COST Action TU1208

Civil Engineering Applications of Ground Penetrating Radar

This presentation is part of the TU1208 Education Pack

Combined use of GPR and deflection measurement devices on roads

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COST is supported by the EU Framework Programme Horizon2020

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Lecture Layout

Basics of road deflection

- Elasticity and cracking, bonding, deflection and layer stiffness

The Falling Weight Deflectometer and Curviameter

- Falling Weight Deflectometer (FWD)
- Curviameter
- Comparison of FWD and Curviameter & Examples of interesting projects where FWD and Curviameter were used

FWD and Curviameter data processing and interpretation

- 1st step: Homogeneous road segments
- 2nd step: Evaluation of the road structural health

Combined use of deflectometers and GPR

New! Traffic Speed Deflectometer and its combination with GPR

Biography and contact details of the Author

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Basics of road deflection

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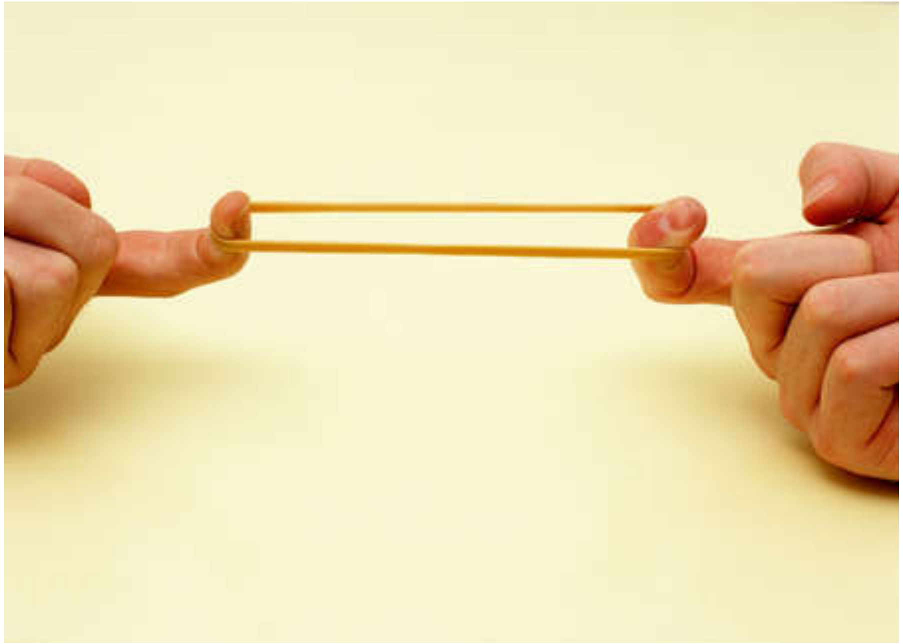
Elasticity and cracking



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Bonding

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Deflection and layer stiffness

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Falling Weight Deflectometer (FWD)

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Deflection measurements with FWD

- Deflection measurements with FWD can be done on all roads (also rigid roads, with concrete)
- FWD customary properties:
  - Force: 50 to 100kN
  - 1 measurement point every 100 m
  - 9 geophones or more (0, 300 mm, ..., 2400 mm)

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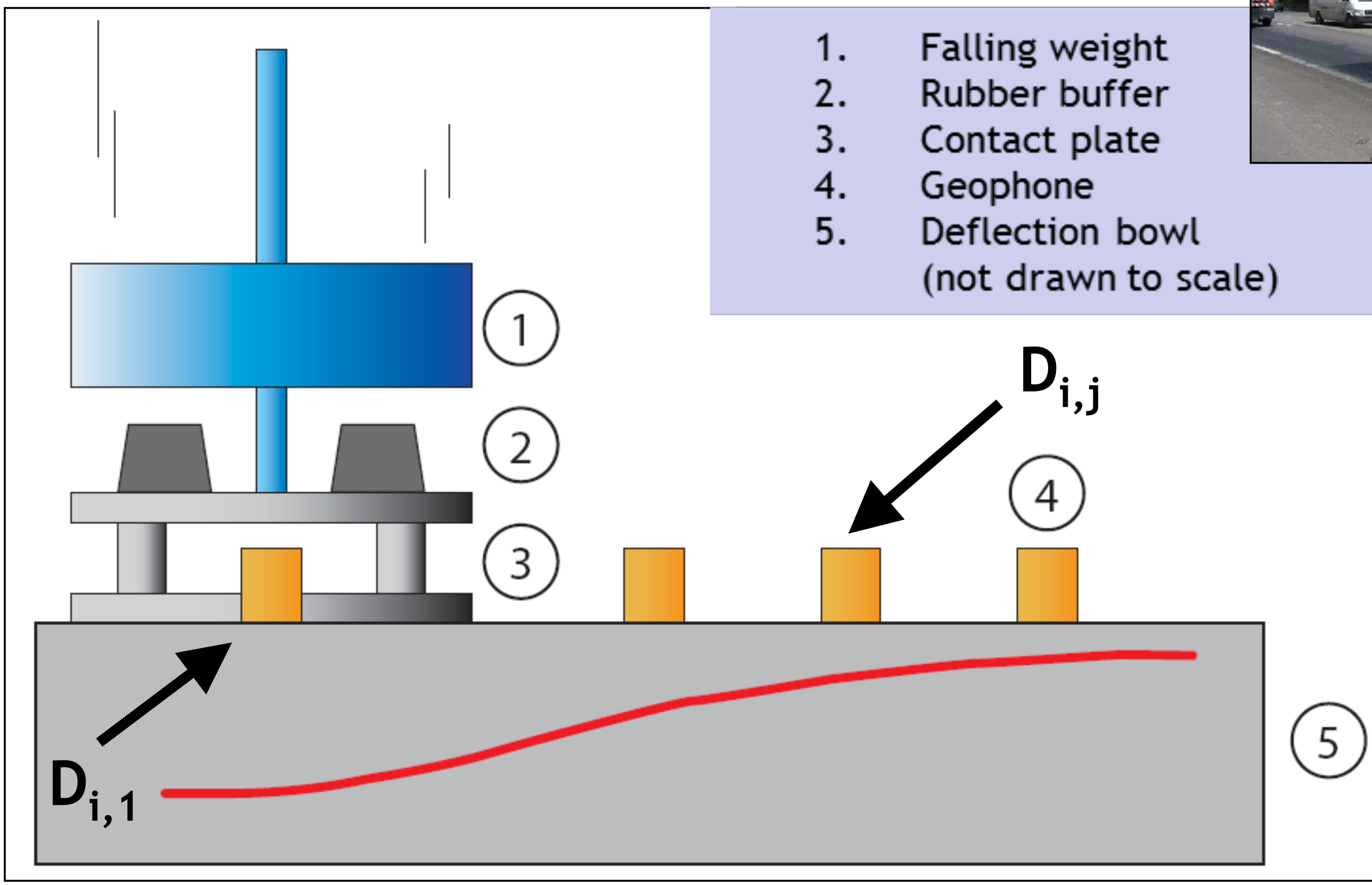
FWD basic principles

- A falling weight generates deflection and this is measured by geophones



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Sensors of the FWD

- 1 force sensor

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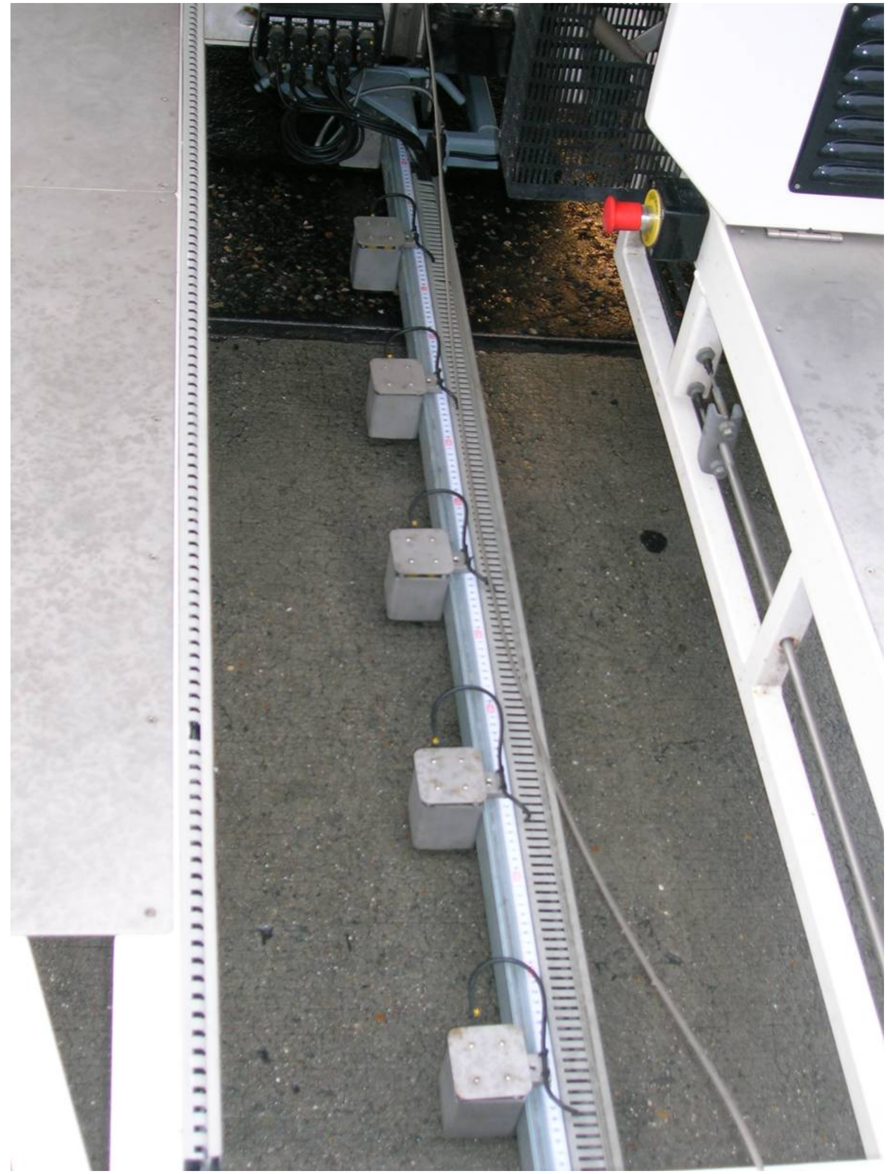
Sensors of the FWD

- 9 geophones (or more)



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Ordinarily reported output of FWD measurements

FWD: 0411-104	Route: N45					File name:		ep9713-1	Date of measure: 29/03/12
	Direction:	Aalst	from	3.440 km	to	3.361 km	band: 1	Force:	50 kN

STATION POSITIONS		DEFLECTIONS (µm)									CHARGE		TEMPERATURES (°C)			Pulse Time	Remarks
N° of station	cumulative distance FWD	D(0)	D(200)	D(300)	D(450)	D(600)	D(900)	D(1200)	D(1500)	D(1800)	Pressure (kPa)	Charge (kN)	Air	Surface	Prof 40	(ms)	
1	3440	68	56	50	46	43	37	33	27	23	697	49.3	18.3	14.8	17.7	28.3	
2	3433	61	50	46	43	41	35	31	26	22	695	49.1	18.4	14.9	-	28.4	
3	3427	62	53	50	46	44	37	32	26	23	698	49.3	18.8	15.3	-	28.4	
4	3419	66	52	47	44	41	36	33	28	25	700	49.5	17.7	15.6	-	28.6	
5	3411	65	54	51	48	47	42	38	32	26	697	49.3	18.6	16.0	-	29.0	
6	3403	80	68	63	57	54	45	40	33	28	686	48.5	18.6	16.0	-	28.6	
7	3395	68	56	52	49	46	40	35	30	26	682	48.2	18.8	16.4	-	28.4	
8	3387	63	53	51	49	48	44	35	28	25	681	48.1	18.8	16.5	-	28.8	
9	3378	61	51	48	46	44	38	35	29	26	683	48.3	18.3	16.6	-	28.8	
10	3369	73	60	56	54	53	48	44	39	30	689	48.7	18.4	16.6	-	28.9	
11	3361	71	62	58	55	52	47	43	37	33	683	48.3	18.1	16.7	-	28.8	

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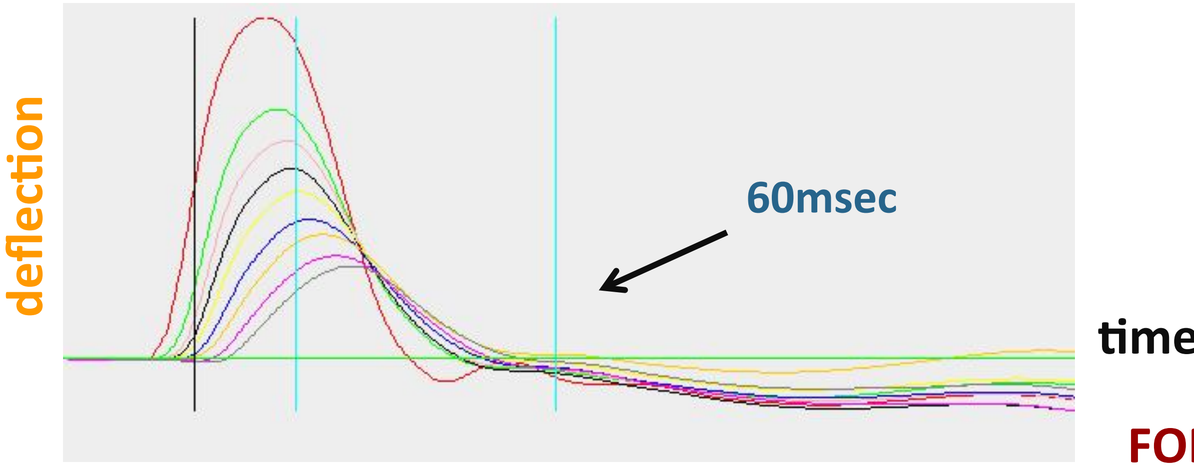
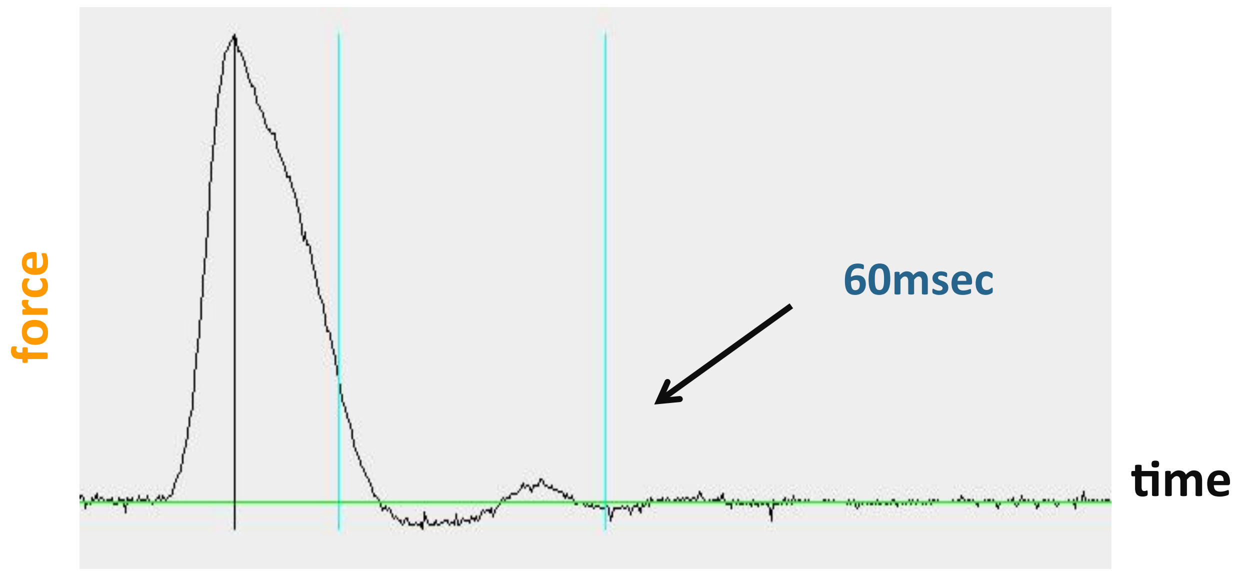
Hysteresis data:
load and displacement for 60 or 120 ms

FOR EACH OF THE GEOPHONES



FORCE SENSOR



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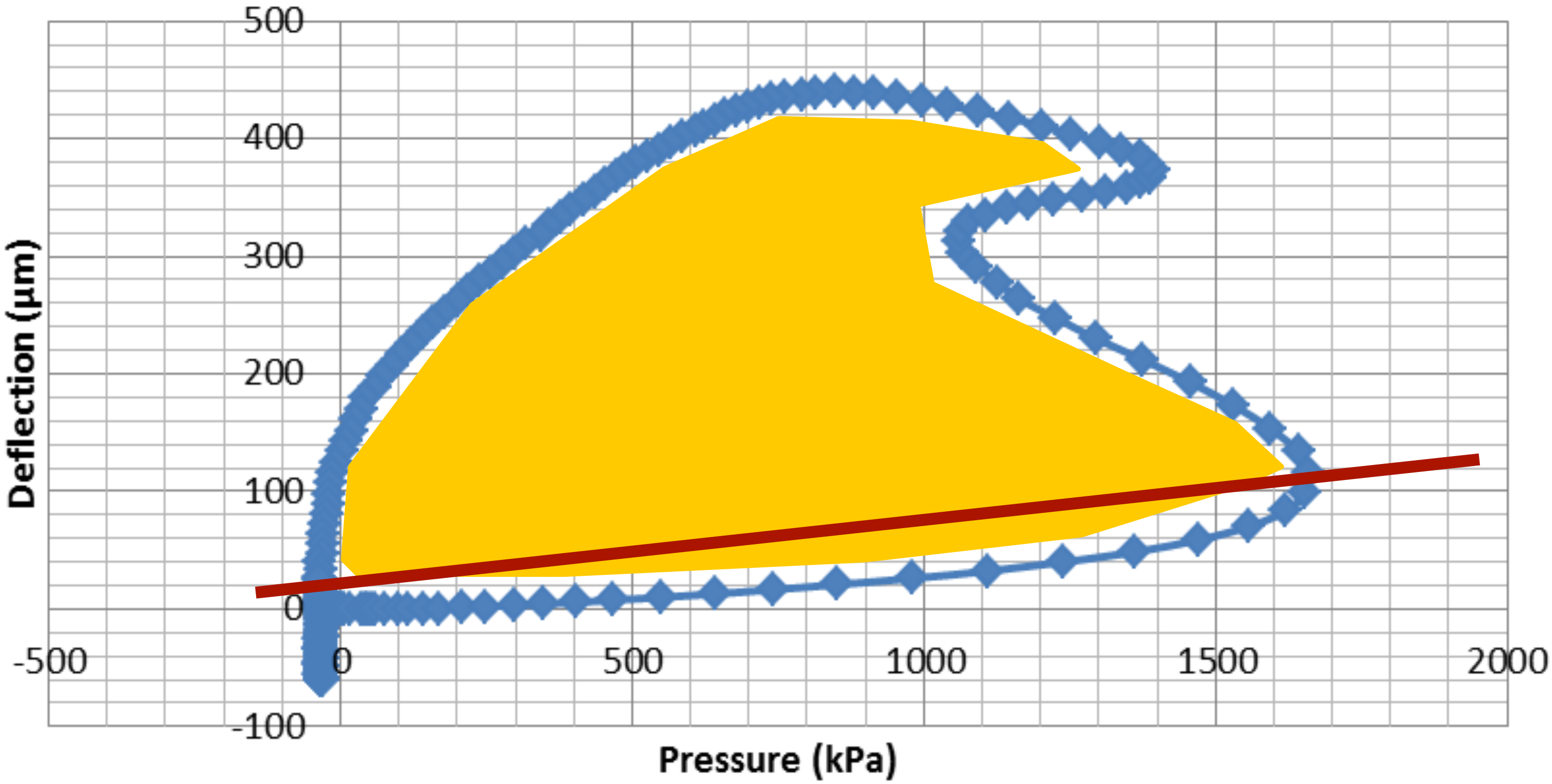
Hysteresis data: load and displacement for 60 or 120 ms

- Load-displacement plot (1 for each geophone): Surface and slope



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Curviameter

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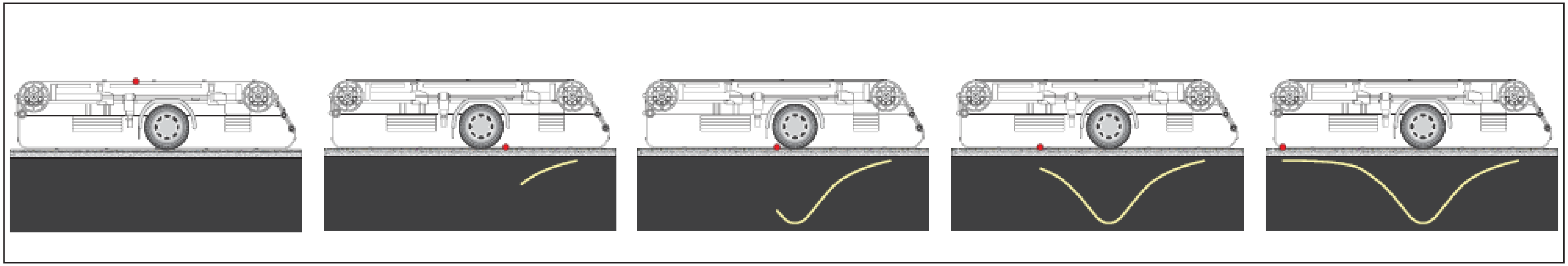
Deflection measurements with Curviameter

- On bituminous surfaces (semi-rigid roads)
  - Curviameter
  - 13T axle (65kN wheel load)

- 1 measurement every 5 m



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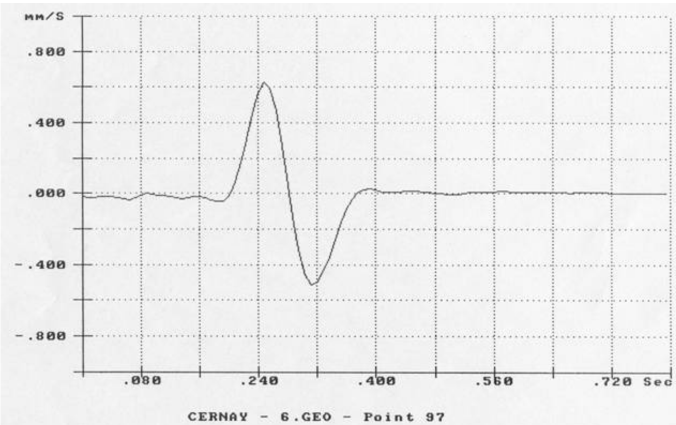
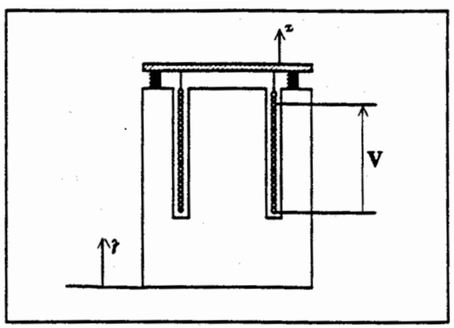
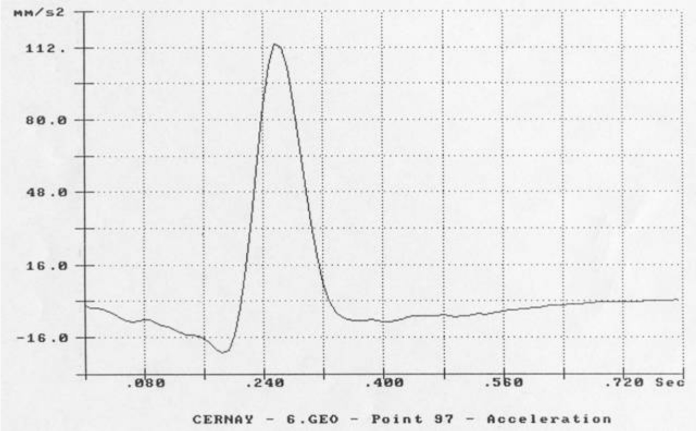
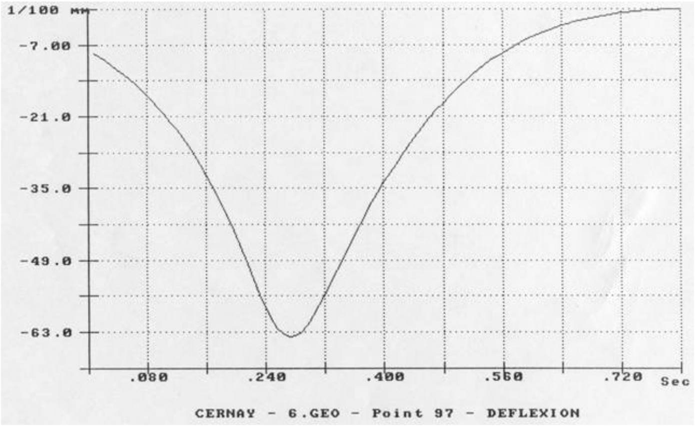
Basic principles of a geophone: signal, acceleration, deflection





$$\gamma(t) = a\frac{dV(t)}{dt} + bV(t) + c\int V(t)dt$$





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Standard reported output of Curviameter measurements

Homogeneous segments					Maximal deflections			Curvature radius		Air temperature			Surface temperature		
Nbr	start (km)	end (km)	length	Nbr of stations	average	std dev	characteristic	average	std dev	T. min.	T. ave.	T. max.	T. min.	T. ave.	T. max.
HS	(km)				(1/100 mm)			(m)		(°C)			(°C)		
1	97.823	98.089	0.266	54	4	2	7	5141	1436	16.0	16.0	16.0	15.0	15.7	16.0
2	98.094	98.120	0.026		Zone Neutralisée										
3	98.125	98.416	0.291	59	3	2	7	5782	1962	16.0	16.0	16.0	16.0	16.0	16.0
4	98.421	98.521	0.100		Zone Neutralisée										
5	98.526	98.717	0.191	39	5	3	11	3650	1595	16.0	16.0	16.0	16.0	16.0	16.0
6	98.722	98.782	0.060		Zone Neutralisée										
7	98.787	99.203	0.416	84	5	2	10	4070	1229	16.0	17.0	17.0	16.0	16.0	17.0
8	99.208	99.424	0.216		Zone Neutralisée										
9	99.429	99.540	0.111	23	4	2	7	3455	575	17.0	17.0	17.0	16.0	16.2	17.0
10	99.545	100.217	0.672	135	8	3	13	2671	758	17.0	17.0	17.0	16.0	16.0	16.0
11	100.222	100.287	0.065	14	17	7	30	1696	909	17.0	17.0	17.0	16.0	16.6	17.0
12	100.292	100.965	0.673	135	8	3	15	2713	764	17.0	17.0	18.0	16.0	16.2	17.0
13	100.970	101.738	0.768	154	15	6	27	1824	503	17.0	18.0	18.0	16.0	16.0	17.0
14	101.743	101.798	0.055	12	6	3	11	2524	1500	18.0	18.0	18.0	16.0	16.1	17.0
15	101.803	101.998	0.195		Zone Neutralisée										
16	102.003	102.676	0.673	135	9	4	17	2275	784	18.0	18.0	18.0	16.0	16.5	17.0
17	102.681	103.283	0.602	121	5	2	10	3893	1298	18.0	18.0	18.0	16.0	16.8	17.0

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Further available Curviameter data

Table with data per station

Cumulated (km)	Nbr Measure	Marks Curviago	Marks Curviago	Deflection (1/100 mm)	Curvature Radius (m)	T° Surface (°C)	T° Air (°C)	Speed (m/s)	Marks operator
97.823	1	D	C	3	5500	15	16	1.7	EVTCOR
97.829	2	D	C	3	5500	15	16	5	
97.834	3	D	C	3	5500	15	16	5	
97.839	4	D	C	3	5500	15	16	5	
97.844	5	D	C	3	5500	15	16	5	
97.849	6			1	8242	15	16	5	
97.854	7			2	4118	15	16	5	
97.859	8		C	2	4118	15	16	5	
97.864	9			2	6992	15	16	5	
97.869	10		C	2	6992	15	16	5	
97.874	11		C	2	6992	15	16	5	
97.879	12		C	2	6992	15	16	5	
97.884	13			3	5514	15	16	5	
97.889	14		C	3	5514	15	16	5.1	
97.894	15			5	5445	16	16	5.1	
97.899	16		C	5	5445	16	16	5	
97.904	17			4	4607	16	16	5	
97.909	18		C	4	4607	16	16	5.1	
97.914	19		C	4	4607	16	16	5.1	
97.919	20			1	7138	16	16	5.1	
97.924	21		C	1	7138	16	16	5.1	
97.929	22			3	5182	16	16	5	
97.934	23			1	4406	16	16	5.1	
97.939	24			3	5678	16	16	5.1	

Table with complete deflection bowl (100 points/bowl) per station

97.823	1	770	654	544	438	340	250	170	96	28	-30	-80	-122	-160	-204	-254	-306	-350	-376	-382	-378
97.829	2	206	236	264	290	316	342	368	394	418	440	462	480	496	510	520	528	536	540	546	550
97.834	3	-118	-146	-170	-190	-204	-218	-230	-244	-260	-278	-300	-322	-346	-370	-396	-420	-444	-466	-486	-504
97.839	4	126	158	190	220	246	266	284	294	298	298	294	288	278	268	258	246	236	228	224	224
97.844	5	-80	-90	-100	-112	-128	-144	-162	-180	-198	-216	-234	-252	-270	-288	-308	-328	-348	-368	-388	-406
97.849	6	-40	-42	-44	-46	-48	-50	-50	-52	-52	-52	-52	-52	-54	-56	-58	-64	-68	-74	-78	-84
97.854	7	-76	-76	-78	-80	-82	-82	-84	-84	-82	-82	-82	-84	-86	-90	-94	-102	-110	-120	-130	-142
97.859	8	-398	-428	-458	-486	-514	-542	-568	-592	-614	-636	-656	-678	-700	-722	-744	-766	-788	-808	-828	-846
97.864	9	-72	-72	-74	-76	-78	-80	-84	-86	-90	-96	-102	-110	-120	-132	-144	-154	-166	-176	-184	-194
97.869	10	-430	-458	-484	-508	-530	-548	-566	-584	-602	-622	-642	-662	-684	-706	-726	-746	-764	-780	-796	-812

...

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Comparison between FWD and Curviameter

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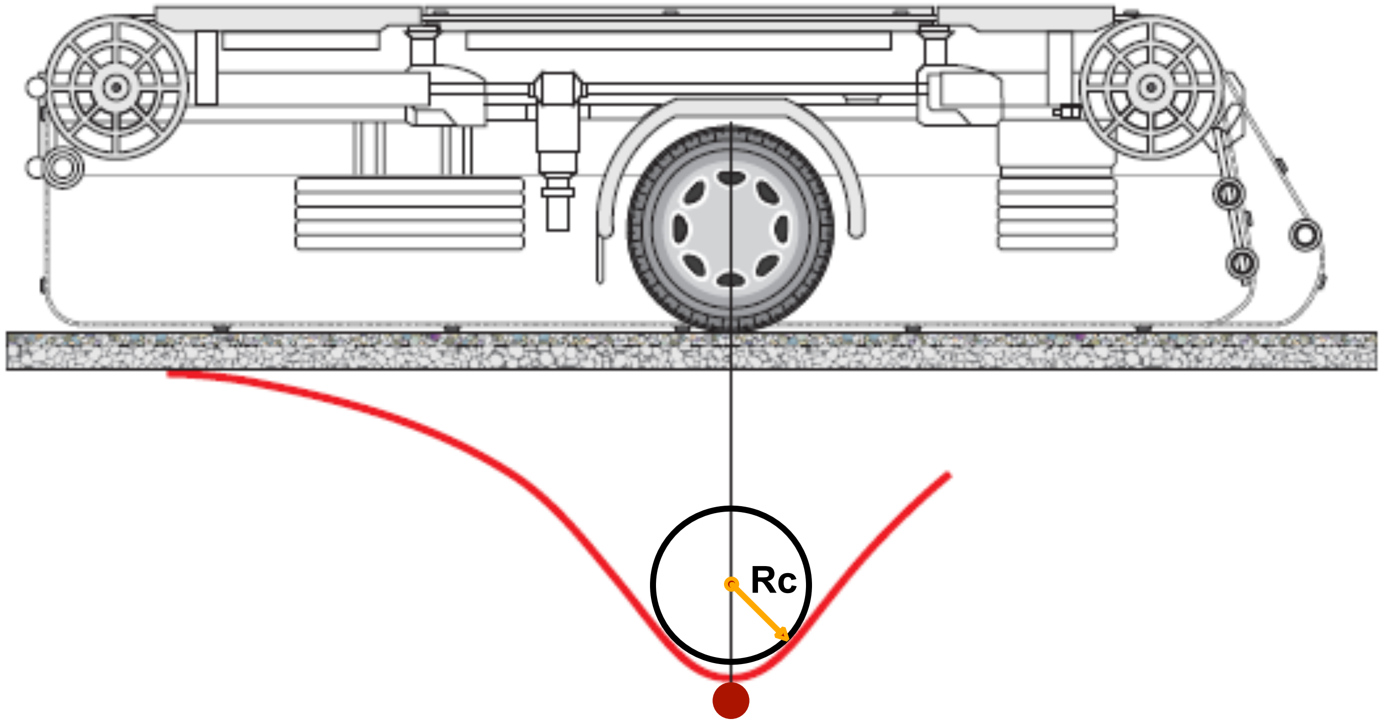
Deflection and Curvature Radius

- Curviameter

  - **Maximum deflection measured radius 100 points on curve**



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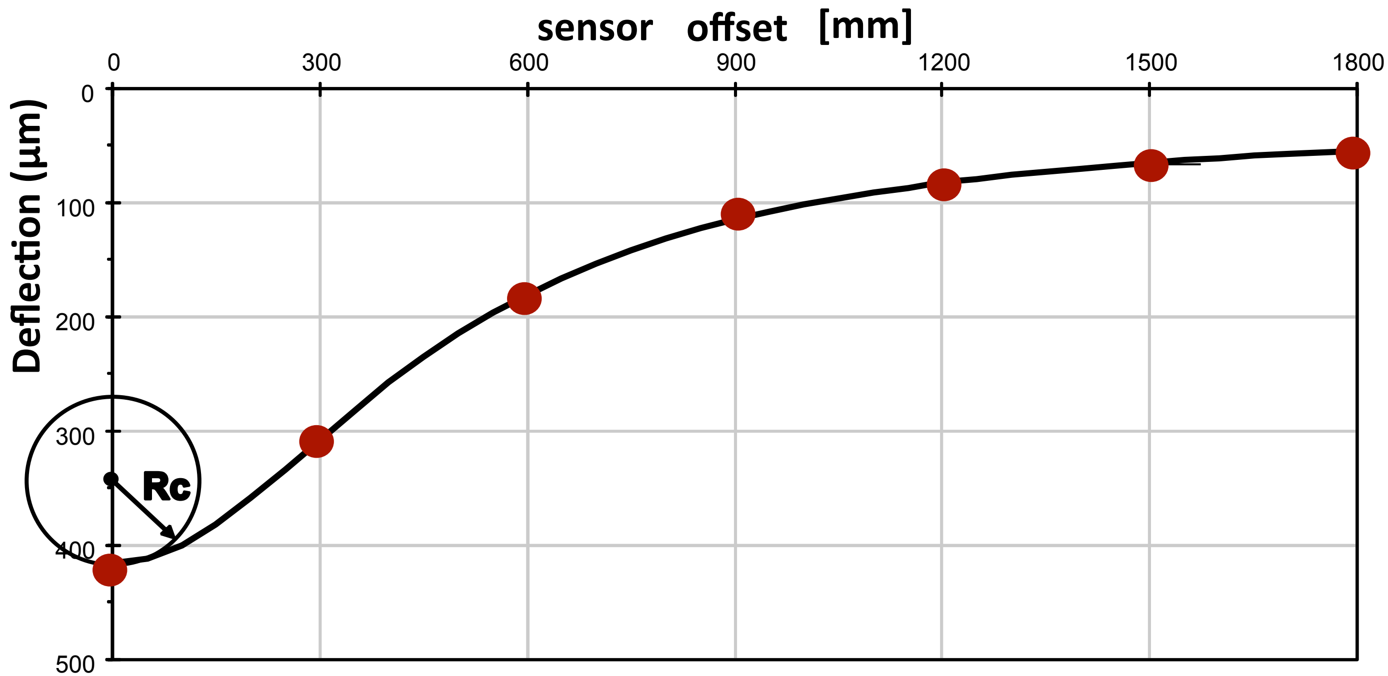
Deflection and Curvature Radius

- FWD

● **Maximum deflection computed radius “hysteresis” data**



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COST ACTION 324: Lacroix Deflectograph, FWD, Curviameter

- COST ACTION 324, Long Term Performance of Road Pavements, Final Report of the Action, 1997 (ISBN 92-828-0308-2)

Example of conversion tables

Table 8E.4 Conversion equations with respect to Dynatest 8000 FWD deflections

Equipment / Structure	FWD KUAB +	Deflectograph *	Curviameter *
semi-rigid	Dyn = 1.837 $KUAB^{0.866}$	Dyn = 1.08 to 0.77 Defl (depending on the pavement thickness)	Dyn = 1.20 to 0.86 Curv (depending on the pavement thickness)
bituminous	Dyn = 1.837 $KUAB^{0.866}$	Dyn = 1.08 Defl (1) Dyn = 1.14 Defl (2)	Dyn = Curv
granular	Dyn = 1.837 $KUAB^{0.866}$	Dyn = 0.98 Defl (1) Dyn = 1.04 Defl (2) Dyn = 1.16 Defl (3)	Dyn = 1.09 Curv

* relationships valid for a load ranging between 50 and 65 kN
\+ relationships valid for a load of 50kN on both KUAB and Dynatest 8000 FWDs
(1) results apply to extended beam long frame Deflectograph (D04) only
(2) results apply to long frame Deflectograph (D03) only
(3) results apply to short frame Deflectograph (D02) only

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FWD vs. Curviameter (ref. PARIS project)

- Normalisation of Deflection Measurements, Technical Memorandum T2 of the PARIS project, 22 September 1998

Maximal deflection

Deflection distance from maximum (in mm)	Linear correlation coefficient (R)	A1 (DCurvia = A1 . DFWD)	A2 (DFWD = A2 . Dcurvia)
0	0.919	1.024	0.955
300	0.962	1.315	0.753
600	0.916	1.662	0.590
900	0.728	1.810	0.514

Table 2: FWD vs. Curviameter in PARIS project

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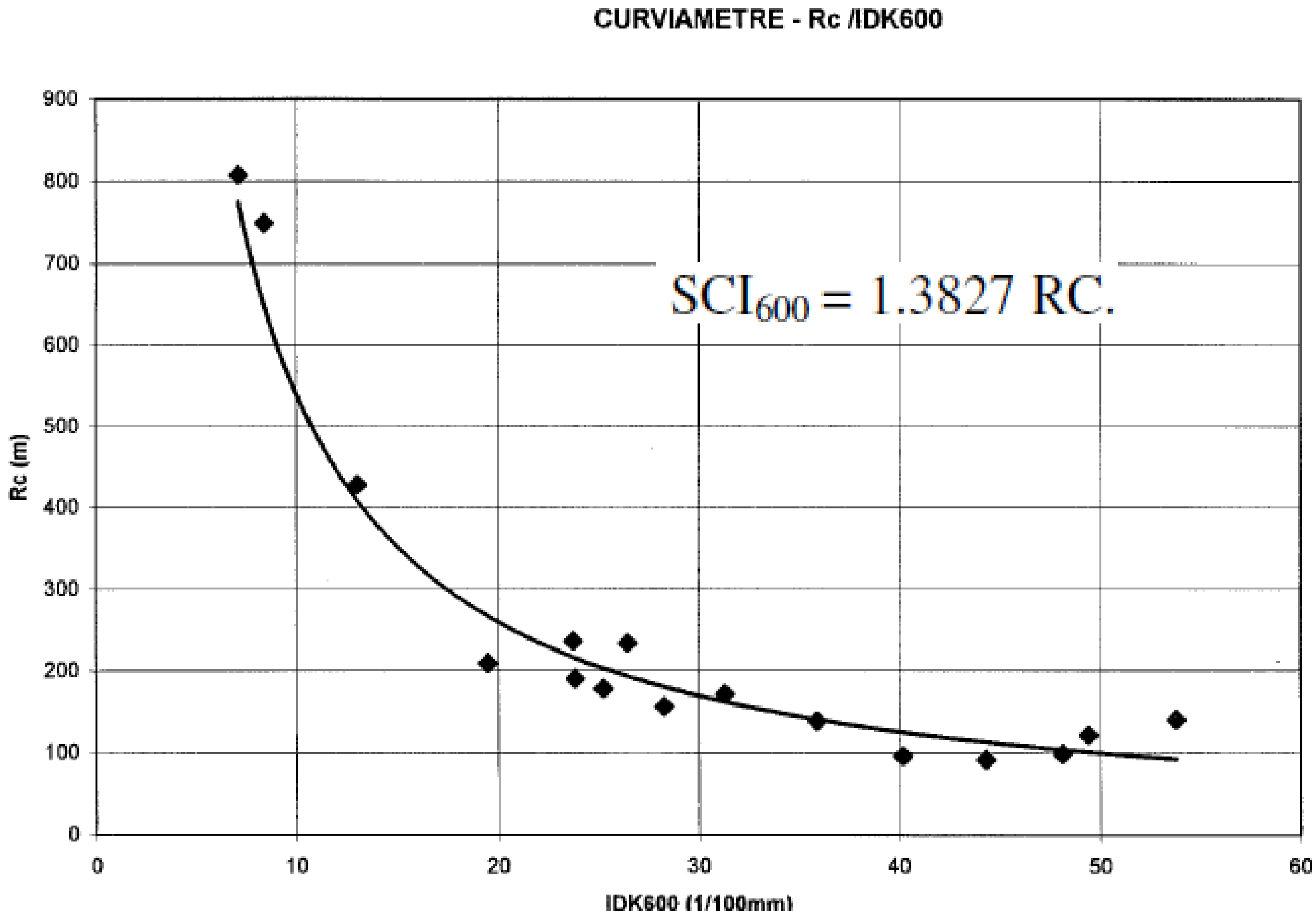
Radius of Curvature and SCI_{600} (ref. PARIS Project)

Curviameter Curvature Radius



FWD IDK_{600}

FWD and Curviameter data processing and interpretation:

1^{st} step – Homogeneous road segments

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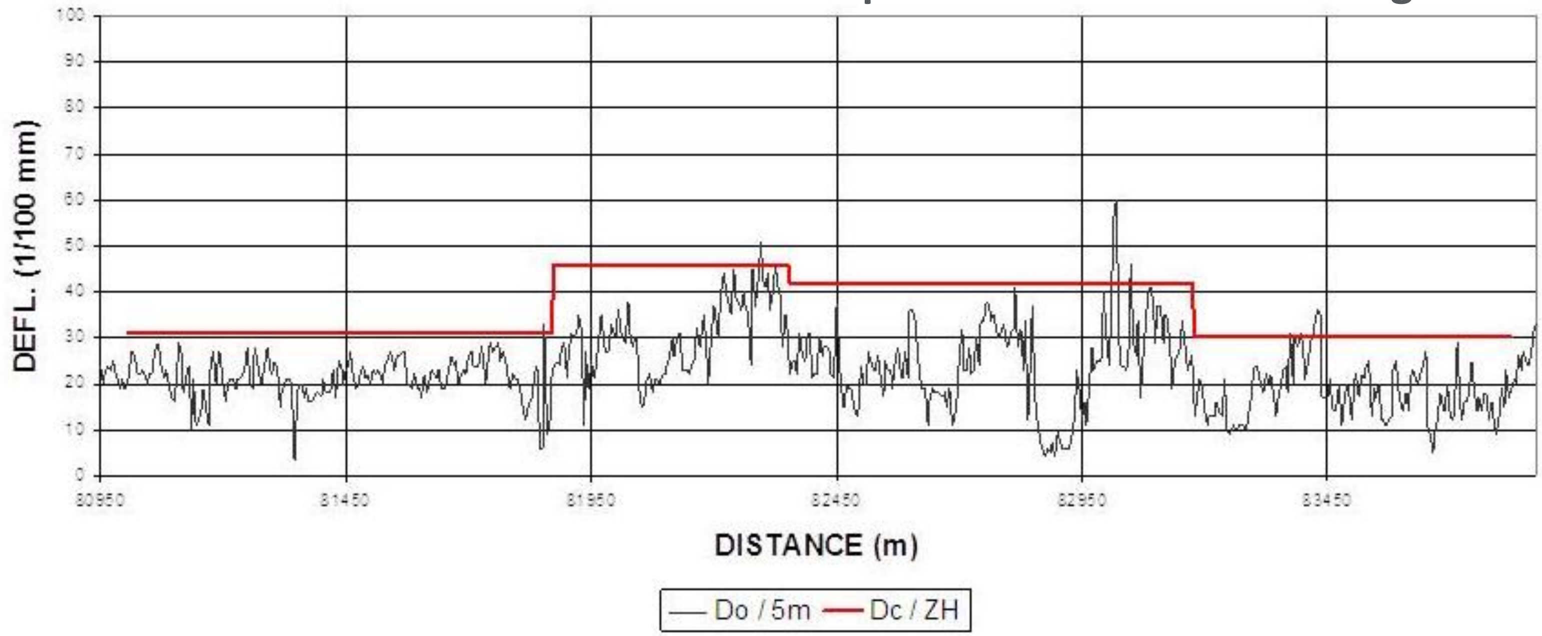
Homogeneous segments from Curviameter data

- By using the maximal deflection, cut the road in “segments” with “homogeneous structural behavior”

Example: Section divided in 4 segments



- For each “homogeneous segment”: Compute the indicators
- Statistics: characteristic deflection in a segment: $D_{char} = D_{max,average} + 2.\sigma$

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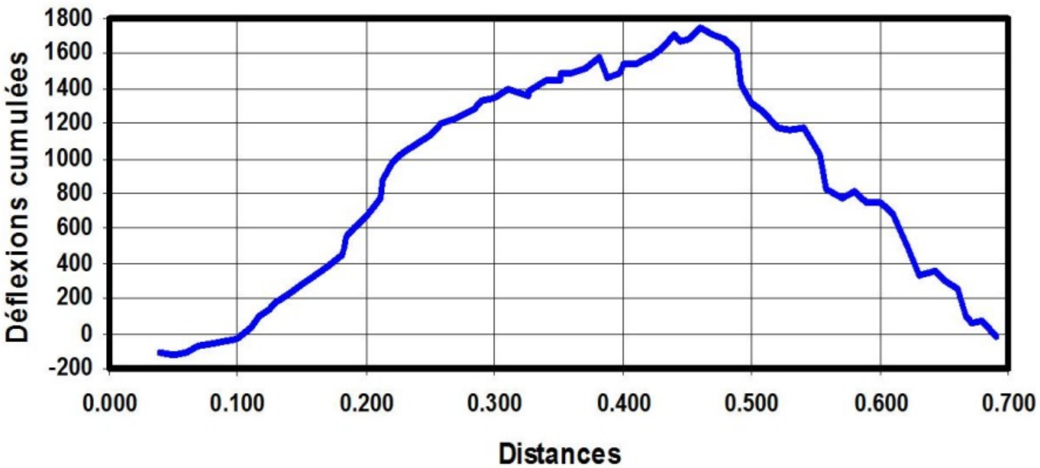
Homogeneous segments from FWD data

- By using the maximum deflections D(0)

Dynamic segmentation by the cumulative sum method (ref. COST 336 of FWD)

S1 = X1 – Xm
S2 = X2 – Xm + S1
S3 = X3 – Xm + S2
…
n stations,
Xi: max. deflection at station i
Xm: mean value of X1,..,Xn



➢ New homogeneous segment when the direction of the curve changes…

➢ Also characteristic deflection in a segment: $D_{char} = D_{max,average} + 2.\sigma$

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FWD and Curviameter data processing and interpretation:

Evaluation of the structural health of a road

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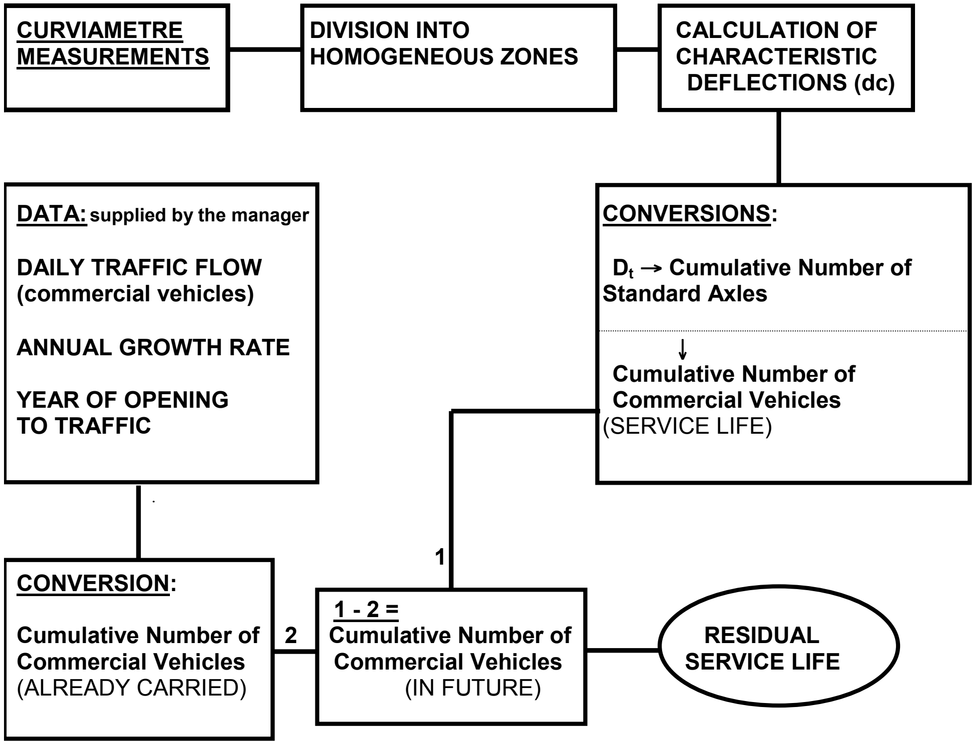
Characteristic deflection - residual life

- Ref. M. Gorski, Residual Service Life of Flexible Pavements and its Impact on Planning and Selecting Priorities for the Structural Strengthening of Road Networks, PIARC XXI World Road Congress, Kuala Lumpur, Malaysia, October 3-9, 1999

Curviameter



(127kN)

$D_{Benkelman} = 1{,}38 \cdot D_{Curvia}$

$D_{char} = D_{max,average} + 2.\sigma$

$$Nst = \frac{2.46 \cdot 10^{12}}{d_c^{\,3}}$$

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$R_c \times D_{MAX}$ α E_2/E_3

Ref.: P. Autret, Utilisation du produit Rd pour l'auscultation des chausses à couche de base traitée, Bulletin de liaison des Lab. des Ponts et Chaussées N° 42, Déc. 1969, 740, pp.67-80.

- For fully flexible bituminous roads, if the structure of the road is in a good conditions, then:
  - The radius of curvature (R_c) multiplied by the maximum deflection (D_{MAX}) is a constant value
  - R_c times D_{MAX} is proportional to E_2/E_3, where
    - E_2 is the elasticity module of the sub-base
    - E_3 is the elasticity module of the formation

as long as the thickness of the sub-base is constant

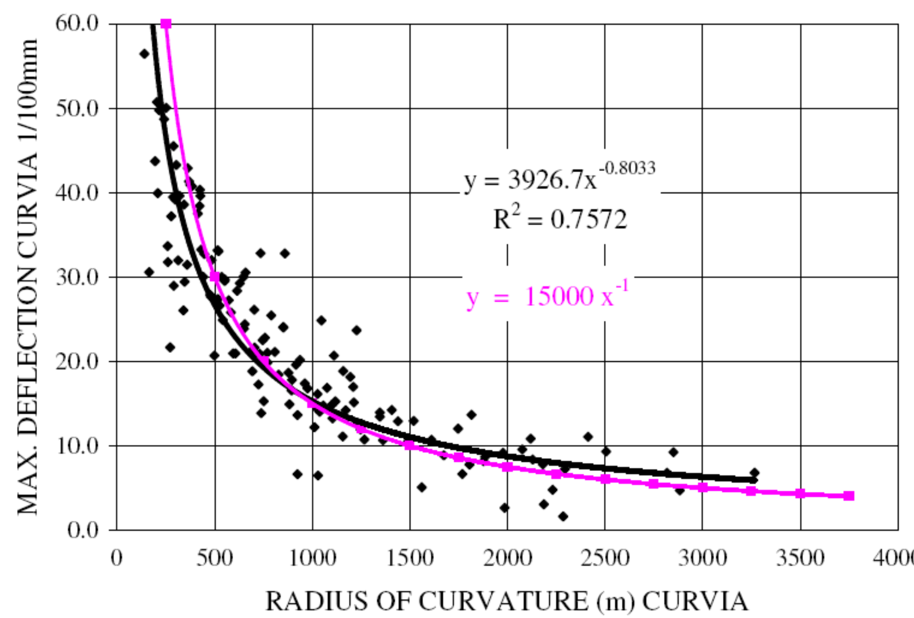

Illustration resulting from BRRC measurements on different road structures

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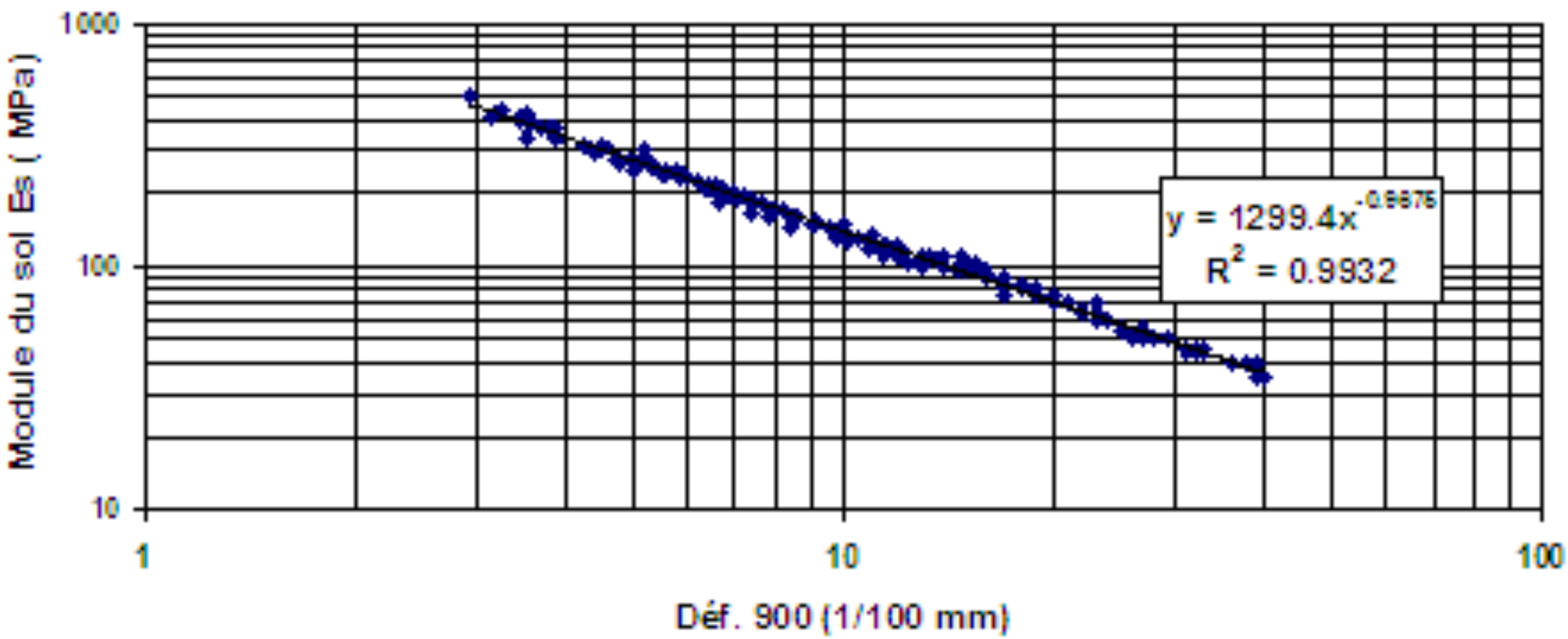
D(900) is related to the ground modulus Es

- Relationship between the ground modulus Es and D(900)…



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Tragfähigkeitszahl - bearing capacity

FWD

Ref. Shafik Jendia, Bewertung der Tragfähigkeit von bituminösen Straßenbefestigungen, Veröffentlichungen des Institutes für Straßen- und Eisenbahnwesen der Universität Karlsruhe, Heft 45, 1995.

- Theory of Boussinesq: $E = 1.061\ p\ (R/Y)^{0.5}$
  - E: E-module of halfspace
  - p: contact pressure
  - R: radius
  - Y: deflection
- Definition: $T_z = (R_c / D_{MAX})^{0.5}$
- S.Jendia proposes radius computation from FWD and T_z as an indicator of the bearing capacity of the whole road structure (a low value of T_z means a weak bearing capacity).

Curviameter

- Why not computing this from Curviameter data…

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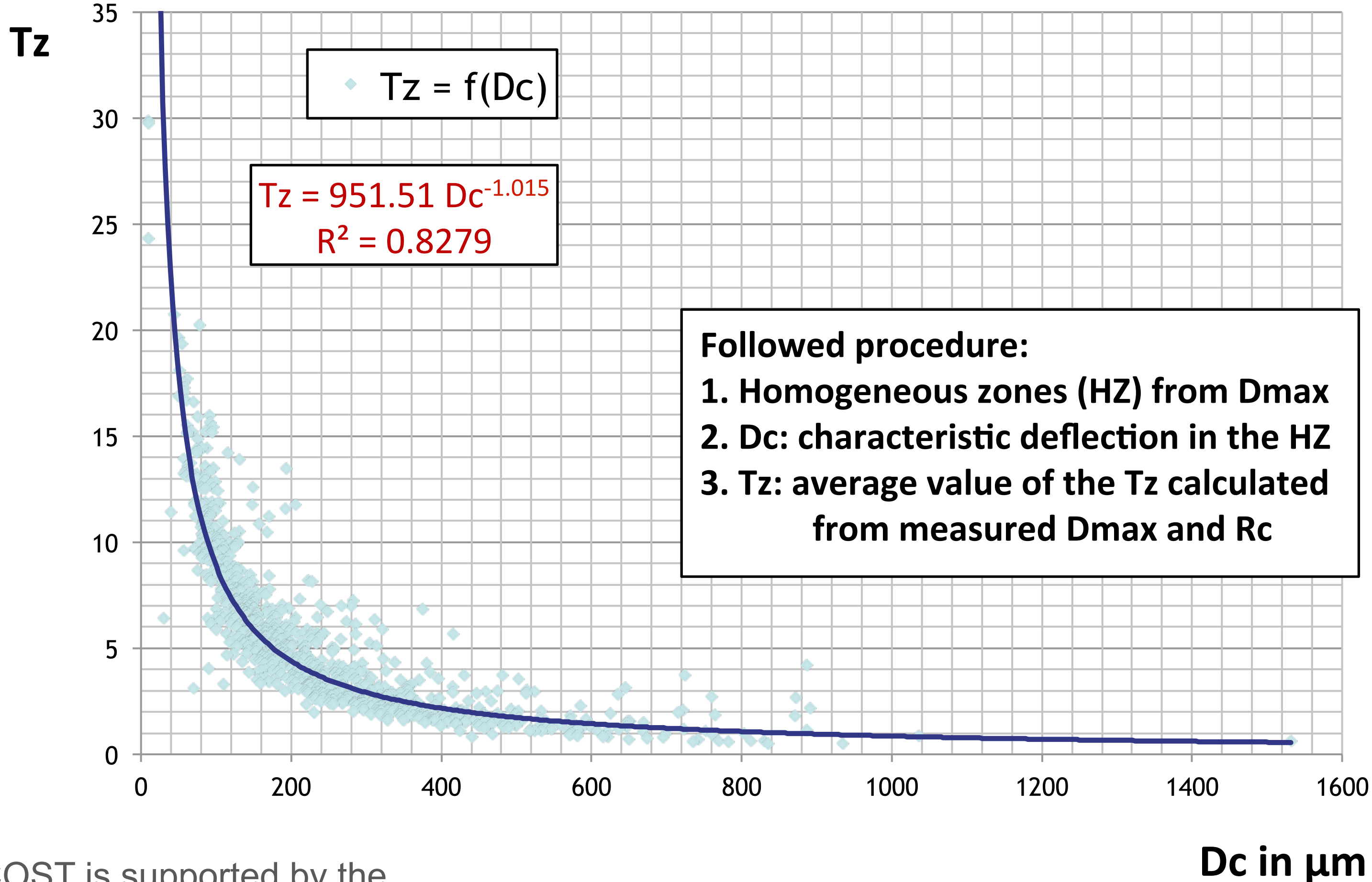
On Belgian motorways and main roads...

- Only Curviameter data, 956 points in the graph (each points corresponds to a homogeneous zone)



Followed procedure:
1. **Homogeneous zones (HZ) from Dmax**
2. **Dc: characteristic deflection in the HZ**
3. **Tz: average value of the Tz calculated from measured Dmax and Rc**

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R_c and bad bond between layers

Curviameter

- A small radius of curvature can be the consequence of:
  - top layer in bad shape, or
  - bad bonding between upper layers, or
  - bad quality of unbound base layer

- The top layer in a bad shape can often be seen at the road surface…

- Road administrators should know about the existence of an unbound base layer…

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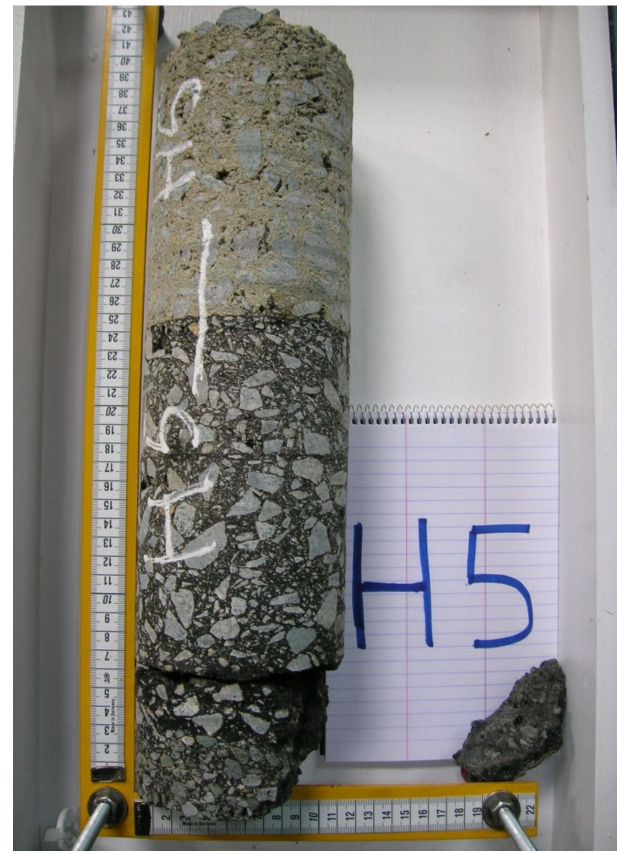
Example: Bad bond at 50mm

Homogeneous zones		Maximum deflection			Radius of curvature			
Begin	End	average	Standard dev.	characteristic	average	Standard dev.	2nd decile	5th decile
(km)		(1/100 mm)			(m)			
17.505	18.395	9	3	16	3187	1273	2110	3034
18.400	19.085	13	4	21	2205	1033	1419	1980

- Homogeneous zones are determined with D_{MAX} only, hence R_c may vary within a zone.
- 2^{nd} decile vs. 5^{th} decile: many “small” R_c values are observed in both zones.
- Higher D_c and lower R_c are observed in the second zone compared to the first zone and evidence of bad bond is found in the second zone by coring…
- Also: many “bad quality” signals are present…



In zone 2: BK 18.705

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Deflections at network level measured by others (not BRRC): Italy

FWD

Ref. M. Crispino, G. Olivari, M. Poggiolo, I. Scazziga, Including Bearing Capacity into a Pavement Management System, Intl. Conf. Bearing Capacity of Road Pavements, Trondheim, Norway, 2005

- Deflections by FWD on a network of motorways, points every 100 m
- Temperature correction
- Transformation in “Benkelman beam” deflections
- Residual pavement life from Swiss standard giving reinforcement thickness versus Benkelman deflection and traffic
- Map of 3 classes:
  - Rehabilitation when residual life < 5 years
  - Allow every treatment when residual life between 5 and 12 years
  - Only maintenance when residual life > 12 years
- This as an extra rule in existing Pavement Management Strategy (PMS)

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Deflections at network level Measured by others: France

Curviameter

Cf.: Ph. Gaborit, H. Di Benedetto, C. Sauzéat, S. Pouget, F. Olard, S. Quivet, Analyse d'une structure de chaussée autoroutière par auscultation in situ et essais en laboratoire, Actes des 30ième Rencontres Univ. de Génie Civil (AUGC et IBPSA 2012), Chambéry,6-8/6/2012

- Curviameter motorway section, 15 km long, measured in 1999 and 2010
- Comparison between D_{MAX} 1999 / 2010 and R_c 1999 / 2010
- Laboratory tests on monsters taken in 2010
- Back-calculation and residual life-time expectance
- Conclusions:
  - Non-destructive test allowed estimating E-modules
  - Estimated E-modules correspond to laboratory tests for the bituminous layers, not for the subgrade though.
  - Both measurements and laboratory tests confirm that residual lifetime expectance is still high for this road section.

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Combined use of deflectometers and GPR

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BRRC: Campaign in Italy

GPR + Curviameter

- A curviameter owned by the BRRC was used to measure D_{MAX}, homogeneous zones, and D_c.
- A GPR owned by the road manager (SINECO) was used to image the layers and measure the thicknesses in all the homogeneous zones.

- Traffic counting at pay boots + assumptions on traffic growth were considered.
- Interpretations:
  - "Easy back-calculation": Residual life of each zone with E_s known from D(900)…
  - Search for "long life (lasting) pavements"…

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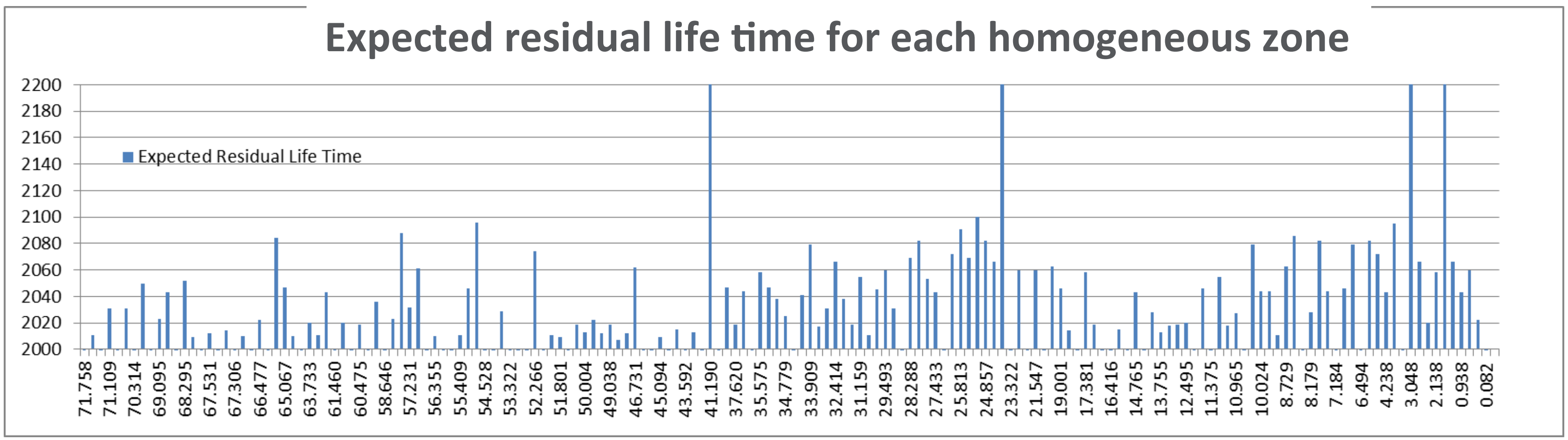
Database of a motorway network (BRRC and SINECO)

Ref. M. Gorski, R.Benetti, M.Garozzo, M.Mori, Investigating long life pavements. A case study, in Advanced Characterisation of Pavement and Soil Engineering Materials, Loizos, Scarpas & Al-Quadi (eds), 2007.

- BRRC curviameter measurements on a SINECO network in Italy (≤ 2003)
- SINECO data about structure (GPR) and traffic data (counted)
- Formation modulus obtained from D(900)
- Back-calculation of E-moduli with 3-layer Odemark model
- With traffic data: expected residual life-time (cf. previous slide)



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Curviameter equipped with a GPR horn antenna

GPR with 2 GHz antenna from BRRC mounted on a Curviameter

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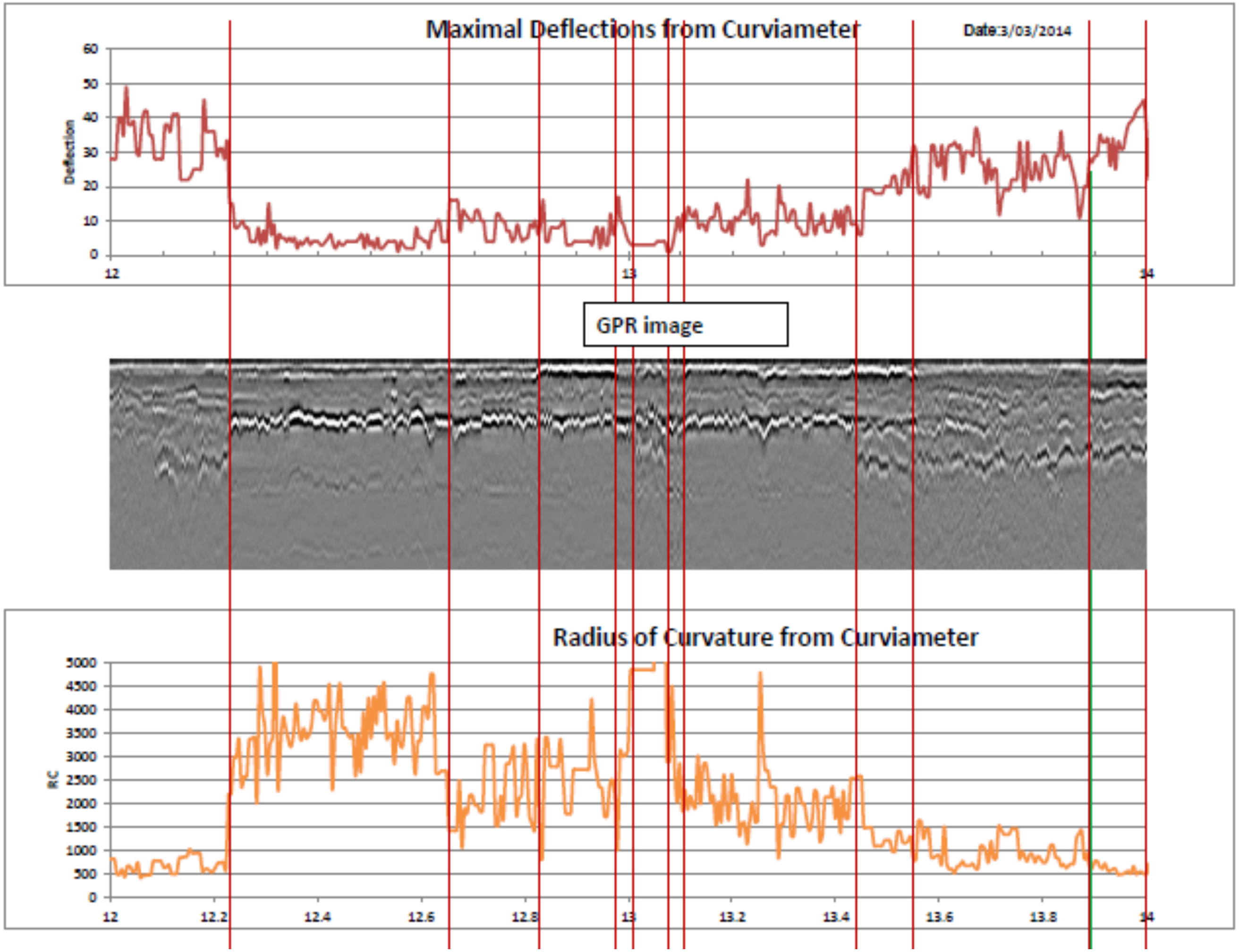
HZ: Comparing GPR images and curviameter data



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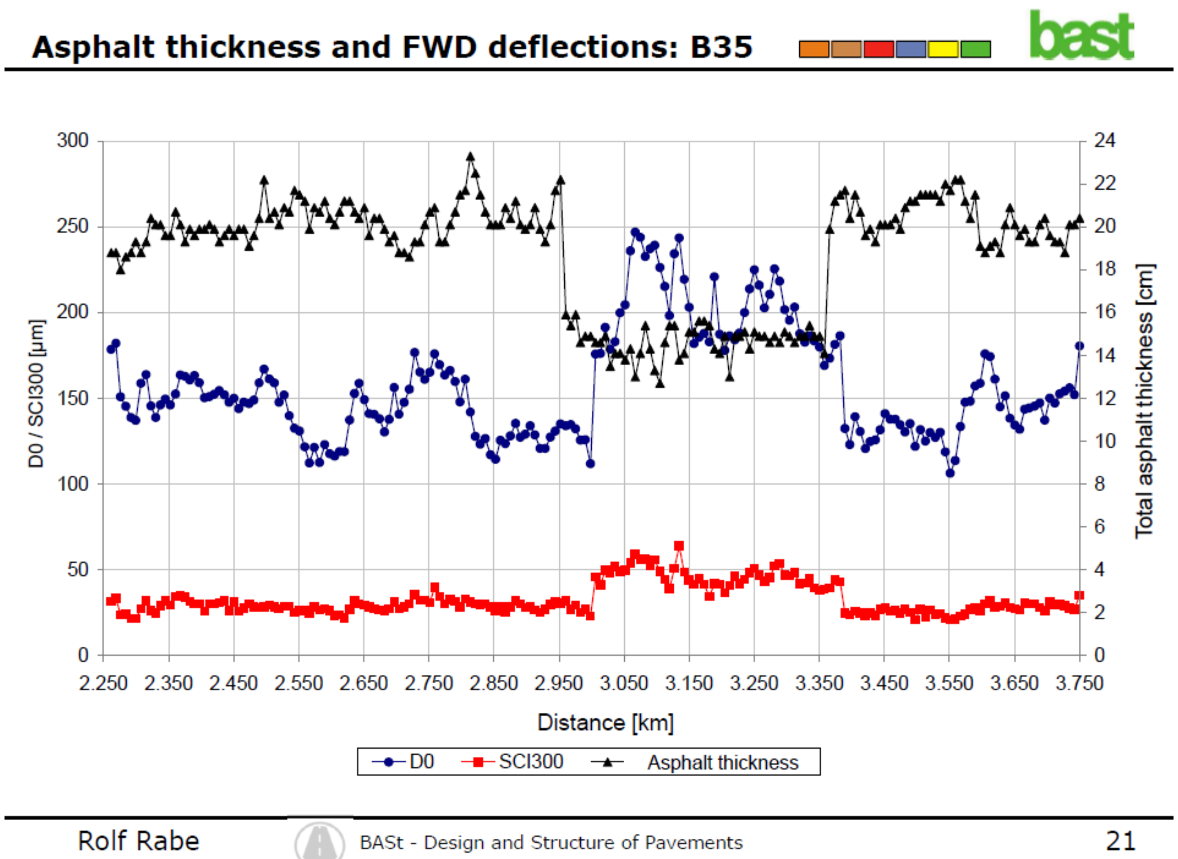
FWD and GPR in Germany (before 2015)

GPR + FWD

Ref. R.Rabe, on Workshop on the Curviameter: Interpretation and Exploitation of Measurements. 28 January 2015 (pm) and 29 January 2015 (am) at the Belgian Road Research Centre in Wavre (near Brussels), Belgium



NEW

Traffic Speed Deflectometer

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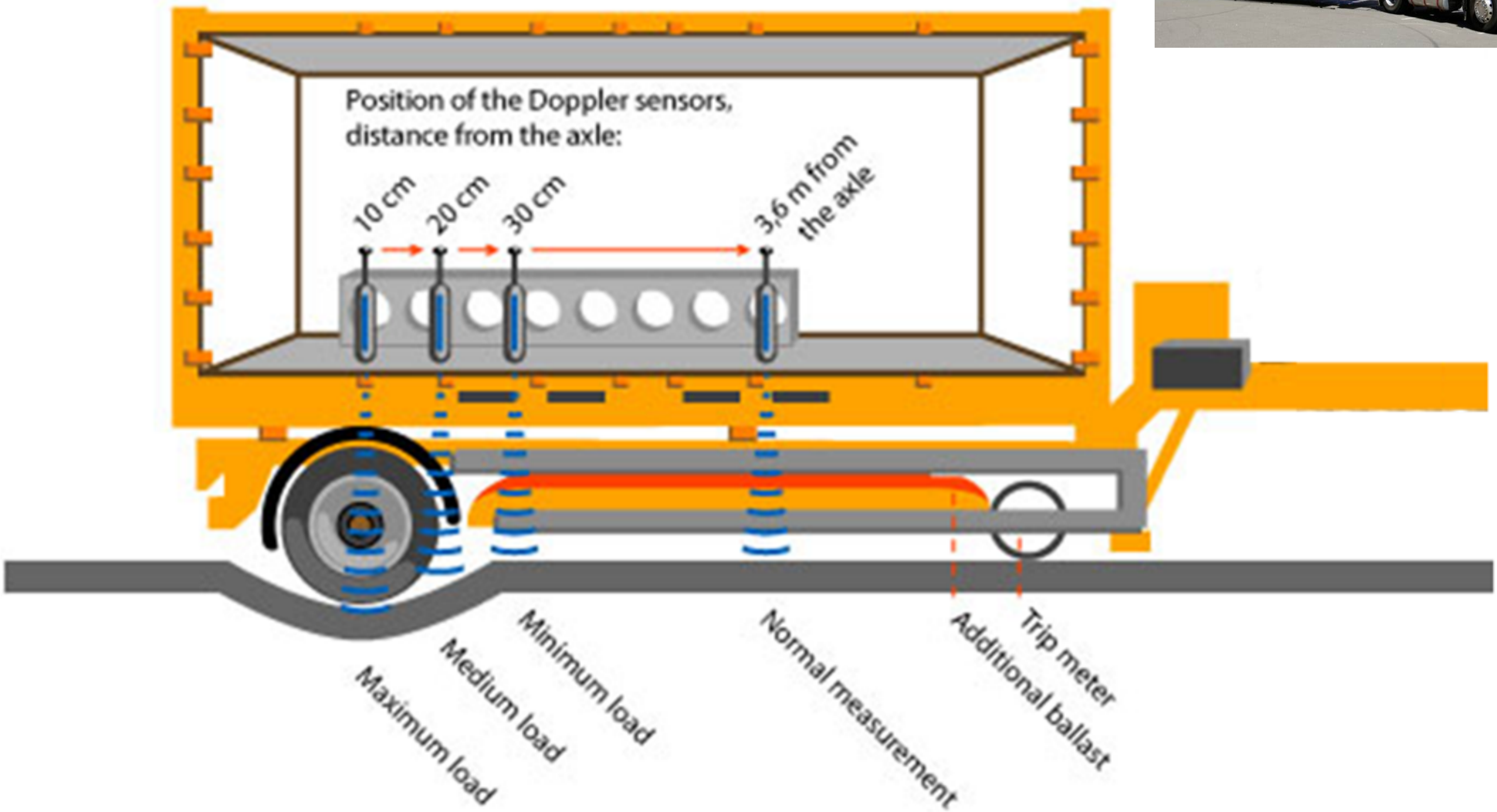
Traffic Speed Deflectometer (TSD)

Ref. Jim Johnson-Clarke (ARRB Group), Use of the Travelling Speed Deflectometer (TSD) in Australia, USA FWD User's Group Meeting (FWDUG), Indianapolis, Indiana, 2014



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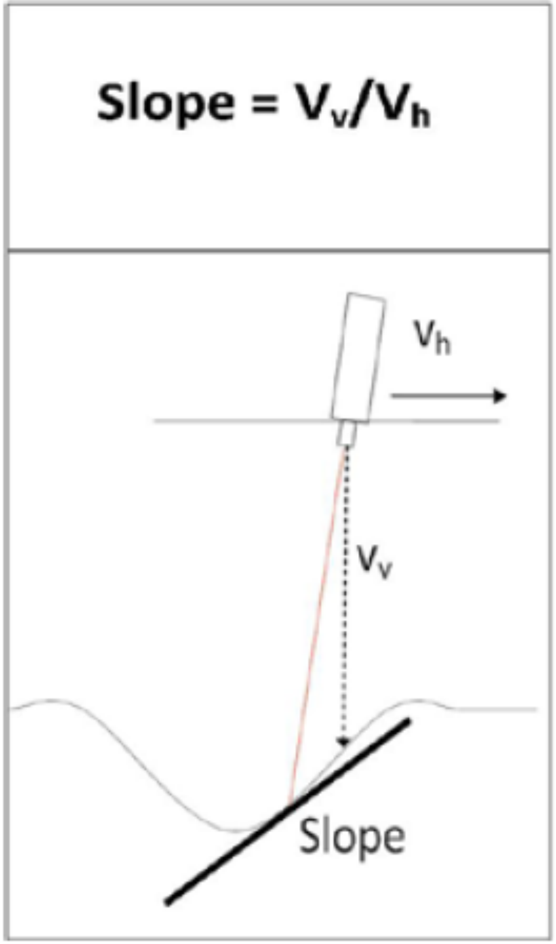
Traffic Speed Deflectometer (TSD)

- Doppler lasers, measuring the slope of the deflection bowl

Ref. Scheme taken from S.W.Katicha, G.W.Flintch, Field Demonstration of the Traffic Speed Deflectometer in New York, TRB, 2015



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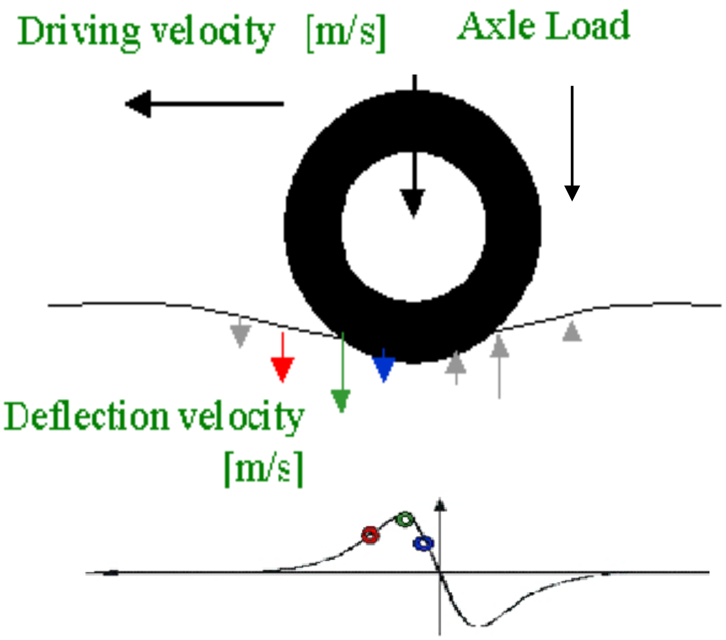
A "Doppler speed sensor" sends a monochromatic laser beam to the road surface and receives the reflected signal.

Doppler effect: The change of the wavelength after the reflection is a function of the relative speed of the road surface. Hence, the speed of the road surface can be determined from the measured wavelength change of the reflected laser-light.



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Combining GPR and TSD in Australia

GPR + TSD

Ref. ARRB, presentation on conference “Pavement Evaluation – 2014” in Blacksburg, VA: http://www.apps.vtti.vt.edu/PDFs/PE-2014/Muller.pdf by Wayne Muller (ARRB Group), Road scanning V2.0: Preliminary results from updated TSD and NM-GPR technologies

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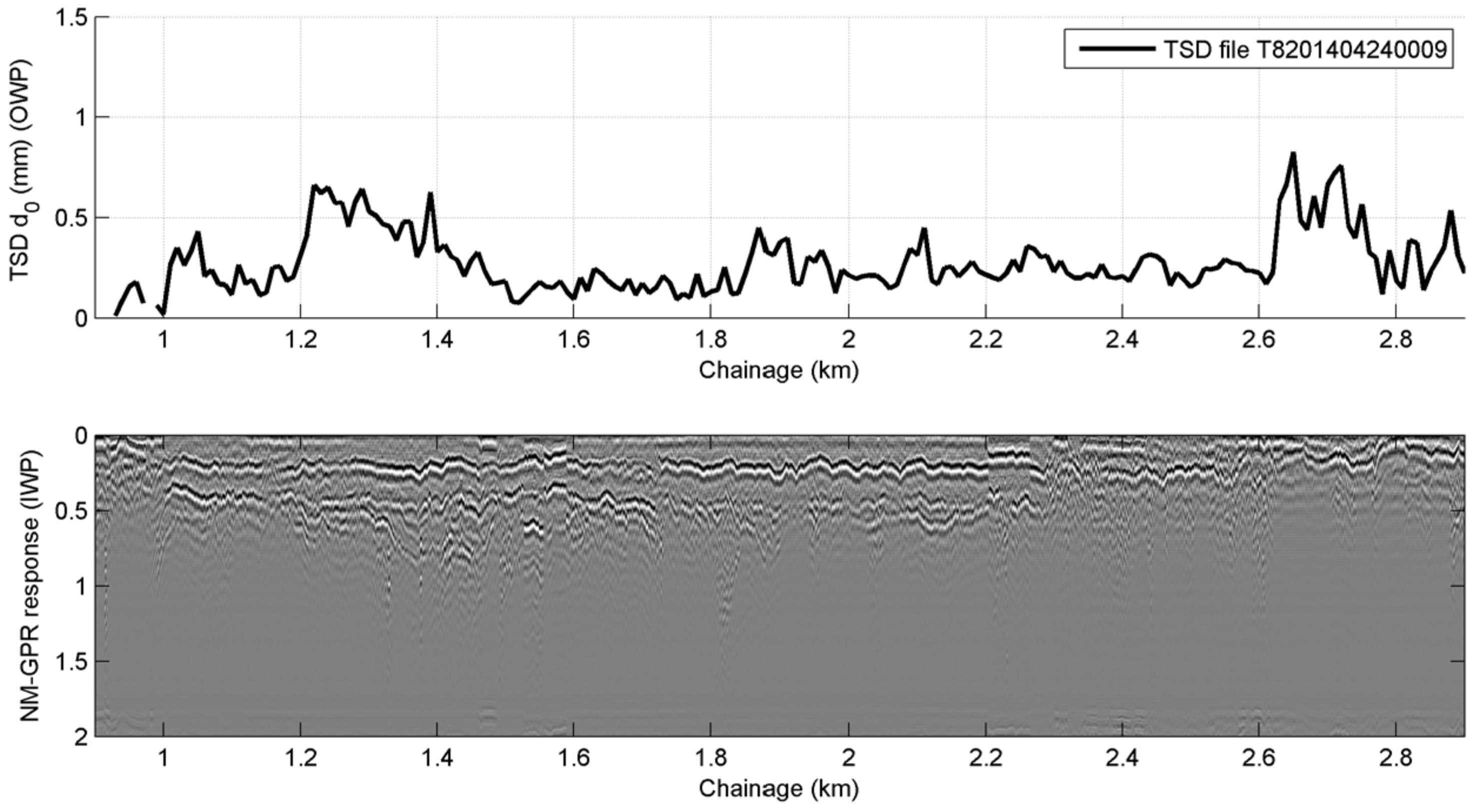
GPR + TSD



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Experiences in Germany (before 2015)

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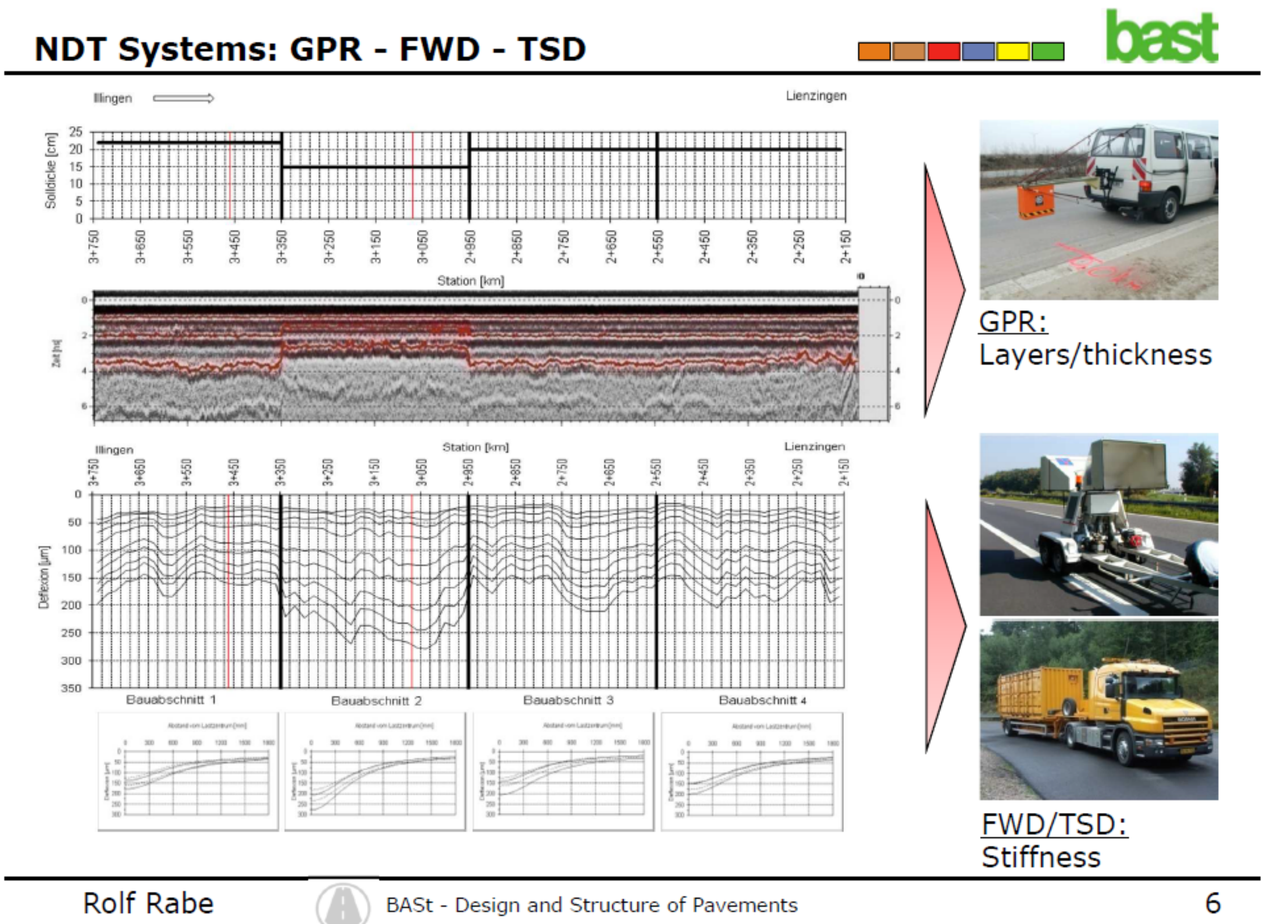

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Author

Dr. Carl Van Geem (c.vangeem@brrc.be) is a researcher in road management and monitoring techniques, since 2004 he is working in the Mobility, security and road management (MSM) division of the Belgian Road Research Centre (BRRC), in Brussels, Belgium. He is a Working Group Member of the COST Action TU1208.

In 1996, Carl Van Geem earned the doctoral degree in technical sciences from the Research Institute on Symbolic Computation (RISC-Linz), Johannes Kepler University, Linz, Austria.

The BRRC has several devices for the evaluation of road surface properties (roughness, skid resistence), for pavement management (visual inspection device “SAND”), and for measuring the bearing capacity of roads (FWD, curviameter, GPR). The main topic of Carl’s research is the interpretation of data obtained with these monitoring devices for an optimal management of road maintenance. Carl participated in several national and international research projects, including a “national pre-normative research project on the indicators of roughness”, the COST Action 354 “Performance Indicators for Road Pavements”, the PIARC technical committee D1 “Management of Road Infrastructure Assets”, and the FP7 project “Tomorrow's Road Infrastructure Monitoring and Management (TRIMM)”.

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Thank you

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