Application of GIS technology in Pavement Management Systems

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Professional paper

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The Geographic Information System (GIS) is a useful technology for managing spatial databases, which are the basis of the Pavement Management System. When creating a pavement management system in GIS, the needs and available resources of individual road authorities should be considered. This paper describes establishment of a simple database management system for small city administrations. The database was created by manual collection of pavement condition data at several unclassified roads in the city of Osijek. Based on collected data, the system calculates the PSI index and compares pavement condition.

Key words:
pavement maintenance systems, GIS, road infrastructure management, databases, pavement condition

Stručni rad

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Primjena GIS tehnologije u sustavima održavanja kolnika

Geografski informacijski sustav (GIS) korisna je tehnologija za upravljanje prostornim bazama podataka koje su osnova sustava za upravljanje kolnicima. Pri kreiranju sustava za upravljanje kolnicima u GIS-u treba uzeti u obzir potrebe i dostupna sredstva pojedine uprave za ceste. U radu je prikazana uspostava jednostavnog sustava za upravljanje i vođenje baze podataka za potrebe malih gradskih uprava. Baza podataka stvorena je ručnim prikupljanjem podataka o stanju kolnika nekoliko nerazvrstanih cesta u gradu Osijeku. Na osnovi prikupljenih podataka sustav proračunava PSI indeks i uspoređuje stanje kolnika.

Ključne riječi:
sustavi održavanja kolnika, GIS, upravljanje cestovnom infrastrukturom, baze podataka, stanje kolnika

Fachbericht

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Anwendung der GIS-Technologie in Straßenunterhaltungssystemen

Das geografische Informationssystem (GIS) ist eine nützliche Technologie für die Verwaltung der räumlichen Datenbanken, welche die Grundlage des Systems des Fahrbahnmanagements bildet. Bei der Entwicklung des Fahrbahnmanagementsystems im GIS müssen auch die Anforderungen und die Verfügbarkeit der Mittel einzelner Straßenverwaltungsbehörden berücksichtigt werden. In der Abhandlung werden die Einrichtung eines einfachen Systems für das Management und die Leitung der Datenbanken für die Bedürfnisse kleinerer städtischer Behörden. Die Datenbank wurde durch manuelles Zusammentragen von Daten über den Zustand von Fahrbahnen einiger nicht kategorisierter Straßen in der Stadt Osijek erstellt. Aufgrund der zusammengetragenen Daten berechnet das System den PSI Index und vergleicht den Zustand der Fahrbahn.

Schlüsselwörter:
Straßenunterhaltungssysteme, GIS, Straßeninfrastrukturmanagement, Datenbank, Fahrbahnzustand

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1. Introduction

The systematic pavement management and pavement maintenance become increasingly important with the advancing age of pavements and related degradation of pavement, which is further aggravated by steady increase in traffic load and infrastructure requirements. An important element in pavement management and maintenance are financial resources, i.e. how to optimally allocate limited resources. An efficient management and maintenance of roads requires systematic and continuous collection of various road condition data, particularly those on pavements condition, as well as good management of databases that are used for storing such information. Spatial databases are the foundation of the entire public road database. They are based on GIS technology in which alphanumeric data are linked to the georeferenced vector spatial data.

The Geographic Information System (GIS) is an information-technology database management tool that enables creation, visualization, query, analysis and interpretation of georeferenced data. It is unique in its ability to integrate spatial data in the form of vectors (points, lines, polygons) and grids with alphanumeric data (attributes). The data visualization capabilities, integrated logical, mathematical and statistical functions for spatial analysis, and the use of topography for decision making, constitute an important advantage of GIS compared to other database management or map creation tools.

GIS is recognized as a useful technology in many fields of engineering, and especially in the planning and maintenance of infrastructure. Given the spatial component of the road infrastructure data, GIS offers an ideal solution for maintaining a road database, which is a basis for decision making and pavement management.

This paper provides an overview of pavement management systems and their integration with GIS, while also presenting the possibility of establishing a simple system for managing and keeping a road database to meet the needs of small-size city administrations. Processes for assessing and comparing pavement condition are also presented.

2. Road infrastructure management

The Pavement Management System (PMS) is described as a set of tools and methods that help decision-makers find a cost-effective strategy for assessing and maintaining pavements in a serviceable condition [1]. It is a systematic process of planning, programming, analysis, construction and research within road infrastructure. Maintenance planning is largely subjected to financial and time constraints, and so the purpose of the system is to help infrastructure managers make decisions, establish priorities, and optimize the overall process. An efficient Pavement Management System is the one that maintains all pavements at a sufficient level of serviceability, that results in low user costs, requires small funds, and does not create adverse effects for the road safety and environment [2]. The development of these systems began in the late 1960s when the emphasis shifted from the design and construction of new road infrastructure to the maintenance and rehabilitation of existing infrastructure. Initially, those were the systems with simple capabilities for data processing, evaluation and ranking of roads based on factors such as pavement or traffic condition. Today, they enable prediction of future pavement condition, economic analysis of preventive or subsequent maintenance activities, creation of long term maintenance plans, optimization and creation of priorities based on multiple components [3].

The Pavement Management System structure is shown in Figure 1. The system consists of the following components: pavement condition survey, road network database, quality evaluation tools, analytical tools and models for predicting pavement properties and user and agency costs, tools providing assistance in decision making and implementation processes [4, 5].

Pavement Management Systems (PMS systems) are also referred to in literature as PMMSs (Pavement Management Maintenance Systems), i.e. the systems that specialise exclusively in the management of pavement maintenance [6, 7]. A variant of these systems that can be found in literature are the so-called Road Information Systems (RIS) [8]. These are unique road databases that usually contain information on roads in the jurisdiction of a particular administration, time of construction, geometry, facilities, drainage, and signs & markings.
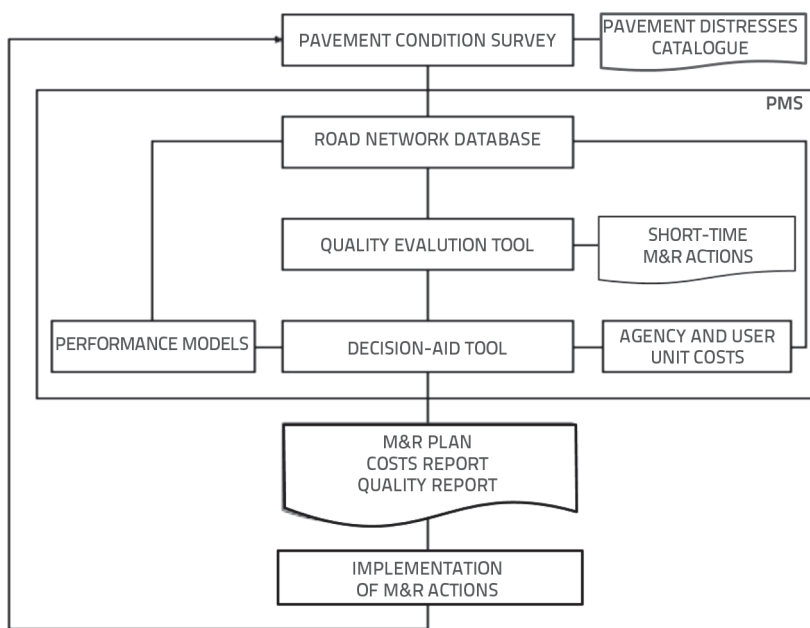

Figure 1. Structure of Pavement Management System [4]

An essential element in the development of a pavement management system is the process of data collection and database creation, since all other system activities are generated on the basis of these initial activities. Before beginning with data collection, it is necessary to carefully select the quantity and the type of data to be collected, the required quality of data and their level of detail, so as to make sure that the data are sufficient for decision making, and that they are compliant with the available equipment and financial resources [9].

The data on pavement condition can be collected manually, by visual inspection, and/or by measuring equipment, or automatically by specially equipped vehicles. In manual data collection, the so-called catalogues of pavement damage are usually used to allow for proper classification of damage, and to make the procedure consistent in all circumstances. The automated data collection is carried out by vehicles equipped with appropriate devices, such as digital cameras, global navigation satellite systems (GNSS), gyroscopes, laser profilographs, and other laser sensors. New technologies, such as drones or LiDAR, are increasingly being explored and applied for recording pavement condition [10]. The data collected in an automated way are fully interpreted and analysed with the help of computer programs in order to obtain appropriate pavement condition results, or are processed in a semi-automated manner in which case trained professionals review the records in order to detect damage. This type of data collection requires expensive equipment, but is faster and more efficient.

When creating a road network model, the position of all collected data should be determined by positioning reference systems. For many years, the linear reference system (LRS) was used in transport infrastructure. In this system, the position of measured data is linked according to its distance from the known starting point of the linear element (e.g. road axis). The automation in data collection also implies the shift to a reference system that is based on geographical coordinates. By using GNSS, the position of each collected data can be determined very accurately based on the longitude and latitude data [11].

The data collected to create databases for pavements and other transport infrastructure facilities include: hierarchy of each road network segment, position of each road network segment, road geometry, number and width of traffic lanes, marginal strips and shoulders, pavement structure data, pavement maintenance history, average cost of road maintenance and rehabilitation, and other data (e.g. traffic signalization, drainage).

Decision aid tools are a component of the PMS system. These decision aid tools can be based on the priority ranking model or on the system optimization model. When ranking priorities, the pavement condition data should be combined into a single index representing pavement quality. After that, pavements are sorted according to a chosen criterion. After assigning ranking to a roadway, it is possible to allocate funds intended for its maintenance and rehabilitation. The ranking and categorization criteria are usually parameters such as road category and class, road significance within the road network, traffic intensity, pavement quality index, etc. Although such models facilitate decision-making, they do not include tools for selecting best strategies for long-term road maintenance and rehabilitation, as such tools require the use of more complicated optimization models. Optimization models are used in an attempt to meet one or more established objectives in order to create the road maintenance and rehabilitation strategy of highest possible efficiency. The objectives are designed to minimize costs (maintenance and rehabilitation costs, vehicle operating costs), achieve the best quality pavements within the available annual funding, and maintain pavement quality as long as possible after the end of the planned road life cycle. In these models, pavement data are initial input parameters and the pavement behaviour model is used to predict future pavement condition. Various maintenance and rehabilitation actions are used as variables for optimization, while boundary conditions to be met during optimisation are available annual funding and minimum pavement quality requirements [12].

3. Application of GIS for pavement management and maintenance system

Due to their spatial analysis capabilities, Geographic Information Systems (GIS) are an ideal tool for improving pavement maintenance systems because the data they contain are of geographic nature [7, 11]. In literature, the integration of these two systems is called either G-PMS or GIS-T (T-transportation) when traffic data are also included.

Using GIS in such systems enables a prompt response regarding interconnection of spatial data, geospatial analysis, analysis of the entire network or its segments, and updating and modifying the road network and relevant data. The data can be grouped in a very simple way using colours according to the type of data, and their attributes or values. In addition, they can be marked by selecting attributes. Zooming in to the required level of detail is also available, and maps and presentations can be created. Also, as to large quantities of data collected by different agencies or participants in infrastructure maintenance activities, GIS provides a very significant help in collecting, integrating and managing these databases [7, 11, 13-15], and the output data are formed in such a way that they can easily be understood by management and public stakeholders [16].

3.1. Worldwide application of G-PMS

The idea of improving pavement maintenance systems by applying the geographic information system has been in use for a number of years in various forms. Literature provides examples of how universities apply it for the purpose of conducting research on a small number of roads, sometimes at the campuses of these universities [7, 17], or in cooperation with local road administrations to create a pavement maintenance system for urban areas [15, 18-20]. In Arizona and North Carolina, such systems have been created by federal government in cooperation with universities, and applied in several districts [13, 21].

Examples in literature mention numerous GIS software products for the creation of such systems: ArcView [7, 20, 22-24], ArcInfo [19], MapInfo [13, 15], ArcGIS [4, 25], Geomedia Pro [6], and ESRI MapObjects [14, 26]. Analyses performed in GIS differ in terms of complexity and range from queries, pavement condition assessments, total annual maintenance cost calculations, and long-term maintenance planning. For example, in paper [22], the criteria used for selecting road pavement maintenance activities are based on an average annual daily traffic of 5 000 to 10 000 vehicles, roughness of up to 4m/km, and the total area under cracks greater than or equal to 10%. In a GIS-based system, these criteria are easily applied by creating queries if the attributes containing traffic, roughness, and cracking data are defined for a given road. In [2z], the map of pavement maintenance priorities is the result of attributes of measured pavement roughness IRI as assigned in GIS. Other papers introduce the pavement condition assessment index: PSR (Pavement Serviceability Rating) [23, 28], PASER (Pavement Surface Evaluation and Rating) [18], CRS (Condition Rating Survey) [20], PCI (Pavement Condition Index) [6, 21, 29], PACES (Pavement Condition Evaluation System) [14], and PSI (Pavement Serviceability Index) [19, 30]. In addition to GIS tools, these papers also mention their use in combination with specialized software products for database creation, pavement management modelling, or decision-making, such as MicroPaver [17, 31], HDM-4 [22], GENENTIPAV-D [19], Visual Basic [26] and some other open source tools, developed either by individuals or at university level [12, 13, 32]. The most comprehensive G-PMS system of this kind, presented in paper [19] for the city of Lisbon, consists of a pavement database, pavement quality assessment tool, and a decision aid tool that takes into account the cost of maintenance and available resources, as well as road user costs.

3.2. Application of GIS in Croatia

In Croatia, GIS technologies are used in the development of spatial plans, property registers, e-cadastres, and geoportals. A review of relevant literature also reveals various applications in timber industry [33, 34] and studies exploring the possibilities and advantages of its application in construction industry – water engineering [35, 36] and road and rail infrastructure [37-39].

An overview of a GIS-based pavement maintenance system operated by Hrvatske ceste (Croatian Roads) is offered in [37]. The system is based on the assessment of pavement condition by means of recorded properties and traffic and, in the future, it should serve as a basis for selecting an optimum maintenance strategy. Due to unsystematic and incomplete transport infrastructure data in the city of Osijek, a pilot project [38] was conducted to create a transport infrastructure database in ArcView software, limited to the strict downtown area of the city. In [39], the authors used GIS to create a cadastre of walls and culverts on two county roads.

The requirement of keeping uniform road databases in Croatia is prescribed by the Roads Act [40]. Road administrations are required to keep such databases, and the manner of doing so is regulated by the *Byelaw on the form, content and manner of keeping databases on public roads and their facilities* [41]. Road database is defined as a "set of interconnected data providing through interaction an information on the condition of public roads and their facilities, integral elements and traffic on those roads, which are used appropriately and under specified conditions for the management, construction, maintenance and ensuring safety of public roads and traffic operated on such roads" [41].

These uniform databases consist of two parts: spatial database and alphanumeric database. The spatial database contains georeferenced vector spatial data on the road axis to which alphanumeric data are linked (road markings, road geometry, information on pavement type and condition, road facilities, traffic, etc.). Defined in this way, these uniform databases are fully consistent with the data defined in GIS; spatial data are equivalent to georeferenced vectors, and alpha-numeric data are equivalent to attributes linked to vectors.

While there are some initiatives and research in this area, it can be noted that the application of GIS for pavement management in Croatian cities is still insufficient. The survey [42] carried out at the level of local government units in eastern Croatia shows that only one out of fourteen surveyed administrations applies GIS for keeping a pavement database. The main reason for this situation are limited and insufficient resources that sometimes fail to cover even the existing pavement damage, which means that the funding is also lacking for the improvement and modernisation of the management system for unclassified roads.

4. An example of GIS use for pavement management in urban areas

Establishing a GIS-based system for keeping a pavement database does not necessarily require purchase of expensive commercial software programs. In other words, this lack of resources is no longer a limiting factor, as an appropriate free software can be used. In this context, creation of a uniform database in a free GIS software for several selected streets in the Osijek district of Donji grad is described below. Although these free software products do not have the commands specially adapted to pavement management, their embedded commands and functions still enable easy creation of a uniform database as defined in the Byelaw [41]. Apart from the database, the pavement condition assessment based on the recorded damage, which can be used when making decisions about maintenance priorities, is also modelled in this example. A free open source software QGIS was used to show that a digital GIS pavement database can be established quite rapidly, and that the database creation and operation requires only the knowledge of basic software, without connecting it to external tools (SQL, etc.).

4.1. About the QGIS software used

Quantum GIS (QGIS) [43] is an open source software created in 2002 with the aim of bypassing commercial software and extending availability of GIS to all personal computers. QGIS

provides easy-to-use user interface, supports many raster and vector data formats, can be upgraded to various additional connections, and its source code can be customized depending on particular needs. Although it is not specifically intended for the use of GIS in traffic infrastructure management, as a free and widely available software it is one of possible solutions for managing databases and unclassified roads pavements by small city administrations. The establishment of such a system could fully meet the needs of small city administrations given the limited resources available to them, traffic structure on their roads, and the requirements set for the infrastructure they manage.

4.2. System creation technology

Five unclassified roads in the Donji grad district of the city of Osijek were selected for designing the system in QGIS. These are smaller access roads with various types of pavement damage. They are managed by the city of Osijek. The existing pavement condition was recorded using GNSS, which recorded the locations of the edge points of each damage. Appropriate measuring equipment was also used to determine the degree of damage. Additional activities included photographing and sketching the damage and filling in a Visual Inspection Form using the *Catalogue of asphalt pavement damage* [44].

Figure 2. Form for entering information on road axis attributes

The data digitization was performed by inputting the axes of individual roads (line elements) based on the GNSS data on the starting and ending point of the segment. Alphanumerical data (attributes), which constitute the pavement database, were linked to the road axes (Figure 2): identification number (id), street name, segment name, road width, type of surfacing, road category, number of traffic lanes, traffic data and parking

lot data. The length of the segment was obtained by inquiring about the length of the mapped road axis vector.

Table 1. Damage attributes

Damage group	Line damage	Surface damage
Attributes	- id – number of demage - type of damage - class of damage - length of damage - id of street where it is located - converted affected - surface	- id – number of demage - type of damage - class of damage - surface of damage - id of street where it is located - vertical deformation

After that, by inputting the AutoCAD drawing (dwg document) containing geographic coordinates of the damage based on GNSS, the damage collected in vector form was digitalized and divided into two basic groups: line damage and surface damage. Linear damage includes longitudinal and transverse cracks, while surface damage includes alligator cracks, potholes, surface layer removal, depressions, patches, and repairs. Attributes defined for each group of damage are shown in Table 1. QGIS enables creation of customized drop-down menus (e.g. a drop-down menu with damage types or damage levels) for faster and easier digitization of data.
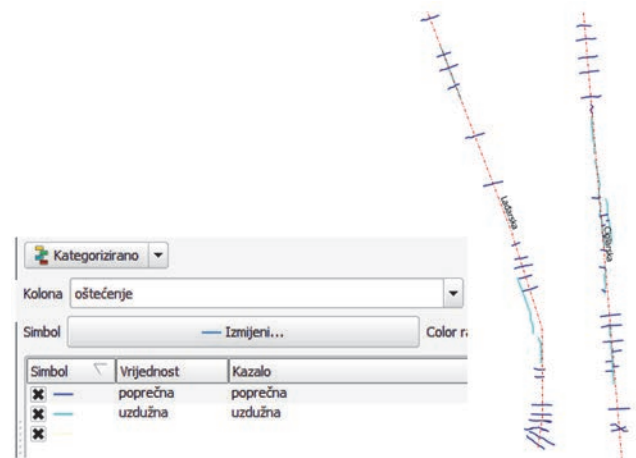

Figure 3. Categorized display of line damage according to type

A system defined in this way, with the associated attributes, is a foundation for creating various queries, analyses and statistics. It enables easy categorization of roads or damage according to their properties (Figure 3), easy isolation of individual types and levels of damage, while also facilitating calculation of the quantity and level of damage of a particular type for each street. For example, Figure 4 shows creation of a query that isolates only grade 3 transverse cracks that are located in segment 3, while other damage on this segment, or damage in other segments, are not displayed. Similarly, a query can be created

about the total number or quantity (length, surface) of damage for a particular segment or for the entire network of roads under study.

Figure 4. Creation of query for selecting grade 3 transverse crucks situated at segment 3

This database was then upgraded by modelling a process for calculating the present serviceability index (PSI). QGIS enables creation of an algorithm that performs the modelled process. In this case, it is a series of commands that are used for calculating the total quantity of individual types of damage categorized by street the damage is related to. Then the pavement condition index PSI is calculated for each street (Figure 5).

The PSI pavement index was selected for this example because it is expressed as a mathematical function of the digitized pavement damage:

$$PSI = 5 \cdot e^{\frac{-0,0002598 \cdot IRI}{4}} - \frac{0,002139}{4} \cdot R^2 - 7 \cdot 0,03 \cdot \left(C + S + P\right)^{0,5} \quad (1)$$

Where: IRI is the longitudinal roughness in mm/km, R is the medium rutting depth in mm, C is the total surface affected by longitudinal cracking in $m^2/100\,m^2$, S is the total surface affected by surface damage in $m^2/100\,m^2$, and P is the surface of patches in $m^2/100\,m^2$. The expression for the PSI index calculation was taken from the aforementioned paper [19] in which the weighting coefficients for individual damage were adjusted to the needs of the urban road network. It was established that the impact of longitudinal roughness and rutting on the ultimate value needs to be reduced in urban areas as, due to lower speeds and shorter travel distances in urban areas, drivers are more willing to accept a less comfortable drive.
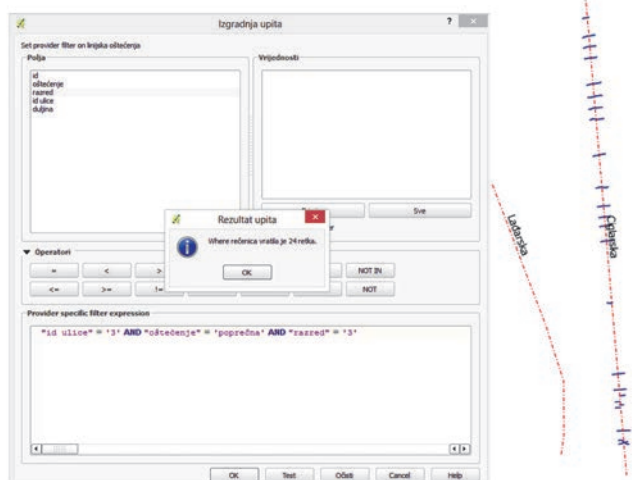
Table 2. Longitudinal roughness [19]

Level of damage	Description of damage	Quantity of longitudinal roughness [mm/km]
S1	User in passenger car does not feel vibrations	2000
S2	User in passenger car occasionally feels low level vibrations	3500
S3	User in passenger car feels smaller vibration on almost the entire segment or occasionally feels strong vibrations	5500

Longitudinal roughness was not measured due to lack of equipment, but values were defined according to Table 2 originating from [19]. Considering the street type and traffic structure, the level of rutting is not pronounced. That is why this phenomenon was neither registered nor digitized. However, rutting is still an integral part of the database and can subsequently be measured and added to already measured damage, if it has to be done in the scope of assessment of condition on the remainder of the road network.
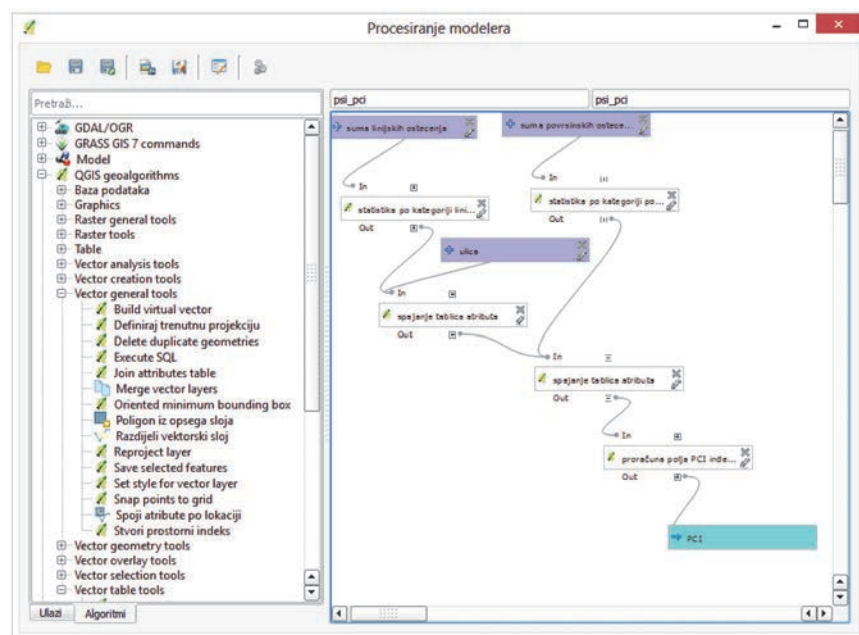
After starting the modelled process, the output information is the new layer containing PSI indexes of recorded pavements. Road axes are categorized based on PSI values and are displayed in various colours (Figure 6). It can be seen that three roads are in a very poor condition with an index between 2 and 2.5, while only one road has an index greater than 3. These results are in accordance with the actual pavement condition. Pavements in Cvjetkova, Banova and Ciglarska streets contain a significant quantity of all types of cracks,
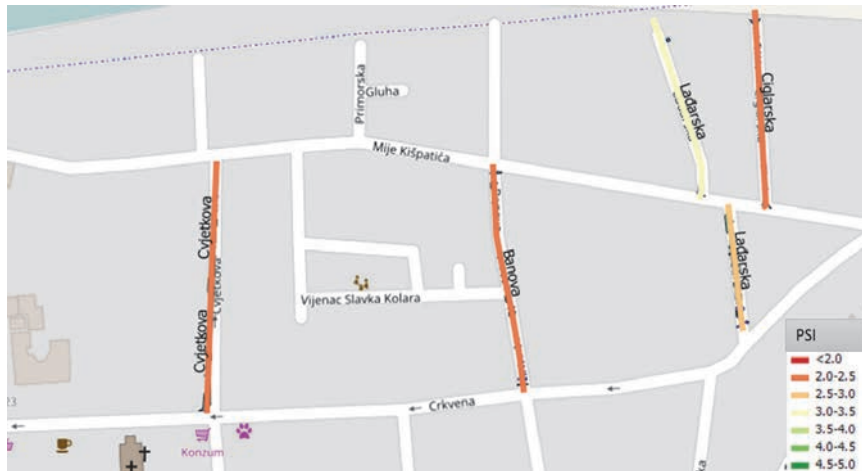

Figure 5. Creating process for calculating the PSI pavement index

are exclusively intended for road infrastructure management, their limiting factor is often the price or the scope and functions that do not necessarily correspond to the needs of a particular road administration. Various GIS technologies can be applied for establishing or keeping a road infrastructure management database. By using GIS, the system can be fully adapted to the operation of any road administration.

In the management of unclassified roads in Croatia, the application of new technologies is hampered by inadequate budget available to local governments. The solution can be found in the application of free software products like QGIS that have proven to be very successful in this example, even though the research was based on a small sample of roads. Existing or newly collected data can be easily digitized resulting in a uniform database, and additional benefits can be obtained by modelling the process, as demonstrated in the process for pavement condition assessment.

Pavement data collection activities should certainly be encouraged and expanded to a greater number of pavements in order to confirm suitability of this database-keeping methodology,

Figure 6. Display of streets categorized according to calculated PSI index

Figure 7. Photographs of actual pavement condition: a) Cvjetkova Street, b) Lađarska Street

potholes and other damage, and they would require pavement rehabilitation or more extensive maintenance operations. The northern part of Lađarska Street contains only lower-grade cracks (PSI index 3 – 3.5), while the southern part contains potholes resulting from war damage (PSI index 2.5 – 3.0).

by comparing the actual pavement condition and condition assessment as expressed by PSI index on a large number of samples. The slowness of local self-governments in the introduction of new technologies is the result of insufficient funding, but is sometimes also due to improper use of resources [42]. The solution should, therefore, be sought in free tools that would greatly contribute to the creation of a comprehensive picture of pavement condition, as well as to an easier definition of maintenance priorities, better allocation of available resources, and systematic use of such resources.

5. Conclusion

GIS tools have great potential in the management of transport infrastructure. Although there are software programs that

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