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2 authors:

Mohammed Taleb Obaidat
Jordan University of Science and Technology; Jadara University

Sharaf Alkheder
Kuwait University

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Integration of geographic information systems and computer vision systems for pavement distress classification

Mohammed Taleb Obaidat *, Sharaf A. Al-kheder [1]

Civil Engineering Department, Faculty of Engineering, Jordan University of Science and Technology (JUST), P.O. Box 3030, Irbid, Jordan

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Abstract

The main objective of this research work was to investigate the potential of integration of geographic information system (GIS), global positioning system (GPS) and computer vision system (CVS) for the purpose of flexible pavement distresses classifications and maintenance priorities. The 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 GPS and a PC-based vision system in a GIS environment. GIS Arcview software was used for the purpose of data display, query, manipulation and analysis.

The developed system provided a safer pavement condition data collection technique, flexible data storage, archiving, updating and maintenance priorities updating. Maintenance priorities were assigned based on priority indices values computed by priority index (PI) or available budget criterion. This technique was cost-effective and offered wise-based decision making for different maintenance activities and programs.

Using average daily traffic (ADT), distance from maintenance unit (R), pavement section area and pavement age, statistical models were developed to forecast pavement distress quantities. It was found that ADT and pavement age variables were the most significant factors in the distresses quantification.

Keywords: GIS; GPS; CVS; Pavement distresses; Pavement conditions; Distresses classification; Maintenance priorities

1. Introduction

In the past pavements were maintained but not managed. Pavement engineers 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 [7]. Pavement distress information is needed to assess maintenance requirements. The distresses of asphalt concrete pavement are any defects or deterioration in the pavement and they can be grouped into the general categories: cracking, distortion, disintegration and skid hazard defects [8]. Many traditional systems were used to evaluate and classify pavement surface distresses [6]. They used operations characterized by: manual operations, time consumption, and not following up technology trends [4]. The research work presented in this paper focuses on the use of GIS, GPS, and CVS in order to collect and analyze different distress data. Arterials of Irbid-Jordan City were taken for the prototype study.

The integration of GPS, GIS and CVS 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 became widely

* Corresponding author. Tel.: +962 79 5604090/2 7201000x22125/22139; fax: +962 2 7250222/2 7201043/2 7095018.
E-mail address: mobaidat@just.edu.jo (M.T. Obaidat).
[1] Tel.: +962 2 7201000x22125/22139; fax: +962 2 7250222/2 7095018.

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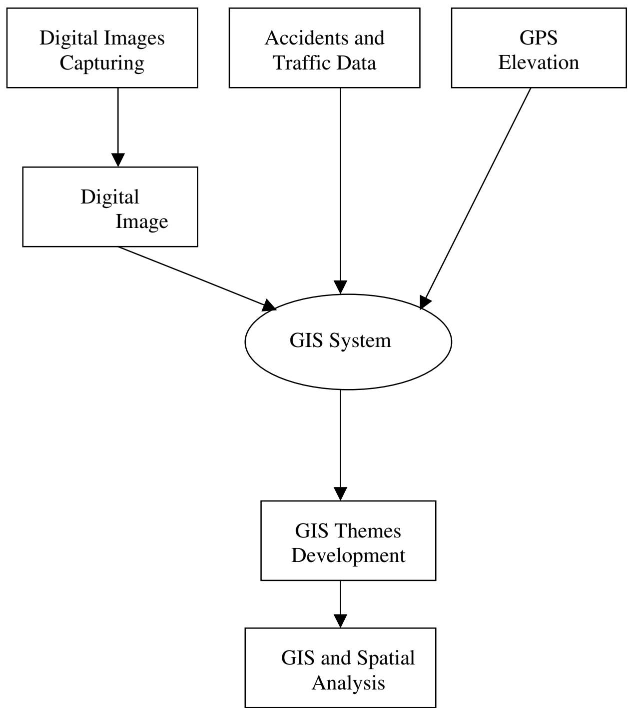

Fig. 1. Flowchart showing the general framework of research.

popular due to its effectiveness in carrying out different research activities economically and safely [3]. Further, researchers will be capable of performing real-time operations, extracting highly accurate data, presenting spatial inventory data, introducing numerous analytical techniques and developing advanced technical systems. Maintenance and operation engineers were also anticipated to use the findings and guidelines of this research work to automate most of their routine decision making activities [1].

The main objective of this paper was to present the feasibility of integrating GIS, GPS, and CVS in order to build digital distress maps linked to locations, useful surface information, and pavement condition databases. Maps showing distribution of maintenance activities over roadway network sections based on available budget and priority indices values were also developed. Using the developed system, distress classification and rehabilitation actions for road network were investigated. Fig. 1 shows a flowchart of the general framework of this research.

2. Database development

To achieve the objectives of this study an integrated database related to 27 arterials, 24 intersections and 37 zones of Irbid-Jordan city were developed. The selection criterion was dependent on covering variables that had different pavement and traffic conditions and central business district (CBD) and non-CBD areas.

The collected data included the following elements:

1. *Pavement condition data.* This database for each road section included distress type, distress severity, distress density, and present serviceability rating (PSR). PSR is the judgment of an observer as to the current ability of a pavement to serve the traffic it is meant to serve; using a subjective scale ranges from 5 (excellent) to 0 (essentially impassable). Other related information included: section identification, section type, section location, section dimensions, distance from maintenance unit and number of digital images for each section.
2. *Other variables.* This database included: (a) Roadway geometry inventory (arterial name, arterial length (m), arterial width (m), median width (m), sidewalk width per side (m), arterial type (divided or non-divided), arterial location (CBD or non-CBD area) and arterial directions (one or two-way)), (b) intersection geometry inventory (intersection name, intersection type, intersection area (m^2) and distance from maintenance unit), (c) traffic data (volumes and peak hour factor (PHF)), and (d) zones and elevations (names, features, parking, altitudes for points).

3. Equipment

The following equipment was used to measure pavement condition quantities, elevations and presenting collected data [1]:

1. *Canon digital camera power shot A5.* The canon digital camera power shot A5 is an easy-to-use, compact digital camera with a large range of functions incorporated into a card-sized body. The camera was used to capture digital images for distressed areas over the road network, after which these images were analyzed for distress measurements. Captured images could then be transferred from the digital camera to the computer.
2. *Off-the-shelf vision system.* The hardware configuration of the PC-based vision system was a part of the surveying and photogrammetry laboratory, at the Civil Engineering Department, at Jordan University of Science and Technology (JUST). The digital image and data acquisition system hardware consisted of a personal computer (PC) equipped with an EPIX frame grabber with 20 MHz pixel close and 1 MB of image memory, and an interactive program called SVIP which was used to digitize the captured images into 256 gray levels. The digitized images were used as a base map for distress measurements.

3. *GPS 48 personal navigator system.* The GPS 48 system provided steering guidance, navigation and direct measurements of the altitude (elevation), latitude and longitude.
4. *GIS Arcview software.* ArcView software brought geographic information to the desktop to visualize, explore, query and analyze data spatially. ArcView was made by Environmental Systems Research Institute [2].

4. Pavement condition measurement

Most types of asphalt pavement distresses were measured through the PC-based vision system analysis (10 distresses out of 16 types). The remaining types of distresses were measured manually due to the limited capability of the used system in image processing and 3rd dimensional measurement. Table 1 distinguishes distresses measured by PC-based vision system analysis from those measured manually. The methodology of automatic distress measurement could be summarized in the following steps:

1. Identify the distressed area and capture series of digital images using a camera mounted on a movable truck. The camera height was about 2 m and its optical axis was 30° below the horizontal line.
2. Repeat the first step for each distressed area on the selected arterial until the camera reached its ultimate capacity of images.
3. Use GPS navigator system to measure altitude and position (latitude and longitude) of a 100×100 m grid. Interpolation method was used to find altitude at each distresses area.
4. Acquire digital images for the mapped distresses using the PC-based vision system.
5. Measure geometrical features of distresses using the PC-based vision system. Distress measurements including distress type, distress severity and distress density were obtained in this step.
6. Repeat steps 1–5 until all captured images are analyzed.

The resulting pavement condition database was used as a data source for GIS system.

5. System's validation

To check the precision and accuracy of the collected distresses data (including distress type, distress quantity and severity level) by vision system compared with those collected manually, a sample of 30 images distributed over the surveyed arterials was used. Table 2 summarizes the accuracy results of the validation process. The results of the analysis, comparison and validation of distress data collected by the vision-based system were consistent, to a great extent (about 96.5%) with the manually collected data. This proves the high accuracy of this system, therefore, it was used in this study to process the distress data.

The validation table of measurements contained the following pieces of information:

- photograph number;
- photograph location;
- types of distresses visible through images associated with there severity levels;

Table 2
Accuracy results from validation process

Average of accuracy	96.4869%
Standard deviation of accuracy (σ)	2.20679%
Coefficient of variation of accuracy (COV)	2.28714

Table 1
Classification of distress measurement methods

Distress number	Distress type	Measurement unit	Measurement method
1	Alligator cracking	Square meter	Camera analysis
2	Bleeding	Square meter	Camera analysis
3	Bumps & sags	Linear meter	Manually
4	Corrugation	Square meter	Manually
5	Depression	Square meter	Manually
6	Edge cracking	Linear meter	Camera analysis
7	Lane/shoulder drop-off	Linear meter	Camera analysis
8	Longitudinal & transverse cracking	Linear meter	Camera analysis
9	Patching & utility cut patching	Square meter	Camera analysis
10	Polished aggregate	Square meter	Camera analysis
11	Potholes	Number	Camera analysis
12	Rutting	Square meter	Manually
13	Shoving	Square meter	Manually
14	Slippage cracking	Square meter	Camera analysis
15	Swell	Square meter	Manually
16	Weathering & raveling	Square meter	Camera analysis

- quantity of distresses obtained through camera analysis in m, m^2 or number units;
- distresses quantity obtained manually in m, m^2 or number units;
- the difference between manual and automated collected distress quantities;
- error or bias percentages of the automatically collected data from accurate manual data; and
- percentages of accuracy of the automatically collected data.

6. GIS themes

Desktop GIS combines the capabilities of display, thematic, and street-based mapping systems along with the ability to analyze geographic locations and the information linked to those locations. Moreover, information can be accessed from vector or raster maps, or maps can 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 theme (coverage).

Themes of pavement condition data and road inventory data were presented and incorporated into Arcview GIS desktop. Presented themes included:

1. *Themes of pavement condition at intersections and arterials.* In this theme detailed description for all elements related to pavement conditions at the studied intersections and arterials was presented. Polygons and polylines features were used to draw intersection

Table 3
A sample of elements in the intersection and arterial pavement condition theme database

Field symbol	Identification
Shape	The shape used to draw each intersection feature (polygon) & arterial section (polyline)
ID	Intersection section or arterial section number
Section ID	Name of intersection
Location	Section Location on the arterials or intersections
Type	Multi-leg rotary or signalized intersection
Length	Section length on the arterial in meters
Width	Section width on the arterial in meters
Number of photos	Number of digital images captured on each section
Distress 1,2,3	Alligator cracking distress type
Severity 1,2,3	L,M,H Alligator cracking severities
Quantity 1,2,3	L,M,H Alligator cracking quantities
Distress 4,5,6	Bleeding distress type
Severity 4,5,6	L,M,H Bleeding severities
Quantity 4,5,6	L,M,H Bleeding quantities
Distress 7,8,9	Bumps & sags distress type
Severity 7,8,9	L,M,H Bumps & sags severities
Quantity 7,8,9	L,M,H Bumps & sags quantities
Distress 10,11,12	Corrugation distress type
Severity 10,11,12	L,M,H Corrugation severities
Quantity 10,11,12	L,M,H Corrugation quantities
Distress 13,14,15	Depression distress type
Severity 13,14,15	L,M,H Depression severities
Quantity 13,14,15	L,M,H Depression quantities
Distress 16,17,18	(L & T) Cracking distress type for intersections theme
Severity 16,17,18	L,M,H (L & T) Cracking severities for intersections theme
Quantity 16,17,18	L,M,H (L & T) Cracking quantities for intersections theme
Distress 16,17,18	Edge cracking distress type for arterials sections theme
Severity 16,17,18	L,M,H Edge Cracking severities for arterials sections theme
Quantity 16,17,18	L,M,H Edge Cracking quantities for arterials sections theme
Distress 19,20,21	Patching distress type for intersections theme
Severity 19,20,21	L,M,H Patching severities for intersections theme
Quantity 19,20,21	L,M,H Patching quantities for intersections theme
Distress 19,20,21	Lane/shoulder drop-off distress type for arterials sections theme
Severity 19,20,21	L,M,H Lane/shoulder drop-off severities for arterials sections theme
Quantity 19,20,21	L,M,H Lane/Shoulder drop-off quantities for arterials sections theme
Distress 22	Polished aggregate distress type for intersections theme
Severity 22	No severity level is defined
Quantity 22	Polished aggregate quantity for intersections theme
Distress 22,23,24	(L & T) Cracking distress type for arterials sections theme
Severity 22,23,24	L,M,H (L & T) Cracking severities for arterials sections theme

and arterial sections. A comprehensive database of all types of distresses associated with their severity levels, priority indices, options for repair and maintenance costs were incorporated into the database. Table 3 summarizes the database attributes and elements used in the associated attributes for the pavement conditions at sections of Irbid-Jordan city arterials and intersections themes. Figs. 2 and 3 show views of the city intersections and arterials pavement conditions.

2. *Other themes*. These themes included: zones theme for 37 zones (polygon shapes), arterials theme for 17 arterials (line feature shapes), roadway network intersections theme for 24 intersections (polygon shapes),

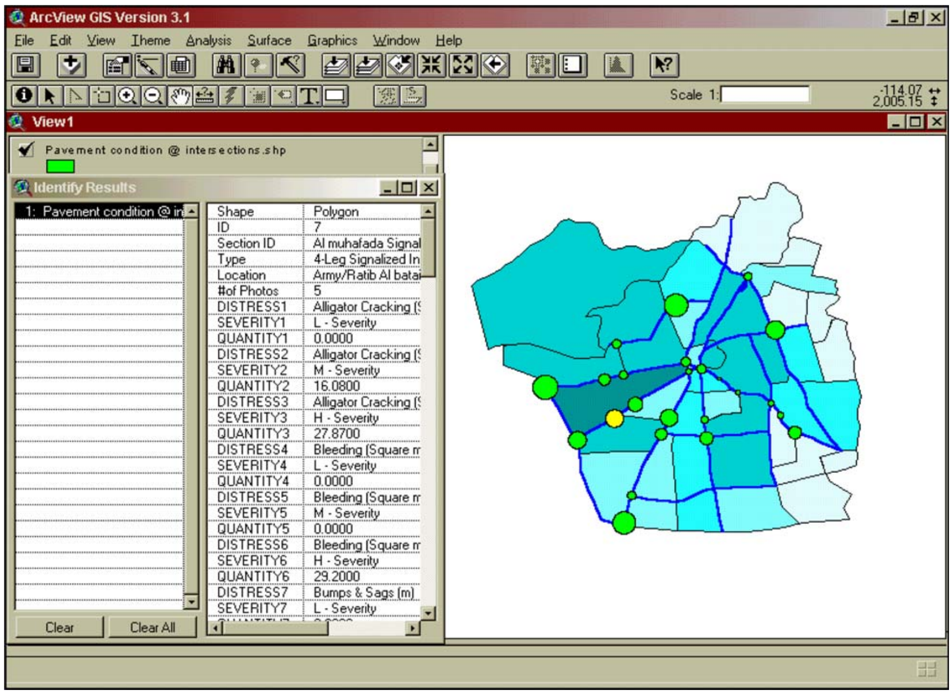

Fig. 2. Intersection pavement condition theme with sample database attributes.

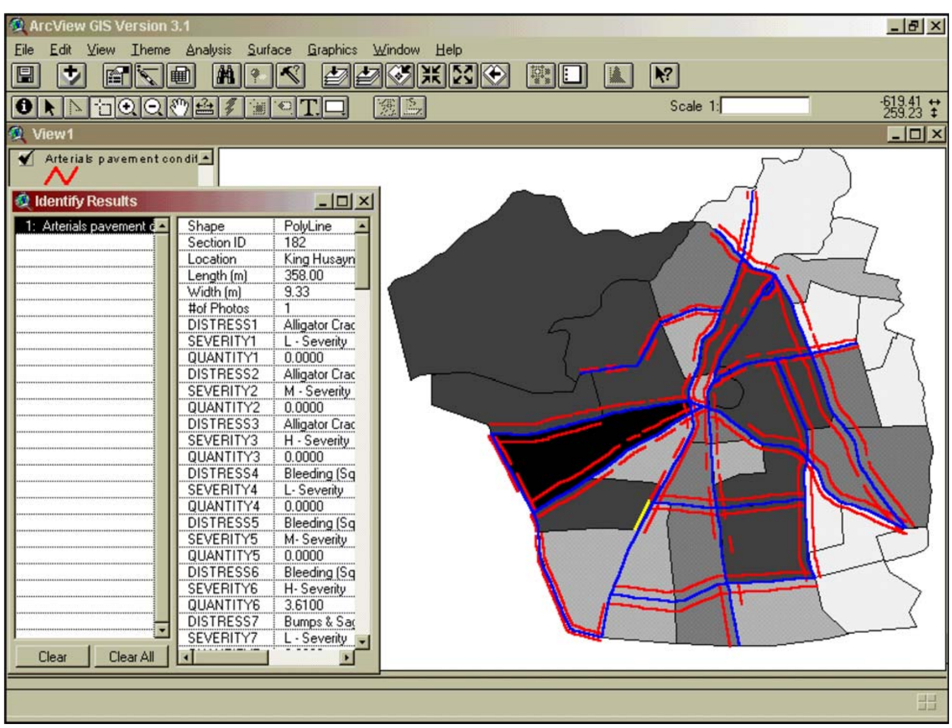

Fig. 3. Arterial pavement condition theme with sample database attributes.

Table 4
Sample of elements in the traffic volumes theme database

Field symbol	Identification
Shape	The shape used to draw each intersection feature (polygon)
ID	Intersection number
Int. name	The official intersection name given by the municipality
Int. type	Multi-leg signalized or unsignalized intersection
PHF	Peak hour factor
NS street	The intersected arterial in the north/south direction
EW street	The intersected arterial in the east/west direction
EB,LT,PC	The left turning passenger cars volumes coming from the west direction
EB,LT,T	The left turning trucks volumes coming from the west direction
EB,TH,PC	The through passenger cars volumes coming from the west direction
EB,TH,T	The through trucks volumes coming from the west direction
EB,RT,PC	The right turning passenger cars volumes coming from the west direction
EB,RT,T	The right turning trucks volumes coming from the west direction
EB,TOT,PC	The total passenger cars volumes coming from the west direction
EB,TOT,T	The total trucks volumes coming from the west direction
WB,LT,PC	The left turning passenger cars volumes coming from the east direction
WB,LT,T	The left turning trucks volumes coming from the east direction
WB,TH,PC	The through passenger cars volumes coming from the east direction
WB,TH,T	The through trucks volumes coming from the east direction
WB,RT,PC	The right turning passenger cars volumes coming from the east direction
WB,RT,T	The right turning trucks volumes coming from the east direction
WB,TOT,PC	The total passenger cars volumes coming from the east direction
WB,TOT,T	The total trucks volumes coming from the east direction
NB,LT,PC	The left turning passenger cars volumes coming from the south direction
NB,LT,T	The left turning trucks volumes coming from the south direction
NB,TH,PC	The through passenger cars volumes coming from the south direction
NB,TH,T	The through trucks volumes coming from the south direction
NB,RT,PC	The right turning passenger cars volumes coming from the south direction
NB,RT,T	The right turning trucks volumes coming from the south direction
NB,TOT,PC	The total passenger cars volumes coming from the south direction
NB,TOT,T	The total trucks volumes coming from the south direction
SB,LT,PC	The left turning passenger cars volumes coming from the north direction
SB,LT,T	The left turning trucks volumes coming from the north direction
SB,TH,PC	The through passenger cars volumes coming from the north direction
SB,TH,T	The through trucks volumes coming from the north direction
SB,RT,PC	The right turning passenger cars volumes coming from the north direction
SB,RT,T	The right turning trucks volumes coming from the north direction
SB,TOT,PC	The total passenger cars volumes coming from the north direction
SB,TOT,T	The total trucks volumes coming from the north direction

themes of traffic volumes at intersections (polygon shapes including: peak hour factors, distribution of traffic volumes by movement type on the approach to each intersection and total volume of intersection approaches), and GPS elevation themes (point shapes). Table 4 summarizes the database elements used for each traffic volume theme.

7. Data analysis and interpretation

Analysis scheme was divided into five parts:

1. *Priority indices calculations*. Priority indices output is a useful method of assigning maintenance priorities of different sections.
2. *Maintenance cost analysis*. Using maintenance unit cost appropriate for each type of distress, the total maintenance cost for each section would be determined and prioritized based on available budget.
3. Querying options for priority indices assignment, budget wise-based decisions and others.
4. Development of practical prediction models for each type of distresses using number of variables based on the degree of their significance.
5. GIS spatial analysis for the GPS elevations database through creating contours, interpolate grid, derive slope, derive aspect and hill shade computation.

7.1. Priority index computation

The limited funds for rehabilitation of arterial pavement sections made it essential to prepare pavement management programs that used performance prediction and cost models together with decision trees to generate several strategies for each pavement section in the network. Priority index (PI) is one of the most important key features in assigning maintenance priorities and hierarchies in any pavement management program. Three approaches were used in this research work to compute maintenance priority index [5,9].

7.1.1. Simple ranking technique (SRT)

This priority model was developed in Egypt. This approach uses the following formula to compute the priority index for each section under study:

$$PI = \frac{DL}{TF * DF}, \tag{1}$$

where defect length (DL) is the sum of defects for one distress type for the entire section; traffic factor (TF) is a constant based on the traffic level prevailing on the section or arterial (TF = 0.1 for average daily traffic (ADT) of 2500 vehicles per day (VPD), 0.5 for ADT between 2500 and 10,000 VPD or 1.0 for ADT greater than 10,000 VPD) and the defect factor (DF) is a numerical value that is assigned for every section on the basis of the defect type and the required treatment as shown in Table 5.

The priority indices are computed using formula (1) for each type of distress in all studied sections. The entire index for the entire section was calculated. Priority indices obtained for all the studied sections could be ranked in descending order according to the index values. This ranking enabled the maintenance authority to assign various maintenance programs for the entire network. It might be noted that the section priority index increased for higher traffic levels and more severe defects.

7.1.2. Formula approach

This approach is based on four factors: PSR, ADT, R (distance from maintenance unit in km) and Class of road (1 for arterials, 2 for collectors and 3 for local streets). The class variable was assigned to one because Irbid arterials were studied.

The factors were normalized (weighted) by dividing each factor by the average value of the variable at the road network. The following equation was used to compute the priority index for all deteriorated sections on Irbid network:

$$PI = (ADT/ADT_{avg.}) * 10/[(PSR/PSR_{avg.}) * (R/R_{avg}.)]. \tag{2}$$

The resulted values of PI were sorted from maximum to minimum in order to rank PI values for every section on each arterial.

7.1.3. Ranking approach

This approach used the same four factors of the formula approach but for each variable the section's data were sorted in descending order. Consequently, three ordered arrays of ADT, PSR and R are constructed. These arrays contained only the rank (identification) of the section as an indication for the PI. The smaller the rank value of the section the higher was the quantity of the variable for that section. The road class variable was excluded because it was assigned a ranking number of 1 for all arterial sections. It should be noted that ADT values were arranged from maximum to minimum, however, PSR and R values were arranged from minimum to maximum because they affected PI inversely. Therefore, the weight of the rank for every section of every variable could be computed from the following formula:

$$W_{ij} = \left[(1/R_{ij})\Big/\left(\sum(1/R_{ij})\right)\right] * (100\%), \tag{3}$$

where W_{ij} and R_{ij} are weight and rank of section i for variable j, respectively.

Then the weight, which is a measure for priority, will be:

$$PI_i = W_{i1} + W_{i2} + W_{i3}, \tag{4}$$

where PI_i is PI for section i, W_{i1} is weight of section i for (ADT), W_{i2} is weight of section i for (PSR), and W_{i3} is weight of section i for (R).

Table 6 summarizes the results of priority indices computations for the arterials of Irbid network using the three approaches described above. It is obvious from the table that the three approaches gave differences in PI results. This was due to the difference in methodologies used in the three approaches. Computed PI of any approach or the average PI could be used for analysis purposes. Once the priorities of sections are known, the budget could be distributed based on the PI values or any other selected criteria.

7.2. Roadway inventory and pavement conditions

GIS themes could be used to produce useful graphs for any attribute of the developed database. This section shows two representative examples of roadway inventory and pavement condition:

Table 5
Assignment of defect factor

Defect	Treatment	Defect factor
Open potholes	Rehabilitation	0.10
Alligator cracking	Rehabilitation	0.15
Reflection cracking	Rehabilitation	0.20
Rutting	Reshape and overlay	0.30
Old patching	Overlay	0.50
Lean surface texture	Surface dressing	0.70
Edge fretting	Edge patching	1.00
Low shoulder	Shoulder works	1.00

Table 6
Priority indices for a number of sections

Section ID	PI, SRT (%)	PI, Formula (%)	PI, Ranking (%)
1	4.65	13.47	10.31
2	24.98	14.35	28.84
3	8.91	15.71	9.84
4	7.23	8.97	6.27
5	10.58	19.45	11.48
6	13.19	7.55	11.42
7	13.74	12.15	16.97
8	18.23	9.91	8.09
9	17.48	13.89	8.14
10	12.94	27.72	18.79
11	10.94	3.23	4.62
12	9.53	6.81	5.07
13	6.61	21.08	14.27
14	6.06	15.71	7.80
15	11.62	53.27	34.21
16	5.35	1.97	3.67
17	10.74	7.40	5.44
18	8.77	17.51	10.39
19	12.00	13.89	29.91
20	11.05	6.84	6.23
21	11.21	13.32	8.99
22	25.72	4.68	9.09
23	13.02	3.93	18.13
24	4.85	10.62	12.04

1. *Roadway inventory*. Roadway inventory data includes type of intersection, intersection area, geometric width of the traveled direction, median width, sidewalk width, divided or non-divided arterial, arterial location, allowable movements on arterial, section length and section width. These could all be represented in chart notation to show the variance of their characteristics on arterials or intersections. Fig. 4 classifies arterials based on their width and types (divided or non-divided). The classification process clearly showed that most of the arterials in Irbid city are divided. Non-divided arterials exposed to higher traffic levels in the two-way directions had a higher potential of deterioration than divided arterials. On the other hand, width classification of Irbid arterials showed that most of them were narrow. This implied that repeated traffic load distributed over small lateral distances concentrates load and leads to a deteriorated pavement.
2. *Pavement condition*. Pavement condition variables had a rich database to configure variations of their quantities of all sections on the roadway network. Therefore, a general idea about which sections have worse conditions than others could be figured out. Thus, maintenance priorities could be setout. Fig. 5 classifies Irbid intersections based on the quantity of alligator cracks. This schematic diagram shows that Al-Quba rotary contributed to the highest amount of alligator cracks. Therefore, this section should be given highest priority of maintenance concerning this type of distress. It could also be seen that some intersections such as Fawara Rotary, Al-shamali Parking Signal and Al-baladieh Signal intersections had zero amount of alligator cracks. Classifications of intersections or arterials sections based on the quantity of each distress type could be

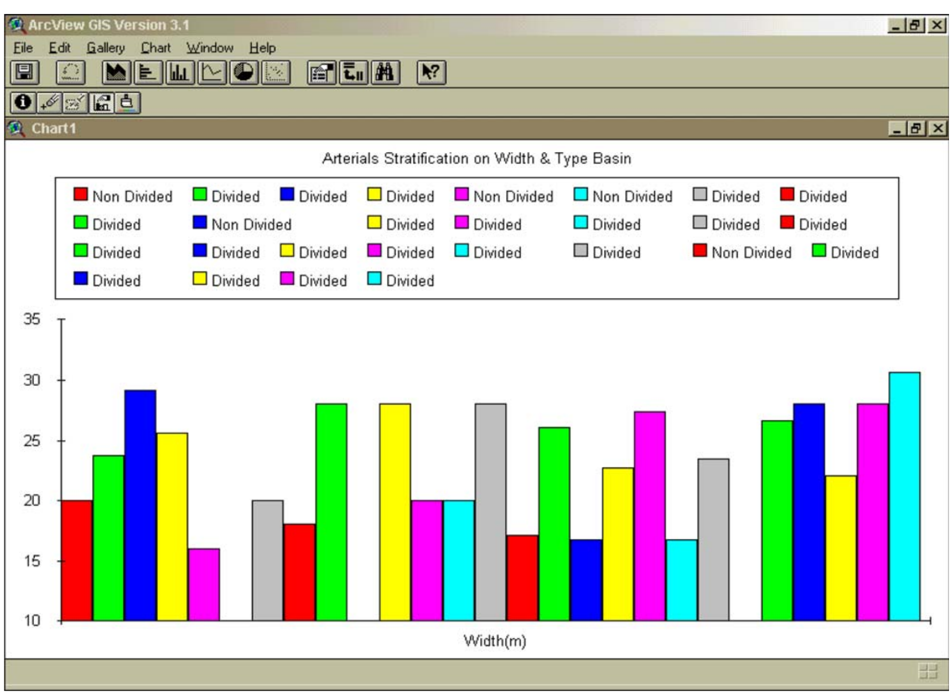

Fig. 4. Arterial classification based on width and type.

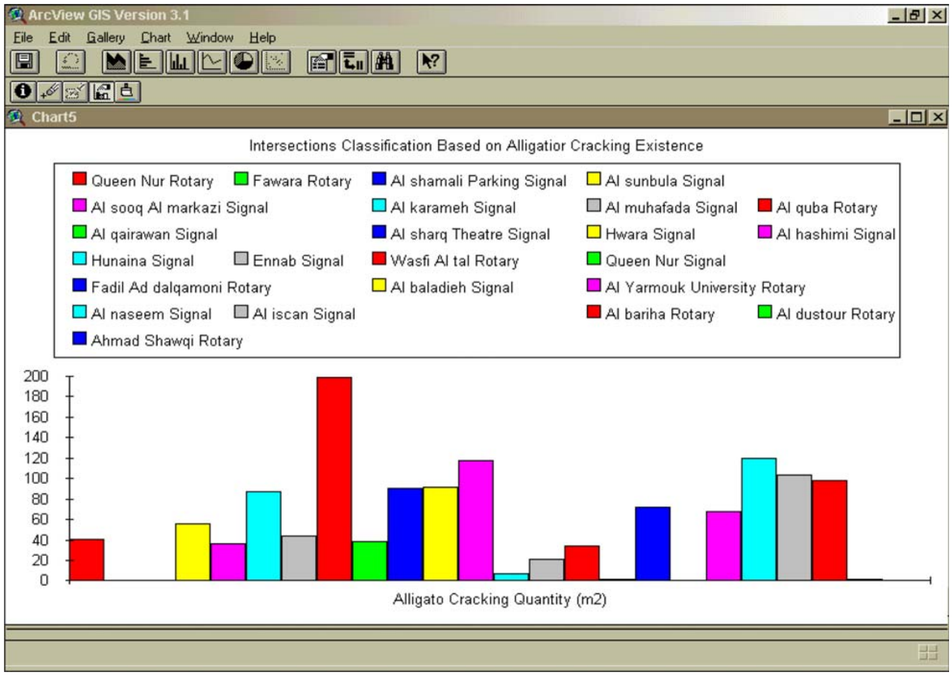

Fig. 5. Intersection classification based on alligator cracking quantities.

performed to compare the severity of distresses among all sections. This procedure would help in giving a quick and rough decision on sections requiring maintenance for certain types of distresses.

7.3. Maintenance costs analysis

The existence of a large amount of deteriorated sections puts a large amount of pressure on a limited maintenance budget. Cost estimation for each section, by summing the cost of maintenance of each type of distress, would be required. This estimation will help in assigning maintenance priorities based on the available budget and in evaluating the effectiveness of different pavement management programs. Therefore, sections would be arranged according to their pavement conditions and at the same time according to their maintenance costs.

The ranking of the pavement sections based on their maintenance costs would give higher priority of maintenance for those sections with higher maintenance costs. That was because those sections that suffered from several types of distresses would cost more than other sections with light distresses types. For example, maintenance costs for sections with distortion-based distresses would be more than those sections with the same distressed areas of weathering type of distresses.

A scheme to estimate flexible pavement maintenance costs was developed. The scheme computes the maintenance cost through the following steps:

1. Identify and measure the quantity of different types of distresses associated with their severity levels for all sections on arterials and intersections.
2. Price the maintenance cost for each type of distress according to their unit prices from records for the last five years. Table 7 summarizes maintenance unit prices in Jordanian Dinners (JD) obtained from two sources: Jordanian Ministry of Public Works (JMPWS) and Jordanian Contracting Association (JCA).
3. Compute the maintenance cost for each section of the road (the cost of each distress and its respective severity level is computed by multiplying its quantity with its respective unit price).
4. Assign maintenance priority for each section based on its maintenance cost.
5. Compute the total maintenance cost for all sections of the network.
6. Select sections to be maintained from previous step according to their ranks and available budget.

Fig. 6 shows a graphical representation of the total maintenance costs in JD required for all distressed intersections of the studied area in Irbid-Jordan.

7.4. Queries and system's advantages

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

Table 7
Maintenance cost of each type of distress for each maintenance unit

Distress type	Maintenance unit	Unit cost (JD)		Mean unit cost (JD)
		From	To	
Alligator cracking	Square meter	2	2.5	2.25
Bleeding	Square meter	0.5	0.6	0.55
Bumps & sags	Square meter	1.45	1.55	1.5
Corrugation	Square meter	1.45	1.55	1.5
Depression	Square meter	2.5	3	2.75
Edge cracking	Linear meter	0.2	0.25	0.225
Lane/shoulder drop-off	Square meter	2	2.5	2.25
Longitudinal & transverse cracking	Linear meter	0.2	0.25	0.225
Patching & utility cut patching	Square meter	2.5	3	2.75
Polished aggregate	Square meter	0.22	0.25	0.235
Potholes	Number (each considered 1 m^2)	2.5	3	2.75
Rutting	Square meter	2	2.5	2.25
Shoving	Square meter	2.5	3	2.75
Slippage cracking	Square meter	1.8	2.2	2
Swell	Square meter	3.5	4	3.75
Weathering & raveling	Square meter	2	2.2.5	2.125

Stage 1: Perform an automated field survey through CVS to identify existing distresses and their quantities and severity levels. This was performed for all distressed sections of Irbid arterials and intersections.
Stage 2: Collect other related data such as geometrical elements of roads and intersections, traffic data, PSR, *R*, etc.
Stage 3: Perform PI computation using the average values of the three methods mentioned before.
Stage 4: Build GIS pavement condition theme with attributes related to distresses information.
Stage 5: Select a threshold value for PI to decide on sections to be maintained based on the available budget as discussed in previous subsection.
Stage 6: Carry GIS query builder process using the selected threshold of PI to find the sections contained within this query.
Stage 7: Carry another GIS query builder process to select the ranked sections based on their PI and available maintenance budget.

Fig. 7 shows a query building process to find sections having PI greater than 10, while Fig. 8 shows

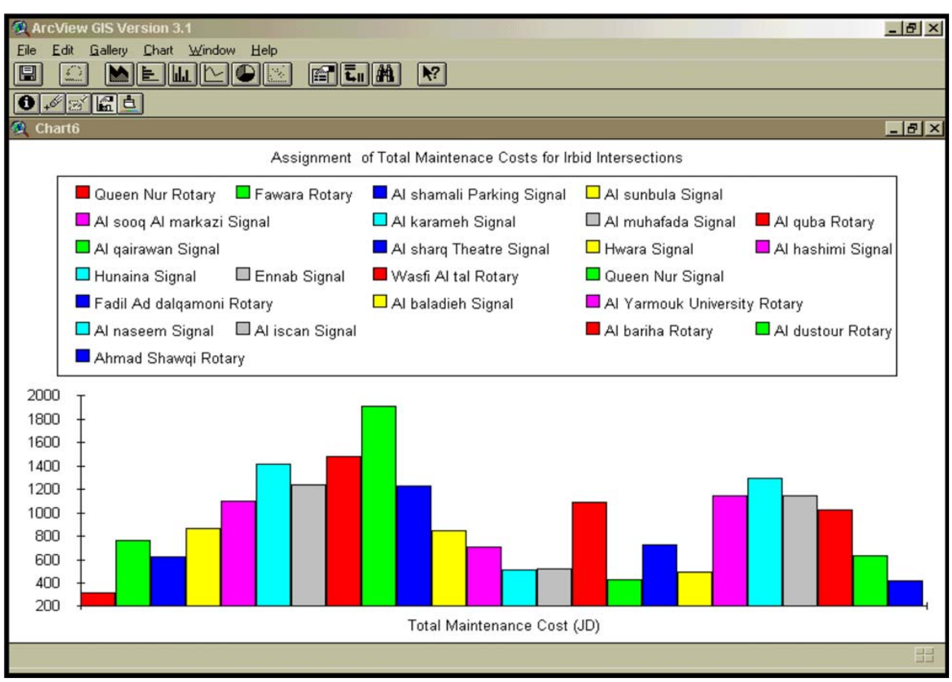

Fig. 6. Intersection classification based on total maintenance costs.

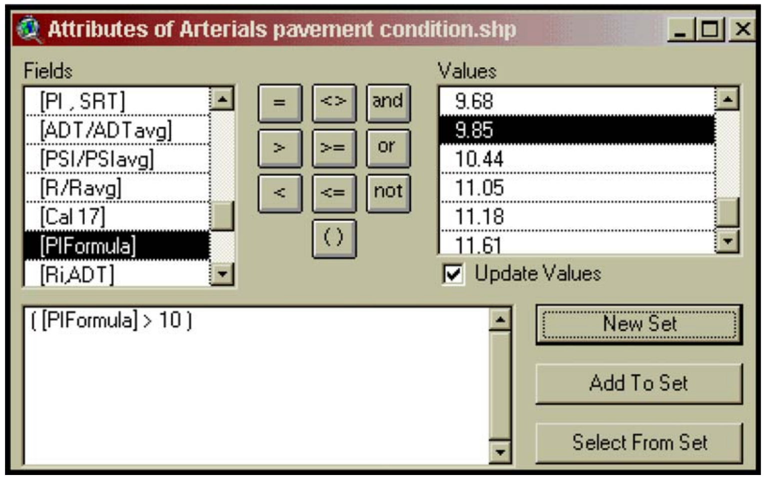

Fig. 7. Query building process for PI greater than 10.

the sections which met the query criterion. Only 13 arterials' sections out of 381 sections met the query criterion. Another query was made on the 13 sections to check if the available budget was sufficient. Of course, if the budget was not sufficient, we should decrease the number of selected sections to fit budget requirement.

Pavement condition data were fruitful material for carrying out different queries. Querying data on sections, such as the existence of various distresses and their respective severity levels, was beneficial. It showed which factors contributed to which type of distress at a specific location. Another advantage of the developed system was its ability to perform combinations of logical operations on the collected pavement management data. Fig. 9 shows an example of the complex queries that could be built by combing expressions together with the and/or operators. The figure queried the H-severity patching and M-severity rutting types of distresses. Results of this query indicated that 143 sections out of 381 arterials' sections contributing to about 37.5% of the total sections of Irbid arterials contained both H-severity patching and M-severity rutting types of distresses. The existence of these distresses on these sections (at CBD) was an indicator of high traffic volumes and poor maintenance programs adapted by Irbid municipality.

Traffic volumes data were also useful for queries to obtain useful indicators for traffic variations on different intersections. The traffic variance on different intersections could be correlated in one way or another to variance of distress occurrence on these sites. Fig. 10 represents the intersections' sections with PHF values above 0.9 pointing to the sections approaching the maximum capacity. These sections were subjected to high traffic conditions leading to a high pavement deterioration rate, compared with other sections. Query results showed that only 9 out of 29 intersections had PHF values greater than or equal to 0.9. Most of these intersections were located in the CBD-area and exposed to uniform, heavy traffic volumes associated with truck movements in the peak periods. This resulted in higher deterioration rates.

7.5. Development of distress models

Information related to pavement condition including distress quantities, ADT, pavement age and distance from maintenance unit (R) were used as independent variables to develop statistical models that expressed pavement condition as a dependent variable. The role of these statistical prediction models was to forecast the pavement distresses quantities using ADT, R, section area and pavement age or log10 of pavement age data. Multiple regression models were used to predict these distresses according to the following equations:

$$\text{Alligator cracking quantity} = -103.532 + 16.123 * R + 136.695 * \log(\text{Age}), \quad (5)$$

$$\text{Bleeding quantity} = -19.941 - 3.638\text{E}-03 * (\text{ADT}) + 13.627 * (\text{Age}), \quad (6)$$

$$\text{Bumps \& sags quantity} = -5.943 + 5.19\text{E}-04 * (\text{ADT}) + 1.542 * (\text{Age}), \quad (7)$$

$$\text{Corrugation quantity} = -66.433 + 4.886\text{E}-03 * (\text{ADT}), \quad (8)$$

$$\text{Depression quantity} = 81.29 + 2.51\text{E}-03 * (\text{ADT}) + 12.675(\text{Age}) - 232.051 \log(\text{Age}), \quad (9)$$

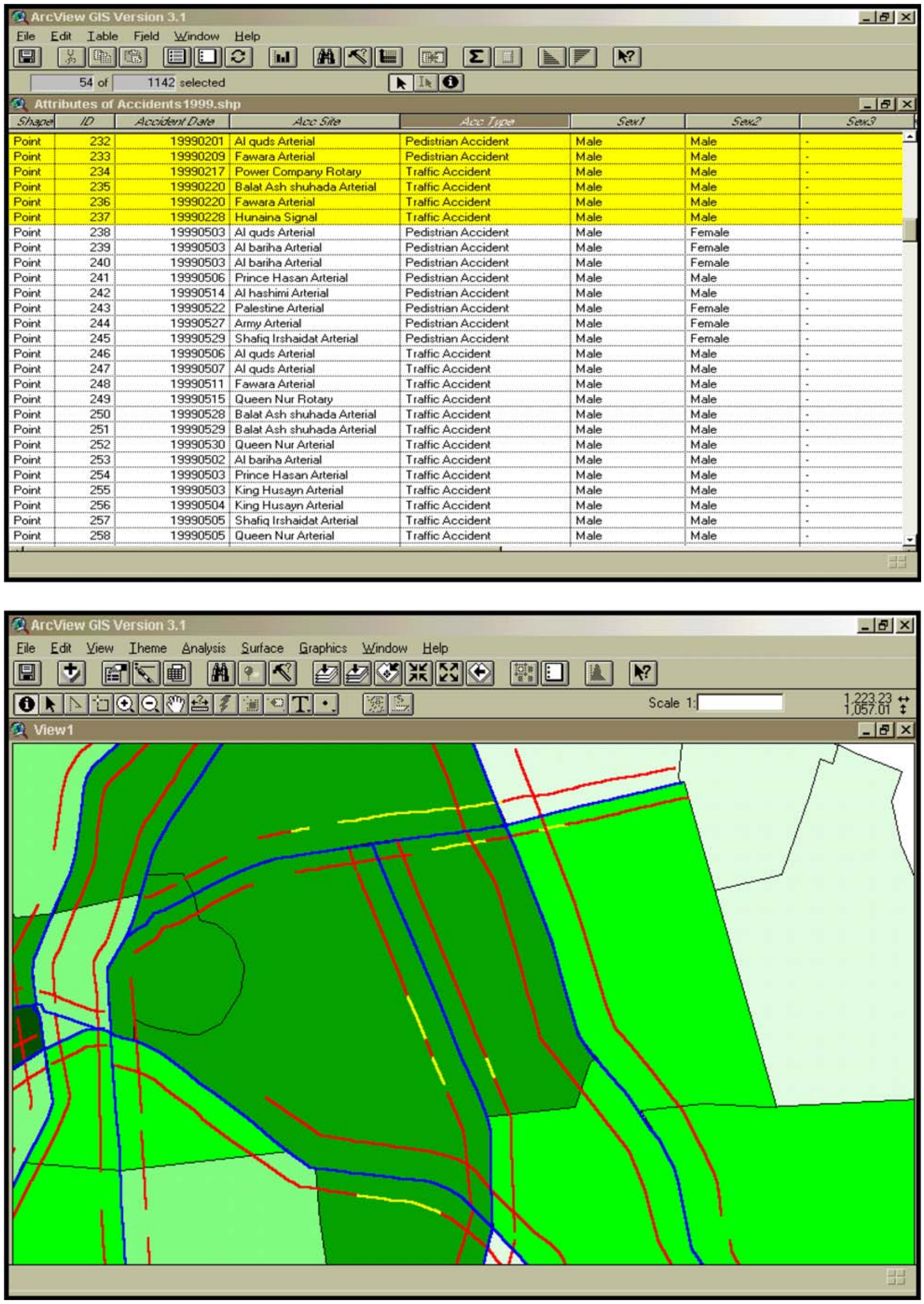

Fig. 8. Sections with PI greater than 10.

$$\text{L \& T cracking quantity} = -89.478 + 4.258\text{E} - 04 * (\text{ADT}) - 5.528 * R - 3.185\text{E} - 04 * \text{Int. Area} + 17.103 * \text{Age}, \quad (10)$$

$$\text{Patching quantity} = -59.911 + 1.117E - 03 * (\text{ADT}) - 5.478\text{E} - 05 * \text{Int. Area} + 13.484 * \text{Age}, \quad (11)$$

$$\text{Polished aggregate quantity} = -83.487 + 4.544\text{E} - 03 * (\text{ADT}) + 3.221 * R + 3.323\text{E} - 04 * \text{Int. Area} - 1.981 * \log(\text{Age}), \quad (12)$$

$$\text{Potholes quantity} = -11.569 + 3.444\text{E} - 04 * (\text{ADT}) + 0.399 * (\text{Age}), \quad (13)$$

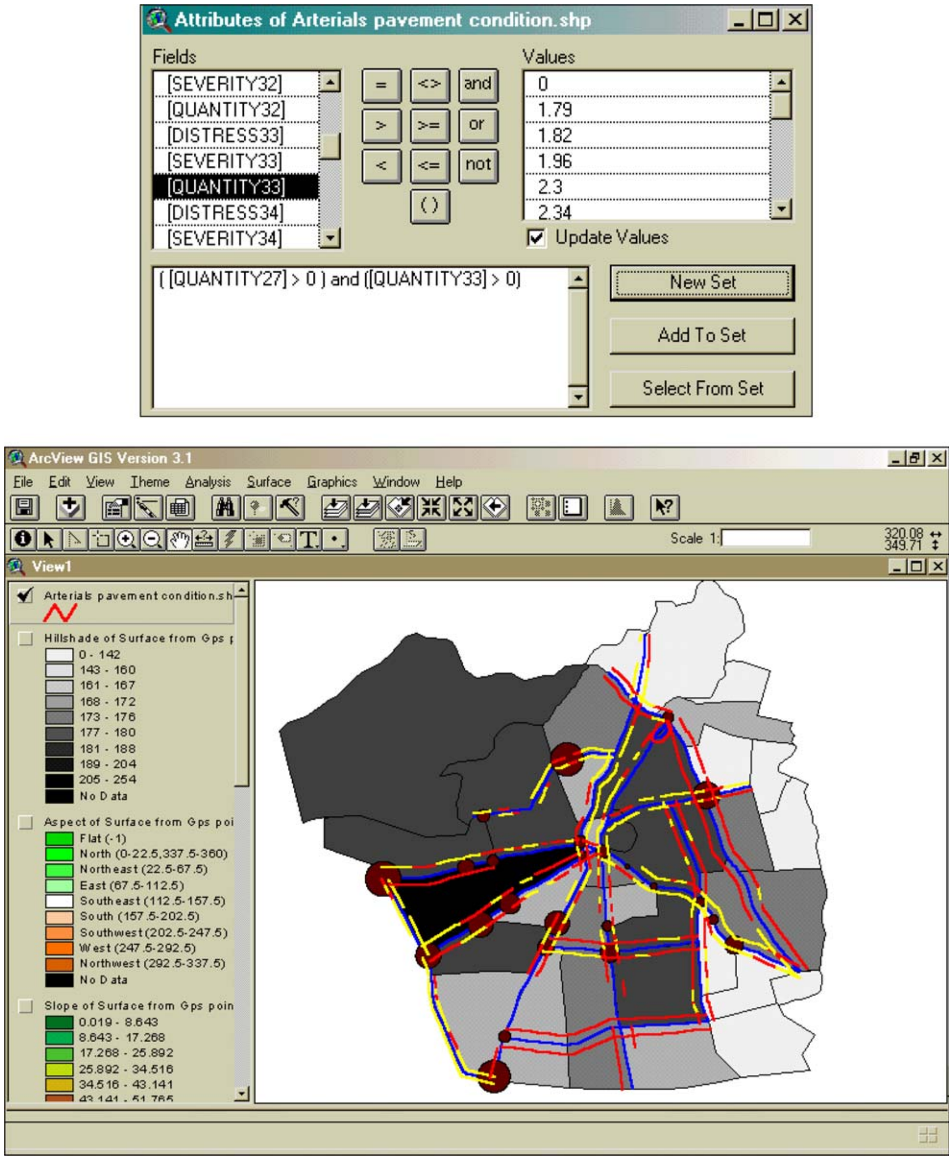

Fig. 9. Query results for H-severity patching and M-severity rutting on arterial sections.

$$\text{Rutting quantity} = 728.9 + 4.252\text{E} - 02 * (\text{ADT}) - 7.368 * R - 10.843 * \log(\text{Age}), \qquad (14)$$

$$\text{Shoving quantity} = -20.897 + 7.832\text{E} - 04 * (\text{ADT}) - 1.526\text{E} - 04 * \text{Int. Area}, \qquad (15)$$

$$\text{Slippage cracking quantity} = -119.105 + 4.237\text{E} - 03 * (\text{ADT}), \qquad (16)$$

$$\text{Swell quantity} = -50.748 + 2.371\text{E} - 03 * (\text{ADT}) - 3.995\text{E} - 04 * \text{Int. Area}, \qquad (17)$$

$$\text{Weathering \& raveling quantity} = -34.119 - 6.139\text{E} - 04 * (\text{ADT}) + 3.802 * R + 15.153 * \text{Age}. \qquad (18)$$

Table 8 summarizes the statistical characteristics 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 involved variables in each distress model on the distress development and extension. In most of the developed models ADT and pavement age variables played a vital role in distresses development, with slightly higher effect of pavement age. This result emphasized the fact that traffic and environmental-based loads were the prime generator of distresses on flexible pavement roads.

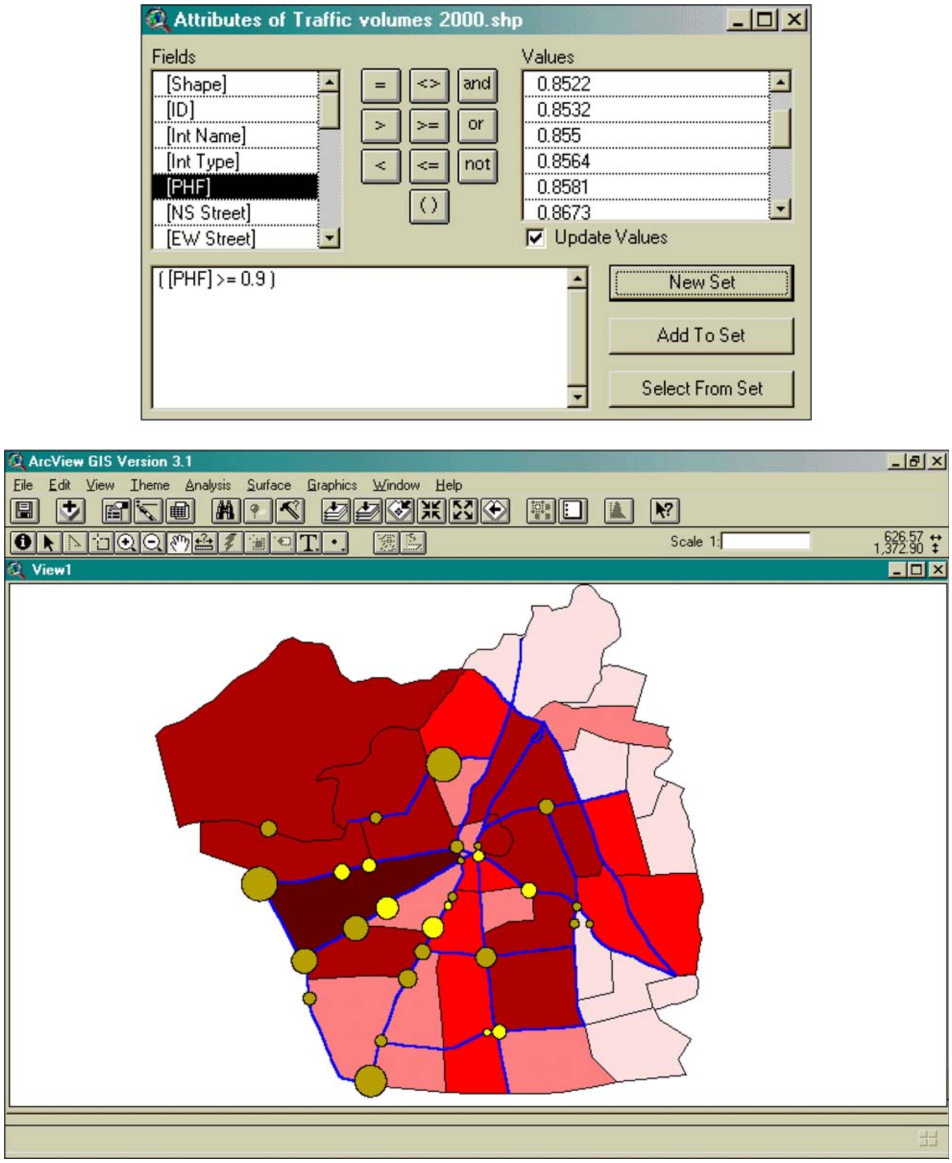

Fig. 10. Irbid intersections having PHF greater than or equal 0.9.

Table 8
Statistical characteristics of the developed distress models

Model	R^2	Adjusted R^2	Significant level	α-Acceptance criterion
Alligator cracking	0.467	0.416	0.001	0.1
Bleeding	0.613	0.459	0.093	0.1
Bumps & sags	0.957	0.952	0.000	0.1
Corrugation	0.926	0.921	0.000	0.1
Depression	0.944	0.935	0.000	0.1
L & T cracking	0.925	0.906	0.000	0.1
Patching	0.957	0.951	0.000	0.1
Polished aggregate	0.963	0.946	0.000	0.1
Potholes	0.804	0.739	0.008	0.1
Rutting	0.910	0.891	0.000	0.1
Shoving	0.939	0.909	0.004	0.1
Slippage cracking	0.872	0.830	0.020	0.1
Swell	0.936	0.915	0.000	0.1
Weathering & raveling	0.969	0.965	0.000	0.1

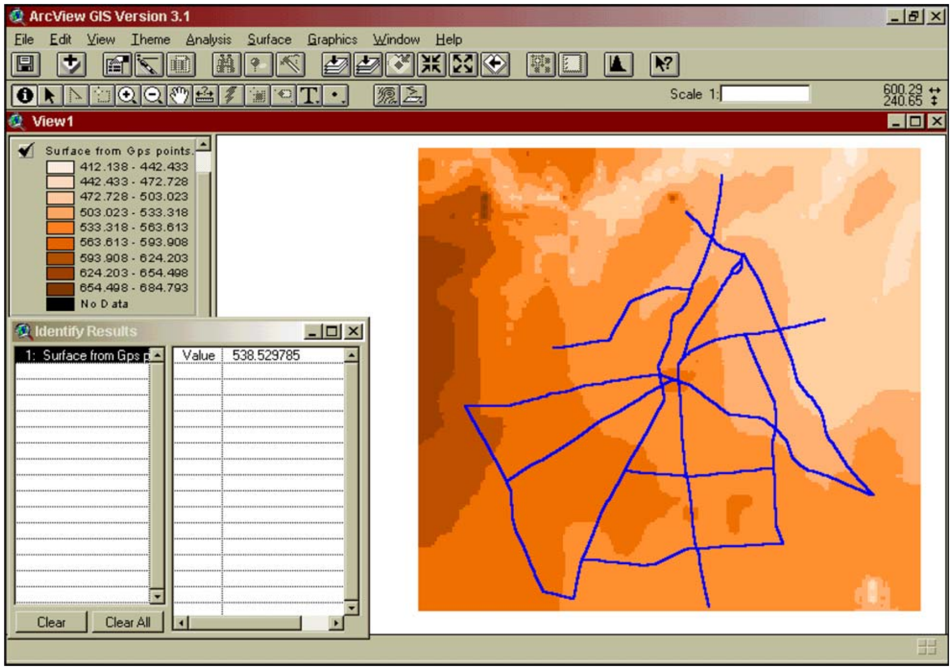

Fig. 11. Grid interpolation for Irbid city utilizing GPS database.

7.6. GIS spatial analysis

Spatial analyst extension provided tools to create, query, analyze and map cell-based raster data and to perform integrated vector-raster analysis using feature-based and grid-based themes. The following spatial analysis options could be performed when utilizing the GPS-elevations database:

1. *Mapping contours*. Contouring produces an output line theme from an input grid theme. The GPS elevation database is one of the best raw data compilations for creating contour mapping. Using the measured GPS elevations and horizontal positions (a grid of 100×100 m) contour maps representing the natural terrain levels were developed.
2. *Grid interpolation*. Interpolated grid surface filled in the gaps of a given point theme by analyzing the points around each location to create a continuous surface. Each cell in the output grid theme represented the value on the surface at that location, according to the surrounding points. Fig. 11 shows the grid interpolation results using the GPS data for Irbid city.
3. *Slope deriving*. Derive slope process involves calculations of the rate of maximum change for locations on a grid theme. Each cell in the output theme contains a continuous slope value represented in degrees. When the input is a grid theme, the rate of maximum change for each cell to its neighbors is calculated using a 3 by 3 pixels window.
4. *Hillshade computation*. Hillshade spatial analysis computes illumination values for a grid. Each cell in the output grid theme represents the illumination at that location on the surface, based on the direction of the sun (azimuth) and its height in the sky (altitude).

8. Conclusions

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

1. An automated system that integrated GIS, GPS and CVS was developed. The system was of great help for pavement distresses data collection, analysis, manipulation, displaying and classification. The system's development is a step toward real-time distresses classification.
2. The developed system could provide users with numerous advantages including:
   (a) A scheme for distributing maintenance priorities based on priority indices values and available budget criterion.
   (b) A scheme to estimate flexible pavement maintenance costs.
   (c) Various spatial and analytical query GIS tools for roadway inventory, pavement condition, severity levels, PI, traffic volumes, contours mapping, grid interpolation, slope deriving, aspect deriving and hillshade computations.

3. Data acquisition for pavement distresses using PC-automatic systems proved to be a quick, money and labor saving system. This in turn showed a great potential for time saving through the use of digital data reduction procedures.
4. Statistical models were developed to quantify each type of distresses. These models utilized influencing variables including ADT, distance from maintenance unit (R), section area and pavement age. The developed prediction models were reliable, accurate and highly significant, represented by the high values of their respective R^2.
5. ADT and pavement age were the most important factors in predicting distresses quantities.
6. Pavement conditions analysis results showed that sections located in the CBD-areas and due to high traffic levels exposures and low maintenance experience, suffered from different types of distresses related to traffic and pavement age parameters.
7. The integration of GIS, GPS and CVS is anticipated to open the door for automated, informative, practical and reliable systems.

The following recommendations could be suggested:

1. Widening the application of such an integrated system over the great municipalities to provide an up-to-date, precise and comprehensive pavement condition database that has the capability to assign maintenance priorities activities and to compare current and future pavement conditions.
2. Applying the PI concept criterion to setup maintenance priorities, maintenance cost, and pavement management programs.
3. Adapting PC-based vision systems for the purpose of distresses data collections and measurements.
4. Adapting traffic management options for municipalities to relieve traffic pressure from CBD roadway networks and to reduce traffic effect on distresses development.
5. Adapting comprehensive maintenance programs based on the integrated, developed system would direct maintenance activities to sections with high deterioration rates rather than a random selection of streets.

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