Integration of Geographic Information System (GIS) and PAVER System Toward Efficient Pavement Maintenance Management System (PMMS)

Mohammed Taleb Obaidat [1), Khalid A. Ghuzlan [2) and Bara' W. Al-Mistarehi [3)*

[1) Professor of Civil Engineering, Jordan University of Science and Technology, P.O. Box 3030, Irbid 22110, Jordan. E-Mail: mobaidat@just.edu.just

[2) Associate Professor of Civil Engineering, Jordan University of Science and Technology, P.O. Box 3030, Irbid 22110 Jordan. E-Mail: kaghuzlan@just.edu.jo

[3) Assistant Professor of Civil Engineering, Jordan University of Science and Technology, P.O. Box 3030, Irbid 22110 Jordan. E-Mail: bwmistarehi@just.edu.jo

* (Corresponding Author).

ABSTRACT

The main objective of this research work was to investigate the potential of integration of Geographic Information System (GIS) and PAVER system for the purpose of flexible pavement distress classification and maintenance priorities. Classification process included distress type, distress severity level and options for repair. A system scheme that integrated the above-mentioned systems was developed. The system utilized the data collected by PAVER system in a GIS environment. GIS ArcGIS software was used for the purpose of data display, query, manipulation and analysis.

The developed system was of great help in identifying, collecting and displaying pavement condition data. Pavement distresses were assigned based on pavement condition index values computed by Pavement Condition Index (PCI). This technique was cost-effective and appropriate for wise decision making for different maintenance activities and programs.

Statistical models were developed to forecast pavement distress quantities using Average Daily Traffic (ADT), climate conditions, socio-economical characteristics and pavement age. ADT and pavement age variables were the most significant factors in distress quantification.

KEYWORDS: GIS, PMMS, PCI, Pavement distresses, Pavement conditions, Distress classification, Maintenance priorities.

INTRODUCTION

In the past, pavement was maintained, but not managed. Pavement engineer's experience tended to dictate the selection of maintenance and rehabilitation (M&R) techniques with little regard given to life-cycle costing or to priority as compared to other pavement requirements in the network (Shahin, 1998). Pavement distress information is needed to assess maintenance requirements. The distresses of asphalt concrete pavement are any defects or deteriorations in the pavement and can be grouped into the general categories: cracking, distortion, disintegration and skid hazard defects (Shahin, 1990). Many traditional systems were used to evaluate and classify pavement surface distresses (Osman and Hayashi, 1994). They used methods characterized by: manual operations, time

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consumption and not following up technology trends (Johnson and Demetsky, 1994). In this research work, it was anticipated to integrate the usage of GIS and PAVER systems in order to collect and analyze different distress data. Arterials, collectors and local roads of Irbid-Jordan City were taken for the prototype study.

The integration of GIS and PAVER systems was anticipated to open the door to fully automated technology applications for distress data collection and pavement surface road conditions, mapping, classification, prediction and analysis. This technology becomes widely popular due to its effectiveness in carrying out different research activities economically and safely (Jaselskis, 1994). Further, researchers will be capable of performing real-time operations, extracting highly accurate data, presenting spatially inventory data, introducing numerous analytical techniques and developing highly technological systems. Maintenance and operation engineers are also anticipated to use the findings and guidelines of this research work to automate most of their routine decision making activities (Al-Mestarehi, 2009).

The main objective of this paper was to present the feasibility to integrate GIS and PAVER systems in order to build digital distress maps linked to location, useful surface information and pavement condition databases. Maps showing the distribution of maintenance activities over roadway network sections based on pavement condition index values were also developed. Using the developed system, distress classification and rehabilitation actions for road networks were investigated.

Data-Base Development

To achieve the objectives of this study, an integrated database related to 35 arterials, 24 collectors and 31 local roads of Irbid-Jordan city was developed. The selection criterion was dependent on covering variables having different pavement and traffic conditions.

The collected data included the following elements:

1. Pavement condition data: this database for each road section included: distress type, distress severity, distress density, Present Serviceability Rating (PSR) and other related information, such as: section identification, section type, section location and section dimensions.
2. Other variables: this database included: a) roadway geometry inventory (arterial, collector or local name; arterial, collector or local length (m); arterial, collector or local width (m); arterial, collector or local type (divided or non-divided) and arterial, collector or local directions (one-or two-way); b) traffic data (average annual daily traffic volume); c) climate condition (rainful, snow, max. air temperature, min. air temperature, max. humidity, min. humidity) and d) socio-economic characteristics (density of population, ratio of number of vehicles to number of houses in every section zone).

The following software was used to measure pavement condition quantities and present the collected data (Al-Mestarehi, 2009):

1. Micro-PAVER Software: Micro-PAVER software was utilized for selecting maintenance and repair (M&R) needs and priorities and determining the optimal time of repair by predicting future pavement condition.
2. GIS Map Software: ArcGIS software brought geographic information to the desktop to visualize, explore, query and analyze data spatially. ArcGIS was made by Environmental Systems Research Institute (ESRI, 1997).

Pavement Condition Measurement

The methodology of automatic distress measurement could be summarized in the following steps:

1. Selecting roads in Irbid city that were divided into branches which are defined as any identifiable parts of the pavement network forming a single entity and having a distinct function. The selected branches are divided into smaller components called sections.

The following factors were considered when dividing branches into sections:

- *Pavement structure*: the structural composition (thickness and materials).
- *Traffic*: the volume and intensity of traffic.
- *Construction history*: the pavement sections should have the same construction history.
- *Pavement rank*: the functional classification (arterial, collector or local).
- *Drainage facilities*: drainage facilities and shoulders should be consistent throughout the pavement section.

2. Dividing pavement sections into sample units with an area of 232 ± (10) m^2.
3. Using hand odometer to measure distress length and area. A straight edge and ruler were used to measure the depth of rut or depression. Distress inspection was conducted by walking over the sample unit and measuring distress type and severity.

The resulting pavement condition database was used as a data source for PAVER system. PAVER software was used to calculate PCI using distress data (type, severity, quantity).

Calculation of PCI Using Pavement System

The following steps were followed to compute PCI and pavement condition rating:

1. Defining the pavement inventory (network, branches or sections).
2. Entering dates and sample information.

The inspection component of PAVER can be launched from the PAVER button bar *via* PCI using the following steps:

1. Clicking on (edit inspection) to enter inspection dates.
2. Clicking on (edit sample unit) to enter the survey information.
3. Entering information on distress (type, severity or quantity).
4. PCI computation.

GIS Layers

Desktop GIS combines the capabilities of display, thematic and street-based mapping systems along with the ability to analyze geographic locations and information linked to those locations. Moreover, information could be accessed from vector or raster maps; or maps could be accessed from information; i.e., it is a dynamic and on-line data acquisition system. Thematic mapping systems enable us to create graphic displays using information stored in a spreadsheet or database. Each map produced is based on layers (coverage).

Layers of pavement condition data, climate condition data, socio-economic characteristic data and road inventory data were presented and incorporated into ArcGIS software. Presented layers included:

1. Layers of pavement conditions at arterials, collectors and local roads; in these layers, detailed description of all elements related to pavement conditions at the studied arterials, collectors and local roads was presented. Polyline features were used to draw arterial, collector and local road sections. All types of distress associated with severity levels, pavement condition index and options for repair and maintenance were incorporated to obtain a comprehensive database. Figure 1 shows a view of the pavement conditions at city arterials, collectors and local roads according to PCI values.
2. Other layers: these layers included: layers of traffic volumes at arterials, collectors and local roads (polyline shapes, including average annual daily traffic volumes), socio-economical characteristic layer (polyline shapes) and climate condition layer (polyline shapes).

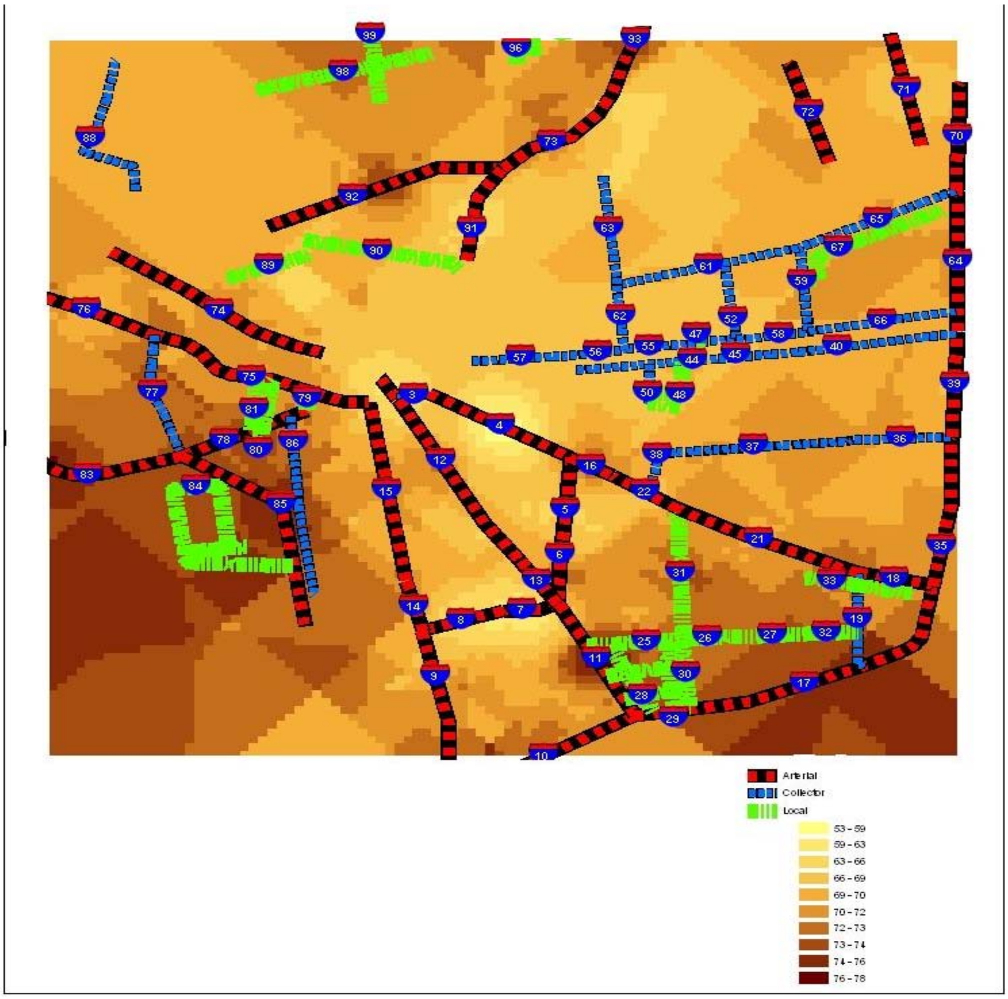


Figure (1): Irbid arterials, collectors and local roads associated with PCI values

Data Analysis and Interpretation

Analytical scheme was divided into five parts:

1. GIS Geostatistical Analyst for the pavement condition database, through Histogram Analyst, Quantity Qualitative (QQ) Plot Analyst and Geostatistical Wizard of model prediction Analyst.
2. Chart Analyst for arterial roadway inventory database, collector roadway inventory database and local roadway inventory database.
3. Querying options for pavement condition index assignment, budget wise decisions, among others.
4. GIS Spatial Analyst for the pavement condition database, traffic volume database, socio-economic characteristics through Clipping Analyst (extract by mask).
5. Developed scheme to integrate PAVER system and GIS.
6. Development of practical prediction models using number of variables based on the degree of their significance.

GIS Geostatistical Analyst

Geostatistical Analyst provides tools to create, query, analyze and map cell-based raster data and perform integrated vector-raster Analyst using feature-based and grid-based layers. The following Geostatistical Analyst options could be performed when utilizing the pavement condition database:

1. Geostatistical Analyst using histogram Analyst: this part of GIS Geostatistical Analyst gives us min., max., count, mean, standard deviation and indication of how the database is distributed. Pavement condition database was one of the best raw-data sources suitable to create histogram Analyst.
2. QQ- Plot Analyst: in this part of GIS Geostatistical Analyst, indication is given of how the database is distributed around the best fit line that refers to any range within which data is correct.
3. Geostatistical wizard of model prediction Analyst: this part of GIS Geostatistical Analyst can use four steps for PAVER output database to create a model that predicts values of PCI that GIS can use instead of using SPSS package Analyst.

Chart Analyst

Charts are among the strong Analyst tools available on the GIS, through which general or specific field trends can be displayed. The chart displays tabular data as business graphics. Every chart is associated with a 'View Table', which displays data from selected records and specified fields. Fields are specified in the chart properties dialog box or from the avenue. The chart may also display a label for each record, by reading the content of a specified field, the record label field.

The values that a chart displays are contained in a two-dimensional array with records in one dimension and fields in the other dimension. The values can be displayed on the chart in two ways. In the first way, groups are displayed by field and contrasts by record. This is the default when a new chart is created. In the second method, groups are displayed by record and contrasts by field.

King Hussein arterial suffers from highest amount of alligator cracking. This means that this section should be given first priority of maintenance concerning this type of distress. Classification of arterial sections based on the quantity of each distress type can be performed for each type of distress to compute the severity of distress among all sections. This helps in giving a quick decision about what sections should have highest priorities for maintenance. Figure 2 shows Irbid arterials based on alligator cracking quantities.

High-traffic volume arterials, such as Yarmouk University arterial, are exposed to an ADT of more than 58,000 vehicles per day, while low-traffic volume arterials, such as Ad-dustor arterial, are exposed to an ADT not exceeding 5000 vehicles per day. This variability in traffic levels covered in this study ensures the effect of such traffic variation on pavement condition status.

Queries and System Advantages

Since one of the most important goals of this paper was to assign maintenance priorities based on PCI and available budget, a scheme for maintenance priority assignment was developed. The scheme consisted of the following stages:

Stage 1: Performing a field survey to identify existing distresses, as well as their quantities and severity levels. This was performed for all distressed sections of Irbid arterials, collectors and local roads.

Stage 2: Collecting other related data, such as: geometrical elements of roads, traffic data, PSR, climate conditions,… etc.

Stage 3: Performing PCI computation using PAVER system.

Stage 4: Building GIS pavement condition layer with attributes related to distress information.

Stage 5: Selecting a threshold value for PCI to decide on sections to be maintained based on the available budget as discussed in the previous sub-section.

Stage 6: Carrying GIS query builder process using the selected threshold of PCI to find the sections contained within this query.

Stage 7: Carrying another GIS query builder process to select the ranked sections based on their PCI and available maintenance budget.

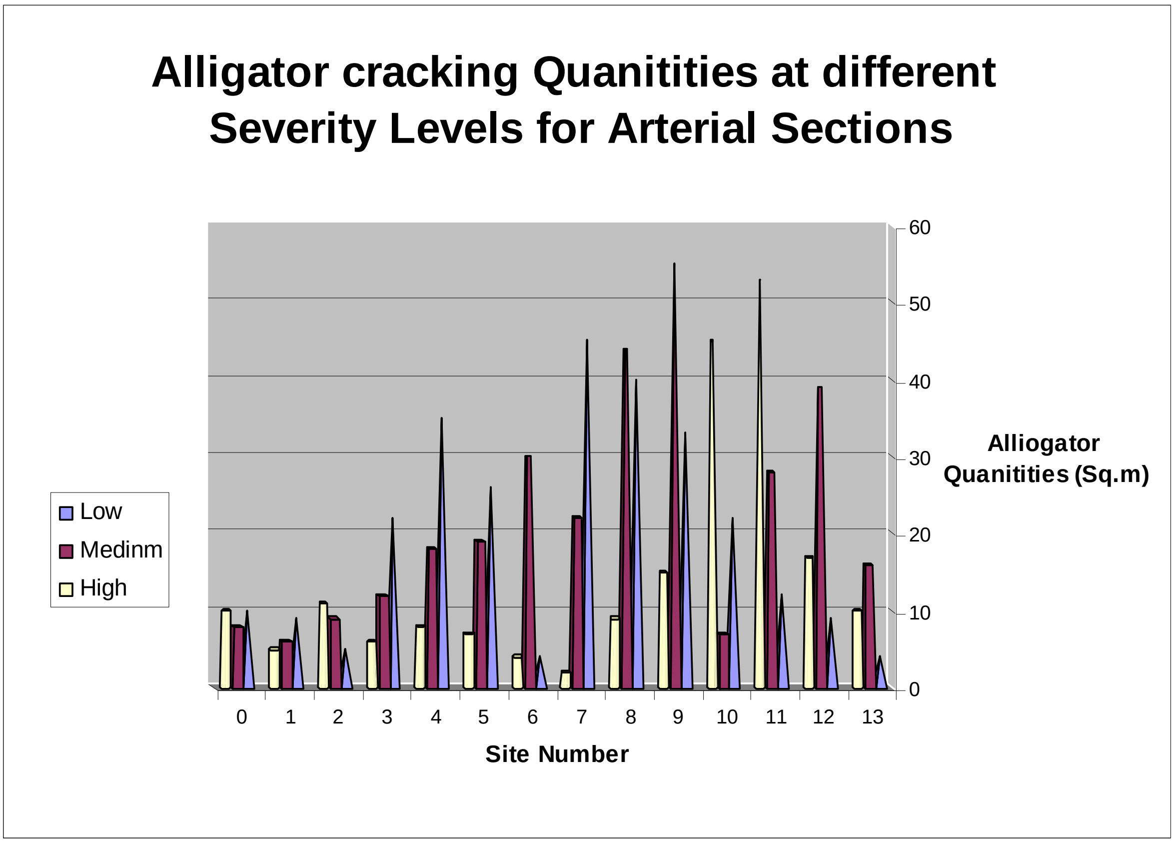


Figure (2): Arterial classification based on alligator cracking quantities

Pavement condition data was a fruitful material for different queries. Queries like those pertinent to the existence of various distresses and their respective severity levels on certain sections were helpful to study the factors which contributed to make such distresses appear at those specific locations. Another advantage of the developed system was its ability to perform combinations of logical operations on the collected pavement management data. Figure 3 shows an example of the complex queries that could be built by combining expressions together with the (*and*) and *(or*) operators. Results of this query indicated that only one section out of 35 arterial sections contributes to about 2.85% of the total sections of Irbid arterials containing both high severity alligator cracking and polished aggregate types of distress. The existence of these distresses on these sections was an indicator of high traffic volume and poor maintenance program adopted by Irbid municipality.

Traffic volume data was also beneficial for queries to obtain useful indicators of traffic variations on different arterials. The traffic variance on different arterials could be correlated in a way or another with variance of distress occurrence at these sites. Arterial sections with ADT values above 20,000 vpd were subjected to high traffic conditions leading to high pavement deterioration rates compared to those of other sections.

Query results showed that 27 out of 35 arterials had ADT values greater than 20,000 vpd. Most of these arterials were exposed to uniform heavy traffic volumes associated with truck movement in the peak periods, which resulted in higher deterioration rates.

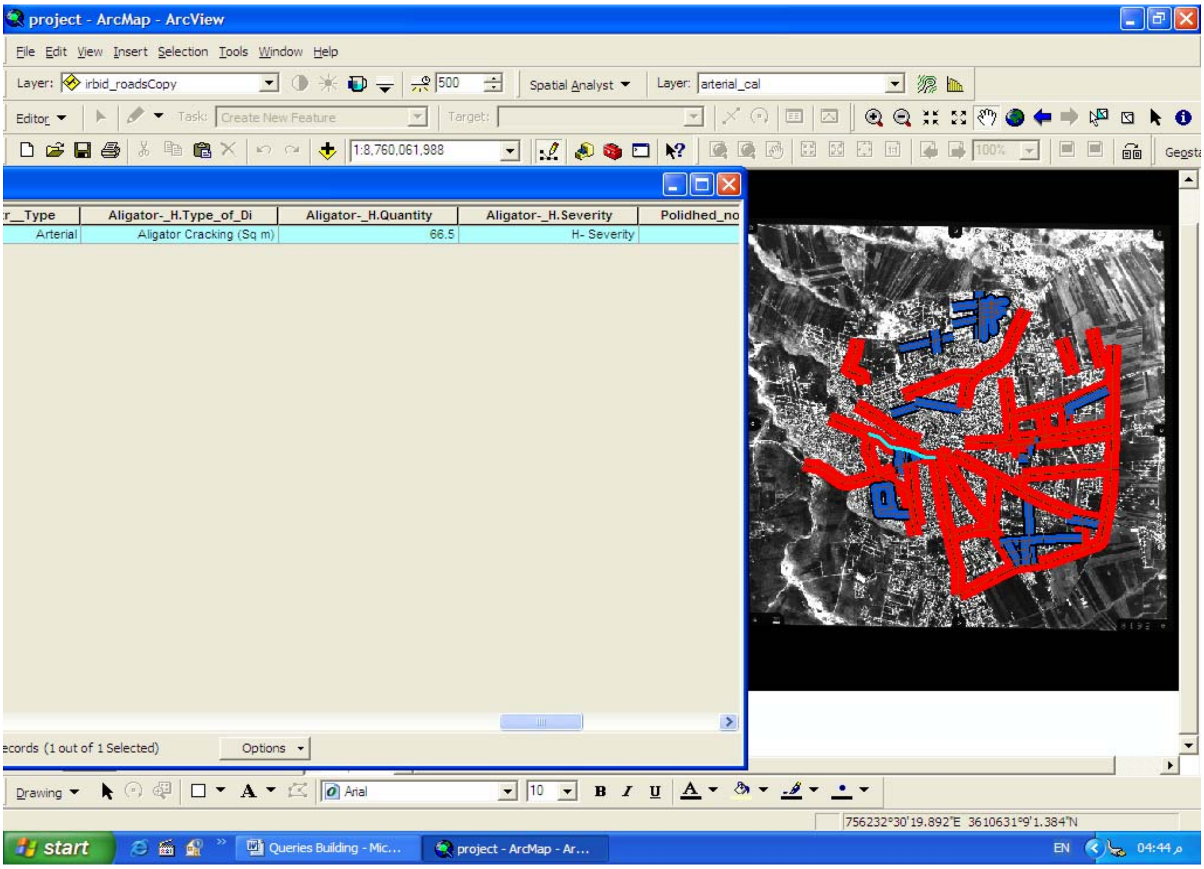


Figure (3): Example of complex logical query building operations

GIS Spatial Analyst

Spatial analyst extension provides tools to create, query, analyze and map cell-based raster data and perform integrated vector-raster Analyst using feature-based and grid-based layers. The following spatial Analyst options could be performed when utilizing the collected database:

1. Clipping Analyst (extract by mask) of polygon sections over density of center points of same sections could be made for pavement database, traffic database and socio-economic characteristics.
2. Clipping operation for arterials, collectors and local roads for PCI, PSR, traffic, density of population, ratio of number of vehicles to number of houses in every section zone was made. Figure 4 shows the clipping results, illustrating PCI values for arterial sections.

Integration of PAVER System and GIS

A new scheme was developed to integrate PAVER system and GIS. PAVER system output was used as input shape file layers in GIS, giving a linkage for wise decisions in the field of highway transportation.

The developed scheme to integrate GIS and PAVER system consists of the following steps:

1. Collecting data (distress type, quantity and severity) and using it as input into the database to run the PAVER system.
2. Computing PCI and PCI rate through the PAVER system.
3. Inserting PAVER output database into ArcGIS as a shape file.
4. Selecting the ArcGIS shape file layer that will make a linkage with the PAVER shape file output layer.
5. Linking the PAVER database shape file layer with

ArcGIS shape file layer by right clicking on the name of the ArcGIS shape file layer. Then, "join and relate" is selected and thereafter “join” is selected.

6. Selecting the section number from the “join data window" that links the two layers of the PAVER system and GIS system.

7. Checking the linkage by opening the attribute table of ArcGIS shape file layer, where PAVER output database becomes part of ArcGIS shape file layer. Figure 5 shows a view of new GIS shape file layer after linkage.

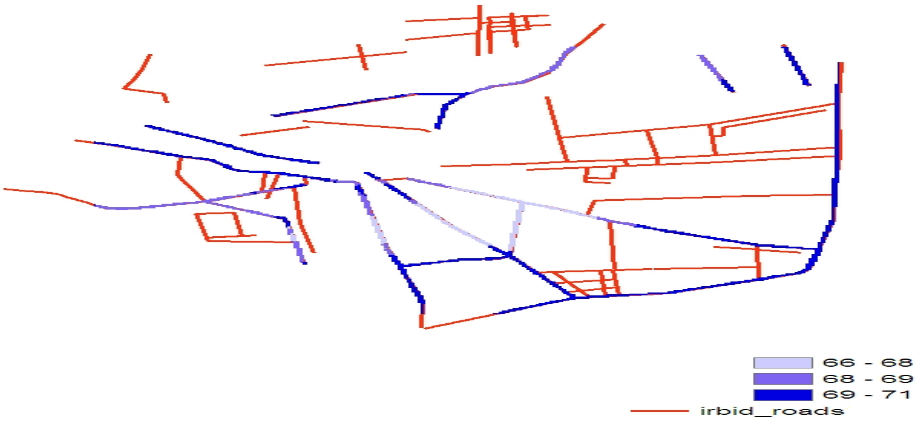
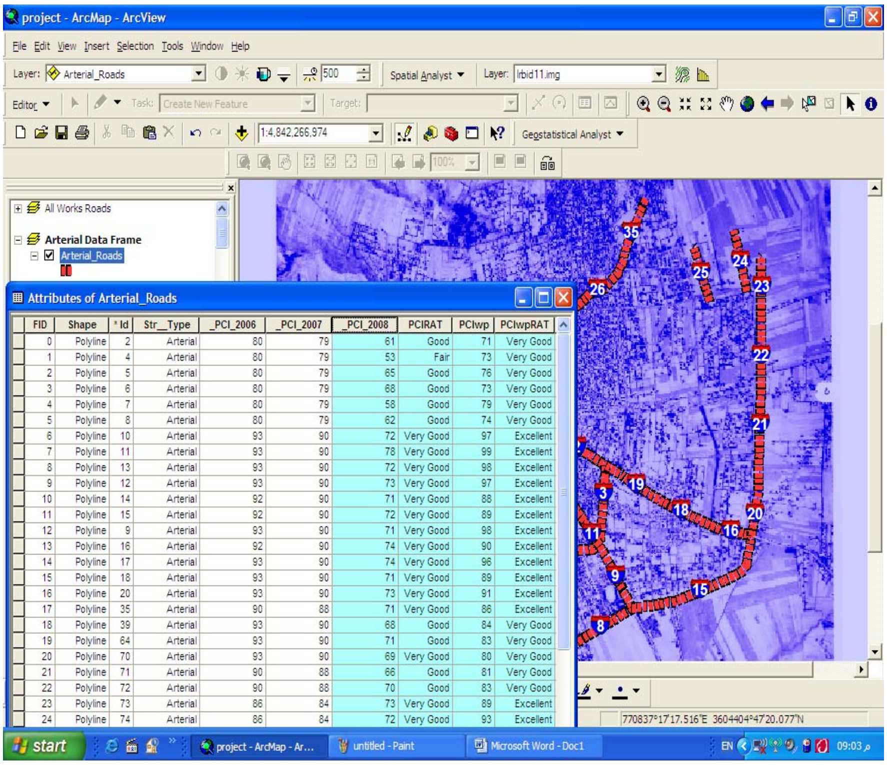


Figure (4): Clipping results, showing PCI values for arterial sections



FID	Shape	* Id	Str__Type	_PCI_2006	_PCI_2007	_PCI_2008	PCIRAT	PCIwp	PCIwpRAT
0	Polyline	2	Arterial	80	79	61	Good	71	Very Good
1	Polyline	4	Arterial	80	79	53	Fair	73	Very Good
2	Polyline	5	Arterial	80	79	65	Good	76	Very Good
3	Polyline	6	Arterial	80	79	68	Good	73	Very Good
4	Polyline	7	Arterial	80	79	58	Good	79	Very Good
5	Polyline	8	Arterial	80	79	62	Good	74	Very Good
6	Polyline	10	Arterial	93	90	72	Very Good	97	Excellent
7	Polyline	11	Arterial	93	90	78	Very Good	99	Excellent
8	Polyline	13	Arterial	93	90	72	Very Good	98	Excellent
9	Polyline	12	Arterial	93	90	73	Very Good	97	Excellent
10	Polyline	14	Arterial	92	90	71	Very Good	88	Excellent
11	Polyline	15	Arterial	92	90	72	Very Good	89	Excellent
12	Polyline	9	Arterial	93	90	71	Very Good	98	Excellent
13	Polyline	16	Arterial	92	90	74	Very Good	90	Excellent
14	Polyline	17	Arterial	93	90	74	Very Good	96	Excellent
15	Polyline	18	Arterial	93	90	71	Very Good	89	Excellent
16	Polyline	20	Arterial	93	90	73	Very Good	91	Excellent
17	Polyline	35	Arterial	90	88	71	Very Good	86	Excellent
18	Polyline	39	Arterial	93	90	68	Good	84	Very Good
19	Polyline	64	Arterial	93	90	71	Good	83	Very Good
20	Polyline	70	Arterial	93	90	69	Very Good	80	Very Good
21	Polyline	71	Arterial	90	88	66	Good	81	Very Good
22	Polyline	72	Arterial	90	88	70	Good	83	Very Good
23	Polyline	73	Arterial	86	84	73	Very Good	89	Excellent
24	Polyline	74	Arterial	86	84	72	Very Good	93	Excellent

Figure (5): Linkage between PAVER database and ArcGIS shape file

Development of Distress Models

Information related to pavement conditions, including: PCI, ADT, pavement age, climate conditions and socio-economic characteristic, was used as independent variables to develop statistical models that express PCI as a dependent variable. The significance of these statistical prediction models was to forecast the pavement condition index, given ADT, climate conditions, socio-economic characteristics and pavement age, by using linear multiple regression models, log10 transformation models or power multiple regression of all previous data. The following linear models were developed for different street types:

For all street types:

$$PCI = -472.843 + 63.730 \times (\text{Min. of Min. Temp.}) - 1.886 \times (\text{Age}) + 2.266 \times 10^{-4} \times (\text{ADT}) + 3.107 \times (\text{Collector}) - 5.277 \times (\text{Min. Humidity}) + 17.170 \times (\text{Max. of Max. Temp.} \quad (1)$$

For arterial streets:

$$PCI = 109.544 + 7.703 \times (\text{Min. of Min. Temp.}) - 1.803 \times (\text{Age}) - 0.615 \times (\text{Max. Humidity}) \quad (2)$$

For collector streets:

$$PCI = 191.542 - 1.195 \times (\text{Max. Humidity}) - 1.914 \times (\text{Age}) + 275.271 \times (\text{Density}) \quad (3)$$

For local streets:

$$PCI = 289.846 - 2.360 \times (\text{Max. Humidity}) - 1.664 \times (\text{Age}) \quad (4)$$

The following variables were used in the above models: air temperature (°C), age of pavement (year), ADT (vehicle/day), humidity (%) and density of population (number/m^2).

Table 1 summarizes the statistical characteristics and independent variables of the developed models represented by the coefficient of multiple determination (R^2), adjusted R^2 and significant level for each of the developed models. From the values of R^2 and adjusted R^2, it is clear that the developed models could be used for prediction purposes. This result confirmed the significant role of the variables involved in each distress model in distress development and extension. In most of the developed models, ADT and pavement age variables played a vital role in distress development with a slightly higher effect of pavement age. This result emphasized the fact that traffic and environment–based loads represent the primer distress generator on flexible pavement roads. Figure 6 shows a scatter plot of the linear relation of the measured and the predicted PCI values for all street types by using SPSS.

Table 1. Statistical characteristics of the developed distress models

Street Type	R^2	Adjusted R^2	Significance Level	F-Value	Degree of Freedom	α-acceptance Criterion
All Streets	0.888	0.886	0.001	384.42	263	0.1
Arterial Streets	0.950	0.949	0.000	643.415	101	0.1
Collector Streets	0.949	0.946	0.001	417.516	68	0.1
Local Streets	0.939	0.938	0.001	694.090	90	0.1

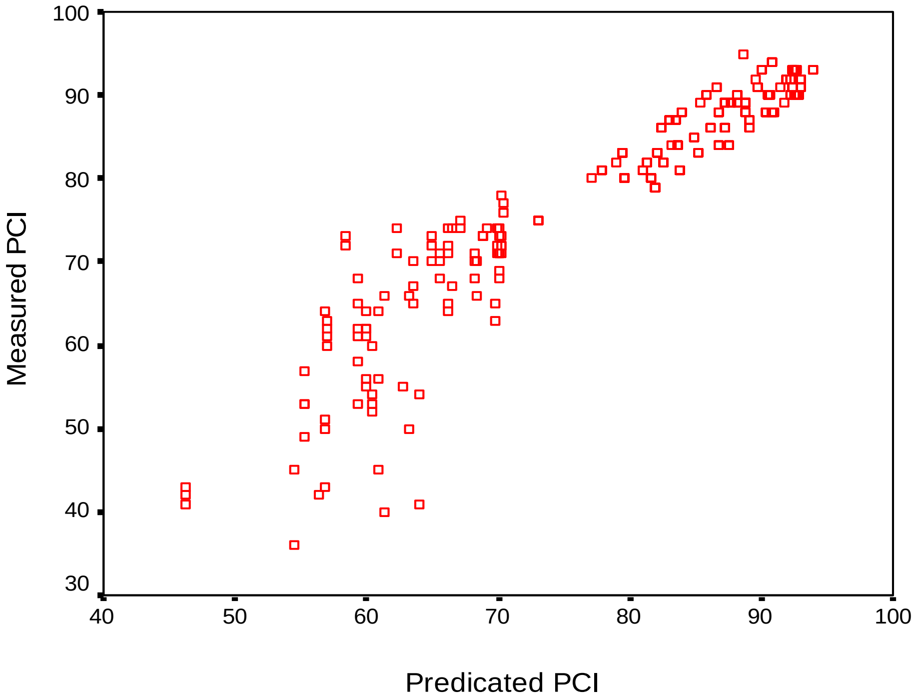


Figure (6): Scatter plot of predicted PCI *versus* measured PCI values for all street types using linear model

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions +were drawn from the analysis and modeling in this research:

1. An automated system that integrated GIS and PAVER system was developed. The system was of great help for pavement distress data collection, analysis, manipulation, displaying and classification. The system's development is a step toward real-time distress classification.
2. The developed system could provide users with numerous advantages, including:
   a. Various analytical tools provided through the GIS system, such as spatial Analyst options that include: density, clipping (extract by mask) and Geostatistical Analyst.
   b. Wide space for chart Analyst: this Analyst was preformed by GIS analytical tools that provide graphical representation of specified fields of the database attributes. General or specific trends characterizing different fields were produced.
   c. Identifying sections with certain types of distress associated with their severity levels and quantities. This would help in assigning concentration to these severe types of distress over the network. Hence, the weak pavement points on the roadway network can be identified. Thereby pavement weaknesses could be improved, rehabilitated and located.
   d. Performing various practical applications and different probabilities of queries. This could help in obtaining useful trends and results through query building process for pavement conditions, in addition to other databases.
3. A scheme that integrates the output of PAVER system into the GIS system was developed.
4. Pavement condition Analyst results show that

sections located in the center of Irbid city, due to their exposure to high traffic levels and low maintenance experience, suffer from different types of distress related to traffic and pavement age parameters.

5. Statistical models were developed to quantify PCI values. These models utilized a number of influencing variables, including: ADT, climate conditions, socio-economic characteristics and pavement age. The developed prediction models were reliable, accurate and highly significant represented by the high values of their respective R^2.
6. ADT and pavement age were the most important factors in predicting PCI quantities.
7. The integration of GIS and PAVER system is anticipated to open the door for highly automated, informative, practical and reliable systems.

The following recommendations could be suggested:

1. Widening the application of such integrated systems over the great municipalities to provide an up-to-date, precise and comprehensive pavement condition database having the capability of assigning maintenance priorities and comparing current and future pavement conditions.
2. Appling the PCI concept criterion to setup maintenance priorities, maintenance cost and pavement management programs.
3. Adapting traffic management options by municipalities to relieve traffic pressure from the roadway network and reduce traffic effect on distress development.
4. Adapting comprehensive maintenance programs based on the developed integrated system, that would direct maintenance activities to sections with high deterioration rates rather than random selection of streets to be maintained.

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