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Development of GIS- and GPS-Based Intelligent Network-Level Road Maintenance and Rehabilitation System

Nagendra R. Velaga [1] ***and Sunder L. Dhingra*** [2]

[1] Corresponding Author: Research Fellow in ITS, Centre for Transport Research, Digital Economy Research Hub, King's College, University of Aberdeen, Aberdeen, AB24 5UA, UK. Email: n.r.velaga@abdn.ac.uk, vnrao1981@gmail.com

[2] Professor, Transportation Systems Engineering, Civil Engineering Department, Indian Institute of Technology Bombay, Powai, Mumbai-400076, India

ABSTRACT

A user-friendly road maintenance and rehabilitation (M&R) system has been developed to find cost effective strategies for maintaining road networks in a serviceable condition. Pavement condition data and spatial road network data were collected using a GPS palmtop, segregated and arranged spatially on a GIS platform. The M&R toolbox, developed in GIS software TransCAD macros (computer program), performs various modules which provide prioritization of maintenance of each link in the network using a priority index approach, suitable rehabilitation strategies, link-wise budget requirements, effect of available budget on vehicle operating cost and road roughness. Furthermore, additional lane requirements based on volume and capacity ratio and its design were also considered. The developed M&R system was implemented for a small part of road network in Mumbai (Bombay) metropolitan area in India. It was identified that the enhanced M&R system, developed in this study, is effective in day-to-day road maintenance and helpful in the decision making process for planning and scheduling of road M&R work.

KEYWORDS: Road maintenance and rehabilitation, Priority index, GIS, GPS.

INTRODUCTION

The main objective of any road maintenance and rehabilitation (M&R) system is to maintain pavements to a high level of serviceability by optimally allocating the available budget in order to achieve the maximum benefits over a given period of time. The M&R of roads at network-level involve systematic collection, storage and retrieval of data, coordinating and controlling different activities, comparing various alternative maintenance strategies, making decisions in an efficient and economic manner and maintaining feedback information (Bandara and Gunaratne, 2001). This demands advanced tools and techniques to carry out data collection and analysis and to provide a user-friendly visual display of output which helps achieve the maximum benefits of such systems.

The use of geographic information systems (GIS) adds tremendous functionality to road M&R systems; they not only help in data collection, analysis and reporting, but also have the ability to interface with external programs and software and to provide simultaneous access to several layers of data (Obaidat and Al-Kheder, 2006). Furthermore, the use of GPS for data collection, using a standard coordinate system or a reference datum, makes it easy to import the information into GIS software and allows users to analyze the collected information in a GIS platform.

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The integration of GIS and GPS for road M&R system can speed-up the data collection process and reduce manpower requirements (Velaga et al., 2006). Moreover, the integrated system can provide details of pavement failures (such as potholes, rutting… etc.) on a digital map, which users can view on a GPS palmtop. This is helpful in locating the pavement failures for day-to-day road repairs. The GIS and GPS integrated system provides significant enhancement of many aspects of road M&R systems (Obaidat and Al-Kheder, 2006).

Software programs are available for network level road maintenance and rehabilitation such as IPMP's pavement management software, PARMMS road manager V3 and the highway development and management system HDM-4 (Odoki et al., 2006). However, these software programs have many limitations (for example, they are not compatible with data obtained from GPS) (Odoki et al., 2006). Moreover, a few road maintenance software programs do not give the freedom to use suitable maintenance strategies that are appropriate for a particular local area. The limitations of the existing software motivated us to develop and test a complete road maintenance and rehabilitation system which can answer some of these constraints. The developed system is particularly beneficial to local road maintenance authorities with numerous demands and limited resources.

A STATE-OF-PRACTICE IN APPLICATION OF GIS AND GPS FOR ROAD MAINTENANCE AND REHABILITATION

The aim of this section is to provide a brief review of the few existing studies on the application of GIS and GPS for road maintenance and rehabilitation. In the early 1990s, Paredes et al. (1990), Simkowitz et al. (1990) and Zhang et al. (1993) demonstrated the applicability of GIS as a tool for pavement management. The main objective of their study was to integrate pavement data from the Pavement Management System (PMS) in a GIS environment to facilitate quick and precise decision-making regarding maintenance and rehabilitation needs of pavements. The display of geographic (or spatial) information on maps is useful for managing transportation information resources (Johnson and Demetsky, 1993; Osman and Hayashi, 1994). Lee et al. (1996) discussed the design and function of GIS-based PMS for Salt Lake city, Utah, USA. Though these initial studies identify the GIS as a powerful tool for road maintenance and management systems, most of them did not completely explore the critical usage of GIS for road M&R systems.

Bham et al. (2001) developed the ArcView GIS-based Pavement Management System (PMS). They used a base map developed in ArcInfo GIS by the Illinois Department of Transportation (IDOT). A weighted benefit ranking (WBR) procedure was introduced to prioritize pavement rehabilitation. Flintsch et al. (2004) documented the state of the practice and knowledge of pavement management applications using Geographic Information Systems and other spatial technologies. Their study identified GIS and other spatial data management and analysis technologies as particularly appropriate for integrating, managing, collecting, cleaning, analyzing and presenting the data. Rao et al. (2006) developed a GIS-based maintenance management system for the major roads of Delhi city in India. The main objective of their study was to develop a database for study roads using GIS. Rao et al. developed thematic maps of road conditions and annual maintenance strategies of the network, based on a structural evaluation by Benkelman Beam Deflection (BBD) measurements (Rao et al., 2006).

Obaidat and Al-Kheder (2006) investigated the potential of integrating geographic information systems, Global Positioning Systems (GPS) and computer vision systems (CVS) for the purpose of flexible pavement distress classifications. It is envisaged that the integration of GPS, GIS and CVS systems is a powerful tool for collecting road condition data economically, accurately and safely. Moreover, they recommended that a complete road maintenance and rehabilitation system using GIS and GPS technologies is helpful in the decision making process.

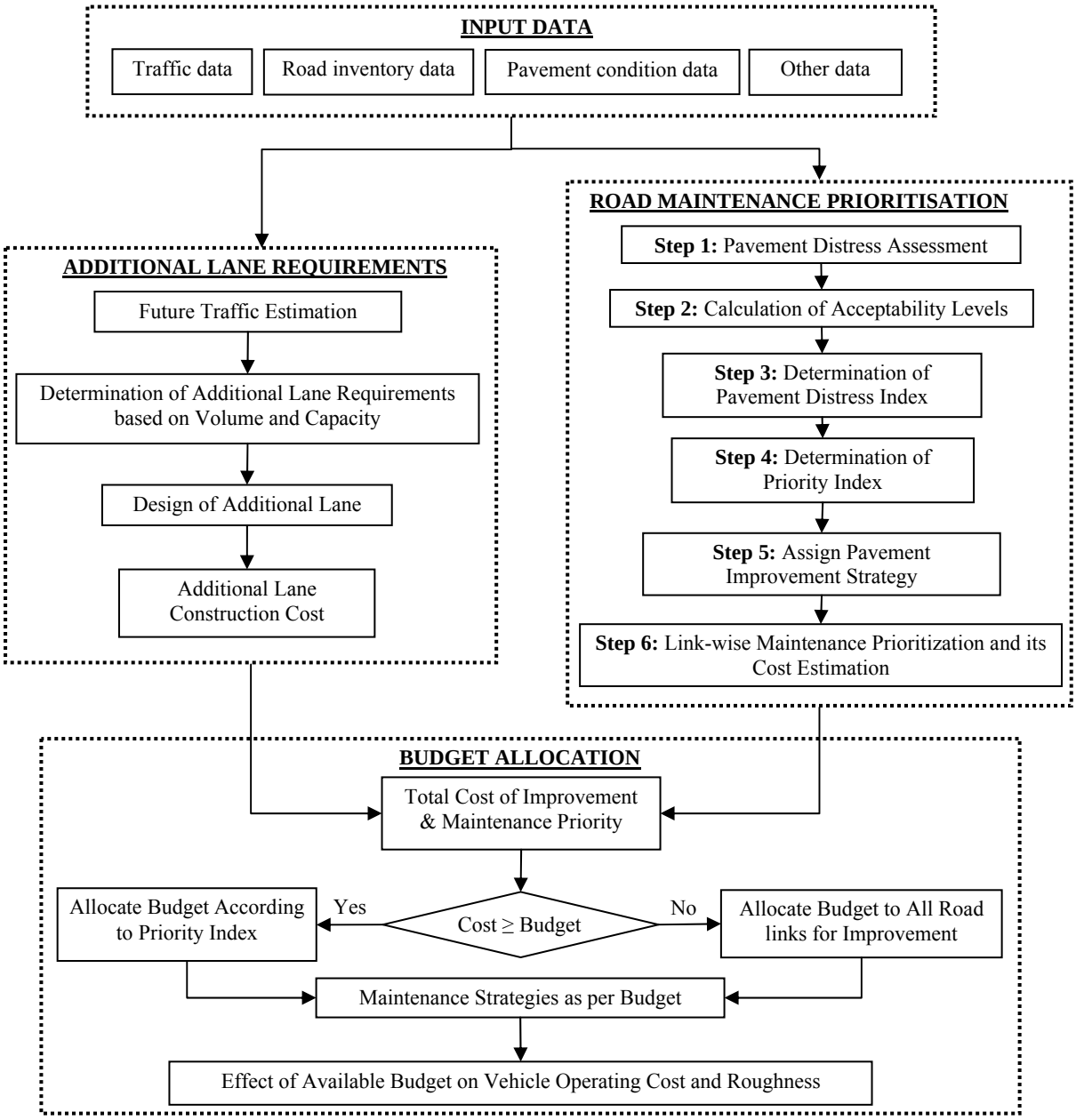

Figure 1: Description of Road Maintenance and Rehabilitation System

Integration of GIS and GPS with a high resolution camera and further using video image processing techniques can be faster for evaluating pavement conditions. However, some road failures, such as drainage failures, edge breaking, road shoulder or road side embankment failure… etc., cannot be collected using video-based techniques. The objective of this research is to develop a road M&R system which can support the decision making process at the time of budget allocation and to allow maintenance engineers to carry out day-to-day or regular maintenance. The main contributions are: (1) Effective and complete integration

of GIS and GPS for the M&R system (2) Supportive way for both day-to-day maintenance and annual budget allocation (3) A very powerful tool for decision making process (4) User-friendly and graphical interface.

DESCRIPTION OF THE DEVELOPED ROAD M&R SYSTEM

This section provides a description of the developed road M&R system by explaining various data inputs to the system, identification of additional lane requirements, prioritization of road maintenance and budget allocation. The procedure is shown in Figure 1.

In Figure 1, the total M&R system is divided into four parts: (1) input data, (2) additional lane requirements, (3) road maintenance prioritization and (4) budget allocation. These four parts are explained in the following sections.

Input Data

As mentioned in Figure 1, the input data includes (1) *traffic data*, (2) *road inventory data*, *(3) pavement condition data* and (4) *other data* such as various road construction and maintenance costs per unit area, vehicle damage factor, lane distribution factor… etc.

Traffic data consists of: link-wise average daily traffic (ADT) on the road, and traffic growth rates. *Road inventory data* comprises: category of road, capacity of road, road length and width, surface type, thickness of different layers, the historical data of original pavements, subsequent renewal information, pavement age, soil conditions such as California Bearing Ratio (CBR) of soil… etc. Part of this inventory data is obtained from office records, and the remainder is collected in the field. *Pavement condition data* consists of: pavement distress data like potholes, cracking, rutting, ravelling, patching and road unevenness. In addition to the distress data, other failures such as: roadside drainage and shoulder failures, sewage manhole failures, damage of signposts and wayside amenities are also collected manually using a GPS palmtop.

Additional Lane Requirements, Design and Cost Estimation

Traffic volume (V) and road capacity (C) for a specific period are calculated, and the volume-capacity ratio (V/C) is used to decide whether an additional lane is required or not. The design of the additional lane is carried out as per the guidelines given in Indian Road Congress IRC: 37-2001, "*Guidelines for the Design of Flexible Pavements*" (IRC, 2001). Furthermore, the construction cost is calculated. In this research, construction rates are taken from the Standard Schedule of Rates (SSR) of Maharashtra, India. However, the construction cost per unit area can be modified by the users depending upon their requirements.

Road Maintenance Prioritization

It is well recognized that each individual pavement distress type contributes in a distinct manner towards the aggregate pavement condition. For each distress type, relative severities are not equivalent. Thus, the determination of the overall distress index must accommodate the relative significance of each distress type and magnitude. The pavement performance data from in-service flexible pavements and their respective acceptability levels and weights from experts' opinions can be used in formulating the priority-ranking model. The pavement sections can be ranked for improvement according to respective Priority Index (PI) values obtained from priority-ranking model (Reddy and Veeraragavan, 2001). Road maintenance prioritization is further explained in the following six steps. These six steps are also highlighted in Figure 1.

Step 1: Pavement Distress Assessment

The first step is the identification and selection of those pavement condition attributes which are considered to significantly influence the overall acceptability of pavements to the user. The flexible pavement can usually be evaluated by five attributes or evaluation measures: unevenness, cracking, rutting, potholes and patching. From a physical condition survey, using a GPS palmtop and bump integrator

(which measures the roughness of the road surface), the type and extent of the above mentioned distresses can be identified and measured.

Step 2: Calculation of Acceptability Level

Acceptability levels are necessary to establish the extent to which a distress manifests itself. Establishing acceptability levels for each distress does not give a clear picture of the overall pavement condition. Therefore, it is necessary to assign a unique distress value to a pavement stretch, so that the extent of the sum of different distresses can be represented. Acceptability levels for five types of distress (cracked area, pothole area, patched area, rut depth and unevenness) are fixed. Table 1 illustrates the models used in this study.

Table 1. Membership Functions for Distresses (Reddy and Veeraragavan, 2001)

Performance Attribute	Membership Function	R^2	N	SE	Weights (W_i)
Cracked Area	AL = Exp (0.0137 - 0.024 CRA)	0.975	21	0.121	0.30
Area of Potholes	AL = Exp (0.073 - 0.077 PH)	0.982	19	0.102	0.25
Unevenness	AL = 1.157 - $1.088*10^{-3}$ RG	0.987	21	0.040	0.25
Patched Area	AL = Exp (0.155 - 0.0398 PT)	0.984	20	0.079	0.10
Rut Depth	AL = 1.03952 - 0.0351 RD	0.996	21	0.022	0.10

Where, AL is the acceptability level (0 to1), CRA is the cracked area of pavement in percentage, PH is the area of potholes in percentage, RG is the unevenness index in cm/km, PT is the patches area of pavement in percentage, RD is the rut depth in mm, N is the sample size and SE is the standard error.

Step 3: Determination of Pavement Distress Index

Pavement surface conditions can be assessed at any time by using an index considering the surface distresses in the form of acceptable level and relative weights. Pavement Distress Index (PDI) can be defined as:

$$\text{PDI} = \left\lfloor 1 - \sum \left(AL_i \times W_i \right) \right\rfloor \times 100 \qquad (1)$$

where, AL_i is the acceptable level of distress i; W_i is the weight of distress type i.

Using equation (1), a unique numerical value can be assigned to any pavement stretch based on the distress condition. This value is a function of the acceptability level and weights assigned to each pavement distress. Based on this, a very good pavement will have a PDI value nearer to 0 and a completely deteriorated pavement will have a PDI value close to 100.

Step 4: Determination of Priority Index

PDI of the pavement sections is determined using the distress weights and acceptability levels. Since traffic is a main factor which causes pavement distresses, traffic factors are to be taken into consideration by assigning weights to different ranges of traffic as well as the functional class of the pavement. The prioritization factors (F), based on functional class and average daily traffic, are used to adjust the PDI values in order to assign greater priority to the higher functional class roads and also to roads with higher traffic levels within a given functional class. In this study, the prioritization factors developed for Indian conditions by Reddy and Veeraragavan (2001) are used. The PI for a pavement section is computed as:

$$\text{PI} = \text{F} * \text{PDI} \qquad (2)$$

where, PDI is the Pavement Distress Index from equation (1) and F is the Prioritization Factor based on functional class and ADT (average daily traffic).

Step 5: Pavement Improvement Strategies

The type of pavement overlay is based on the PI. Eleven types of pavement overlays (with combination of Bituminous Macadam (BM), Bituminous/Asphaltic concrete (BC/AC) and Premix Carpet (PMC)) are commonly used in India. The PI and the corresponding overlay type are given in Table 2. Using the PI, the model assigns the different overlay type strategies (Strategy I, Strategy II, Strategy III) to the pavement sections.

Table 2. Overlay Type Based on Priority Index (Reddy and Veeraragavan, 2001)

Priority Index	Priority	Overlay Type Strategy
Strategy I		
25-30	6	75mm BM and 20mm PMC
30-35	5	50mm BM and 40mm BC
35-40	4	100mm BM and 20mm PMC
40-45	3	75mm BM and 40mm BC
45-50	2	50mm BM and 80mm BC
>50	1	100mm BM and 40mm BC
Strategy II		
10-15	3	40mm BC
15-20	2	50mm BM and 20mm PMC
20-25	1	80mm BC
Strategy III		
<5	2	Routine Maintenance
5-10	1	20mm PMC

Step 6: Link-wise Maintenance Prioritization and Its Cost Estimation

Road maintenance prioritization in the network is carried out using the Priority Index calculated in equation (2). Unit cost of each overlay type is one of the inputs to the system. Using this unit cast, the system calculates link-wise cost of recommended road maintenance. The scheduling of pavement maintenance should start with those pavements having the highest score of PI.

Budget Allocation

The developed M&R system calculates the required budget for road maintenance and widening, and this is then compared to the available budget. Here, the available budget value is provided by the user. If the availability of the budget is more than the required amount, then the recommended maintenance and widening of roads are carried out throughout the network. Otherwise, the maintenance priority is assigned to the road links in the network, as per the ranking of the calculated PI value. Moreover, the system provides information to the users on the effect of the available budget on vehicle operating cost (VOC) and roughness. In this study, VOC is calculated using the road user cost models developed by the Central Road Research Institute (CRRI), India.

STUDY AREA

To evaluate the performance of the developed road M&R system, a small study area was considered in Powai in the Mumbai (Bombay) metropolitan area of India. The total study area is approximately 400 acres, with a population of 14,000. A detailed road network of the study area is digitized in the GIS software Trans CAD, and is shown in Figure 2. The total road network is divided into 23 links. Based on traffic conditions,

connectivity and importance of the road, the total network was divided into three categories of road: major roads, minor roads and other roads. In total, 3.64 km length of major roads, 2.62 km length of minor roads and 0.91 km length of other roads were considered.

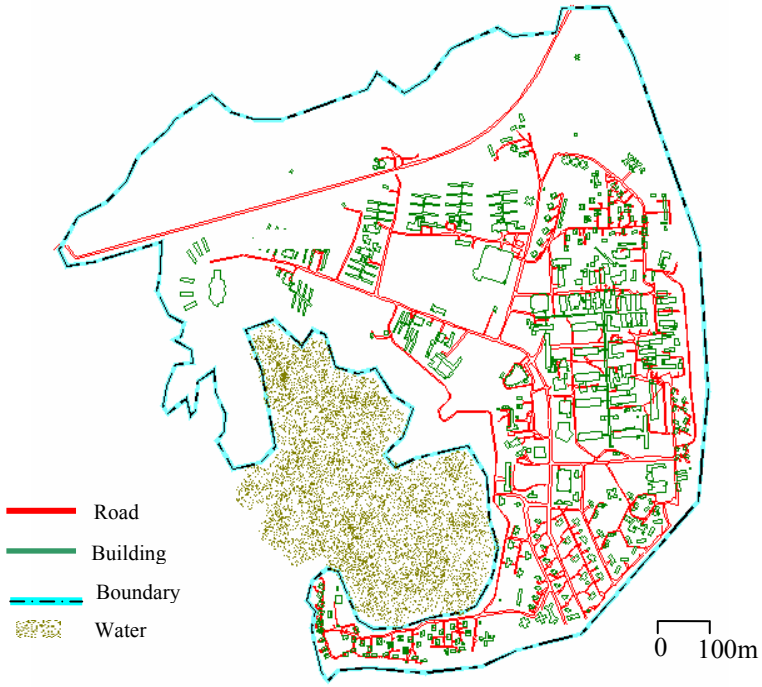

Figure 2: Study Area

DATA COLLECTION USING GPS AND SYSTEM IMPLEMENTATION IN GIS SOFTWARE

Geo-coordinates are assigned to the digital map using 'rubber sheeting' process in GIS software TransCAD; and this geo-referenced map is exported to a GPS palmtop. Data dictionaries are developed using the software program '*GIS pathfinder office*' and transferred to GPS. A data collector logs information in the form of 'features' and 'attributes.' Also, these data dictionaries allow users to collect various point features (such as potholes, manhole failures… etc.), line features (such as type of shoulders, number of lanes… etc.) and area features. Moreover, the user can enter the details of the failure in a GPS palmtop in the field, while collecting the data. The field data collected using GPS palmtop is segregated and arranged spatially on the GIS platform. Each road section is represented with a unique identification number (ID). Furthermore, the link-wise percentage of each failure is calculated. Figure 3 shows the pavement failures in the study area.

Link-wise average daily traffic (ADT), and other basic inventory data (such as road category, length, width, surface type, thickness of different layers, the historical data of original pavements, subsequent renewal information, pavement strength… etc.) are obtained from local government authorities. The pavement roughness is measured on each road section with 'Fifth Wheel Bump Integrator', and, a CBR test (socked condition) of sub-grade soil is carried out for additional lane design.

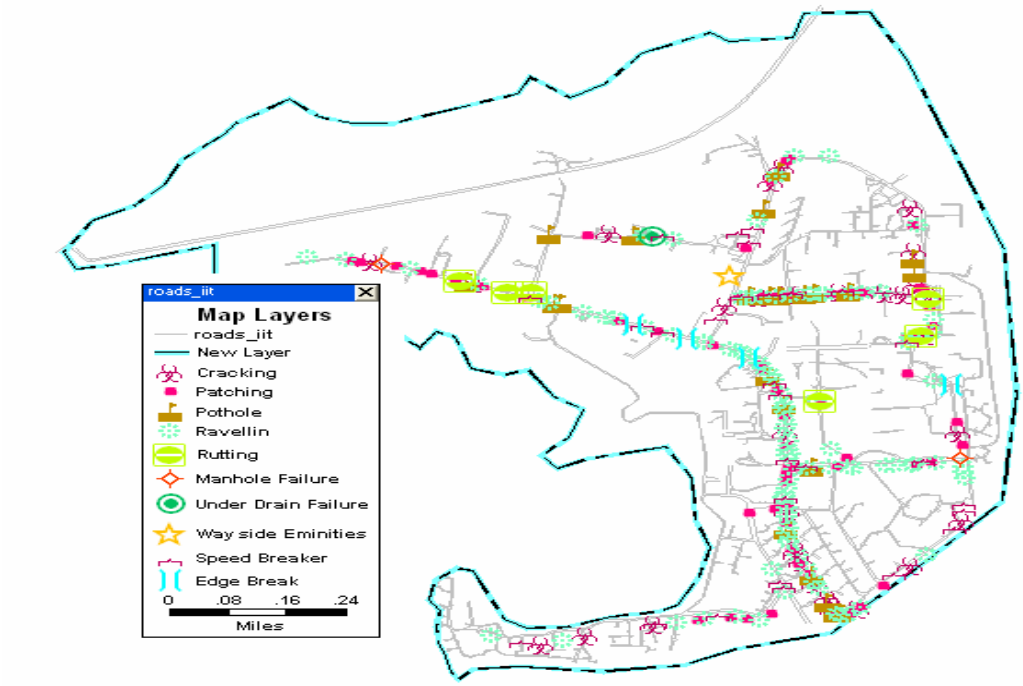

Figure 3: Pavement Condition Data

The road M&R system is implemented in GIS Software (TransCAD GIS developer's Kit). It is convenient for maintenance authorities to accomplish the day-to-day or routine tasks schedule by simply clicking a single button or choosing a single menu. It not only alleviates the cumbersome procedures involved in analysis and data presentation process, but it also allows the end users to work on the applications developed with minimal knowledge about TransCAD. As a result, handling of routine tasks will become easier, thus reducing the cost of training. In the following section, the performance of the developed road M&R system is described.

PERFORMANCE OF DEVELOPED ROAD M&R SYSTEM

The developed system is capable of forecasting the requirement of additional lanes and their design, calculating annual budgetary requirements, allocating funds for improvements based on the priority ranking and identifying the effect of the available budget on vehicle operating cost and road roughness. Moreover, user-friendly strip charts are produced for routine maintenance work. This section describes various modules developed in the M&R system.

Regular Road Maintenance

In the proposed road M&R system, in addition to pavement failures on road surfaces (for example potholes, rutting… etc.), other failures, such as road shoulders damage, road medians and footpath failures, damage to signposts… etc., are also collected using a GPS palmtop. The geo-coordinates of these failures are helpful for the regular maintenance of the transport infrastructure. For instance, the road failure data on GPS helps road maintenance authorities easily identify the exact location of the failure. After repairing the failure, the data set will be updated in the GPS by the maintenance authority. Moreover, the developed system

can also provide user-friendly strip charts in *Microsoft Excel* form for regular maintenance of roads at network level. Various modules developed in the M&R system are explained below.

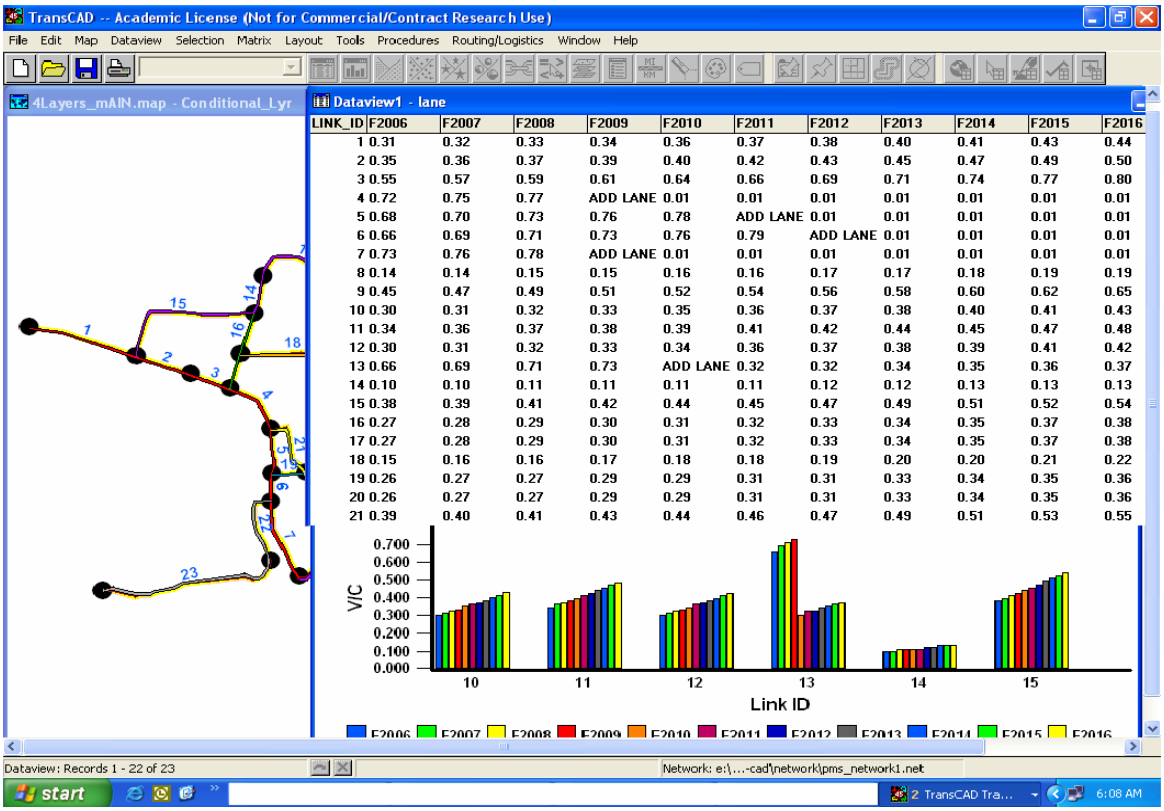

Figure 4: V/C Ratio Progression

'Traffic Forecast and V/C Ratio Calculation, Identification of Additional Lane Requirements and Its Design' Module

Figure 4 shows the road network along with link number, link-wise V/C progression and additional lane requirements for the analysis period. The graphical representation of volume and capacity ratio is provided by the system for the analysis period. The additional design module is based on IRC: 37-2001, "*Guidelines for the Design of Flexible Pavements*" (IRC, 2001). The additional lane design for the study area is shown in Figure 5.

'Priority Ranking and Allocation of Budget' Module

Link-wise PI and budgetary forecasting, for the study area, are shown in Figure 6. The first column in Figure 6 shows the link ID, followed by maintenance requirements and link-wise PI in columns two and three, respectively. The fourth column shows the link-wise cost of maintenance (in lakhs, Indian rupees; where 1 lakh is equal to 100000 rupees). An accumulated cost of maintenance is provided in column five.

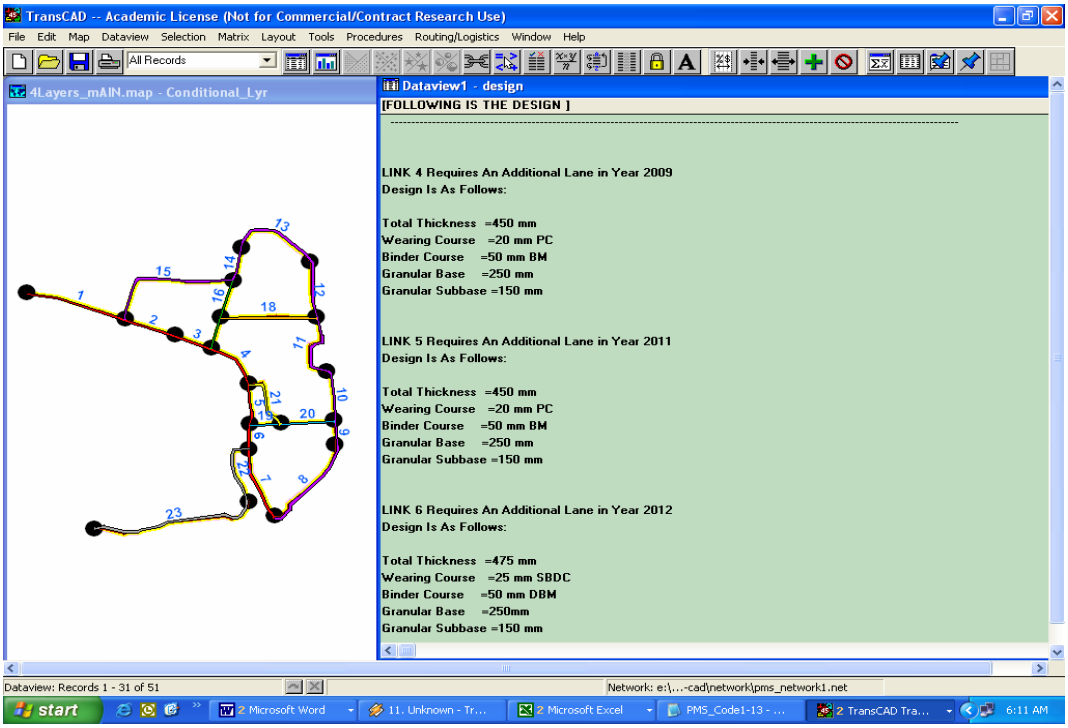

Figure 5: Design of Additional Lane

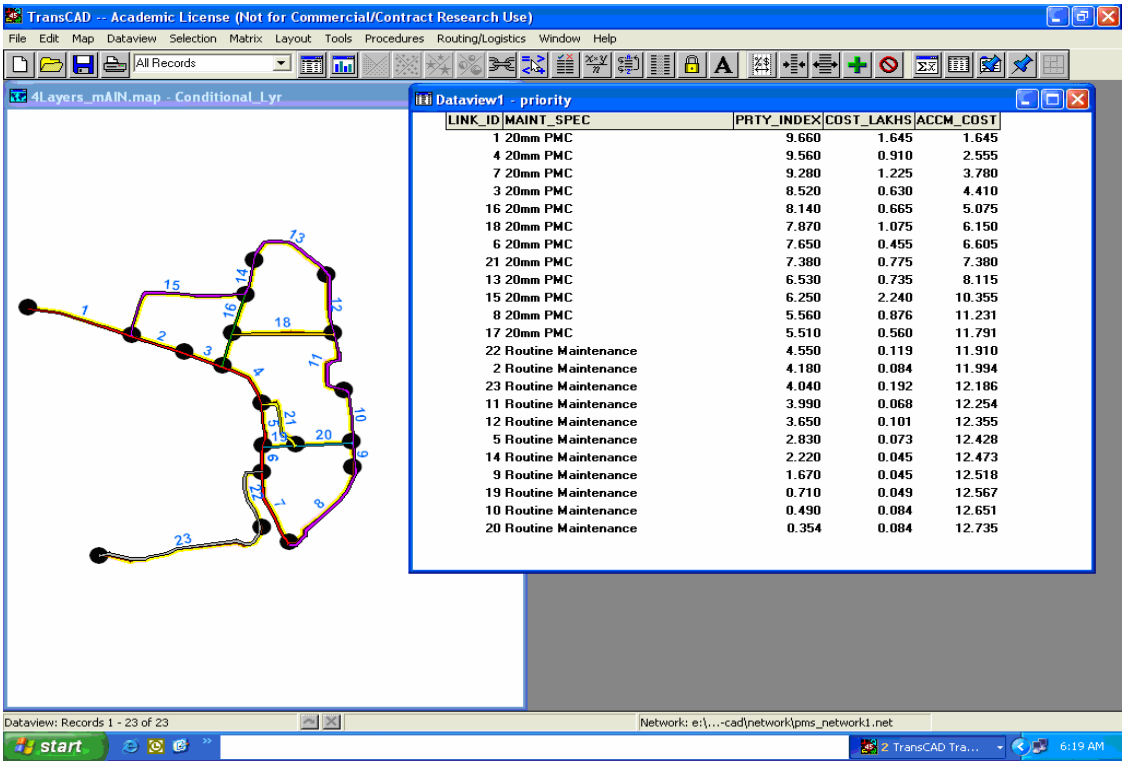

Figure 6: Road Maintenance Strategies and Their Prioritization

'Effect of Available Budget on Roughness of Road Surface' Module

This module is quite useful in finding the overall condition/health of a road network in terms of average roughness of the road surface. Also, this kind of analysis helps in ranking the alternative networks based on average roughness. In this analysis, overall condition (roughness) of the road network is measured for different budget scenarios, for the current year. Five different budget availability scenarios (i.e. *do nothing*, 25%, 50%, 75% and 100% of the total budget) are considered. Results of this module are depicted in Figure 7. The total budget requirements (in lakhs), percentage of available budget, available budget in lakhs and roughness (mm/km) are shown in columns two, three, four and five, respectively. The graphical representation of roughness with available budget is also provided in Figure 7.

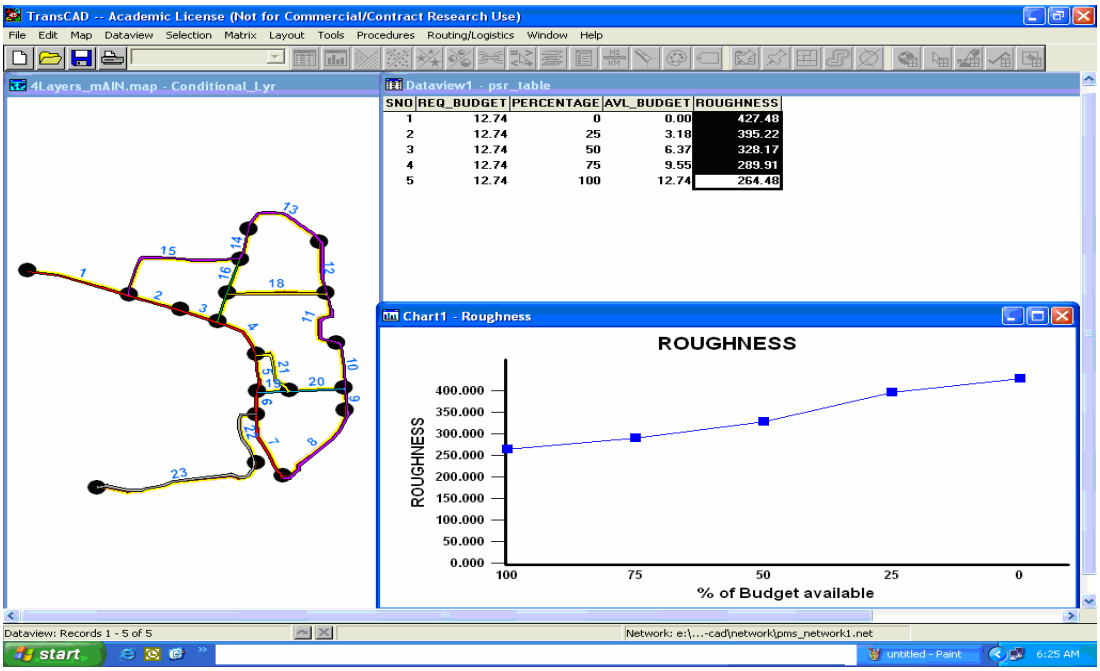

Figure 7: Effect of Available Budget on Road Roughness

The developed M&R system also allows users to gauge the savings on vehicle operating cost with different available budget scenarios. In this study, vehicle operating cost is calculated using the road user cost models developed by the Central Road Research Institute, India (CRRI, 2001). For the purpose of analysis, two different categories of budget availabilities (i.e. 'Do Nothing' and 100 percent of total budget availability) are considered. With the 100 percent budget availability, the vehicle operating cost saving is 14.64 lakhs over the network.

CONCLUSIONS

The present study demonstrates a simple and comprehensive road maintenance and rehabilitation using GIS and GPS for highway agencies with a limited budget allocation for road maintenance. The M&R system developed in the study, by virtue of its user friendliness, wide range of modules and graphical interface, will serve as an effective tool in the decision making process. Moreover, the complete integration of GIS and GPS with the M&R system will provide greater accessibility to the database, which can be shared by

various planning and maintenance authorities. Furthermore, the use of GPS not only helps in the data collection process but is also useful in locating failures (such as drainage failures, potholes… etc.) for day-to-day maintenance. The developed system is particularly beneficial to local road maintenance authorities with numerous demands and limited resources. The developed system is successfully implemented for a case study. It is identified that the developed M&R system is not only effective in the decision making process for planning and scheduling of road M&R works, but is also helpful for local maintenance authorities to carry out regular road repair works. In this study, a priority index approach was used to decide upon the pavement maintenance strategy, which is empirical in nature. Further studies can be conducted using existing mechanistic methods for the selection of maintenance/treatment instead of an empirical approach.

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