LATENT CONDITION STRUCTURE OF ASPHALT CONCRETE ROADS IN FINLAND

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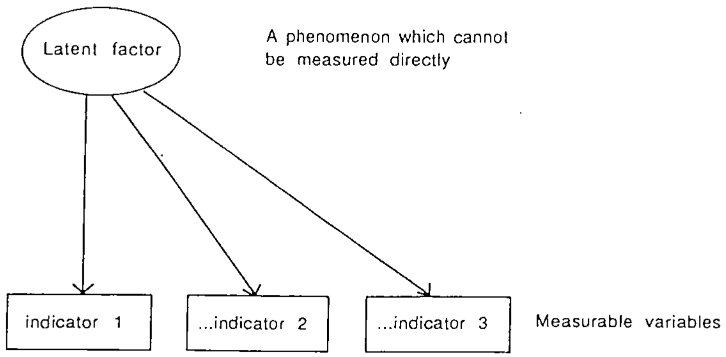
1. INTRODUCTION

Road condition is measured using various engineering indices, rutting, roughness, distress, bearing capacity etc. Experience shows that this is not enough. Concepts such as riding quality and present serviceability have been developed to describe user perceived condition which cannot be measured directly. These familiar concepts have been developed by using subjective judgment, condition measurements and regression analysis.

The basic idea behind these indices is that condition measurements do not actually measure road condition, as it is something unmeasurable. However, it can be caught by several different measured variables. The way this can be made operational is through latent structure analysis or by using LISREL (LInear Structural RELationship) models. They are used in this paper to formulate 'road condition', i.e. the unobservable condition behind the measured variables.

The concept factor is used as an unobservable variable revealed and quantified by measurable indicator variables. In graph 1 the rectangles represent observed quantities and the ellipse represents the unobserved latent variable.

Graph 1



A factor and its measurable indicator variables

Indicator variables measure different sides of the latent factor and in this way makes it possible to quantify its structure. Variables with high mutual correlations are believed to arise from the same common phenomenon. When a factor is built up mathematically from observable and measurable variables it is possible to investigate and describe a phenomenon better with distinct aspects and find out which of the indicators are best for measuring it. For instance, distress is seen through various measured indicators such as alligator cracking, longitudinal cracking and other defects on road surface.

The hypothesis of five factors is based on the earlier work by Talvitie and Olsonen (1988) who formulated factors for Finnish asphalt concrete roads. They discovered that five factors, 'rutting', 'geometry', 'distress', 'bearing capacity' and 'road width', adequately describe the physical properties of the road roughness being inferred as "the smoking gun". Based on this result the condition of asphalt concrete roads is described by four factors, 'rutting', 'roughness', 'pavement distress' and 'bearing capacity'. In the Finnish PMS (Thompson et al, 1989) each of these was substituted by the most suitable variable.

Now that data is also available for roughness and deflections in road structure it is possible to build up latent factors, 'rutting', 'roughness', 'distress', 'pavement bearing capacity' and 'subgrade bearing capacity'. The estimation method used here, the LISREL models (see appendix for technical details), makes it possible to formulate these latent factors and estimate their loadings and mutual correlations. In addition, estimation of factor scores produces operational indices for these factors. In order to achieve a more general picture of road condition a further hypothesis of two second order factors was included. The five first order factors were used to reflect 'surface condition' and 'subgrade condition'.

2. DATA

Three distinct methods are used to provide information about road condition in Finland (table 1). Road surface distress is measured by visual inspection from a car that moves at a speed of about 30 km/hour. The records are sums of defects in 100-meter sections. Transverse and longitudinal roughness are measured with a special vehicle produced by the Technical Research Centre of Finland that measures a wide variety of variables of which IRI (international roughness index) and rut depth are normally used. The measurements are averages in 100-meter sections. Bearing capacity of road construction is measured with a KUAB-falling weight deflectometer that is a dynamic device providing information about pavement and subgrade deflections. For each road section it produces two variables for subgrade condition; BCI (base curvature index) and AMITK (design bearing capacity of subgrade), whereas SCI (surface curvature index) and TMITK (design bearing capacity of pavement) are variables for pavement construction. The variables KEVK (the lowest seasonal bearing capacity, spring), SP (spreadability) and DEV (deviation of bearing capacity) are also used.

Condition variables are grouped in table 1 to give an idea of the five first order factors. Traditionally, condition is defined by one measured variable per factor. Rut depth is used for rutting, IRI is used for longitudinal roughness, and the lowest seasonal bearing capacity KEVK is used for bearing capacity. Distress is the only condition 'factor' that uses several measured variables. The index for road distress is

distress=1.0*(alligator cracking)+1.0*(ravelling and coarse aggregate loss)+ 1.0*(patches)+0.5*(longitudinal cracking)+0.4*(transverse cracking)+ 0.1*(longitudinal meander and midlane cracking).

The above index is widely used even though the weights and variables are chosen on a subjective basis. It is interesting to compare this index to a mathematically produced index that is evaluated in this paper in the same way as Ramaswamy and McNeil (1991) successfully compared PSI and PSR using factor analysis. The new variable, a weighted sum of distress variables, can be constructed from the factor scores.

Table 1

Variable	Unit	Measurement
RUTTING		Special vehicle
Rut depth	mm/ m	with laser-,
Transverse roughness	mm/ m	ultra-sonic and
LONGITUDINAL ROUGHNESS		adp-equipment.
IRI	mm/ m	Same as
Bumps	#/100 m	above.
DISTRESS		
Alligator cracking	$m^2/100$ m	
Longitudinal cracking	#/100 m	
Transverse cracking	m/100 m	Visual
Cracking, large	m/100 m	inspection
Longitudinal meander and midlane cracking	m/100 m	of defects.
Ravelling and coarse aggregate loss	$m^2/100$ m	
Flushing	m/100 m	
Patches	$m^2/100$ m	
BEARING CAPACITY		
BCI (base curvature index)	0,001 mm	KUAB-
AMITK (design bearing cap. of subgrade)	MN/m^2	falling weight
SCI (surface curvature index)	0,001 mm	deflectometer.
TMITK (design bearing cap. of pavement)	MN/m^2	
SP (spreadability)	%	
KEVK (the lowest seasonal bearing cap.)	MN/m^2	
DEV (st. deviation of bearing cap.)	MN/m^2	

The variables measured on asphalt concrete roads in Finland.

The model presented in this report uses condition measurements from asphalt concrete roads in Finland. The data covers most of the country but it is not randomly selected. All data was measured in the summer of 1991 and measurements were deleted in the case of maintenance work. This model does not take into account the simultaneity of deterioration and maintenance which Ben-Akiva and Ramaswamy (1989) presented in their latent structure analysis.

LISREL models presuppose that the variables have a multivariate normal distribution. Most of the variables in the data are skewed but easily become symmetrical when transformed by logarithm function. Variables that describe pavement distress are exceptionally skewed. As much as over 90 % of the data has zero value. One possible assumption is that distress variables have a conditional binomial distribution: 0=no defects, 1=defects exist and they have a continuous distribution. Attempts were made to simplify these variables as dichotomous ones. The correlations for dichotomized variables are called polyserial and polychoric correlations (Olsson, 1979) and they can be utilized in the LISREL models. But estimated correlations appeared to be unrealistic and the idea was rejected.

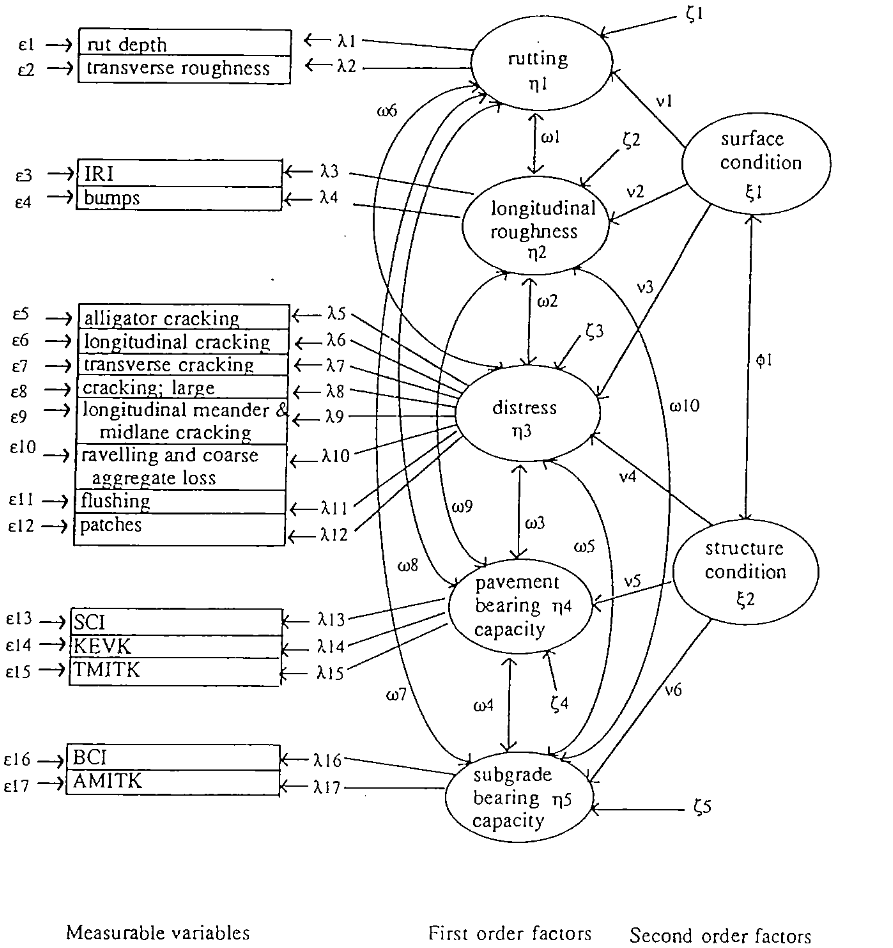
The data for rutting, roughness and distress was collected for every 100 metres of road, but the bearing capacity data are averages and percentiles of each road section that is ca. 3.3 km in length. Averages on road sections were calculated for rutting, roughness and distress in order to obtain independent observations. These averages also caused distress variables to become more symmetrical. The data consists of information from 1.559 kilometers and 468 road sections. Table 2 includes mutual correlations between transformed indicator variables used in the following analysis.

Table 2

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
A Ruts	1																
B Transverse roughness	0.225	1															
C IRI	0.028	-0.124	1														
D Bumps	-0.025	-0.085	0.602	1													
E Alligator cracking	-0.078	0.046	0.258	0.154	1												
F Longitudinal crack.	0.046	0.14	0.09	0.056	0.424	1											
G Transverse crack.	0.099	0.181	-0.117	-0.102	0.098	0.215	1										
H Cracking, large	-0.036	0.031	0.109	0.042	0.281	0.333	0.109	1									
I Longitudinal meander and midlane cracking	0.087	0.087	-0.29	-0.016	0.372	0.482	0.358	0.245	1								
J Ravelling and coarse aggregate loss	-0.057	0	0.239	0.183	0.352	0.199	0.09	0.23	0.208	1							
K Flushing	-0.1	0.34	0.103	0.082	0.387	0.159	-0.032	0.314	0.105	0.265	1						
L Patches	-0.063	-0.03	0.182	0.051	0.319	0.189	0.051	0.213	0.105	0.371	0.229	1					
M SCI	0.049	-0.035	0.336	0.276	-0.283	0.136	-0.197	0.076	-0.107	0.087	0.117	0.154	1				
N TMITK	0.014	0.069	-0.515	-0.4	-0.408	-0.184	0.129	-0.184	-0.07	-0.223	-0.169	-0.237	-0.792	1			
O KEVK	-0.013	0.041	-0.462	-0.391	-0.375	-0.181	0.15	-0.133	-0.035	-0.178	-0.133	-0.193	-0.829	0.949	1		
P BCI	0.057	0.228	0.286	0.164	0.23	0.242	0.077	0.119	0.162	0.162	-0.065	0.111	0.42	-0.61	-0.552	1	
Q AMITK	-0.097	-0.13	-0.36	-0.243	-0.283	-0.204	-0.064	-0.109	-0.21	-0.171	-0.003	-0.109	-0.311	0.637	0.584	-0.745	1

Simple correlation matrix of transformed indicator variables. Correlation coefficients are based on 468 observations and they are statistically significant at the 5% level if their value exceeds 0.088.

Graph 2

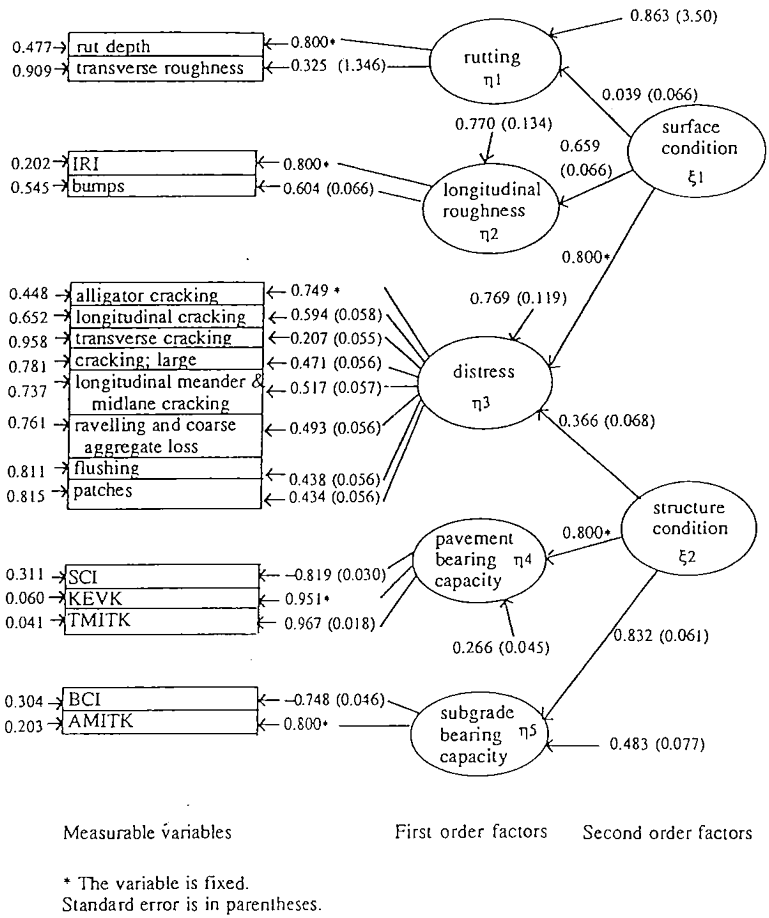


The hypothesis of asphalt concrete road condition described by a confirmatory second order factor analysis.

4. RESULTS

The results of estimation are shown in graph 3. The overall fit of the model is satisfactory: 91.4 per cent of the variation in the correlation matrix is explained (RMR=8.6 %). Also, the D-values for η– and ξ -factors prove adequate overall measuring ability for both first and second order factors.

Graph 3



Test statistics for model fit:

χ^2=702 (df=114) GFI=0.84 RMR=8.6 % D(η)=1.00 D(ξ)=0.82

R^2(η1)=0.2 %R^2(η2)=36 %R^2(η3)=20 %R^2(η4)=70 %R^2(η5)=59 %

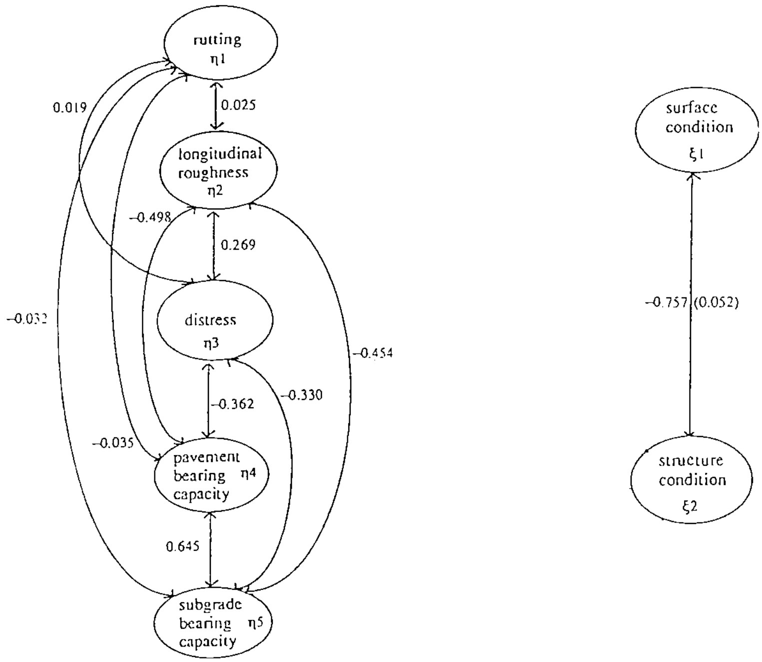
The LISREL model for asphalt concrete road condition with two second order factors: surface condition and structure condition.

Rutting confirms that rut depth is a more important variable than transverse roughness. However, the rutting factor has the highest variances, probably because of the data problems mentioned earlier. Traffic volume could be included in rutting. Longitudinal roughness factor is best measured with IRI, but bumps also provide substantial information of longitudinal roughness. The most important indicator for distress is alligator cracking although other defects also have a significant influence. Only transverse cracking seems to be of minor importance (weight=0.2). A possible assumption was that transverse roughness does not indicate distress. Both of the bearing capacity factors have high loadings for their indicator variables. These factors also have the highest reliabilities (R^2) among the first order factors.

The second order factor, 'surface condition', has high loadings for distress and longitudinal roughness, but rutting has no influence. 'Structure condition' is composed equally of bearing capacity factors, and distress had an unexpected positive weight that was hard to explain.

Rutting is uncorrelated with other factors (graph 4), which influences the second order factors. The correlation between surface condition and structure is large.

Graph 4



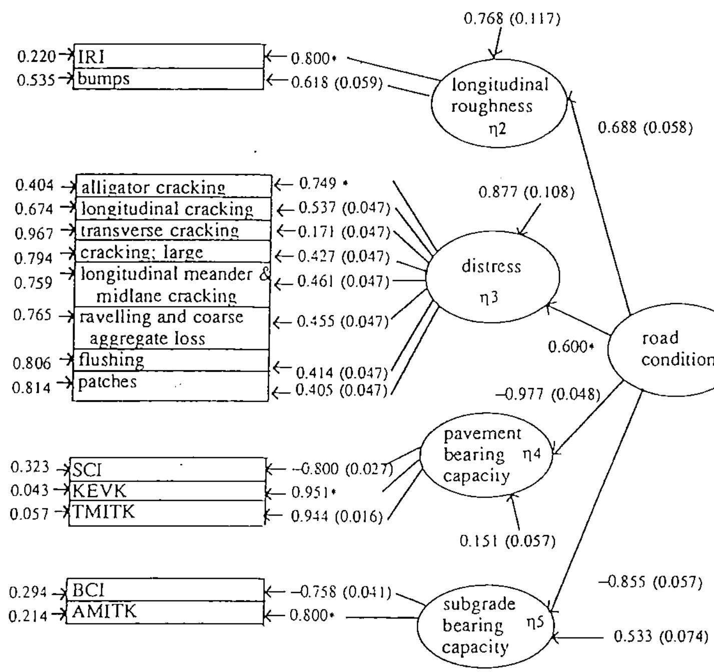
The estimated mutual correlations between the first and second order factors.

The analysis gives the following indices to be used as measures of road condition: rutting=1.0*rut depth+0.2*transverse roughness,

longitudinal roughness=1.0*IRI+0.28*bumps,
distress=1.0*(alligator cracking)+0.4*(ravelling and coarse aggregate loss)+ 0.3*(patches) + 0.5*(longitudinal cracking) + 0.1*(transverse cracking)+ 0.4*(longitudinal meander and midlane cracking) + 0.4*(cracking, large),
pavement bearing capacity=1.0*KEVK+0.7*TMITK-0.11*SCI, and
subgrade bearing capacity=1.0*AMITK-0.6*BCI.
The distress index varies slightly from the current distress definition (see section Data).

Owing to the problems with rutting another model specification was estimated. Rutting was excluded and only one second order factor, road condition, was formulated. Results in graph 5 are satisfactory and are in accordance with the earlier model. Loadings for the second order factor indicate that pavement and subgrade bearing capacities are more significicant for road condition than roughness or distress. But a definitive conclusion cannot be drawn because rutting was excluded.

Graph 5



Test statistics for model fit: χ^2=570 (df=87) GFI=0.84 RMR=9.5 % D(η)=1.00 D(ξ)=0.89

R^2(η2)=38 %R^2(η3)=29 %R^2(η4)=86 %R^2(η5)=59 %

LISREL model for aspahlt concrete roads with one second order factor, road condition.

5. CONCLUSIONS

The existence of five condition factors, 'rutting', 'longitudinal roughness', 'distress', 'pavement bearing capacity' and 'subgrade bearing capacity', seems obvious. These factors were also made operational with correspondent indices. In addition, the mutual correlations between different factors were satisfactory.

Rutting seemed to have small correlations with other road condition variables (table 2) and this caused the elimination of the rutting factor in the LISREL model. The poor correlations need to be investigated further. All maintenance work must be recorded in the FinnRA Road Data Bank and the inclusion of traffic volume in rutting should be considered. One possibility would be divide rut depth with traffic volume.

One of the aims was to form the overall structure of asphalt concrete roads using two second order factors, 'surface condition' and 'structure condition'. However, only one factor, 'road condition', was achieved. Athough the model used only one second order factor, the hyphothesis of two second order factors was not rejected.

The study confirms that a simple and comprehensive road condition description is possible. Management systems can benefit this compact and interpretable model.

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APPENDIX

This paper uses a second order confirmatory factor analysis model that can be formulated with the equations

$$y = \Lambda_y \eta + \varepsilon$$

$$\eta = \Gamma\xi + \zeta .$$

This is a special case of a general LISREL model that consists of three separate equations, two factor models (1) -(2), and a structural model (3) (Jöreskog and Sörbom, 1989)

$$x = \Lambda_x \xi + \delta \qquad (1)$$

$$y = \Lambda_y \eta + \varepsilon \qquad (2)$$

$$\eta = B\eta + \Gamma\xi + \zeta . \qquad (3)$$

Vectors η and ξ are called latent variables or factors, and matrices Λ_x and Λ_y include the weights to measure the importance of indicator variables **x** and **y** to latent variables. Vectors ε, δ and ζ are error terms. The structural equation (3) links two different measurement models and expresses their mutual dependency. Γ is a matrix for structural parameters between η and ξ. B -matrix includes structural parameters within η -factors. Matrices Λ_x, Λ_y, Γ, B imply parameters to be estimated, as well as covariance matrices Θ_ε=cov(ε), Θ_δ=cov(δ), Ω=cov(η), Φ=cov(ξ), and ψ=cov(ζ). The model has assumptions: $E(\varepsilon) = E(\delta) = E(\zeta) = E(\xi) = E(\eta) = 0$. The error terms ε, δ and ζ are uncorrelated with each other, and δ and ζ are uncorrelated with ξ and η.

The construction of a LISREL model includes the following phases: model specification, model indentification, estimation, and hypothesis testing and tests for model sufficiency.

The model specification means the search for the right model formulation that best describes the phenomenon. Analysis in this report is based on the confirmatory factor analysis where model specification is made before the actual estimation with the help of earlier information. It differs totally from the classical (explorative) factor analysis where parameter estimates are mathematically rotated in order to achieve interpretable results.

Checking the identification guarantees that each parameter can be estimated uniquely. Identification may require the researcher to fix some parameters a priori. A usual method is to fix one of the λ_{ij}'s in every factor to one.

Estimation minimizes the function $F=(s-\sigma)'W^{-1}(s-\sigma)$ with respect to free parameters of the model. Vector s includes all elements in the sample correlation matrix S and σ includes all elements in the theoretical correlation matrix Σ calculated from the model parametrization. W is a weight matrix that takes into account the estimation method and distribution properties of variables. Variables in the sample correlation matrix S are assumed to be continuous and to follow the multivariate normal distribution. Correlation estimates for rank order variables have been developed (Olsson, 1979). Correlations are described as polychoric (between two rank order variables), or polyserial (between a continuous and a rank order variable). The maximum likelihood method is the most commonly used estimation method. It is based on an assumption of a multivariate normal distribution. ML produces efficient parameter estimates if the model is correctly specified. Estimates are consistent if observed variables are not kurtose. In the case of polychoric or polyserial correlations a WLS (weighted least square) -estimation should be used instead of ML-estimation (computer program LISREL. Jõreskog and Sõrbom, 1988).

LISREL analysis measures whether the model is sufficient for the data. The χ^2-test implies the fit of the model. However, it is sensitive to sample size but can successfully be used to compare a pair of hierarchial models. A goodness-of-fit (GFI)-index, a root mean square residual (RMR)-test and reliabilities (D) are also used. Reliabilities of variables (R^2), modification indices (MI) and normalized residuals are used for testing variables and observations.

Five indices - rutting, longitudinal roughness, distress, pavement bearing capacity and subgrade bearing capacity - are calculated with a linear regression technique using factor scores that are

$S_{ki}=\Sigma_{j=1}(s_{kj}X_{ji})$ $k=1,...,5$

where

S_{ki}=factor score for factor k and observation i

s_{kj}=scoring coefficient for factor k and variable $j=1,..,17$

X_{ji}=value of variable j for observation i.