FIELD INVESTIGATION OF FACTORS AFFECTING SKID RESISTANCE VARIATIONS IN ASPHALT PAVEMENTS

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Abstract. Pavement management activities consist mainly of three sequential yet interconnected processes: condition assessment, performance prediction and needs analysis. On this basis, knowledge of the evolution of skid resistance over time is important for pavement maintenance/rehabilitation planning. Seasonal and long term variations have a significant effect on skid resistance evolution. In the present study this effect is thoroughly investigated by modelling field data to provide a structure for the evolution of skid resistance in asphalt pavements. The considered field data includes the results of skid resistance measurements that were performed along 29 highways pavement sections of similar asphalt mix properties, with a fixed slip system (Grip Tester), over a period of four years and during different seasons. The developed model addresses that skid resistance is strongly related to the past level of surface friction, traffic, temperature and precipitation. The model was verified with a high degree of statistical certainty ensuring that mistakes have not been made in implementing the model. Furthermore, it was validated as its predictions have matched additional experimental data, with high precision (95% confidence level). This result produces evidence in support of the statement that the developed model provides accurate information about the variations of skid resistance in asphalt pavements.

Keywords: asphalt pavements, skid resistance, variations, grip tester, modelling.

1. Introduction

Skid resistance is one of the most important pavement surface characteristics, as it is associated with both pavement serviceability and road safety. Its importance has increased over the years due to increased demands for safer roads and the desire for greater highway user comfort (Rao *et al.* 2010; Wang H., Wang Z. 2013). Pavement surfaces must ensure adequate levels of skid resistance for the vehicles in order to perform safe manoeuvres (Harish *et al.* 2013). As skid resistance of a pavement surface decreases, the accident rate increases (Kuttesch 2004). This road safety issue is further amplified on wet pavements because the contact between the tires and the road is reduced and the water acts as a lubricant (Wilson 2006). Numerous studies have demonstrated the significant safety benefits of a targeted approach to improving skid resistance in high risk areas where frequent braking takes place rather than attempting to improve skid resistance to high levels over the whole network. The resistance to skidding is therefore one of the fundamental requirements that road engineers must consider in pavement design to provide a safe travelled surface (Čygas *et al.* 2008). Furthermore, skid resistance is nowadays an aspect of regular pavement condition monitoring

that enables road authorities to be proactive in efficient and effective management of the road network.

With the passage of time, due to traffic loads, weather conditions and the aging of materials, a loss of surface characteristics occurs and therefore, pavement maintenance or intervention is required in order to preserve the pavement surface to its initial level or to some newly acceptable functional level. Hence, it is vital for road authorities to know when surface friction will reach the minimum acceptable level. Periodical pavement monitoring, at present, is undoubtedly the most efficient process to determine the surface friction. However, for planning pavement maintenance and the prioritization of friction restoration, the knowledge of the evolution of skid resistance, in order to predict when a pavement's friction will reach the minimum acceptable level, is required.

Factors that influence skid resistance include amongst others, both traffic loads and environmental conditions (air temperature and rainfall). The present study investigates the effect of these factors on skid resistance by modelling field data to provide a structure for the evolution of skid resistance in asphalt pavements. The developed model is verified and validated ensuring the probability of success

in conducting the simulation study. The research findings are presented below.

2. Background

Skid resistance is an important factor and several studies have researched the issue over the past several decades. Ahammed and Tighe (2009) documented the correlation between traffic and the skidding characteristics of wet road surfaces. The study's findings emphasized that skid resistance measurements must be considered strictly in relation to the time of year they were taken (Cerezo *et al.* 2012), as the lowest values were recorded during the summer. In summer prolonged periods of dry weather allow the fine particles that are polished off the pavement surface to accumulate resulting in a loss of both microtexture and macrotexture. This action together with the contamination from vehicles, (oil, grease etc) lead to lower skid resistance during summer. Due to heavy precipitation in the fall, the fine material is flushed out exposing a coarser aggregate surface. Rainfall also flushes out the drainage channels between aggregates and thus increases the macrotexture of the pavement. In addition it is believed that the polishing action of the aggregate is reduced in winter as in wetter periods the water film covering the pavement acts as lubricant and reduces the polishing effect of vehicles on the surface aggregates (Jayawickrama, Thomas 1998). This trend is independent of the asphalt mix type. Furthermore, it has also been demonstrated that the effect of traffic on skid resistance is not cumulative (Oh *et al.* 2010). A possible explanation that is generally accepted is that while traffic is likely to polish the surface, other factors usually identified as weathering are acting in opposition, thus restoring the microtexture of the exposed aggregate. Thus, the resultant skid resistance represents equilibrium between the effects of certain naturally occurring conditions on one hand, and those of traffic on the other hand (Oh *et al.* 2010). Other research has indicated a significant relationship between Skid Number (*SN*) and weather, including temperature at the time of measurement, average monthly precipitation and the number of dry months since the last significant precipitation (Jayawickrama, Thomas 1998; Oh *et al.* 2010). The combination of these factors cause seasonal variation in *SN* (Oh *et al.* 2010). In addition, *SN* is inversely related to Average Daily Traffic (*ADT*). Finally, the pavement age has a negative relationship with *SN*.

McDonald *et al.* (2006) indicated that variations in skid resistance from day to day, seemingly due to rainfall patterns and local weather conditions, are superimposed on an annual cycle. An attempt was made to determine the parameters used to predict the influence of seasonal and short term effects on skid resistance measurements made with a locked wheel tester. Models were developed for short term changes in surface friction, correlating the dry spell factor and pavement temperature or a function of rain. Other models have been developed for predicting the low skid resistance in terms of *SN* during fall from friction measurement at any time during the year, with the hypothesis that

seasonal variations are caused by polishing of microtexture and wear of macrotexture (Saito, Henry 1983).

According to a number of studies (McDonald *et al.* 2006; Baran 2011; Hosking 1992; McDonald *et al.* 2009; Fuenetes, Gunaratnue 2009), the measured coefficient of friction tends to decrease with increasing air temperature as the temperature change has an effect on the frictional properties of the tire, thus leading to an indirect effect on skid resistance that is available to road users. The mechanism involved in the variation due to temperature changes is attributed to hysteresis of the rubber tire (Jahromi *et al.* 2011). Hysteresis is the energy lost upon elastic recovery, in the form of heat, when a rubber tire is compressed as it slides over the pavement. At higher temperatures the rubber becomes more flexible leading to less energy loss. Higher temperatures thus lead to a decrease in the measured skid resistance (Jayawickrama, Thomas 1998). Tire temperature tends to be proportional to air and pavement temperature, with higher tire temperatures leading to decreased measured coefficients of friction. Finally, increased pavement temperatures lead to a reduced coefficient of friction. Others, however, have found that pavement temperature has a significant effect on pavement frictional measurements (Bazlamit, Reza 2005) and on the sensitivity of the measurements to the speed (Luo 2003). This results in the pavement temperature effect on the measured number being dependent on the testing speed. At low speed pavement friction tends to decrease with increased pavement temperature, whereas at high speed, the effect is reverted and pavement friction tends to increase with increased pavement temperature.

Various models have been developed for long term skid resistance variation. One such model correlates *SN* with Marshall Stability, Marshall Flow, air voids and equivalent traffic and indicates that a mix with higher stability will exhibit higher skid resistance because of the mix's greater capability in resisting the coarse aggregate immersion in the matrix. In contrast, skid resistance will increase with increased flow. Ahammed and Tighe (2009) developed two models for the flexible pavement's long term friction. The parameters of the first model include pavement age in years after an early age increase in surface friction, temperature during the testing, dry versus wet weather code, freeze versus no freeze weather code and measurement speed. In the second model the same parameters are taken into account, except the pavement age has been substituted with the cumulative traffic passes after an early age increase in surface friction. In spite the fact that all correlations factors were statistically significant the R^2 values were low.

The majority of the available research, at present, addresses skid resistance prediction with a locked wheel system. In contrast, the present research, as it has been already mentioned, investigates the issue utilizing a fixed slip system.

3. Objectives and methodology

In many cases research on seasonal and long term variations of pavement surface friction is insufficient with

inadequate results or models. This research has attempted to closely evaluate these two aspects to quantify the seasonal and long term variations of asphalt concrete pavement surface friction and provide road authorities a supplementary tool for the programming of the rehabilitation or maintenance works. More specifically the objectives of the present study are on the one hand, to investigate and quantify the effect of environmental factors (such as ambient temperature, rainfall and dry spells) and on the other hand, to investigate and quantify the effect of traffic loads on long term surface friction variations.

For this purpose, skid resistance measurements were performed over a period of four years along 29 trial highway sections, using a Grip Tester system. The Grip Tester is a fixed slip system, with the measuring wheel fitted with a smooth tire as described in *ASTM E1844-08 Standard Specification for a Size 10 and 4–5 Smooth Tread Friction Test Tire*, that is geared to rotate at a proportionally different rate, thereby producing a 14.5% slip relative to the drive wheels. This slip ratio is the critical slip and it is the point at which a peak friction occurs. Thus, Grip Tester simulates vehicles with Anti-Locking Brake System (*ABS*) that are designed to apply brakes on and off repeatedly, such that the slip ratio is held near the pick coefficient of friction.

The skid resistance measurements were carried out continuously at a speed of 50 km/h on the right wheel path over a wet surface. Water was supplied by an automatic pump system that created a 0.25 mm water film depth under the slipping wheel, according to the manufacturer standards. The data was recorded and averaged at 10 m intervals.

Table 1. Composition of asphalt mixture

Sieve size	Lower limit	Composition	Upper limit
	Percent passing		
19.0 mm (3/4 in.)	100	100	100
12.5 mm (1/2 in.)	85	95.0	100
9.5 mm (3/8 in.)	60	77.8	90
4.75 mm (No. 4)	20	29.5	50
2.36 mm (No. 8)	5	22.0	25
1.18 mm (No. 16)	3	15.1	19
300 μm (No. 50)	0	7.1	10
75 μm (No. 200)		3.9	
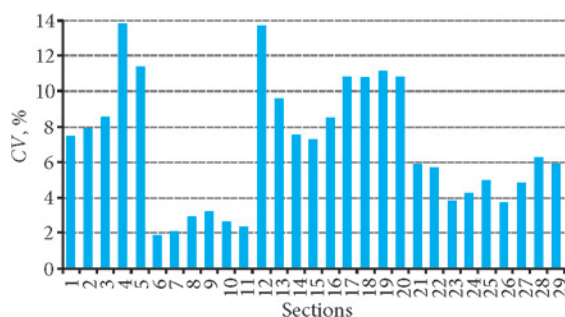
Fig. 1. *CV* values of *GN* data (first set of measurements)

All sections were hot mix asphalt concrete pavements, with both similar mix design and aggregate type used for their construction. All pavement sections consisted of an antiskid surface layer, representing open mixtures that correspond to Mix Designation O-5 (Table 1), as defined in the *ASTM D-3515 Standard Specification for Hot-Mixed, Hot-Laid Bituminous Paving Mixtures*.

The aggregate type used in the mix design was steel slag and was produced using a 25-55/70 asphalt penetration modified with polymer and a binder content of 4.0% by mass of the mixture. The air void content of the asphalt mix is 11.5% by mass of the mixture.

The sections were constructed at different time periods (different age pavements) with the latest to have been constructed in August 2004. The lengths of the sections range from 500 m to 5400 m. No surface distresses were observed and the pavements structural capacity was adequate.

In order to investigate the seasonal variations in skid resistance, measurements were performed during the night twice a year, in the winter period usually after long period of rains and in the mid summer period. For the regarding period one set of measurements at each section were performed. Meteorological data (air temperature during the measurement and precipitation) were also recorded. The precipitation refers to the cumulative rainfall of 2.5 mm or more, for the seven days preceding the measurements, since skid numbers decrease and reach a minimum value after seven days of dry weather (Saito, Henry 1983). Air temperature ranged from 2 ºC to 15 ºC in the winter period, while in the mid summer period ranged from 20 ºC to 28 ºC.

For the investigation of the long term variations in skid resistance, appropriate traffic data was obtained (cumulative *ADT*). The Annual Average Daily Traffic (*AADT*, vpd) ranged from 7230 to 79 112.

4. Data analysis

4.1. Skid resistance modelling

In the framework of the present study, the variability of Grip Number (*GN*) data of each section and for every set of measurements was investigated. Thus, the Coefficient of Variation (*CV*) was calculated and was found less than 20% in every case. Fig. 1 shows the *CV* of *GN* data of each section for the first set of measurements. Therefore, the average *GN* values are taken into account in the analysis process since they are considered to be representative in all cases.

The monitoring of the pavements under investigation was not initiated immediately after construction but at minimum three years later, thus there is no data of the initial skid resistance condition. The first set of measurements were undertaken at least three years after the construction, as this is after the early life period (approx 2.5 years) where an increase in pavement surface friction is observed (Rezaei, Masad 2013). On this basis, a variable expressing the condition of the pavement in terms of skid resistance at the time of the first set of measurements, referred to as GN_{in}, was considered as an input variable in the analysis process. In addition, the traffic data considered in the analysis

process refers to the cumulative *ADT* from the initial set of measurements.

In order to investigate the seasonal variations in skid resistance, for simplicity purposes, two factors were taken into account, the air temperature during the measurements and the cumulative precipitation of the seven days prior to the measurements. Due to the fact that the cumulative precipitation did not seem to be statistically significant, for defining the different climatic conditions as far as rainfall is concerned, an indicator variable was used that expresses the dry versus wet weather code, with a value equal to 1 if the cumulative rainfall in the seven days preceding the measurements was greater than 2.5 mm and a value equal to 0 where the cumulative rainfall in the 7 days preceding the measurements was less than 2.5 mm.

It is noted that, in the present study, the macrotexture is not used as a parameter in the model. This is due to two reasons. The first is that the aim of the model is to predict skid resistance without the need to perform any kind of measurements. The second is that the variations in macrtotexture are, as it has been previously mentioned, partially attributed to the environmental conditions (temperature and rain) that are included in the model. Furthermore, Grip Tester measurements are mostly influenced by the microtexture, since the testing wheel rotates at a 14.5% slip relative to the drive wheels. Since the actual speed of the testing wheel is low, microtexture is the dominant parameter that influences the measured skid resistance in terms of *GN* (Livneh 2009).

The sample size was 203 observations with $\overline{GN} = 0.47$ and $Var(GN) = 0.013$. The analysis results showed a linear regression between *GN* and the above mentioned variables. Specifically, Eq (1) provides this correlation corresponding to a coefficient of determination $R^2 = 0.79$.

$$GN = 0.259 + 0.629GN_{in} - 0.004TV + 0.061DW - 0.006T,$$

where *GN* – the measured *GN*; GN_{in} – the initial *GN* as defined above; *TV* – the traffic volume expressed as cumulative *ADT* multiplied with 10^{-6}; *DW* – the dry versus wet weather code (dry weather = 0 and wet weather = 1); *T* –the air temperature, $^{\circ}$C, during the measurements.

Table 2 shows the ANOVA summary, while Table 3 shows the coefficients of the independent variables and the constant.

The regression sum of squares measures how much variation is in the modelled values, the total sum of squares measures how much variation is in the observed data and the residual sum of squares measures the variation in the modelling errors. The mean square is the sum of squares divided by the degrees of freedom (*df*). The *F* ratio is the ratio of the amount of systematic variance (due to experiment or effects of independent variable) and the amount of unsystematic variance. The *F* ratio is the ratio of two mean square values. If the null hypothesis is true, *F* value is close to 1. A large *F* ratio means that the variation among group means is not due to chance but systematic. A large *F* ratio appears both when the null hypothesis is wrong (the data are not sampled from populations with the same mean) and when random sampling happened to end up with large values in some groups and small values in others.

The column labelled B under unstandardized coefficients indicates how the dependent variable *GN* changes, on average, given that the independent variable goes up one unit. The Standard Errors (*Std. error*) are the standard errors of the regression coefficients. The column labelled Beta under standardized coefficients indicates how many standard deviations the dependent variable *GN* goes up given that the independent variable has gone up one standard deviation.

The *p*-value (sig.) for the coefficients of the independent variables are < 0.05, which means that the null hypothesis (coefficients = 0) is rejected and as such all of the independent variables included in Table 3 are statistically significant to the prediction of dependent variable *GN* and are included in the model.

In spite of the fact that the correlation of determination is fair to good ($R^2 = 0.79$), further analysis was

Table 2. ANOVA summary

	Sum of squares	*df*	Mean square	*F* ratio	*p*-value (sig.)
Regression	2.071	4	0.518	180.418	0.000
Residual	0.568	198	0.003		
Total	2.640	202			

Table 3. Coefficients for *GN* prediction model

Model	Unstandardized coefficients		Standardized coefficients	*t*	*p*-value (sig.)
	B	*Std. error*	Beta		
Constant	0.259	0.025		10.495	0.000
T	−0.006	0.001	−0.437	−11.138	0.000
GN_{in}	0.629	0.039	0.550	16.322	0.000
DW	0.061	0.009	0.258	6.555	0.000
TV	−0.004	0.001	−0.219	−6.496	0.000

performed to determine the accuracy of the model. Fig. 2 shows the Normal Probability Plot (P-P) of the regression standardized residuals. That is, the model is fit and a normal probability plot is generated for the residuals from the fitted model. If the residuals from the fitted model (points) are not normally distributed (line), then one of the major assumptions of the model (normality) has been violated.

The Normal Probability Plot shown in Fig. 2 shows a strongly linear relationship. There are only minor deviations from the line fit to the points on the probability plot. Therefore, the normal distribution appears to be a good model for these data. Further to this, the scatter plot of residuals (ε_i) has shown that they are randomly distributed about a line with $\overline{\varepsilon_i} = 0$ and with no particular trend. That means that the other assumption of the model (homoscedasticity) is not violated.

Fig. 3 summarizes the GN measured values (GN_m) and the GN predicted values (GN_p) in box plots. The illustrated box plots are based on the median and inter-quartile range. The upper edge (hinge) of the box indicates the 75th
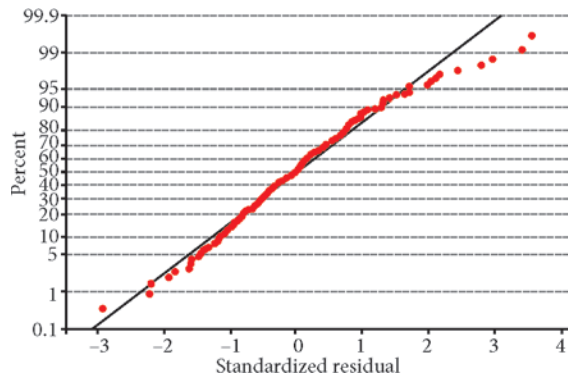

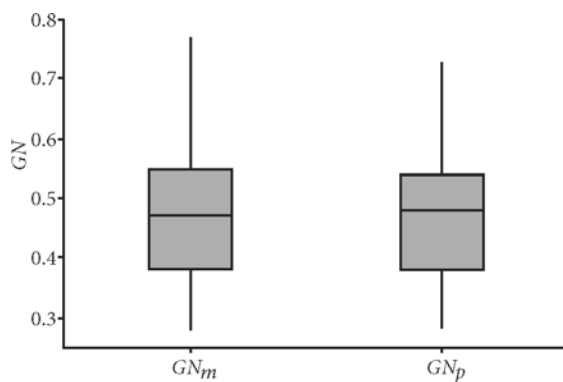**Fig. 2.** Normal Probability Plot (P-P) of regression standardized residuals

Fig. 3. Variation of GN_m and GN_p values

Table 4. Paired Samples *t*-test for GN_m – GN_p

Samples	Mean	95% confidence interval of the difference		*p*-value (sig.)
		Lower	Upper	
GN_m–GN_p	0.000	–0.0073	0.0073	1.00

percentile of the data set and the lower hinge indicates the 25th percentile. The range of the middle two quartiles is known as the inter-quartile range. The line in the box indicates the median value of the data. The ends of the vertical lines or "whiskers" indicate the minimum and maximum data values.

In Fig. 3 the box plots that describe the GN_m and GN_p values are narrow meaning that GN_m and GN_p data ranges are small. Also, GN_m data is symmetric as the median is in the centre of the box plot and for this reason median value i.e. 0.47 is considered to be representative of the GN_m data set. Thus, GN_p data is slightly asymmetric as the median is not exactly at the centre of the box plot; however, as the box plot is narrow the median value of GN_p i.e. 0.48 is considered as representative of GN_p values. Thus, in summary GN_m values and GN_p values are very close.

In order to produce evidence in support of the statement that the values of GN_m and GN_p seem to be similar, a paired samples *t*-test with a confidence level of 95% was applied in order to investigate if differences are statistically significant. Based on the analysis, a probability value *p*-value ≥ 0.05 indicates that there is no statistically significant difference in GN values. Conversely, a *p*-value < 0.05 indicates that there is a statistically significant difference in GN values. Results are shown in Table 4.

As shown in Table 4 the GN_m values don't differ significantly from those predicted from the model (GN_p), since *p*-value >0.05. Taking all the above into consideration, it is believed that the developed model for the prediction of skid resistance is sufficient.

4.2. Model verification

In the framework of the present study, in addition to the development of a skid resistance prediction model, a verification process was performed in order to investigate the model's performance and accuracy when applied on new data. For this, skid resistance measurements were performed on all sections in the winter period 2011. Data concerning the air temperature during the measurements, cumulative rainfall for the seven days prior to the measurements and traffic, was also collected Fig. 4 shows the CV of GN data of each section for the set of measurements performed during the winter period 2011 (W_{11}). The CV was less than 20%, so the average GN values were considered to be representative and were taken into account in the analysis process.

In Fig. 5 the mean GN measured values (GN_m–W_{11}) and the GN predicted values (GN_p–W_{11}) for each section are presented.

In order to investigate whether the differences between the measured GN_m–W_{11} values and the predicted GN_p–W_{11} values are statistically significant, a paired samples *t*-test was performed. The results are presented in Table 5.

As shown in Table 5 the GN values measured in the winter period 2011 (GN_m–W_{11}) don't differ significantly from the values predicted from the model (GN_p–W_{11}), since *p*-value > 0.05. Therefore, the developed model seems to

be adequate for the prediction of variations in skid resistance of the considered HMA pavement surface.

The applicability of the this model in other asphalt pavement surfaces with different mix design, aggregate type or even climate conditions, is subject to further investigation in order for the model to be calibrated under the local conditions and pavement surface type.

5. Conclusions

For planning pavement maintenance activities, the evolution of skid resistance is of paramount importance. Variations in skid resistance result from both seasonal and long term variations. In the present study, both factors were taken into consideration for the development of a model applied for the prediction of the evolution of skid resistance when measured with a fixed slip system (Grip Tester). The following conclusions are drawn:

1. It was proved that the measured skid resistance index (Grip Number) is correlated fairly to good with the traffic volume, the dry or wet conditions, the air temperature during the measurements, as well the initial level of skid resistance that was defined using the first set of measurements of skid resistance index.

2. The latter produces evidence in support of the statement that a pavement's skid resistance at a given time is closely related to the initial or a past level of pavement's friction. The vision of the initial level of skid resistance provides road authorities the potential of predicting skid resistance even when the pavement monitoring was not initiated after construction period. In any case the developed model is valid provided that the period of early life increase in friction has passed.

3. The model was verified with a high degree of statistical certainty ensuring that mistakes have not been made in implementing the model.

4. Furthermore, it was validated as its predictions have matched additional experimental data with high precision. Specifically, the analysis results showed that the Grip Number values predicted from the model were similar to those measured and the differences were not statistically significant at a 95% confidence level. Therefore, it is believed that the model developed in the framework of the present study is efficient and produces consistent results. However in order to generate its use, the model should be calibrated under the local conditions and pavement surface type.

It is worthwhile mentioning that pavement skid resistance is an important pavement evaluation parameter because inadequate skid resistance will lead to higher incidences of skid related accidents and road agencies have an obligation to provide users with pavement that is reasonably safe. Thus, the prediction of skid resistance would facilitate the process of implementing pavement preservation programs. On this basis, models applied for the prediction of the evolution of skid resistance are believed to be used as supplementary tools to support pavement management
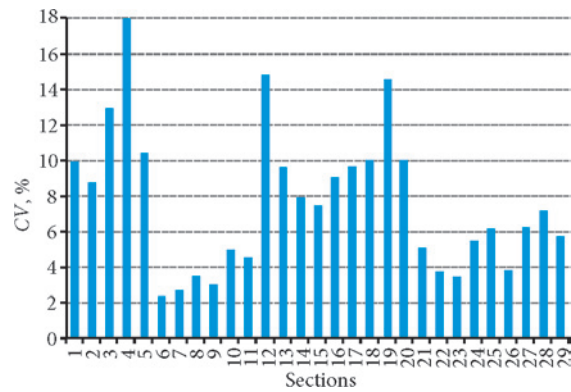

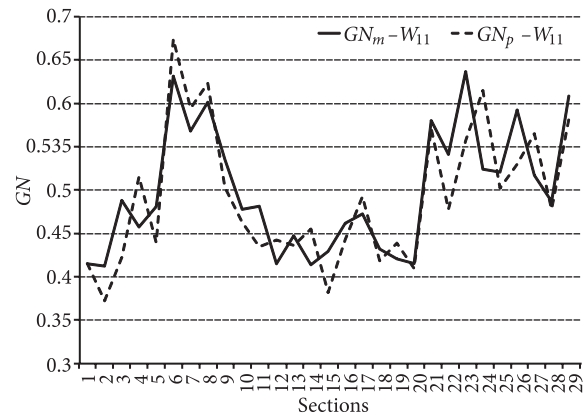**Fig. 4.** *CV* values of *GN* data (winter period 2011)

Fig. 5. *GN* measured values (GN_m–W_{11}) and *GN* predicted values (GN_p–W_{11}) for the winter period 2011

Table 5. Paired Samples *t*-test for GN_m–W_{11}–GN_p–W_{11}

Sample	Mean	95% confidence interval of the difference		*p*-value (sig.)
		Lower	Upper	
GN_m–W_{11}– GN_p–W_{11}	0.008	–0.0076	0.0242	0.297

activities. However, for the determination of the actual pavement's skid resistance condition, field measurements are always necessary.

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