Non-destructive tests in roads and airfields

A study of the Falling Weight Deflectometer

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Abstract

Road infrastructure is a high value asset in the development of modern society where its perceived quality translates into a fundamental role in security, economy, competitivity and sustainability of the free flow of goods and merchandise. The gradual degradation of that quality through time should be evaluated in such a manner that maintenance and rehabilitation efforts can be timely planned and carried out to maintain its specified minimum quality requirements. In pavement condition assessment, there are several parameters that gauge pavement quality. For structural surveys, the Falling Weight Deflectometer (FWD), is the main non-destructive testing equipment used to assess the bearing capacity of road and airfield pavements. This test's results are very relevant in several contexts, for example, a survey for bearing capacity in existing road or airfield pavements requiring rehabilitation intervention.

The present dissertation's objective is to assess the precision and uncertainty performance in measuring deflection and to analyze its influence in the quality of results from the testing campaign, therefore assessing the structural capacity of existing pavements (backanalysis), in view to evaluate the structural quality and support a rehabilitation project.

The adopted methodology consisted in a proficiency test scheme (PTS) field test compliant with ISO/IEC 17043 featuring a fleet of three FWD from different manufactures and owned by portuguese operators. The obtained deflection data was firstly processed for repeatability and reproducibility, and afterwards analyzed for uncertainty quantification. Lastly, the resulting data was used for a sensitivity analysis featuring the uncertainty of the measured deflection influence on the mechanical properties (elastic moduli) estimated from the field survey (backanalysis) on flexible pavements.

The experimental research results confirmed a satisfactory repeatability of deflection measurements. In contrast, the reproducibility is difficult to achieve in most cases. Consequently, the uncertainty levels revealed to be high. Uncertainty and precision revealed to be dependent of pavement type and deflection magnitude. Uncertainty presented high values for flexible pavement and for high deflections. Regarding to the sensitivity analysis on the uncertainty's influence on the FWD results interpretation, it was concluded that the flexible pavements presented higher sensibility to uncertainty mainly when gauging for stiffness on the foundation layers.

Keywords: falling weight deflectometer, pavement, repeatability, reproducibility, uncertainty, backcalculation.

1 Introduction

Looking at the European Union statistic data, the Trans-European networks in transport (TEN-T) plays a vital role to promote people and goods circulations between member states (Eurostat, 2014). By promoting business and easy people circulation, transportation strategies are an effective way to tackle inclusion of state members and its citizens. Eurostat data referring to modal split of transportation in EU (Eurostat, 2017) shows that road transport is still by far the most common, representing about 75% of total tonne-kilometers of freight transported. Data forecasts expect a continuing rise of freight transport by road in the foreseeable future. Consequently, new and existing infrastructure assets can benefit from planned maintenance to prolong its life span and reduce the involved financial costs. In a report commended by the European Commission (Steer Davies Gleave, 2009), EU countries invested in total €859 billion in its transport infrastructure sector between 2000 and 2006. A significant portion of the budget was used towards road maintenance to keep existing infrastructures at an acceptable level of service. This sector has proven its significance given the large sum invested thus incentivizing pavement engineering to continually improve (COST, 1997).

Maintenance and rehabilitation (M&R) requires both minimizing administration and user costs while still maintaining infrastructures at high level of service (Meneses & Ferreira, 2012). To manage pavements at network level, administration rely on pavement management systems (PMS) which aggregate road condition data by road sections. This information is in turn analyzed to clearly prioritize interventions to the most critical road sections (Fwa, et al, 2000). Road and airfield administrations are the main clients for the services provided by pavement condition assessment companies. These survey proceedings are regulated by international standards (ASTM, 2008, 2009) using equipment capable of measuring and recording pavement parameters to assessment its condition. One of the most used equipment today is the Falling Weight Deflectometer (FWD), a stationary impulse load deflectometer which will be studied in the following sections of present dissertation.

Although equipment manufacturers guarantee high reliability and repeatability levels through periodic calibration, generally, equivalent models from different manufacturers are less likely to reproduce each other's measurements. Several authors research (Garg, 2002; Murphy, 1998; Rocha et al, 2004) mention the repeatability and reproducibility issues associated with the FWD which should be taken in consideration and carefully assessed in practice. To empower administration decision makers with informed decisions while executing pavement surveys, it is necessary to experimentally analyze the actual reliability level of existing FWD fleets in current available service providers and thus clearly quantifying existing differences.

This dissertation aims to investigate the precision performance of a FWD fleet under a controlled environment, and mainly to quantify the level of uncertainty in deflection measurements which ultimately influence the quality of the backcalculation process. It is crucial for the administration to have a good understanding of the uncertainty involved in this process which may lead to rehabilitation project designs that may prove to be ineffective and financially inefficient.

2 Falling Weight Deflectometer

2.1 Operation principle

The basic principle behind the deflectometer is a mechanism of hydraulic lifters that elevate a predetermined mass of weights to a certain height then drops. This mass generates a force on impact thought a set of rubber bumpers producing a load cycle equivalent to a vehicle wheel in normal traffic speeds. The FWD is highly mobile when compared to other type of static and rolling wheel equipment giving administration entities the flexibility necessary to perform surveys in a broad area in limited time. Given its operation principles and a computerized user interface, the FWD has been recognized as the preferred method to perform deflection measurements.

Prior to testing the pavement’s load-carrying capacity it is necessary to specify parameters on which the test is to be conducted, essentially to define the test protocol: test location and its structural constitution, load force values, loading plate diameter, geophone positions and pavement surface temperature.

Load force

The load force necessary for a pavement test depends mainly on the pavement type (flexible or rigid). Higher load produces more impulse on the pavement and thus higher deflection readings. Depending on the pavement constitution, a rigid pavement will require higher load to generate a deflection value within the system’s geophone resolution and range.

Dampening system

The weight dropping mechanism generates a pulse of force that is transmitted to the ground through a dampening system. This load pulse is comparable to the action of a wheel axle on the pavement. The load pulse transmitted to the pavement is shaped as a half-sine curve similar to the actual impulse produced by a wheel axle. During the development of the FWD system, the rubber bumpers acting as dampers for the falling weight plates were identified as determinant to the force curve shape generated (Bohn, 1989). For these reason, the configuration of weight plates and the number rubber buffer in the system may significantly change the shape of the load pulse generated and, consequently, the value of load pulse time and the resulting deflections.

Load pulse

Load pulse is the time that the FWD takes to fully deploy the impulse load on to the pavement. This force cycle is configured to be shaped as a sine curve and the duration and magnitude of the force applied by the FWD is representative of the load pulse that would be induced by a vehicle in movement (Garg, 2002). The load pulse is a parameter measured in milliseconds and can vary between 25 and 60ms, depending on what kind of wheel axle is being simulated. Pulse time is particularly important to control in multi-layered pavements that are flexible, cohesive soils or saturated soils, for it may influence to some degree the obtained deflection measurements. The dampening system comprises from rubber materials which means that its behavior change depending on the conditions tested on: temperature, load level and even the buffer physical shape change the spring effect “constant”.

Geophones

The FWD can have up to 9 geophones attached to the trailer. These sensors are evenly spaced and directed radially away from the center of impact. The geophones capture minute surface displacement (analog signals) and interpret them as electronic signals enabling computers to record even small amount of surface movement. The resulting array of deflection measurement from the impact center produce a graph named the Deflection Basin which helps visualize the structural capacity of the layers below surface.

2.2 FWD Accuracy

Although FWD are commonly requested by administrations for routine campaigns, several authors (Van Gurp, 1991 and Murphy, 1998) have given evidence of lack of reproducibility between a FWD fleets. Researchers Rocha et al (2004) presented a thorough literature review on the accuracy and precision of FWD. The main possible sources of uncertainty in FWD measurements most commonly reported in the literature are related to its buffers and the pavement stiffness. The shape, size, age and stiffness of rubber buffers impact the peak load, the rise time and the load pulse shape, and in consequence the magnitude of the deflections (Chen et al, 1999; Lukanen, 1992). Having calibrated load cells and calibrated deflection sensor does not offset the different equipment characteristics, such as, rubber buffers shape and hardness, the thickness and quality of rubber pad under the load plate, the type of deflection sensor, sensor positioning in the frame, and other factors that impact the load pulse shapes and deflection readings. FWD time histories produced by one equipment are different for another FWD, producing different peak force values. This implies that data collected from different FWD are not intercomparable, even in the case of fully calibrated equipment.

3 Proficiency test

A fleet of three FWD joined the Proficiency Test Scheme compliant with ISO/IEC 17043 (ISO, 2010) (Table 1). The test site pavement layer composition was obtained with a coring sample and from archived design plans (Table 2). A test protocol was followed requiring several rounds of drop tests to be performed (ASTM, 2009), with only the last three drops were considered for later data analysis (ASTM, 2008).

Table 1 - Main specifications of FWD equipment

Manufacturer	Carl Bro	KUAB	Dynatest
Model	Carl Bro PRI 2100	KUAB 240	Dynatest 8002
Year of acquisition	(*)	2004	2002
Load range [kN]	7-250	30– 240	7-120
Load pulse time [milliseconds]	20-30	30	20-30
Diameter of load plate [cm]	30 and 45	30 and 45	30 and 45
Type of deflection sensors	Seismometers	Geophones	Geophones
Deflection sensor range [µm]	2.2	(*)	(*)
Relative accuracy of deflection sensors	1 µm ± 2%	(*)	2 µm ± 2%

(*) Not available

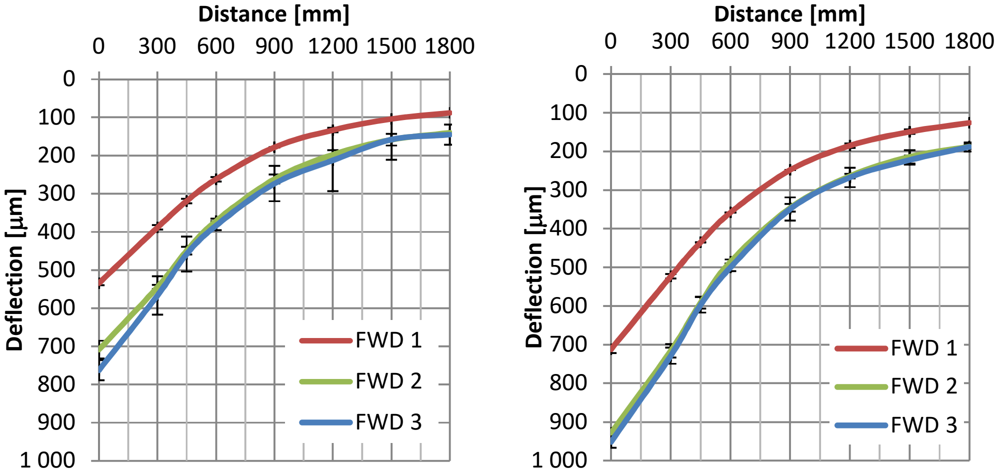
Table 2 – Characteristics of the test sites

Site	Pavement	Layer	Material	Thickness [cm]
1	**Asphalt concrete**	**Surface**	Asphalt concrete	5
		Base	UGM $^{(1)}$	20
		Subgrade	Soil-cement	15
			Sandy soil	15
2	**Concrete**	**Surface**	Concrete slab	20
		Base	Paving stones	12
		Subgrade	Soil-cement	$^{(2)}$
			Sandy soil	$^{(2)}$

$^{(1)}$ - Unbound granular material; $^{(2)}$ - Unknown

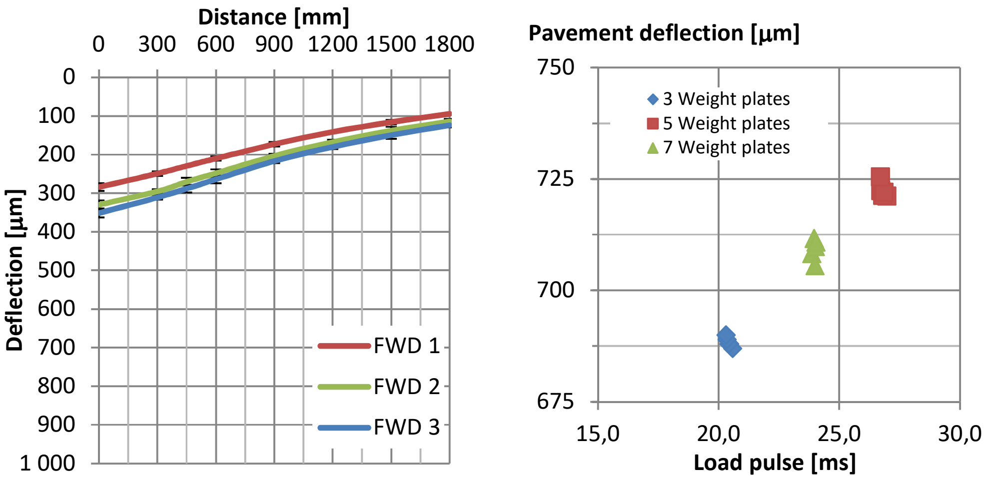
Table 3 – Test protocol

Site	Load peak [kN]	Deflection sensors distance [cm]	Load plate diameter [cm]
1	65, 90	0, 30, 45, 60, 90, 120, 150, 180	30
2	90		



a) 65kN, flexible pavement

b) 90kN, flexible pavement



c) 90kN, rigid pavement

d) Load pulse in relation to deflection values

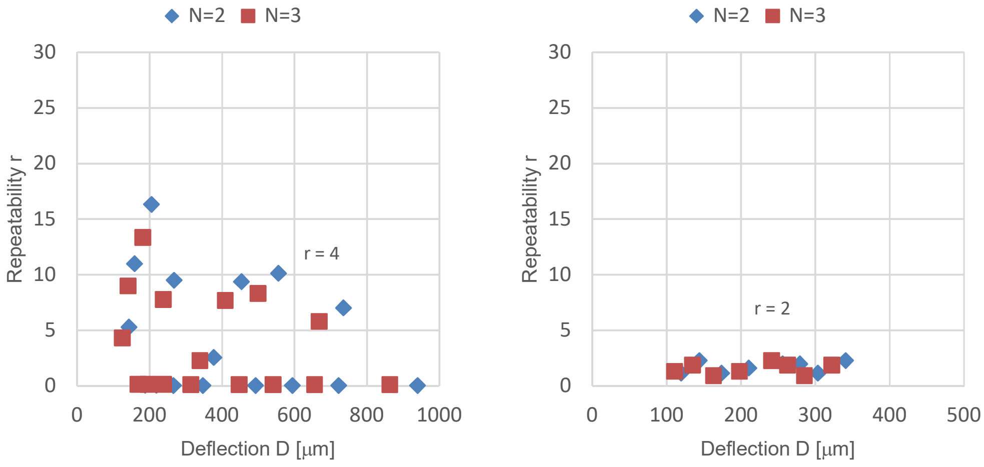
Figure 1 - Deflection charts and Load Pulse influence in deflection measurements

The deflection results were plotted in graphs representing complete deflection basins for each FWD measurement in the same marked location. One of the equipment (FWD 1) showed clear bias by recording values consistently shifted by a constant factor in relation to the rest of the test sample. It was later investigated and discovered that technicians had preset the computer software to allow smoothing filtering of the pulse load signals at a frequency different from the recommended in the manufacturer's manual (150 Hz instead of 60 Hz).

4 Data Analysis

4.1 Repeatability and reproducibility

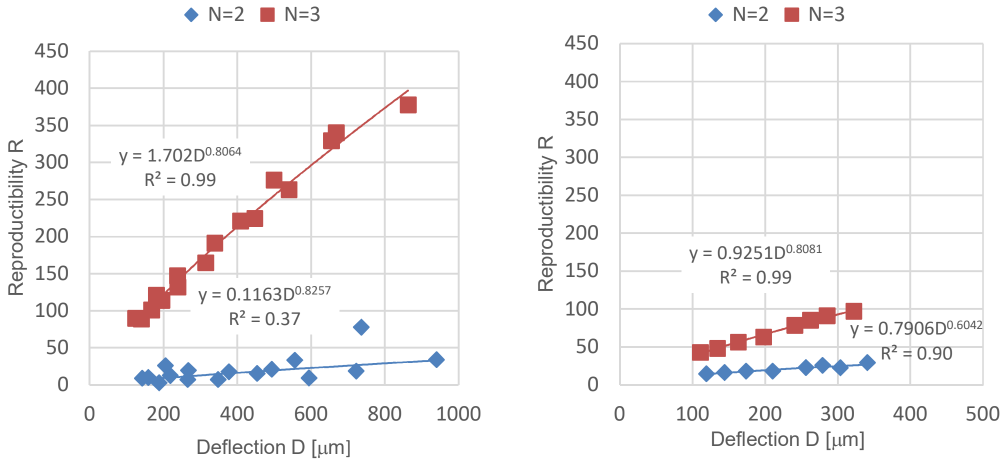
Analyzing Figure 2, repeatability limit for both N=3 and N=2 seems to scatter uniformly settle around r=4 and r=2, respectively for Site 1 (flexible pavement) and Site 2 (rigid pavement). Figure 3 presents the reproducibility limits with trend lines and their respective expressions. For Site 1, being a flexible pavement, the limit for N=3 increase rapidly when deflection values also increase towards peak values in the center of test impact. Serving as an indicative example, for a given deflection D=300 μm, R=169. With the N=2 scenario, without FWD 1 contribution, reproducibility limits clearly drop to acceptable values and trend line stay almost flat in the entire deflection range. In the same line of example as above, for a D=300 μm, limit is returned as R=13. Same analysis is valid for Site 2 reproducibility limits, although predictably, for rigid pavements, the trend line presents a smaller slope, for given D=300 μm, R=93 (N=3) and R=25 (N=2).



a) Site 1

b) Site 2

Figure 2 – Repeatability limits for deflection measurement



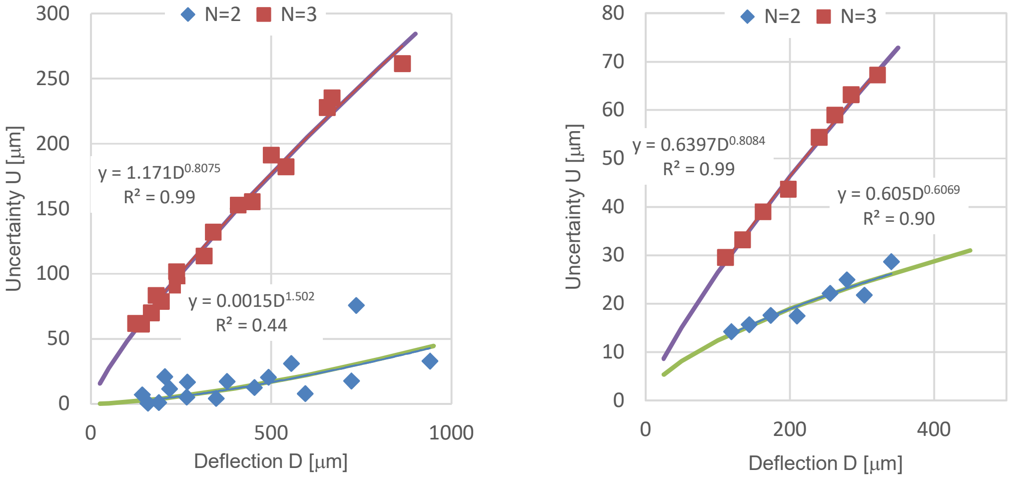
a) Site 1

c) Site 2

Figure 3 - Reproducibility limits for deflection measurements

4.2 Uncertainty assessment

When comparing with the N=3 case, the critical values are significantly smaller for N=2, representing the case in which a FWD fleet presented satisfactory repeatability and reproducibility. Figure 4 presents the graph for the deflection mean of the means values as a function of their respective critical values. The model indicates a good fit (R^2=0.99) mainly from N=3 cases. It is noticeable a positive trend for which the critical value increases with the deflection magnitude. To express this relationship resulted from the PTS experiment, a trend line was plotted and its governing equation will serve as the model behavior rule to calculate critical values for given any deflection.



a) Site 1 b) Site 2

Figure 4 - Uncertainty of deflection measurements

4.3 Sensitivity analysis

The aim is to extrapolate the uncertainty data and apply it in a sensitivity analysis on standardized flexible pavements suggested in the portuguese pavement design manual, known as MACOPAV (JAE, 1995). These pavement models are used in real world practice by pavement designers and so the results should constitute a close approximation to a real-world application. As the scope of this study is only flexible pavements, the uncertainty critical values will be obtained with equation 1:

$$Y = 1.171D^{0.8075} \qquad (1)$$

The analysis makes use of standardized flexible pavements models suggested by MACOPAV design manuals. Each pavement model has attributed reference moduli values for each type of layer and finally, through BISAR multilayer elastic linear pavement design software (Shell, 1995), the models deflection basin were calculated.

Table 4 resumes part of the backcalculated elastic moduli for the class F3 subgrade pavements subjected to 65 kN and 90 kN surface loads. It shows in a clear manner that the MACOPAV models presented convergent estimation of layer moduli for either 65 kN or 90 kN. In this way, the FWD fleet measurement uncertainty is now represented in the form of layer moduli, with the higher and the lower limits of the interval. In this form, it is possible to assess the range of moduli uncertainty when performing field surveys and even evaluate financially the same uncertainty although this study is outside the scope of the present dissertation.

Table 4 – Interval of pavement layer moduli, F3 subgrade class, 65 kN and 90 kN

Asphalt bound base, T6, 65 kN			Asphalt bound base, T1, 65 kN		
RMS 3.6%	**Reference**	**RMS 0.9%**	**RMS 3.6%**	**Reference**	**RMS 2.3%**
E_{max} (1)	E (2)	E_{min} (3)	E_{max} (1)	E (2)	E_{min} (3)
4700	4000	3000	4500	4000	3000
300	200	160	400	200	140
175	100	70	200	100	70
Asphalt bound base, T6, 90 kN			**Asphalt bound base, T1, 90 kN**		
RMS 4.0%	**Reference**	**RMS 2.7%**	**RMS 3.5%**	**Reference**	**RMS 1.2%**
E_{max} (1)	E (2)	E_{min} (3)	E_{max} (1)	E (2)	E_{min} (3)
4500	4000	3000	5000	4000	3500
300	200	180	390	200	150
165	100	70	190	100	75

Units in MPa; (1) – Layer modulus for stiffer limit layer composition; (2) – Layer modulus initially assumed; (3) – Layer modulus for softer limit layer composition.

The variation in moduli values necessary to adjust the initial reference moduli to the critical values boundaries were expressed in function to the asphalt concrete material content in relation to the pavement total thickness (in percentage). From top to bottom, Top layer - Base - Sub-base - Subgrade, both the granular material layer required more adjustment, reaching as high as 80%, leading to stiffer layers for pavements with higher content of asphalt concrete (more than 40%). Pavement models with higher AC percentage present higher sensitivity to FWD uncertainties

4.4 Test site backcalculation

Regarding test site 1, the PTS results confirmed the findings included in chapter 4.3. The backcalculation of deflection measurements resulted in three different pavement designs, each influenced by the uncertainty already mentioned. In the event of a rehabilitation project, these results could directly affect the possible project solutions, namely when determining the necessary thickness of the overlay design, poising financial impacts on the project's final cost.

Table 5 and Table 6 show deflection plot charts with BC deflection curve layered on top. RMSE obtained were between 6.0 to 8.4%. High RMSE values were obtained representing that the pavement model might not exactly match the actual pavement.

Table 5 – Backcalculation results for Site 1, 65 kN

Layer	Material	Thickness [cm]	Seed moduli	FWD 1	FWD 2	FWD 3
Surface	**AC**	**5**	**4000**	**9500**	**6000**	**7000**
Base	**UGM**	**20**	**900**	**600**	**600**	**500**
Sub-base	**Soil-cement**	**15**	**900**	**1200**	**600**	**900**
	Sandy soil	**15**	**50**	**200**	**90**	**75**
	Sandy soil	**100**	**30**	**40**	**50**	**40**
RMS%				**7.4**	**6.5**	**6.6**

AC – Asphalt concrete; UGM - Unbound granular material; Root Mean Square Error (%)

Table 6 – Backcalculation results for Site 1, 90 kN

Layer	Material	Thickness [cm]	Seed moduli	FWD 1	FWD 2	FWD 3
Surface	AC	5	4000	9000	6000	6500
Base	UGM	20	900	700	600	650
Sub-base	Soil-cement	15	900	1200	600	600
	Sandy soil	15	50	80	90	80
	Sandy soil	100	30	45	60	50
RMS%				8.4	6.2	6.0

AC – Asphalt concrete; UGM - Unbound granular material; Root Mean Square Error (%)

5 Conclusions

Road and airfield pavement management is getting increasing attention in the engineering and business management fields as an opportunity to develop more technologically advanced and efficient methodologies to assess pavement condition at a network level, while enhancing the performance of the asset management in a competitive business sector.

The proposed dissertation developed an experimental research featuring three FWD from different manufacturers (Dynatest, Carl Bro and KUAB). A proficiency test scheme developed to retrieve data from the FWD fleet to assess uncertainty's influence on test results. The main conclusions were:

- Repeatability and reproducibility limits result were dependent of deflection magnitude as well as pavement stiffness.
- Repeatability limit for the flexible pavements test site was r=4 and for the rigid pavement test site r=2.
- Reproducibility limits were higher and in function of any given deflection value. The trend line presented a steep slope, which towards the higher range of deflection presented the maximum reproducibility limit. For an assumed deflection of D_f=300 nm, flexible pavement test site limit value was R=169 and for the rigid pavement test site, the limit value was R=93.

The backcalculation analysis performed under FWD uncertainty resulted in a range of interval for estimated moduli, representing the type of varying results that may be obtained attending to the reproducibility issues reported by literature. Backcalculation methods are not 100% straightforward and depends on several input parameters, such as the seed moduli, layer thickness, temperature, the pavement model, etc. The exercise of backcalculating MACOPAV standardized pavement models produced a study of measured deflections that were backcalculated to layer moduli for two peak nominal loads, 65 and 90 kN. The result was a converging set of pavement layer moduli interval, which in turn can be evaluated and expressed with a financial meaning. The main conclusions were:

- The adjustment of the backcalculated curves in relation to the uncertainty boundary was satisfactory. The RMS error achieved in each iterative process was below 4%.
- The variation in moduli values necessary to adjust the initial reference moduli to the critical values boundaries were expressed in function to the asphalt concrete material content in relation to the pavement total thickness (in percentage) and several conclusions were found:
    - Granular material layer required more adjustment, reaching as high as 80%, leading to stiffer layers for pavements with higher content of asphalt concrete (more than 40%). Foundation layers also required more adjustment, around 80%.

- Backcalculated moduli sensitivity to FWD uncertainties are directly linked to the pavement’s flexibility, i.e., highly flexible pavements are affected with higher uncertainty’s influence.

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