order to augmented the dataset.
902 More robust methods are investigated to augment the data and increase the quality of this data
903 includes the Generative Adversarial Networks (GANs) [136], [144] or incremental random
904 sampling (IRS) [77]. Although many efforts have been made with the aim of automating the tasks
905 of inspection and monitoring of the roads. The reliable autonomous interpretation of the GPR
906 records remains a paramount in the nowadays research projects. In addition, IDA approaches have
907 been proven to be an efficient tool that can facilitate this process in its different stages (Table 3).

908 Table 3. An overview of road inspection methods that use GPR and incorporate intelligent data analysis

Inspection task	References	Data set preparation	Pre-processing	Feature extraction	classification/detection	Target
Object detection - characterisation of objects embedded in transport infrastructures	[120]	Field data collection	Thresholding of signal amplitude. Manual labelling of data library	CNN		Automatic classification of the hyperbola, manhole cover, layer interface and subsoil background.
	[119]	Field data collection	Data Augmentation. Manual labelling of data library	CNN	YOLO model	Automatic classification of rainwater wells, cables, non-metallic and metallic pipes, steel reinforcement.
	[123]	Numerical simulations and field data collection	ATRD	Ensemble of CNN and LSTM		Automatic diameter identification of the cylindrical buried objects
	[130]	Numerical simulations and experimental open GPR datasets	de-"wow" and amplitude gain	Wavelet scattering network	SVM	Automatic pipe location and diameters for non-intensive data sets
	[128]	Numerical simulations and field data collection	-	CNN	Faster-RCNN algorithm	Automatic detection of buried objects with few training samples
	[136]	Numerical simulations, field data collection and open GPR datasets.	GANs	Single-stage object-detector		Automatic buried objects detection via hyperbola detection, attempts to address the scarcity of GPR data.
	[134]	Numerical simulations	-	-	"Three-point	Automatic identification of buried pipes (e.g.,

					rounding” method	diameter, and position)
Damage detection on transport infrastructure	[127]	Field data collection	Shifting and "basis pursuit- based background filtering" algorithm	CNN		Automatic underground cavity identification in roads
	[126]	Field data collection	-	CNN, Super resolution image generation, and automated classification phase		
	[132]	Field data collection	-	Faster-RCNN algorithm		Automatic pavement distress detection
	[144]	Numerical simulations	Signal eigenvalue extraction	BP neural network		Automatic classification of loose damage
	[131]	Field data collection	Filtering	YOLO model		Automatic recognition and location of concealed cracks in pavements
	[77]	Field data collection	Filtering and IRS	CNN	YOLO model	Automatic moisture detection and location
	[133]	Numerical simulations	-	SVM		Layer thicknesses estimation

909
910 The limitation of IDA methods depends on the reliability of the GPR data set, and amount of the
911 data which can be trained and tested, and based on these, the validation and the accuracy of the
912 trained model is essential in order to provide an effective tool. Therefore, the interoperability of the
913 ML results to a decision making model which can be used from owners/operators of the road
914 transport infrastructures in an easy predictive model, which require some IDA expertise.

915 6. Remarks and Further trends

916 GPR is nowadays a consensual tool for continuous layer thickness assessment at traffic speed.
917 Moreover, several other essential pavement characteristics for structural monitoring can be
918 observed, such as settlements, layers debonding and water presence.

919 The main challenge for continuous structural monitoring is the data processing interpretation and
920 integration due to the significant volume of information gathered during GPR data acquisition.

921 Building Information Modelling (BIM) developments as a tool that can integrate the evaluation
922 results in an updated pavement model are also addressed. The BIM model automatically integrates
923 the B-scan results that can reflect the evolution of pavement condition along the life cycle and

924 represent a base for performance indexes development and validation [145]–[147]. Automated and
 925 new technologies such as machine learning, digital twins, and robotic platforms are widely
 926 conducted. Lately, there have been many innovative research projects funded by various
 927 institutions in Europe and globally. They provide better road transport infrastructures, mostly thus
 928 are robotic inspection and real-time monitoring approaches of various research gaps in the field of
 929 road pavements. Some of the above-mentioned projects are illustrated in Table 4.

930 Table 4. On-going innovative research projects in the assessment of the road transport infrastructures.

No.	Project Acronym	Title	Description	Funded by
1	CoDEC	Connected Data for Effective Collaboration	To study the key means for successful implementation of Building Information Modelling (BIM) principles within the European highways industry, in particular with regards to freeing and enriching data flow to and from Asset Management Systems (AMS)	CEDR (Conference of European Directors of Roads) under grant agreement no 859887 (https://www.codec-project.eu/)
2	PANOPTIS	Development of a Decision Support System for increasing the Resilience of Transportation Infrastructure	To improve the resiliency (ability to adapt) of the road infrastructures and ensuring reliable network availability under unfavourable conditions, such as extreme weather, landslides, and earthquakes.	Horizon 2020 research and innovation programme under grant agreement no 769129 (http://www.panoptis.eu/)
3	HERON	Improved Robotic Platform to perform Maintenance and Upgrading Roadworks	To develop an integrated automated system to perform maintenance and upgrading roadworks, such as sealing cracks, patching potholes, asphalt rejuvenation, autonomous replacement of CUD elements and painting markings, but also supporting the pre/post-intervention phase including visual inspections and dispensing and removing traffic cones in an automated and controlled manner.	Horizon 2020 research and innovation programme under grant agreement no 955356 (http://www.heron-h2020.eu/)

931
 932 One another significant future trend is the use of remote sensing to monitor settlements of
 933 pavements. It is helpful as it is available free of costs by European satellites (Copernicus European
 934 Program). The combination of satellite data with radar images is crucial to interpret the service
 935 state of pavements better. Several studies performed on pavement evaluation have proven this
 936 approach's efficiency, mainly on subsidence and road profile [110], [148], [149].

937 The importance of advanced monitoring technology that integrates interpretation and modelling
 938 are highlighted as tools for pavement management systems. It provides a confident diagnosis of
 939 the structural condition of existing pavements and enables economically efficient maintenance that
 940 guarantees the pavement's proper behaviour and an extended life cycle. Following the previous
 941 sections, GPR is an NDT method that makes it possible to assess the pavement's structural health

942 and service state, and therefore to make rational decisions in terms of management, maintenance,
 943 repair actions, and cost analysis to the road pavement. As for other NDT, the objective is to
 944 optimize the decisions, which means making the most possible best decision at the best time to
 945 maximize its impact while minimizing the cost of repair and maintenance. Several cases of GPR
 946 use for decision-making purposes already exist in the literature. Table 5 presents two cases studies
 947 related to the use of decision-making approaches based on GPR data. These cases are linked to the
 948 road pavement itself (repair actions for cracks, treatment of water in the pavement, cleaning and
 949 routine maintenance actions, etc.) and to networks embedded in the pavement (water works,
 950 electricity or gas supply, etc.). Using various and suitable types of data analysis could be a key
 951 support to provide valuable structural health knowledge on pavements, leading to an optimised
 952 approach for repairs and maintenance. The use of GPR is still localized, both in time and in space
 953 and can be a useful support for decision-making owners/operators. The future of the use of GPR
 954 might be the routine and scheduled use of GPR, combined with other sensors and installed on
 955 automated vehicles, for continuous and real-time assessment of the road infrastructure and
 956 application of response actions.

957 Table 5. Summary of previous studies related to decision-making methodologies based on GPR data for road
 958 pavements

No.	Problematic (Hypothesis)	Approach	Use of GPR technology	Remarks	Reference
1	Use of GPR technology to provide quantitative information for improved decision making and reduced operating costs.	Multi-scale pavement GPR data Analysis (MPGA)	Yes	The testing and demonstration showed significant potential for quality control using GPR.	[150]
2	A real case study, focusing on a set of GPR images for optimizing maintenance management of Water Supply Systems	Multi-criteria decision making (MCDM)	Yes	Significant results are shown on the decision-making approach based on GPR data	[151]

960 CRediT authorship contribution statement

961 **Coordination of the project:** Mezgeen Rasol, **Conception:** Mezgeen Rasol, Jorge Pais and Mercedes Solla.

962 **Writing, Reviewing, Materials, and Revision process:** Corresponding authors, and all co-authors has
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12 972 Authors declare there is no conflict of interest. The funders had no role in the design of the study; in the
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19 975 References

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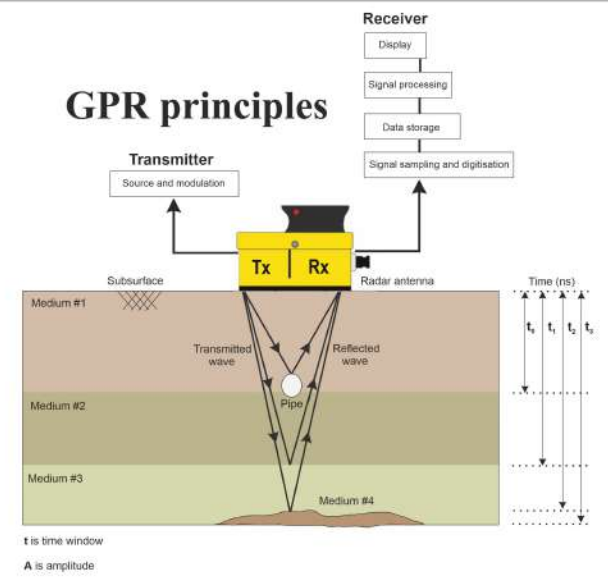
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1 Principles of GPR, and objectives of the study

GPR principles

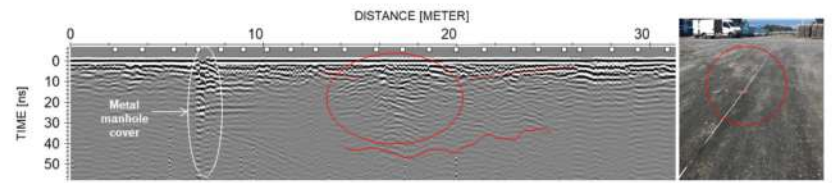


Research gaps vs contribution

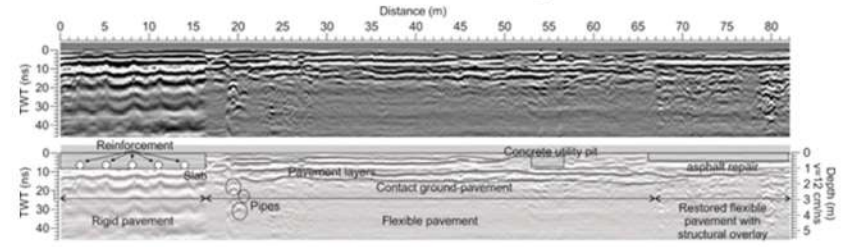
Current research gaps	Main brief contribution of study
1. Lack of possible review study to understand main distresses in road pavements, and the efficiency of GPR in the monitoring process.	1. comprehensively review of diverse distressed in road pavement, and illustrating the capacity of GPR, which can be a useful source for road engineers, and researchers in road pavement monitoring.
2. The main intelligent data analysis approaches which can be efficient for enhancing radarimages interoperability, and provide significant decision-making tools for road transport owners, or operators.	2. State-of-the-art of the machine learning based approaches are presented, and this could support researchers are working on developing decision-making tools, and enhance a better interoperability of radar images

2 Road transport distresses

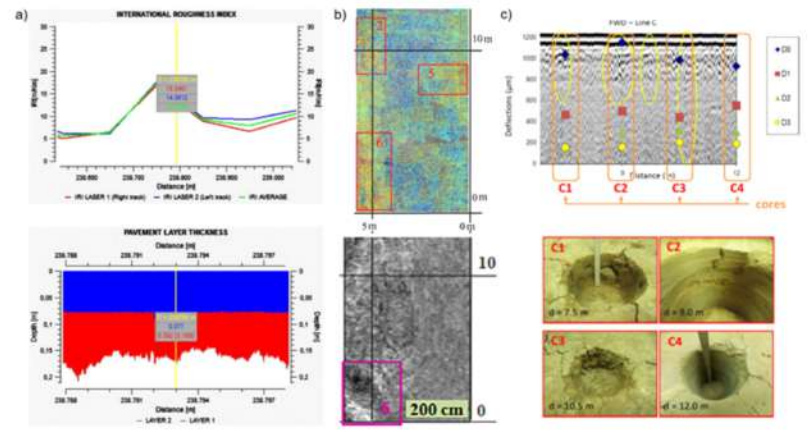
Settlement and filling subsidence



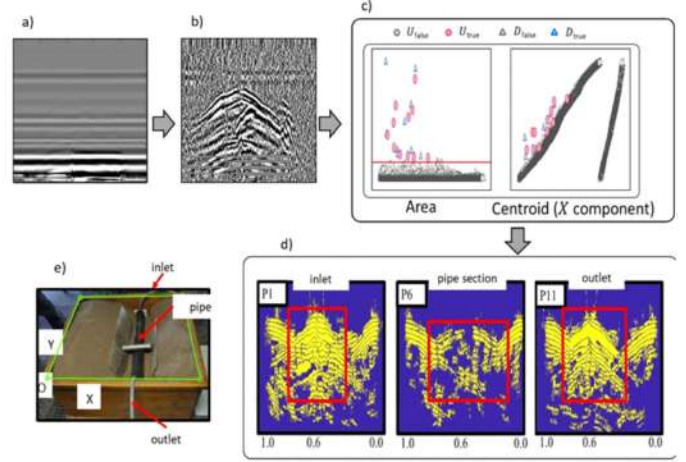
Discontinuities in between layer thicknesses



Incorporation of NDTs with GPR



Machine learning based approaches



3 Incorporation of other NDTs with GPR and Intelligent data analysis