The ZAG-VP Longitudinal Profilometer

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SYNOPSIS

Evaluating road unevenness and taking the right steps forward according to established road conditions has an important role in PMS systems. With an increase in road unevenness the dynamic loading caused by vehicles increases non-linearly. This results in a non-proportional decrease in road pavement performance, causing more problems to road owners and managers. As road evenness also relates to riding comfort, it is also very important to road users. This refers to both roads in-use and to new roads. Before newly constructed roads are opened to traffic, their evenness should be inspected.

To evaluate road evenness, reliable and precise measuring equipment is needed. The ZAG-VP longitudinal profilometer can perform measurements over a large range of speeds, which suits efficient measuring performance that does not affect traffic speed on different road networks, road categories, road conditions or traffic flow. This measuring equipment took part in FEHRL's exhaustive project on road evenness, which was held in the Netherlands and Germany. A lot of measuring equipment, from all over Europe, took part in this so-called FILTER project, and it was found that the ZAG-VP equipment measures road profiles well compared to the others.

The paper shows how the ZAG-VP longitudinal profilometer was used in Slovenia for all the above-mentioned cases - quality control, management and research area. For some years now we have been faced by a national programme of motorway construction. Measuring the real longitudinal profile is needed to define the level of evenness for the newly constructed roads. On one hand, the intention for the investor (in our case the state) is to ensure good quality of works, while, on the other hand, the road manager is interested in a good initial condition level. The investigation level for road evenness and financial deductions for not achieving the required level of works were defined. The equipment was also used in the research works, e.g. when determining the relation between road evenness and vehicle dynamic loading.

The ZAG-VP Longitudinal Profilometer

INTRODUCTION

When assessing the performance of roads, the evenness of a pavement cannot be overlooked. It is an important factor in evaluating pavement condition and is closely related to riding comfort, which is so important to road users. It can also affect road safety, and initial evenness influences the pavement's long-term evenness and lifetime.

The ZAG-VP longitudinal profilometer was successfully used in the research field, when the influence of longitudinal evenness on road pavement deterioration was determined.

We are now able to show the dynamic loading caused by vehicles when measuring road unevenness. With these results we can show to road owners or managers the non-linear increase of dynamic loading on uneven roads and the non-proportional decrease in road pavement maintenance.

Reliable measuring equipment is needed to evaluate road evenness, which is capable of producing a pavement profile representation with high accuracy. The high-speed measuring device ensures monitoring measurements and quality control measurements are performed at large scale. This is an important issue in countries where major construction works are carried out. The ZAG-VP longitudinal profilometer can perform measurements at a large range of speeds, which suits efficient measuring performance, which does not affect traffic speed on different road networks, road categories, road conditions or traffic flow.

Accelerated construction of new motorways in Slovenia over the past decade has manifested a need for both an adequate measuring device and technical specifications concerning road pavement evenness. Measuring the real longitudinal profile is needed to define the level of evenness for newly constructed roads. On one hand, the intention for the investor (in our case the state) is to ensure good quality of works, while on the other hand, the road manager is interested in a good initial condition level.

The paper shows how the ZAG-VP longitudinal profilometer was used in Slovenia for all the above-mentioned cases - research area, quality control and road management.

DESCRIPTION OF THE MEASURING DEVICE

Since 1999 the longitudinal pavement profile measurements have been performed in Slovenia with high-speed equipment.

The ZAG-VP (ZAG longitudinal profilometer) measures the pavement longitudinal profile, using an accelerometer and an angular-variable differential transformer. It is a high speed monitoring device, with no impact on the results when moving at speeds from 30 to 120 km/h, so it does not affect traffic speed on any of the road networks [1].

Easy to mount on an ordinary car, the main components of the longitudinal profilometer are: an accelerometer, an angular-variable differential transformer, an odometer and a laptop computer inside the vehicle.

The working principle of the device is shown in Figure 1.

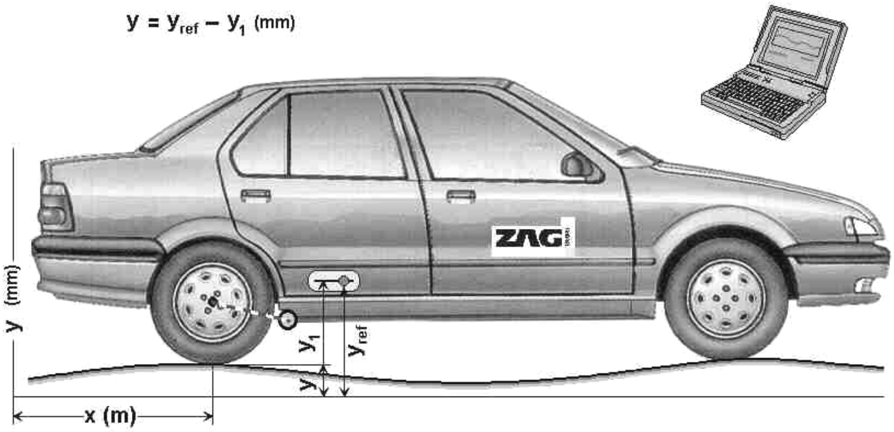

Figure 1. Working principle of the ZAG-VP longitudinal profilometer

An accelerometer is fixed in the vertical direction to the sprung mass of the car. A referential electric signal, which defines the absolute displacement of the sprung mass as a function of the horizontal distance travelled, is obtained by double integration and filtering of the measured accelerations (a simple GMR inertial reference). An angular-variable differential transformer is fixed on the rear axle of the vehicle (see Figure 2) and is used to measure the angle of the oscillating arm of the rear wheel. The data from this transformer are used to define the vertical distance from the road pavement [2].

Figure 2. Position of the angular-variable differential transformer

While the operator is performing measurements, the longitudinal profile can be monitored. Data processing is performed later in the office and depends on the monitoring purpose:
- for pavement management purposes, the IRI (International Roughness Index) values are calculated for 10 m sample sections,
- for quality control, both the irregularities under 4 m straightedge and IRI Index are calculated.

This measuring equipment took part in FEHRL's exhaustive project on road evenness, which was held in the Netherlands and Germany. A lot of measuring equipment, from all over Europe, participated in this so-called FILTER project, and it was found that the ZAG-VP equipment measures road profiles well compared to the others [7],[8].

SURVEYING THE PERFORMANCE OF SLOVENIA'S NATIONAL ROADS

In Slovenia the motorway network is managed by the Motorway Company of the Republic of Slovenia - DARS. The other lower-ranked networks - some expressways, all the main roads and the regional roads networks are managed by the Directorate of the Republic of Slovenia for Roads.

The measurements are performed on all networks since the working speed of the longitudinal profilometer may vary from 30 to 120 km/h, thus not affecting regular traffic. High-speed monitoring shows its significance even more if the measurements are done on a large scale, e.g. over the whole network of national roads, which in Slovenia represents around 6000 km of roads.

When surveying the evenness of national roads under management of the Directorate, the IRI values for 10 m sample sections are calculated from the measured longitudinal profile. Assessment of road condition is done using the criteria from Table 1. IRI values are set for the condition levels according to the traffic level on roads, expressed in AADT.

Table 1. Riding comfort criteria for in-service roads

	Condition				
AADT	Very good	Good	Fair	Poor	Very poor
> 10000	< 1.8	1.8 - 2.5	2.5 - 3.4	3.4 - 4.5	> 4.5
5000 to 10000	< 2.0	2.0 - 2.8	2.8 - 3.8	3.8 - 5.0	> 5.0
3000 to 5000	< 2.2	2.2 - 3.1	3.1 - 4.2	4.2 - 5.5	> 5.5
2000 to 3000	< 2.4	2.4 - 3.4	3.4 - 4.6	4.6 - 6.0	> 6.0
1000 to 2000	< 2.6	2.6 - 3.7	3.7 - 5.0	5.0 - 6.5	> 6.5
500 to 1000	< 2.8	2.8 - 4.1	4.1 - 5.5	5.5 - 7.0	> 7.0
200 to 500	< 3.0	3.0 - 4.5	4.5 - 6.0	6.0 - 7.5	> 7.5
< 200	< 3.2	3.2 - 4.9	4.9 - 6.5	6.5 - 8.0	> 8.0

The analyses are usually done over IRI values for 10 m sections and presented as in the two following figures. In Figure 3 the condition of the Slovene national roads for the years 2002/2003 is presented.

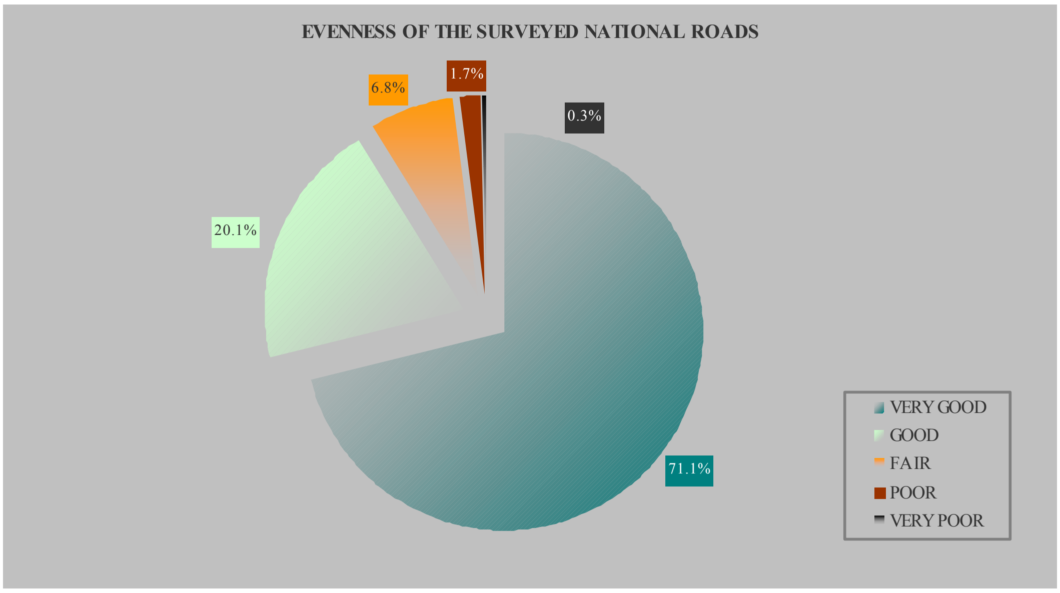

Figure 3: Overview of the condition of almost 6000 km of Slovene national roads

In Figure 4, the proportion of condition levels can be observed for each road category. In this case, the condition of the following road networks is presented: expressways (EW), main roads (two categories M1 and M2) and regional roads (four categories R1 to RT).

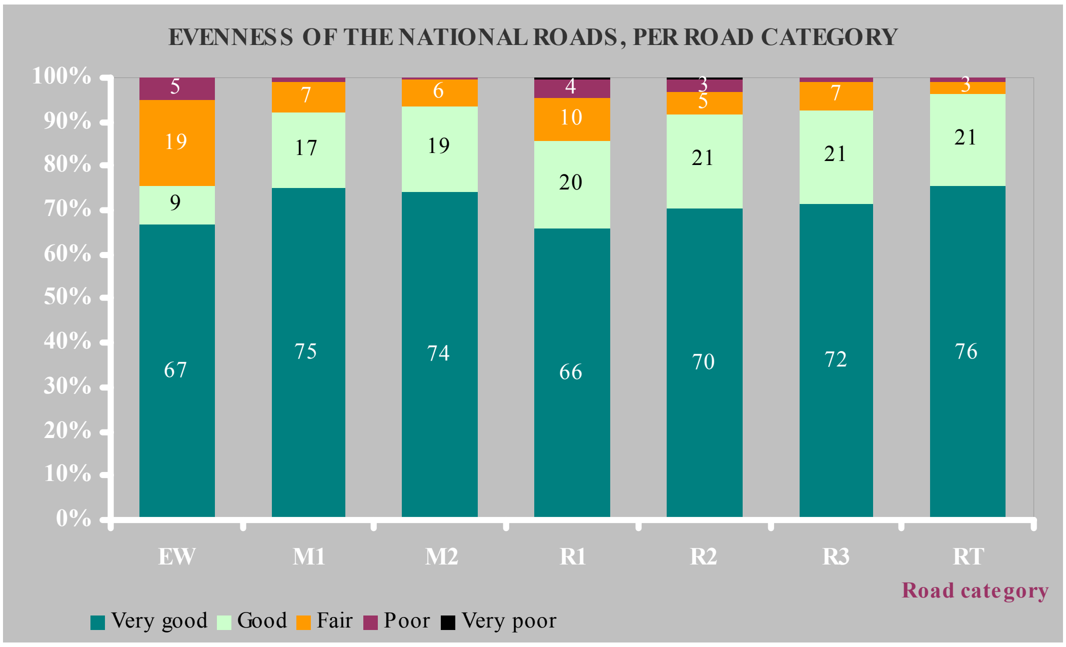

Figure 4: Condition levels for each road category

For the above-mentioned road networks the monitoring is performed "one way", since unidirectional coverage is considered to provide a sufficient and adequate summary of the condition of the network.

QUALITY CONTROL OF INITIAL EVENNESS

Technical Regulations

When newly constructed road sections or reconstructed road sections are assessed, the evaluation of pavement evenness is based on the measured longitudinal profile. Attention is paid to two issues:
- irregularities under a 4 m straightedge, and
- evaluation of riding comfort, based on the IRI Index.

There are two regulations that define the allowed deviation from the straightedge. The valid criteria, which are taken into account are defined in the General and Special Technical Conditions [3] for wearing and sealing courses. The allowed deviation from the 4 m straightedge is:
- 4 mm for heavily and very heavily trafficked roads,
- 6 mm for less trafficked roads.

Newly constructed motorway sections

In year 1999 we started with the longitudinal pavement profile measurements with high-speed equipment, software processing of the measured longitudinal profile defining surface imperfections, and calculating the IRI Index. Up until the year 2003 this was done only informatively for 50 m sample sections, whereas assessment was done using the World Bank [4] suggested criteria. For new pavements, calculated IRI Index values from 1.4 to 3.4 can be expected, according to the IRI roughness scale. Since there was not enough useful data concerning longitudinal evenness for Slovenian roads on this matter, the World Bank IRI values range was adopted in order to assess the condition of roads. At the time, this part of the assessment was done informatively, and the results were later used to modify the road condition evaluation procedure.

Several years ago, the Slovenian national motorway construction program was adopted. Since then construction works have begun on a large scale, resulting in 300 km of new motorways. For every new road section constructed by companies under contract, quality control of the accomplished works was performed. Within the quality control system, the initial evenness of these roads was surveyed.

It became evident that existing criteria could not fulfil needs of Slovenian road users. The serviceability of pavements was frequently found to be at an unsatisfactory level, in spite of fulfilling these quality requirements.

Based on the measured profile data new criteria with new threshold values have been defined for evaluating the road surface condition of the roads in-use and that of newly constructed roads. Furthermore, acceptable evenness condition levels after the warranty period of 5 years were defined. Methods for defining these new criteria are described in the following section.

Statistical evaluation of the motorway network data

At the time, that it was decided to adapt the assessment criteria, more than 200 km of motorways had been analysed. The calculated IRI values for 50 m sample sections were found to range between 0.40 and 6.00, with an average IRI value of 1.24. The standard deviation of the population was 0.47, with a 95% confidence level of 2.18. It should also be mentioned, that quality control measurements on newly constructed road sections are performed on each lane and in both directions.

The World Bank criteria only occasionally indicated unsatisfactory initial evenness. In spite of this, on several occasions riding comfort turned out to be at an insufficient level.

As a result, on the basis of the achieved quality of works by contractors and the existing practice in Europe, the calculation of the IRI Index for 20 m and 100 m sample sections for quality control purposes was proposed. The latter sample section is especially recommended as a general evaluation instrument for riding comfort appraisal [5].

The next step was to select a limited sample of 37 km of motorways from the 208 km available. For this limited length of newly constructed roads the IRI Index for 20 m and 100 m sample sections were calculated by processing the stored longitudinal profile data. Calculated IRI values for 20 m sample sections ranged between 0.13 and 4.60, with an average IRI value of 0.93. The standard deviation was 0.50, and the 95% confidence limit was 1.93. On the other hand, the calculated IRI values for 100 m sample sections ranged between 0.30 and 2.50, with an average IRI value of 1.06. The standard deviation was 0.36, and the 95% confidence limit was 1.78. A summary of the analysis with minimum, maximum and average values (Avg), standard deviations (SD) and 95% confidence limits is shown in Table 2.

Table 2. Overview of the results of the calculations

Sample section	Min	Max	Avg	SD	95%	Sample length
20 m	0.13	4.60	0.93	0.50	1.93	37 km
50 m	0.40	6.00	1.24	0.47	2.18	208 km
100 m	0.30	2.50	1.06	0.36	1.78	37 km

It was additionally determined that major evenness deficiencies occur at the interface of roadways and viaducts (bridges). Although a lot of attention is paid to these joints during construction, they still remain weak spots, making the ride of vehicles bumpy and uncomfortable. The following analysis was performed on a measured longitudinal profile of a representative road section, a section with a viaduct included in it. Compared were the conditions before and after maintenance works, which were carried out close to each other. This is why the road section condition excludes influence other than those caused by the maintenance works. The results are presented in Table 3.

Table 3. Summary of the results of the analysis on a representative section

Maintenance	Sample section	Min	Max	Avg	SD	95%	No of data
Before	20 m	1.4	4.5	1.99	0.40	2.79	169
	50 m	1.6	3.3	2.08	0.36	2.80	68
	100 m	1.7	3.2	2.08	0.28	2.64	32
After	20 m	0.7	4.3	1.39	0.53	2.45	169
	50 m	0.5	1.5	0.83	0.25	1.33	68
	100 m	1.1	3.0	1.54	0.38	2.30	32

On a representative section three calculations of the IRI Index were performed: for 20 m, 50 m and 100 m long sample sections. The calculations were made using the longitudinal profile data, measured just before and after the maintenance works were applied. In Table 3 the minimum, maximum and average obtained values are presented. From the next columns the standard deviations, 95% confidence limits and number of processed singular IRI values can be seen.

In the further analyses attention was focussed on the sample sections, where deviations from the straightedge above 4 mm were found. For these faulty spots the IRI values (for the 20 m, 50 m and 100 m long sample sections again) were examined closely. A summary of the deviation levels and IRI values for different sample sections is shown in Table 4.

Table 4. Distortion under straightedge and IRI values

Deviation from the straightedge (mm)	IRI (20 m)	IRI (50 m)	IRI (100 m)
8	3.0	2.2	2.2
9	2.4	2.2	2.1
10	4.4	3.4	3.2
10	4.1	2.9	2.5
11	4.1	3.0	2.3
14	3.0	2.3	2.4

When comparing the IRI values calculated for the 20 m sample sections with the values for other two sample sections, a significant difference between them was found. There is a considerably difference between the IRI values for the 20 m and 50 m sample sections (about 30%), whereas the values for the 100 m sample sections are about 10% lower than the values for the 50 m sample sections.

On some sample sections deviations of the pavement surface, from a true planar surface with higher texture wavelengths, were observed when examining the longitudinal profile. Therefore, for these sections, a similar comparison as described above was carried out. As can be seen from Table 5, the calculated IRI values for the 20 m sample sections were found to be the highest ones.

Table 5. Comparing IRI values for different sample sections

Distance (m)	IRI (20 m)	IRI (50 m)	IRI (100 m)
60 – 80	2.4		
80 – 100	1.9	2.1	2.0
140 – 160	2.3		
60 – 180	2.7	2.8	2.4
180 – 200	2.6		
280 – 300	1.5	1.9	2.0
300 – 320	4.6	3.1	2.4

As a result, it was decided that for quality control purposes three steps have to be accomplished before assessing the evenness of newly constructed road sections:
- performing the measurements of a longitudinal profile,
- establishing deviations under a 4 m straightedge, and
- calculating the IRI Index values for 20 m and 100 m sample sections.

New assessment criteria

Finally, with regard to the road network classes and traffic levels, new criteria were prepared. This was done both for the newly constructed road sections and for the in-use road sections after the warranty period of 5 years. The threshold values are shown in Tables 6 and 7.

Table 6. Criteria for newly constructed road sections

	IRI for 20 m sections		IRI for 100 m sections	
	Limit	Upper limit	Limit	Upper limit
Higher ranked and higher trafficked roads	2.0	2.6	1.2	1.8
Lower ranked and lower trafficked roads	4.0	4.6	3.0	3.8

Table 7. Criteria for road sections after the warranty period

	IRI for 100 m sections	
	Limit	Upper limit
Higher ranked and higher trafficked roads	1.8	2.5
Lower ranked and lower trafficked roads	3.8	4.5

If the achieved quality of works is better than the limit, the works are treated as adequate. When the evenness of the surveyed road sections is between the limit and the upper limit value, the accomplished works are treated as insufficient and are liable to financial penalties. Evenness evaluated worse than the upper limit shows poorly done works. In this case they are treated as valueless and are subject to the supervisor's judgement and decision regarding further steps that are to be taken.

Taking into account the above described analyses and criteria for evenness condition assessment at the network level, criteria according to the condition level were defined. They are shown in Table 8.

Table 8. Criteria for evenness condition assessment

	Condition level				
	Very good	Good	Fair	Poor	Very poor
Higher ranked and higher trafficked roads	< 1.2	1.2 - 1.5	1.5 - 2.2	2.2 - 3.1	> 3.1
Lower ranked and lower trafficked roads	< 2.6	2.6 - 3.5	3.5 - 4.3	4.3 - 4.9	> 4.9

Financial penalties

In spite of encouraging contractors to make their work as good as possible, some surface imperfections cannot be avoided. As explained before, imperfections under a 4 m straightedge are detected (level and length) and IRI Index values for 20 m and 100 m sample sections are calculated from the longitudinal profile. Taking into account the threshold values (see Tables 6 and 7) for the spots where the imperfections are detected, these areas are treated as insufficiently completed works. Considering the length and width of these non-adequate road subsections, the financial penalties are calculated.

Financial penalties are calculated following the formulae described below. Firstly, the factor for insufficiently completed works (K) is calculated:

$$K = \frac{X_L}{X_{UL} - X_L}$$

The deviation (D) from the limit value is calculated using the following formula:

$$D = K * \frac{X_{IMP} - X_L}{X_L}$$

The financial deduction (FD) for each item (imperfection under 4 m straightedge – H_{4m}, IRI values for 20 m and 100 m sample sections – IRI_{20m} and IRI_{100m}) is calculated as follows:

$$FD = \left(\sum D^2 * A\right) * C$$

Where:
X_L is the limit value,
X_{UL} is the upper limit value,
X_{IMP} is the detected imperfection or calculated IRI value,
A is the area of insufficiently completed works,
C is the penalties costs per area unit.

Finally the total penalties (TP) for the insufficiently completed works are calculated by summing the financial deductions for each item. As it can be seen from the formula below, weights are applied to the separate items.

$TP = (0,65 * (FD\ for\ H_{4m})) + (0,30 * (FD\ for\ IRI_{20m})) + (0,05 * (FD\ for\ IRI_{100m}))$

This procedure has now, with the new regulations, turned into a compulsory calculation for 20 m and 100 m sample sections with the new criteria. This means that financial penalty for contractors for not achieving the work quality criteria can apply.

APPLICATION OF LONGITUDINAL PROFILE MEASUREMENTS IN THE RESEARCH FIELD

In this section the use of the longitudinal profilometer in a research project, as an example, is described. Some of the results of the study, based also on longitudinal evenness measurements, are shown.

The objective of this study [6] was to define the relationship between the road unevenness and the dynamic effects on pavements, caused by lorries.

A computer program based on the method of finite elements was developed to simulate of the influence of an imaginary vehicle on the measured longitudinal profile. For the vehicle, the mass was known and the spring constant and damping factor were defined. Models for trucks with two and three axles were used in this simulation to obtain the simulated results.

The ZAG-VP longitudinal profilometer was used to measure the pavement evenness of the test sections. Afterwards, the parameters of the simulation models were calibrated by comparing the measured and the simulated results. The measured results were obtained by driving the above-mentioned trucks with known dynamic characteristics over the test sections with a whole spectrum of longitudinal evenness, as expressed by the IRI Index.

The results confirmed the assumption that the dynamic effects on the road pavement increase when pavement unevenness gets worse, no matter whether the trucks are empty or fully loaded.

Based on the calculated dynamic effects on the road pavement, calculations were performed of the economic consequences to road owners and road users. In this economic evaluation different traffic categories and longitudinal evenness levels were taken into consideration.

For road owners the calculations included the influence of accelerated pavement deterioration due to delayed maintenance measures. This was done by considering the larger financial investment for maintenance works compared with what investment would be needed in the case of immediate and adequate response.

For road users the calculations included the socio-economic effects of the expenses and the travel time for road users and goods transportation financial evaluation. In these economic evaluations, the effect of different road categories as well as the technical characteristics of the roads, structure of the traffic and the speed of the traffic flow, were considered.

In Figure 5 the results are shown for fully loaded trucks with two axles. From Figure 5 it the increase of dynamic wheel load can be observed, expressed by means of the dynamic coefficient (C_D), when the road gets more and more uneven.

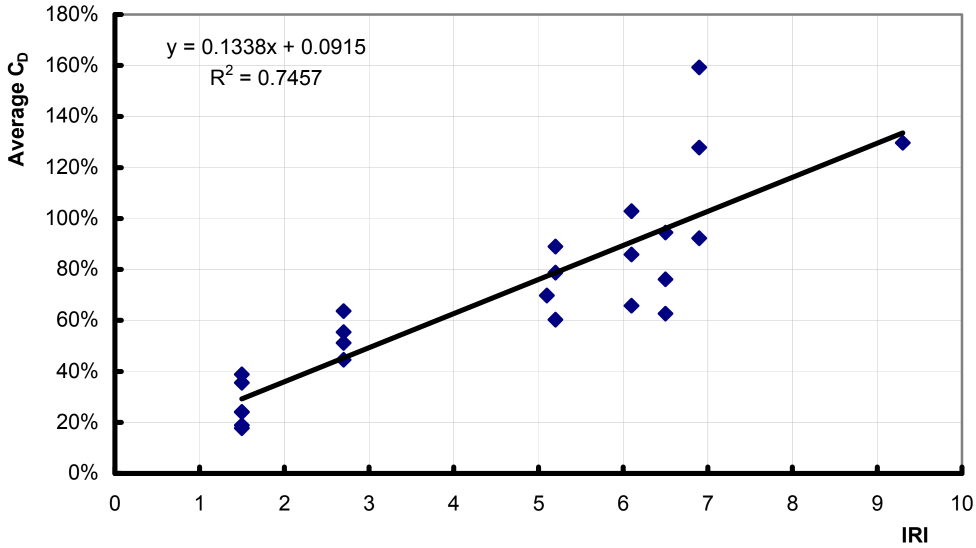

Figure 5: Relation between the dynamic wheel load and road unevenness, for a truck with two axles

The increase in dynamic wheel load is also shown in Figure 6, this time for trucks with three axles.

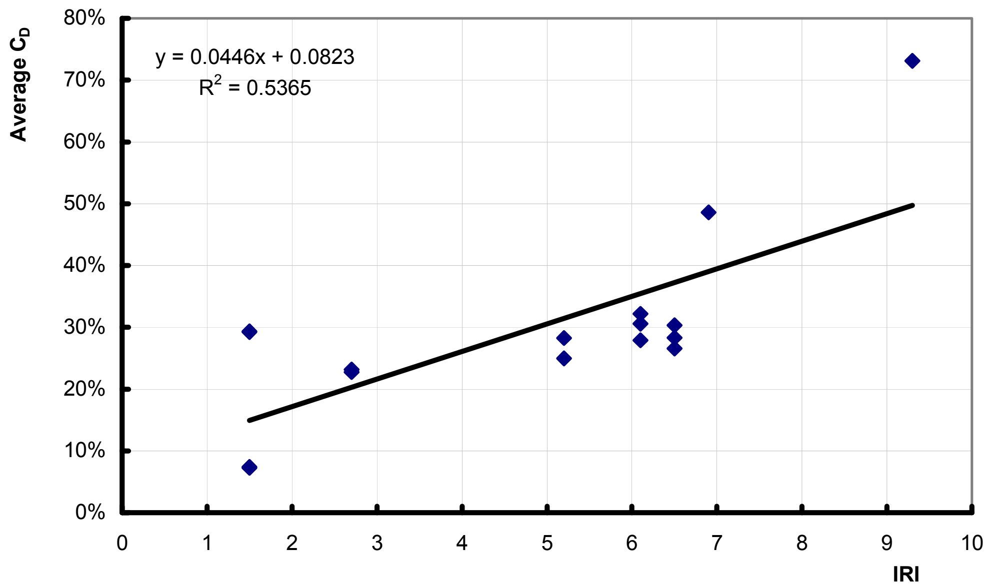

Figure 6: Relation between the dynamic wheel load and road unevenness, for a truck with three axles

CONCLUSIONS

Making efficient decisions in management of the road networks requires from the road authorities or managers having enough knowledge of the surface and structural condition of the roads at any particular moment. Information on pavement serviceability, structural capacity, surface condition and road safety is to be assessed and properly used within the appropriate pavement performance models and economic analyses. Without reliable and sufficient data on the real condition of the road, which is collected with use of the different monitoring equipment, pavement management system(s) cannot exist.

Quality control cannot be done with reliable monitoring equipment only, since, for the assessment of pavement condition, correct and reasonable criteria are also needed. As happens in many cases, the serviceability of pavements was found to be not at a satisfactory level, in spite of fulfilling the quality requirements. This was the reason for preparing new criteria for the evaluation of pavement unevenness, which have already come into force.

The works should be supervised as this ensures higher performance and quality. This holds good for road works as for any other type of works. The ZAG-VP high-speed longitudinal profilometer turned out to be very appropriate equipment for performing measurements of the road pavement evenness.

In addition, the equipment was very useful in the field of the research area.

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