DEVELOPMENT OF AN INFRASTRUCTURE COEFFICIENT BY AN ANALYTIC HIERARCHY PROCESS AND ITS RELATIONSHIP TO SAFETY

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The study has four main objectives: (1) to test the correlation between different infrastructure characteristics and crash-rates, and trends; (2) to develop an Infrastructure Coefficient (IC) that represents the overall infrastructure characteristics of two-lane rural highways; (3) to develop a crash-prediction model for two-lane rural highways in which the IC developed is the independent variable; and (4) to estimate and quantify the contribution of the infrastructure as a whole to highway crashes.

Infrastructure is defined in this study as the highway and its geometric features: alignment, road-side elements, sight-distances, presence of guardrails, access-points, roadway consistency, and additional variables that all together measure the overall infrastructure quality of a highway. The first phase in the development of the IC involves an examination of the correlation between different infrastructure characteristics and crash-rates. In the second phase, the Analytic Hierarchy Process (AHP) is utilized to develop the IC. Finally, a crash-rate prediction model that relates crash-rates to IC for two-lane rural highways is developed.

The IC that was developed consists of a linear combination of five infrastructure characteristics: road consistency, lane width, road-side score, percentage of highway with a no-passing zone, and number of access points per unit length. These five characteristics were found to have the most significant contribution to safety among all the characteristics included in this study. A model for the prediction of crash rates based on the proposed IC is calibrated and presented.

It is suggested that this model be used to evaluate the safety level of existing or planned highways. This study also found that, at a 99% confidence level, a highway with good infrastructure quality reduces crash-rates by 44% on average compared with a highway with poor infrastructure quality.

Key Words: Crash-prediction, Infrastructure characteristics, Analytic Hierarchy Process (AHP), Crash-rate, Two-lane rural highway

1. INTRODUCTION

Crashes usually result from a combination of four contributing elements – the driver, the road, the vehicle, and the environment. Drivers are often involved in crashes because of their own errors, but also because they are affected by a combination of highway and/or vehicle elements. It is certainly not only the driver who bears responsibility for the occurrence of crashes. Henderson[1] concluded that focusing too much on the driver as the cause of a crash often masks the ability to see other causes whose amelioratization could reduce crash rates, as well as crash severity. The approach that attributes crashes solely to drivers is promulgated by many transportation professionals, particularly in law-enforcement agencies, who continue to consider human factors as major contributors to road crashes. One possible reason for this line of thinking is that the relative contribution of highway infrastructure as a whole to the occurrence of crashes, unlike the contribution of other elements, has not yet been fully quantified.

This paper has four objectives: (1) to test the correlation between the different infrastructure characteristics and crash-rates, and their trends; (2) to develop a numerical coefficient to rate highway infrastructures; (3) to develop a crash-rate prediction model for two-lane rural highways; and (4) to estimate and quantify the contribution of the infrastructure as a whole to highway crashes. The investigation approach chosen is the Analytic Hierarchy Process (AHP), a decision-making method developed by Saaty[2] that reduces complex decisions to a series of pair-wise comparisons and synthesizes the results.

AHP was chosen for this study in order to develop an Infrastructure Coefficient (IC) by attributing a specific weight to each infrastructure characteristic to reflect its relative importance to road safety compared with the other characteristics considered in the study. Multiplying each of the weights by its appropriate infrastructure value and summing up all the results yields the IC value for the specific roadway segment.

The uniqueness of the proposed approach and of the IC developed is that they incorporate most features–although not all of them–of a highway's infrastructure. This study defines Infrastructure as the highway and its geometric features, which include alignment, road-side elements, sight-distances, presence of guardrails, access points, design consistency, and additional variables that, all together, measure the overall quality of the highway alignment and its elements.

Developing an IC has likely significant benefits in assessing whether specific highways are potentially dangerous because of their infrastructure characteristics alone. Transportation agencies could also use the proposed coefficient when evaluating several design alternatives in order to select an alternative that potentially will have lower crash-rates.

Rural highway infrastructure has different tangible components, such as lane and shoulder widths, sight-distance availability and no-passing zone lengths, road-side characteristics and their proximity to obstacles, and a number of access points/kilometer. Another important feature of rural highways is the consistency of the alignment design, both vertical and horizontal. A key objective of this study is to include the various infrastructure components (as defined in this study) in an aggregated coefficient and, based on this coefficient, to predict future crash-rates on two-lane rural highways.

2. LITERATURE REVIEW

This section contains two parts. The first part will concentrate on studies that have dealt with individual roadway elements and their relationship to safety. The second part will concentrate on crash-prediction models. The first part presents a review of a large group of studies on the impact of specific highway elements on safety.

Zegeer and Council[3] conducted a study of the impact of cross-sectional roadway elements on safety. Such elements included lane width, shoulder width, roadside features, and others. They found that improving roadsides can contribute to a 44% reduction in crashes while shoulder widening can reduce crashes by up to 49%. Elvik[4] found that guardrails reduce both crash rates and crash severity. Fink and Krammes[5] proposed that the degree of curvature was a good predictor of crash rate on horizontal curves. Ogden[6] studied the effect of paved shoulders on crashes on two-lane rural highways in Australia and found that shoulder-paving was associated with a statistically significant reduction in accident frequency with casualties. An extensive literature review conducted by Hauer[7] on shoulder width and shoulder type concluded that roads with paved shoulders were associated with fewer accidents than were similar roads with soil (unsealed) shoulders and that wider shoulders were associated with fewer run-off-the-road and opposite-direction accidents, which accounted for some 40%-60% of all accidents. However, wider shoulders may also be associated with more of the "other" accidents. Papayannoulis et al.[8] who conducted a study on access spacing, observed that doubling the access density from 10 to 20 access points/mile increased accident rates by 40%. They found that the greater the frequency of access points (driveways and intersections), the greater was the number of crashes. Polus and Mattar-Habib[9] developed a model to estimate road consistency and showed that crash rate decreased as design consistency on two-lane rural highways improved.

The literature provides a long list of studies on the impact of individual infrastructure elements on crashes. Elvik and Vaa's[10] handbook of road safety measures contains an extensive review of studies worldwide on the various types of infrastructure features and their relationship to crash rates.

Much literature addresses the problem of accident-rate estimation and the identification of the various factors affecting this rate. Most of the previous work done on developing crash-prediction models concentrated on different regression methods, such as linear, Poisson, and negative binomial regressions. Joshua and Garber[11] used multiple linear and Poisson regressions to estimate truck accident rates, using traffic and geometric characteristics as independent variables. Miaou et al.[12] proposed a Poisson regression model to establish empirical relationships between truck crash-rates and highway geometric and traffic data for 8,779 miles of rural interstate highways in the U.S. Hadi et al.[13] using data from the Florida Department of Transportation's Roadway Characteristics Inventory (RCI) system, estimated a negative binomial (NB) regression for accident rates on various types of rural and urban highways with different traffic levels. Vogt and Bared[14] employed both a Poisson and a negative binomial regression to develop a crash-prediction model for both two-lane road segments and three-legged and four-legged intersections. Later, Daniel et al.[15] developed Poisson and negative binomial accident-prediction models for truck crashes on Route 1 in New Jersey; using a database developed in New Jersey for 1998 and 1999, they included signalized intersections. Karlaftis and Golias[16] on the other hand, examined the relationship among rural (two-lane and multi-lane) road geometric characteristics, accident rates, and their prediction, using a rigorous non-parametric statistical method known as a hierarchical tree-based regression (HTBR).

Mayora and Rubio[17] developed a negative binomial multivariate crash-prediction model for the Spanish national network's two-lane rural roads. The data set contained 3,450 kms of rural roads having several road and traffic characteristics. The R-square of the model was found to be 0.87. Zhang and Ivan[18] employed negative binomial generalized linear models (GLIM) to evaluate the effects of a roadway's geometric features on the incidence of head-on crashes on two-lane rural roads in Connecticut. They defined three models, which they estimated on the basis of all valid combinations of the significant variables. The researchers used Akaike's Information Criterion (AIC) to select the best of the three models, which was the one that included the sum of absolute change rates of horizontal curvature. Polus et al.[19] developed a crash-prediction model that related crash-rates to an IC by using smallest space analysis. This IC was a linear weighted combination of several infrastructure characteristics.

From the first part of the literature review, it can be concluded that most previous studies dealt with one infrastructure characteristic and its impact on safety. None of these studies dealt with the impact of the entire infrastructure as a whole on crash rates. The second part of the literature review leads to the conclusion that none of the previous models, except for Polus et al.[19], developed an IC that summarized and incorporated various infrastructure characteristics and then used it as an independent variable in the models. All previous crash-prediction models offered several infrastructure characteristics as independent variables.

Therefore, the significance of the present study is twofold: (1) its quantitative estimation of the contribution of the infrastructure as a whole to crash rates; (2) its inclusion of various infrastructure characteristics in a representative aggregated IC, which is then used as an independent variable in the crash-prediction model.

3. DATA COLLECTION

The data collection consisted of three parts:

a. Selection of highway segments: This study focused on two-lane rural highways in northern Israel. Most rural roads in Israel are undivided two-lane highways. Twenty-five different segments were randomly selected; most were several kilometers long, the average length being 7.4 km. All segments selected connect two major intersections although typically there were several minor intersections in between them. It was not possible to break each road segment into smaller segments because many small segments did not have any crashes. An increase in the crash-history data-base by collecting accident data from previous years was considered, but deemed not a desirable approach because of the very real likelihood of geometric changes and/or changes in flow (such as speeds, volumes) and vehicle characteristics (such as new ABS equipment, second generation airbags, etc.).

b. Collecting infrastructure characteristics: For each highway, 12 infrastructure parameters were measured (detailed in Table 1); these included, among others, topography, lane and shoulder widths, degree of road-side hazards (depending on the proximity of adjacent trees, rigid obstacles like rocks, steep ditches), shoulder drop-off at the end of the shoulder (i.e., difference in height elevation between the paved shoulder and the unpaved road-side), number of access points per unit length, number of access points with acceleration and deceleration lanes, length of no-passing zones (considered a surrogate variable for sight-distance), length of road segment where a guardrail was required according to existing guidelines vs. length of the highway where a guardrail was actually provided, and road consistency (which will be discussed later in this section). The horizontal and vertical alignment parameters were obtained from "as-built" plans, and those parameters were used to calculate the consistency measure. All other infrastructure characteristics were obtained directly from field measurements.

c. Crash data for the same highway segments: This data was obtained from files of the Israel Central Bureau of Statistics for five consecutive years, 1997 through 2001. Highway segments that had significant infrastructure changes (e.g., widening and paving of shoulders, construction of long guardrails, or intersection control and channelization changes) during the five years for which the crash data were collected were eliminated from the data set.

The data included crash numbers and traffic volumes, from which rates could be determined. All crashes

Table 1 Main infrastructure characteristics of 25 highway segments

Road No.	Length (km.)	Lane Width (m.)	Shoulder Width (m.)	Mean Access Points per Km. (Points/km.)	Percentage of Intersection with Speed Change Lane (%)	Percentage of Hwy with No-Passing Zone (%)	Percentage of Hwy with G-R (%) *	Percentage G-R Required vs. Existing G-R (%)	Shoulder Drop-off (cm.)	Topography **	Road-Side Score ***	Consistency ****
1	13.76	3.75	2.65	2.00	18%	9%	38%	55%	17.50	3	4	2.48
2	9.89	3.85	2.60	2.12	7%	27%	24%	0%	7.50	3	2	2.13
3	5.92	3.80	2.75	0.51	33%	15%	100%	0%	0.00	1+2	5	2.38
4	7.39	3.80	2.90	0.68	7%	23%	74%	0%	5.00	1	5	2.66
5	7.07	3.75	2.65	1.98	11%	28%	57%	M.D.	22.50	3	4	1.17
6	6.61	3.75	2.65	1.13	19%	20%	88%	M.D.	22.50	3	5	2.41
7	6.32	3.75	2.40	2.53	6%	8%	38%	0%	0.00	3	6	2.10
8	5.12	3.60	2.50	1.07	47%	23%	33%	0%	0.00	3	7	0.99
9	10.72	3.70	2.60	0.42	10%	7%	44%	0%	2.00	3	6	2.57
10	7.43	3.65	2.50	0.87	23%	35%	63%	0%	2.00	2+3	6	2.60
11	10.20	3.70	2.75	0.88	17%	33%	58%	0%	4.00	2+3	6	0.98
12	7.30	3.85	2.75	0.55	17%	16%	81%	4%	0.00	1	5	2.68
13	8.85	3.35	1.20	3.62	3%	15%	27%	9%	17.50	2+3	2	0.01
14	12.77	3.45	1.00	1.10	25%	53%	40%	0%	0.00	1	3	0.00
15	6.96	3.80	2.35	1.51	6%	40%	34%	44%	11.00	1	4	0.57
16	6.72	3.40	0.70	1.93	7%	30%	17%	237%	2.50	3	1	0.75
17	5.27	3.20	1.20	0.76	0%	25%	29%	M.D	6.00	1	2	0.00
18	5.17	3.45	2.00	1.26	14%	15%	27%	94%	0.00	2	2	1.50
19	6.00	3.65	1.20	1.58	0%	33%	25%	17%	17.50	1	2	0.44
20	3.93	3.45	2.20	2.16	6%	42%	26%	46%	0.00	1	2	0.47
21	9.35	3.20	0.60	1.07	0%	53%	21%	12%	0.00	1	1	0.00
22	10.00	3.25	1.20	1.85	11%	9%	27%	M.D.	0.00	1+3	1	0.02
23	9.00	3.65	2.65	1.94	15%	53%	77%	0%	0.00	1	5	0.19
24	4.19	3.10	1.10	1.43	8%	73%	35%	127%	2.50	1	3	0.04
25	6.70	3.40	1.70	1.94	19%	19%	31%	66%	5.50	1	2	0.81

+ M.D. – Missing Data
* G-R – Guardrail
** Topography – Mountainous (1), Hilly (2), Level (3)
*** Road-Side Score – Note Table 3.
**** Consistency – Poor (RC≤1.0), Moderate (1<RC≤2), Good (RC>2.0)

Note: Scores of Infrastructure features are presented in Tables 2 and 3.

in the data set involved human casualties (i.e., damage-only crashes were not included). In other words, light, serious, and fatal crashes were included in this study. It was not possible to conduct the different statistical analyses for each severity level or for each type of accident separately, since the number of crashes over a period of five years would not be sufficient for attaining statistically significant results. An increase in the crash- history data through collecting accident data from previous years was considered, but deemed not a desirable approach because of the very real likelihood of geometric changes and/or of major significant flow (speeds, volumes) and vehicle characteristics (ABS, airbags). The data set, at the end, consisted of 1,035 crashes that occurred on the 25 highway segments for which data were collected for the five-year period.

For the purpose of this analysis and the statistical method used, it was preferred to convert the actual physical dimension of each element (e.g., lane width, percentage of intersections with speed-change lanes, etc.) to categorical variables. The physical dimensions were grouped into ranges, separated by thresholds, and the values were substituted with a score for each range. Low score values (such as 1) represented a poorly designed, seemingly dangerous infrastructure, and higher score values (up to 7 for the road-side characteristics) represented an apparently safe and well-designed infrastructure. These elements received a surrogate nominal numerical score that represented the attributes of the infrastructure and its relative risk to drivers. Scores for 10 of the 12 infrastructure elements are presented in Table 2, while Table 3 presents the road-side scores.

Some thresholds that were established in order to allocate the different infrastructure characteristics to representative ranges were based on engineering judgment. Others were set by dividing the whole domain into an equal number of ranges. For example, shoulder width was categorized into four ranges. The first range-category included all highway segments with a shoulder width of less than or equal to 0.9 m; this threshold was set, since in this case when a driver decides to stop on the shoulder, for example in emergency situations, part of the car will intrude into the through lane because this shoulder width is less than the average width of a car. The second category contains shoulder widths between 0.9 m and 1.8 m; in this case, most of the car's width will be away from the lane, but the shoulder width is still not enough to give a driver sufficient space to remain on the shoulder for a repair if needed. The third category (1.8 m – 2.4 m) gives enough space for both the car and the driver's movement around the car; however, it is not enough for trucks. Lastly, category four (2.4 m – 3.0 m) provides sufficient shoulder width for trucks. Shoulder drop-off, on the other hand, was categorized into two levels. The first category includes highway segments with shoulder drop-offs of less than 5 cm. In this case, run-off-the-road instances will not cause loss of control. When the shoulder drop-off is greater than 5 cm, running off the shoulders onto a road-side area will in most cases result in a serious crash. A similar approach was used to set the thresholds of road consistency, topography, and lane width. As noted, the thresholds of the remaining infrastructure characteristics were set by dividing the whole range into an equal number of spans.

The consistency-parameter value, which was calculated by a model (developed in a separate study by Polus and Mattar-Habib[9]) that provides the actual consistency values for a given highway design, showed that this value was moderately (R-square=0.55) related to crash-rates on two-lane rural highways (Fig. 1). The consistency was determined by the amount of variability in operating speed along a two-lane highway and was measured by two independent variables: (1) the area bounded by the longitudinal speed-profile and the average operating speed and (2) the standard deviation of speeds. Speed-prediction models for curves and tangent segments were used to estimate speeds, based on the geometry, during the calibration of the consistency model. As the variability in speed increased, the consistency of the highway segment decreased. Consistency was classified by three thresholds−poor, acceptable, and good−and its scores ranged accordingly from 1 to 3. For more details on the

Table 2 Scores for infrastructure, topography, and consistency features

Score	Shoulder Width (m.)	% of Highway with G-R* (%)	Number of Access Points/km.	Percentage of G-R* Required vs. Existing G-R* (%)	Shoulder Drop-off (cm.)
1	≤0.9	0% – 20%	3.00 – 3.65	>100%	>0.05
2	0.9 – 1.8	20% – 40%	2.35 – 3.00	50% – 100%	0.00 – 0.05
3	1.8 – 2.4	40% – 60%	1.70 – 2.35	0% – 50%	
4	2.4 – 3.0	60% – 80%	1.05 – 1.70		
5		80% – 100%	0.40 – 1.05		
Score	**Lane Width (m.)**	**Topography**	**% of Highway with No-Passing Zone**	**% of Access Points with Acceleration/Deceleration Lanes**	**Consistency**
1	3.00 – 3.30	Mountainous	60% ≥	0% – 9%	RC≤1 (Poor)
2	3.30 – 3.60	Hilly	45% – 60%	9% – 18%	1<RC≤2 (Moderate)
3	3.60 – 3.90	Level	30% – 45%	18% – 27%	RC>2 (Good)
4			15% – 30%	27% – 36%	
5			0% – 15%	36% – 45%	

* G-R – Guardrail

Table 3 Road-side criteria score

Score	Road-Side Features
1	• No guardrail along most of the segment length (L_{GR}<30%) • Shoulder width less than 0.9 m. • Shoulder drop-off greater than 0.05 m. • Rigid obstacles within 9.0 m. or less from the pavement edge • Slope of ditch steeper than 4:1; ditch more than 0.40 m. deep, no guardrail • No recovery area beyond shoulder
2	• Features as for Score 1, except that the shoulder width is more than 0.9 meter
3	• Guardrail length between 30% and 70% of the segment length • Shoulder width from 0.9-1.8 m. • Dangerous roadside features, such as rocks or cuts, cliffs, but with guardrail • Portion of road without guardrail has rigid obstacles within 9.0 m. of pavement edge or a shoulder drop-off of 0.05 m. or more or no recovery area beyond shoulder
4	• Features as for Score 3 except that the shoulder width is more than 2.4 meters
5	• Guardrail length greater than 70% of the segment length • Shoulders wider than 2.4 m. • Dangerous roadside features, such as rocks or cuts, cliffs, but with guardrail • No shoulder drop-off and recoverable road side
6	• Guardrail length is between 30% and 70% of the segment length • Shoulders wider than 2.4 m. • Moderate roadside compared to Score 5 • No shoulder drop-off and no rigid obstacles closer than 9.0 m. from pavement edge
7	• Shoulder wider than 2.4 m. • No shoulders drop-off • Rigid obstacles at a distance greater than 9.0 m. from pavement edge • Wide recovery area beyond shoulders • Side slope flatter than 4:1 • Length of guardrail 30% or less of segment length

development of the road consistency model, see Polus and Mattar-Habib[9].

The Road-Side Score (RSS) that was developed in the present work (Table 3) is based on the most pertinent features of the road side, such as shoulder width, slope at the edge of the shoulders, presence of rigid obstacles, and the existence of a drop-off at the edge of the shoulder. RSS ranged from 1 for very dangerous road sides (narrow shoulders, no recovery area beyond the shoulders, rigid obstacles near the pavement) to 7 for very safe road sides (shoulder wider than 2.4 m, no shoulder drop-off, side slopes flatter than 4:1, and a wide recovery area beyond the shoulders). The shoulder drop-off criterion refers to the drop between the far edge of the shoulder and the road-side area. This measure was adopted from very similar roadside-hazard ratings developed by Zegeer et al.[20] to characterize the accident potential for roadside designs found on two-lane highways. It was later incorporated into the crash-prediction model developed as a part of the Interactive Highway Safety Design Model[21].

4. PRELIMINARY ANALYSIS

Several regression analyses of the correlation between crash-rates and each infrastructure parameter were conducted prior to the main analysis. The purpose of the preliminary analyses was to investigate the trend of the relationships between individual parameters and crashes in order to identify whether they behaved according to expected engineering judgment and whether they were in agreement with previous findings.

Some of the most significant regression analyses are illustrated in Figures 1-3. These figures also present the mathematical relationships and R-square values. The regression results showed the following:

a. The trend of the impact of each individual parameter on crash-rates was as would be expected by engineering judgment and as was found in most previous studies. In regard to the impact of shoulder width on crash-rates, the literature review revealed different results. Some authors found that as shoulder width increases, crash-rates decrease[22,23]; others found that crash-rates increase as shoulder width increases beyond a certain width[24]. In this study, crash-rates on rural roads were found to decrease monotonically as shoulder widths in the range of 0.45 m-3.00 m increased.
b. The infrastructure characteristics with the highest R-squares and those with the most significant relationship to crash-rates were road consistency, lane width, shoulder width, road-side score, percentage of highways with guardrails, no-passing zone percentage, and access points.
c. As can be noticed in Figures 1-3, the correlations are relatively low, because there is a relatively high dispersion of the data. This was expected, since crashes happen as a result of numerous and different factors, with each factor contributing differently to the occurrence of a crash. Moreover, these factors and their relative contribution typically change from one crash to another.

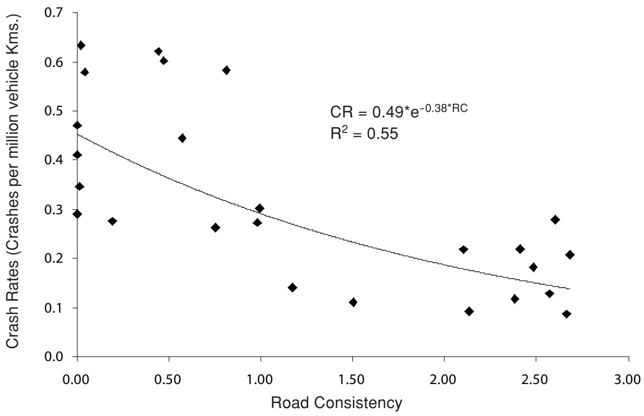

Fig. 1 Crash-rates vs. road consistency

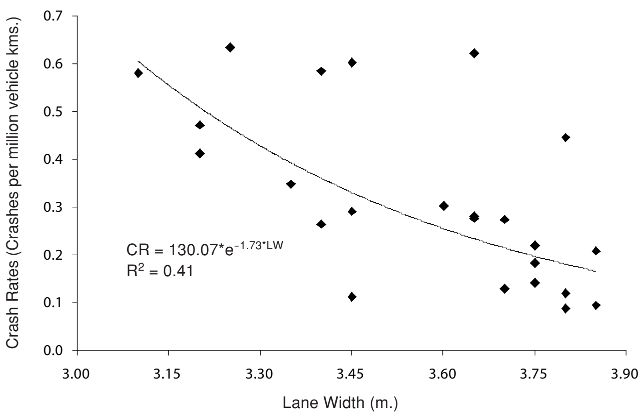

Fig. 2 Crash-rates vs. lane width

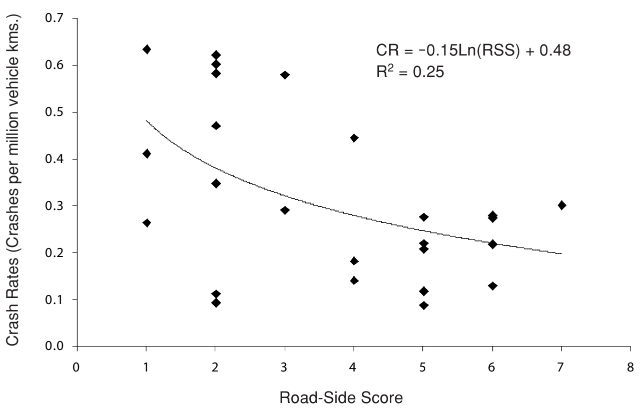

Fig. 3 Crash-rates vs. road-side score

Since the variables for the road-side score (RSS) developed in this study (see Table 3) were already accounted for in the road-side score variable, there was no need to consider them again as independent variables. The main analyses were conducted with five infrastructure characteristics: road consistency, lane width, percentage of highway with a no-passing zone, number of access points/km., and road-side score. These were chosen from the total of 12 variables for four main reasons: (1) they show the most significant relationship to crash-rates, (2) together they provide a description of both the horizontal and vertical alignment of the roadway, (3) some of these characteristics are included indirectly through the RSS measure, and (4) the remaining infrastructure characteristics showed weak relationships to crash-rates.

Another examination that was conducted during the preliminary analysis evaluated the relationship between the number of crashes and the average daily traffic volumes on the roads studied. This relationship was expected to be non-linear as some researchers have suggested[25,26]. However, this study assumed that the relationship between crash numbers and traffic volume was linear, for two reasons: (1) after testing, no significant difference was found between the linear and parabolic relationships; (2) the Average Daily Traffic (ADT) on most segments was below 10,000. Other studies have shown that a non-linear relationship starts at higher traffic volumes. Therefore, the volumes in this study were assumed to be on the linear portion of the otherwise generally non-linear relationship.

As a result of this linearity, further analyses were conducted with crash-rate data without the need for any additional adjustments to the impact of traffic volume. In a linear relationship, each traffic volume has a single crash-rate value that is proportional to the traffic volume itself (but this is not true in a parabolic relationship). Figure 4 presents the linear and parabolic relationships between crash numbers and traffic volumes.

5. DEVELOPMENT OF AN INFRASTRUCTURE COEFFICIENT (IC) BY THE ANALYTIC HIERARCHY PROCESS (AHP)

The main purpose of using the AHP was to rank the road infrastructure characteristics according to their contribution to safety. This was done by attributing a specific weight to each characteristic. These weights were then computed and determined by the AHP method. The IC for a specific road segment can be computed by multiply-

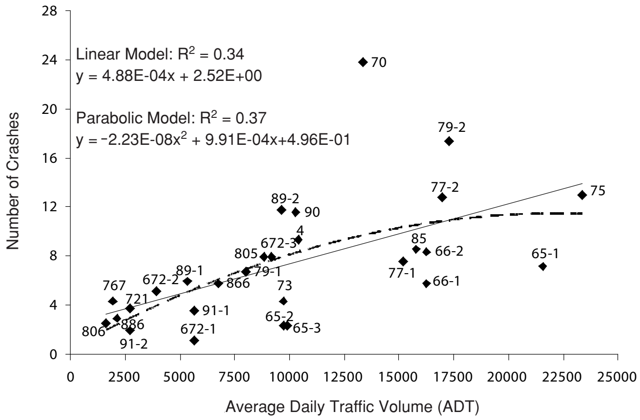

Fig. 4 Relationship between number of crashes and ADT volumes on all 25 highway segments (the number next to each data point is the road number)

ing the weight of each infrastructure characteristic by its appropriate infrastructure-characteristic value for the specific road segment and adding up the products. The importance of the IC coefficient lies in its enabling roadway engineers and practitioners to rank the different roadway segments according to their IC, which represents the overall infrastructure characteristics of a segment and is not based on a single infrastructure measure. Roadway segments with high IC values represent a relatively good quality of roadway design (with low crash-rates), and segments with low IC values represent a relatively poor quality design (with high crash-rates).

5.1 AHP - background

The AHP, first developed by Thomas Saaty[2], is a mathematical decision-making technique that incorporates both qualitative and quantitative factors. The AHP has increased in use and popularity because the process reflects the way people think and make decisions, which is by simplifying complex decisions to a series of one-on-one comparisons and synthesizing the results. Moreover, the AHP method has many applications in the transportation field in general. For example: the evaluation of different transportation projects that include the decision making process. Saaty[27] introduced five examples of applications of the AHP in order to illustrate the different uses of this approach in multicriteria decision methods in transportation analyses. These examples included a commuter route selection hierarchy, a best mix of routes to Pittsburgh's new International Airport, a benefits/costs hierarchy to choose the best mode to cross a river, a planning hierarchy for a transport system and a simple dependence with feedback cycle to choose a car when criteria depend on the alternatives. Hu and Shi[28] used the AHP method for ITS projects evaluation. Trevor[29] used the AHP method as a tool for infrastructure management. Sangjin[30] used the AHP method for prioritization of international highway network development. Other examples and studies can be found in the literature.

The purpose of the present study was to rate the five infrastructure characteristics (defined above) according to their relative importance and contribution to safety. Rating the relative contribution to safety of all five infrastructure characteristics simultaneously is a complex task. However, because the AHP method is a technique that simplifies decision-making, it was deemed a very appropriate and highly efficient method for use in the present case. Also it was selected during this study to analyze the infrastructure impact on safety because it is actually the only method that does not assume linearity as other multivariate analyses do and it fits most goals of the study, particularly the objective of developing a single measure (IC) for roads' infrastructure. Further justifications and limitations of using the AHP method are discussed in section 5.3 below.

The AHP method includes four basic axioms:

Reciprocal Axiom: When any two objectives, O_i, O_j (i, j indices), are given to a decision-maker, that person is able to compare them under any criterion C_i, so that: $a_{ij}=1/a_{ji}$ (where a_{ij} is the relative importance of O_i compared with O_j under criterion C_i, and a_{ji} is the inverse of a_{ij}).

Homogeneity Axiom: The elements being compared should not differ by more than an order of magnitude in any cluster.

Synthesis Axiom: Judgments about or the priorities of the elements in a hierarchy do not depend on lower-level elements; this axiom will not be needed in the case under discussion.

Expectation Axiom: Individuals who have reasons for their beliefs make sure that their ideas are adequately represented for the outcome to match their expectations.

The first major task in the AHP method involves the estimation of a normalized set of weights of the different objectives. These weights assist the decision-maker in comparing various alternatives. (In our analysis, the objectives are the different infrastructure characteristics, and the alternatives are the various road segments.) The weights are mapped from a matrix of pairwise comparisons, $A=(a_{ij})$, which are positive and reciprocal. Thus, given matrix "A", (1):

$$A = \begin{pmatrix} 1 & a_{12} & .. & .. & a_{1n} \\ 1/a_{12} & 1 & .. & .. & a_{2n} \\ . & & & & . \\ . & & & & . \\ 1/a_{1n} & 1/a_{2n} & .. & .. & 1 \end{pmatrix} \quad \text{........................(1)}$$

Where:
A = pairwise comparison matrix, in which the number in the i_{th} row and j_{th} column gives the relative importance of O_i compared with O_j;
n = number of objectives;
$a_{ij} = 1/a_{ji}$ for all i, j=1, 2, . . ., n.

The problem that remains is to map a set of weights, $W_1, \ldots, W_n$, from matrix "A" for the objectives $O_1, O_2, \ldots, O_n$ (infrastructure characteristics) through an understanding of how the pairwise comparisons a_{ij} convert to weights W_n.

In an ideal situation, the pairwise judgment is made by computing the following ratio: $a_{ij} = W_i/W_j$ (i, j=1, 2, . . ., n), where W_i is the weight of objective i and W_j is the weight of objective j. This means that the judgment matrix (matrix "A" - pairwise comparison matrix) is actually the ratio of the relative weight attributed to objective O_i to the relative weight attributed to objective O_j, Therefore, matrix "A" can be rewritten as a set of weight ratios:

$$A' = \begin{pmatrix} \frac{w1}{w1} & \frac{w1}{w2} & .. & .. & \frac{w1}{wn} \\ \frac{w2}{w1} & \frac{w2}{w2} & .. & .. & \frac{w2}{wn} \\ . & & & & . \\ . & & & & . \\ \frac{wn}{w1} & \frac{wn}{w2} & .. & .. & \frac{wn}{wn} \end{pmatrix} \quad \text{..............................(2)}$$

The weights are the eigenvector corresponding to the largest eigenvalue of matrix "A", denoted by λ_{max}. In the ideal case, the value of the largest eigenvalue is n, whereas non-consistency of matrix "A" yields higher values. Therefore, Saaty[2] suggested that the consistency of matrix "A" be measured by the consistency index C. I. = $(\lambda_{max}-n)/(n - 1)$.

The closer this index is to 0, the more consistent are the pairwise comparisons.

5.2 Application of the AHP for weighting infrastructure characteristics

The matrix cells for the pairwise comparisons describe the relative safety importance of each two infrastructure characteristics. This means that a comparison for its importance to safety of each infrastructure characteristic with all other infrastructure characteristics accounted for in the study will be included in the matrix (5×5). Table 4 describes the infrastructure characteristics that were chosen for the construction of the IC in descending order of their importance to safety.

It was difficult to identify a sufficiently large pool of experts in highway safety design in order to achieve a reliable grading of the relative contribution to safety of each infrastructure characteristic. Therefore, the approach adopted in this study was to determine importance based on the R-square and t-test results of the regression relationships found in the preliminary analysis of the relationship of each infrastructure characteristic to the crash-rate. For example, because road consistency explains about 55% of the crash-rate variance, which was the highest among the infrastructure characteristics selected and the most significant according to the t-stat result (−5.34), it was considered to be the most important road characteristic for safety and given a grade of 5 (Table 4). In contrast, access points are the least important to safety, since this characteristic had the lowest R-square in the same analysis and the lowest t-stat result (1.69); it therefore received a grade of 1 (Table 4).

In order to construct the matrix of pairwise comparisons of the infrastructure characteristics, Saaty's scale (Table 5) was used to help in determining the pairwise judgments[2].

For example, according to Saaty's scale[2], if objective "i" is more important than objective "j" under a chosen criterion, then aij equals 4 in the pairwise com-

Table 4 Grading, according to R-square, of the infrastructure characteristics chosen

Infrastructure Characteristic	R- Square	t-stat	Grade
Road Consistency	0.55	−5.34	5
Mean Lane Width	0.41	−3.98	4
Road-Side Score	0.25	−2.75	3
% of Highway with No-Passing Zone	0.14	1.94	2
Access Points/km.	0.04	1.69	1

parison matrix. In our analysis, the objectives are the different infrastructure characteristics, and the criterion according to which the objectives are compared is road safety. For example, when comparing road consistency and access points/km., there is a difference of 4 grades between these two characteristics (which is the maximum difference between any two infrastructure characteristic grades – Table 4) because road consistency (Grade=5) is more important to safety than are access points/km. (Grade=1). When judged according to Saaty's scale[2] (Table 5), road consistency is much more important to safety than are access points/km.; therefore, $a_{ij}=8$ (see Table 6).

Based on Table 5 and Table 6, the matrix of pairwise comparisons of infrastructure characteristics – Matrix "A" – was constructed and is presented in Table 6.

In Matrix "A," the number in the ith row and jth column gives the relative importance of the infrastructure feature in the ith row compared with the infrastructure feature in the jth column. The problem that remains is to map a set of weights, $W_1, \ldots, Wn$, from Matrix "A" for the objectives $O_1, O_2, \ldots, O_n$ (infrastructure characteristics) through an understanding of how the pairwise comparisons aij convert to weights Wn.

In this case, the largest eigenvalue of Matrix "A," shown in Table 6, is 5.0966, resulting in a consistency index of 0.024, which is considered to be sufficiently close to 0. The corresponding eigenvector of the weights (normalized so that they add up to 1) is presented in Table 7. Now, the IC can be computed for each roadway segment and the 25 roadway segments ranked by multiplying each of the weights from Table 7 by the appropriate infrastructure-characteristic value for each roadway segment and summing up the results. This is done using Equation 3:

$$IC=0.26\cdot LW-0.09\cdot NPZ+0.45\cdot RC+0.15\cdot RSS+0.05\cdot AP \quad \ldots(3)$$

Where:
LW - lane width (m.);
NPZ - percentage of highway with a no-passing zone (%);
RC - road consistency;
RSS - road-side score (note Table 3);
AP - number of access points/km. (points/km.);

The coefficients of Equation 3 are, of course, the calculated weights, taken from Table 7.

It is important to remember that for the purpose of this analysis and the statistical method used, it was preferable to convert the actual physical dimension of each element (lane width, percentage of intersections with speed-change lanes, etc.) to categorical variables. Furthermore, since the coefficients of Equation 3 are actually normalized weights, it was necessary to present the infrastructure characteristics in terms of the nominal variables of an equal number of categories (in our case, five categories) in each scale. Low scores on these scales indicate poor infrastructure quality (e.g., narrow lane width, bad consistency, etc.), and high scores a good infrastructure quality. If IC is calibrated versus crash-

Table 5 Saaty's (1980) pairwise judgment scale[2]

Pairwise Comparison	a_{ij}
Objective i is much more important than Objective j	8
Objective i is more important than Objective j	4
Objective i is slightly more important than Objective j	2
Objective i is of equal importance as Objective j	1
Objective i is slightly more unimportant than Objective j	0.5
Objective i is more unimportant than Objective j	0.25
Objective i is much more unimportant than Objective j	0.125

Table 6 Judgment values according to relative importance to safety

	RC	LW	RSS	%NPZ	AP
RC	1	2	4	4	8
LW	0.5	1	2	4	4
RSS	0.25	0.5	1	2	4
%NPZ	0.25	0.25	0.5	1	2
AP	0.125	0.25	0.25	0.5	1

RC = Road consistency
LW = Lane width (m.)
RSS = Road-Side Score (note Table 3)
%NPZ = Percentage of highway with a no-passing zone (%)
AP = Number of access points/km. (points/km.)

Table 7 Weighting infrastructure characteristics according to AHP method

Infrastructure Characteristics	Weight
RC	0.45
LW	0.26
RSS	0.15
%NPZ	0.09
AP	0.05
Σ	1.0

RC = Road consistency
LW = Lane width (m.)
RSS = Road-Side Score (note Table 3)
%NPZ = Percentage of highway with a no-passing zone (%)
AP = Number of access points/km. (points/km.)

rates, therefore, it may be possible to estimate the safety level of a new or existing roadway based on its infrastructure components. This is of tremendous importance when assessing various alternatives and conducting an economic evaluation, when it is necessary to allocate funds to the most cost and safety-efficient projects. Alignment characteristics, then, could be converted to safety levels by using the IC coefficient.

5.3 Advantages and possible limitations of using the AHP method

The AHP method was found to be a very appropriate and highly efficient method for determining the relative contribution to safety of each infrastructure element. This results from the following advantages of this method: (a) It enables obtaining the relative weights of various elements–the infrastructure, in this study–by "one-on-one" comparisons conducted by a pool of experts. In this study, it was difficult to find a sufficiently large pool of highway design and safety experts, and therefore it was necessary to resort to a unique approach whereby weights were determined by the R-square and t-test results of the regression relationships found in the preliminary analysis (b) It is among the simplest of multi-attribute decision-making methods, which bypass the potential pitfalls of asking vague questions in long surveys; (c) It permits a certain degree of inconsistency and can be measured and quantified. AHP is the only method that can tolerate inconsistencies and, unlike neural networks, it allows the results to be interpreted.

On the other hand, this method has some possible limitations: (a) Each pair of attributes must be checked, which may be a tedious task because of the large attribute sets. In the present study, only a handful of attributes existed, and therefore this was not a limitation; (b) If the importance of attributes differs by more than an order of magnitude, AHP cannot be used. In this study, however, two-lane rural highways are, in general, not much different from one another, and therefore this limitation did not exist; (c) The addition of a new attribute can change the order of importance of the old attributes. However, this study had a fixed (5 elements), pre-determined number of attributes, and so this concern was not an issue.

6. CRASH PREDICTION BY THE INFRASTRUCTURE COEFFICIENT (IC)

The IC represents the overall infrastructure characteristic of the highway. Based on the data collected and the relative weights of each variable as determined by AHP, the relationship between crash-rate (CR, in crashes/million vehicle-km.) and the IC was calibrated and is given in Eq. (4):

$$CR = 1.004 \cdot \exp^{-0.401 \cdot (IC)} \qquad (4)$$
$$R^2 = 0.56$$

This relationship, which is presented in Figure 5, can be used to predict crash-rates on new or existing two-lane highways, based on their infrastructure elements. Note that one of the infrastructure elements is road consistency; this needs to be calculated separately according to the Polus and Mattar-Habib[9] model.

The linear correlation coefficients between each two infrastructure features were examined. Some infrastructure features were strongly correlated; for example, lane widths with road consistency (0.75), shoulder widths with road-side score (0.77) and shoulder widths with lane widths (0.85). Some of these correlations were expected because they conform to common engineering judgment and are due to reasonable design practice. For example, more use would be made of guardrails in an area with mountainous terrain, which also has less design consistency and more no-passing zones. Furthermore, often, although not always, roads with high-standard design elements have quality elements in all their geometric features, and these are correlated. These strong correlations, however, may prevent the use of the models presented (Eqs. 3 and 4) to identify the exact contribution of each individual element to expected crash-rates. This issue can be investigated in future research.

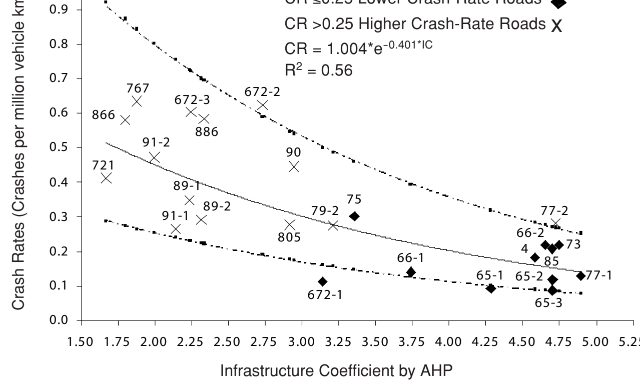

Fig. 5 Relationship between crash-rates and IC calculated by Eq. (4)

7. FURTHER TESTS

An additional purpose of this study was to examine the extent of the impact of poor infrastructure quality on crash-rates. The sample of 25 roadway segments included in developing the crash-rate prediction model was divided into two samples (good quality and poor quality), based only on each segment's IC as given in Eq. (3). The first sample consisted of those roadway segments that had an IC above 3, and the second sample those with an IC below 3. The threshold of IC=3 that separates presumably good from supposedly poor quality road designs was found to be the threshold that yields the highest ratio between crash rates on poor quality road segments and crash rates on good quality road segments. As shown in Figure 5, roadway segments with a higher IC have lower crash-rates. In order to ascertain whether the average crash-rate for each of the two samples of roadways in the study (lower crash-rate roadways and higher crash-rate roadways) was significantly different from each other, a t-test was conducted. The null hypothesis is that the two samples have the same average crash-rates, and the alternative hypothesis is that they have different crash-rate averages. Based on the t-test, it was found that, at a 99% confidence level, a highway with a good quality of infrastructure reduces crash-rates by 44% compared with a highway with poor quality infrastructure.

8. CONCLUSIONS AND FURTHER RESEARCH

The purpose of this research was to develop an IC that represents the overall characteristic of a highway and to develop a model that correlates this IC with crash-rates on two-lane rural highways. The research approach that was adopted is called the AHP. The IC developed enables highway planners and safety auditors to predict crash-rates based on the infrastructure features of a highway. This coefficient can be used when evaluating several alternatives for a new highway and even when rehabilitating existing highways so as to improve their overall safety features.

The literature repeatedly indicates the major contribution of the human factor to crashes. However, this study found that bad infrastructure contributes significantly to crashes. This study also shows that it is possible to distinguish between lower crash-rate roads and higher crash-rate roads by means of their overall infrastructure characteristics. Well-built and maintained highways can reduce crashes by 44%, compared with highways with bad infrastructure, and this finding is at a 99% confidence level. As a result of this very significant finding, more focus should be placed on upgrading the infrastructure characteristics of roadways; for example, investing in the elimination of road hazards by improving alignment consistency, upgrading such roadside features as paving shoulders, building guardrails where necessary, and fencing steep side-slopes.

Further research could concentrate on the following: (1) validation of the models developed by increasing the data set of rural two-lane highways; (2) the development of crash-prediction models based on ICs for other types of highway facilities (e.g., freeways, intersections); (3) use of the AHP approach to validate and test proposed crash-prediction models for two-lane rural highways in other countries; (4) further evaluation of potential correlations between ICs and their impact on crash prediction; and (5) developing crash-prediction models that account for vehicle and human features besides the infrastructure features.

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