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Enhanced Pavement Preservation Using A Lane-based, Image-Tracking, GIS-enabled, and Life-cycle Activity Integrated Chuning PMS

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Abstract: Highway construction in China has grown rapidly for the past 10 years, reaching 60,300 km in 2008. Opened to traffic in 2006, the Chuning Highway is an 84.5 km, 4-lane strategic highway connecting the Anhui Province and the Nanjing economic region in Jiangsu Province. Based on Chuning Highway's unique characteristics, a new lane-based, image-tracking, GIS-enabled, and life-cycle activity integrated pavement management system (PMS) is proposed to enhance the operations and decision-making processes of pavement preservation. While it is still technically challenging to implement such a detailed level PMS on a large-scale statewide roadway network, the proposed PMS has been successfully implemented to store and manage more than two years of pavement condition survey data, detailed axle-load traffic volume, pavement structural design, roadway plan drawings, and pavement and roadway images. Cases have demonstrated the benefits and the feasibility of implementing the proposed system to improve pavement preservation decision-making and operations. The developed system provides a framework to integrate lane-based life-cycle activities for developing a reliable pavement performance forecasting model and accurate life-cycle cost analysis. It is also hoped that the developed system provides important guidance for developing a detailed lane-based PMS on a large-scale roadway network.

Key words: GIS-enabled, Image-tracking, Lane-based, Life-cycle activity integrated, PMS.

Introduction

Highway construction in China has grown rapidly for the past 10 years**.** The highway mileage totaled 60,300 km in 2008, second in the world [1]. In order to attract more private sector participation in highway construction, many of the highways are built through public-private partnerships (PPP). The Chuning Highway is a typical PPP project in China.

Opened to traffic in 2006, the Chuning Highway is part of the Nanlo strategic highway connecting Nanjing City in the Jiangsu Province and Loyang City in the Henan Province in China. The 84.5 km 4-lane Chuning Highway starts at station 10k+900 (near Nanjing City) and ends at 95k+400 (Mingguang City) in Anhui Province. The Chuning Highway connects two cities, Mingguang and Chuzhou, in Anhui Province with the Najing economic region in Jiangsu Province, as shown in Fig. 1. The highway has a closed toll system with four toll plazas, located at all entry and exit points. The users receive a ticket upon entering the highway and are charged based on the vehicle classification and distance traveled upon exiting. A semi-rigid pavement with 16 cm asphalt on the top of 56 cm soil-cement-lime stabilization is used on the highway.

As a PPP project, the Chuning Highway has been financed and constructed, and it will be operated, maintained, and managed by a private company [2] for 25 years; then it will be transferred to the transportation department in Anhui Province. For now, it is managed by the Anhui Chuning Highway Development Co. Ltd (Chuning Company), which was formed in 2002 to construct, operate, and maintain the Chuning Highway. The construction team was dismissed after the highway was built, and only a few engineers were retained to manage the highway maintenance. The company has restructured to carry on the tasks of operation and maintenance. With the limited personnel resources and the focus on toll collection, all maintenance and rehabilitation work has been contracted out.

The unique characteristics of the Chuning Highway include (a) the significance of the highway in connecting different provinces, (b) a single 84.5 km 4-lane project, which is typically not very long and is operated by a single organization (e.g. Chuning Company), (c) a toll-collection operation focus, (d) a strong investment return incentive, (e) limited personnel and expertise in pavement preservation and management, and thus, needing a system for maintenance contractors, and third parties (consultants and experts) to effectively store and mange pavement preservation and management activity data, (f) contracting out all pavement

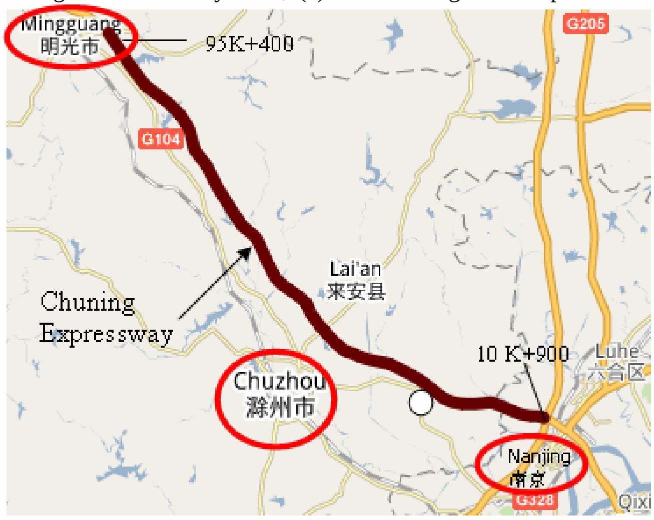

Fig. 1. Chuning Highway Connecting Cities of Najing and Chuzhou.

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maintenance and rehabilitation activities, and thus, needing a system to provide effective communications among different parties, including pavement engineers, managers, condition evaluation contractors, maintenance contractors, and third parties (consultants and experts). Pavement management has progressed from a concept in the 1960s to a working process in the 1970s and to a significant degree of implementation in the 1990s. However, improvements in application and implementation have not been matched by the improvements in the fundamental technologies of pavement management [3]. Pavement Management Systems using Information Technology [4, 5] and Geographic Information System (GIS) [6] have been developed and implemented successfully to for managing a large-scale roadway pavement (e.g. 29,000 centerline km) with a centerline-based linear reference system (LRS). Although it is still technically challenging to implement such a PMS on a large-scale statewide network (composed of state, county, and city roads), the Chuning Pavement Management System (Chuning PMS) is proposed to explore the feasibility of implementing a new lane-based, image-tracking, GIS-enabled, and life-cycle activity integrated pavement management system (PMS). The proposed PMS uses (a) a lane-based linear reference system (LRS) instead of centerline-based LRS to record the detailed level of pavement condition; (b) images to track pavement deficiencies and pavement preservation performance; (c) web technology to facilitate the data management and dissemination and communications among different parties; (d) GIS technology to facilitate data visualization and spatial analysis. These deigns effectively improve Chuning Highway pavement preservation and operations.

The developed Chuning PMS is designed to enhance pavement preservation, management, and communication among various parties (pavement engineer, manager, condition evaluation contractor, maintenance contractor, and third parties – consultants and experts). A lane-based LRS allows the pavement conditions to be integrated based on an individual lane rather than a centerline used in the centerline-based LRS. This granularity enables engineers to apply different maintenance treatments in different lanes instead of applying one maintenance treatment to all lanes. In addition, web and GIS technologies are used to facilitate pavement condition data query, analysis, visualization, and reporting.

The developed system is also designed to spatially integrate all life-cycle activities and to assist in making informed decisions, in enabling prompt response, and managing different pavement preservation-related activities ranging from conducting a routine condition survey, issuing a work order to the maintenance contractor, performing maintenance, and inspecting maintenance quality under extreme weather conditions. A life-cycle cost analysis (LCCA) considers not only the initial construction cost but also the maintenance costs (e.g. routine maintenance, minor, major, and rehabilitation cost). Currently, the integration of maintenance records remains a challenge in the PMSs. The maintenance records are maintained by different offices, and they often use different spatial reference systems and have different project limits. The Chuning PMS was designed to integrate the maintenance activities. A work order can be issued in the Chuning PMS, and the planned and actual treatment method, cost, and time are recorded as part of the maintenance history to support a reliable LCCA. A knowledge base, including different distress definitions and their measurements, maintenance methods, etc. is established to store and manage the pavement preservation and management knowledge. The knowledge base can be updated and is available on the web for different parties to support various operations ranging from condition assessment to determination of adequate pavement preservation method. The knowledge and experience specific to the Chuning Highway can be accumulated.

This paper is organized as follows. The unique characteristics of a typical PPP highway project in China are presented, and the needs for developing a lane-based, image-tracking, GIS-enabled, and life-cycle activity integrated PMS with web and GIS technologies are identified. Then, the Chuning PMS is presented. Three cases are presented to demonstrate the benefits and feasibility of implementing the Chuning PMS. Finally, conclusions and recommendations for future enhancements are made.

Chuning PMS Development

This section presents the two phases of the development of the Chuning PMS. Phase I included the development of a comprehensive database and functions to support the pavement condition evaluation, preservation, and management. Phase II included the development of a pavement performance forecasting model; it will include refined treatment criteria after the historical pavement condition evaluation data are accumulated and the effects of different treatment methods are evaluated. Phase I was completed and successfully implemented in 2008; it stores more than two years of pavement condition data, including data of International Roughness Index (IRI), Falling Weight Deflectometer (FWD), and pavement distresses along with historical roadway and pavement design data. This section presents the modules developed and implemented in Phase I.

The Chuning PMS consists of (1) a database designed to track all pavement life-cycle activities, from roadway design to reconstruction, so a future life-cycle cost analysis will be possible, and (2) pavement condition data query, analysis, and visualization capabilities, and reporting tools that allow the different parties (e.g. pavement engineer, manager, condition evaluation contractor, maintenance contractor, and third parties – consultants and experts) to streamline the pavement preservation and management decision-making process, and (3) a knowledge base, including a set of pavement distress definitions, condition evaluation procedures, and maintenance criteria. New knowledge, such as the treatment methods particularly effective for the Chuning Highway, can be added. The Chuning PMS consists of six modules: Documentation, Pavement Inventory, Analysis and Reporting, Maintenance, Other Roadway Assets, and Data Management. They are briefly described below:

1. Documentation Module. This module enables engineers to store and query various roadway design documents, such as plans and profile drawings, pavement structure designs, and typical section drawings. This module serves as an electronic library for storing and querying roadway design data, including pavement design. Users can query a location for a specific design document (e.g. pavement structure design), and the corresponding drawing of the pavement structural design can be

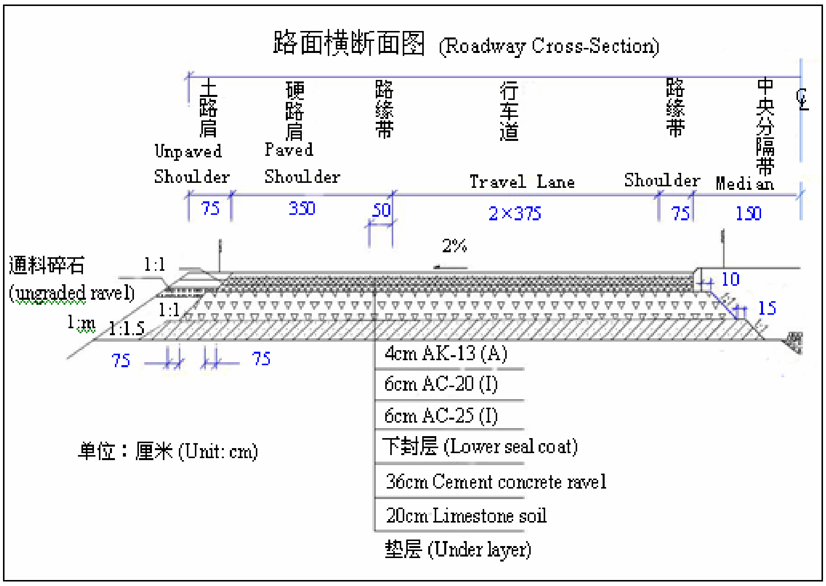

Fig. 2. Pavement Structural Design.

accessed, as shown in Fig. 2. The semi-rigid pavement design is different from the full depth pavement design used in the U.S. The drawing shows a semi-rigid pavement designed with 4 cm AK-13, 6 cm AC-20, 6 cm AC-25, 36 cm cement concrete ravel, and 20 cm lime-treated soil. This information is available on the web, giving engineers and managers easy access.

2. Pavement Condition Inventory Module. This module includes all the pavement condition evaluation procedures. The knowledge base for identifying and measuring the pavement distresses in this module can be accessed anywhere and anytime via web access and used for pavement condition evaluation training. For example, users might want to know how a transverse and longitudinal crack is measured. This module provides an example of the definition and measurement of longitudinal cracking. All of the pavement condition evaluation information can be easily accessed through the web. For the pavement condition data collected in the field, this module provides the upload function for engineers to upload the data (e.g. IRI, FWD, and pavement distresses and rating). In addition, images of pavement distresses can be uploaded into the system. Once the pavement condition data is uploaded, engineers can access this information from the internet through the Analysis and Reporting module.
3. Analysis and Reporting Module. This module analyzes and visualizes various data, including pavement rating, pavement distresses, FWD, IRI, and images with different formats. The case study will show the detailed utilization of this module.
4. Maintenance Module. This module determines the adequate treatment method based on pavement conditions and, most importantly, the treatment actually applied and the corresponding treatment cost, which can be recorded. The pavement maintenance guide from the "Technical Specification of Maintenance for Highway [7]"can also be accessed through the web. This information will enable a benefit-cost analysis to be performed by evaluating different treatment methods [8].
5. Other Assets Module. This module manages assets other than pavements to demonstrate the benefits of a roadway asset management system. Currently, engineers can query the bridges by station and retrieve the corresponding bridge information, such as length, structure type, and span. The condition evaluations of these assets are not available yet, and they could be developed in a separate module. This module is intended for agencies that would like to extend beyond a PMS to a complete roadway asset management system in the future.
6. Data Management Module. This module allows authorized users to manage the data and users in the system (e.g. add a new user and remove incorrect data).

Comprehensive Pavement Condition Inventory

This section introduces the comprehensive data collected on the Chuning Highway with a special focus on the pavement condition evaluation data. The data is collected and managed using the Chuning PMS. Utilization of this data will be presented in the next section.

The Chuning PMS maintains a comprehensive inventory of its pavements and a few selected assets (e.g. bridges). The data stored covers the activities over the pavement life cycle, including pavement design data, pavement construction data, pavement condition survey data, maintenance and rehabilitation records, and detailed axle-load traffic data to effectively support the determination of adequate pavement preservation. The design data maintained in the Chuning PMS include but are not limited to roadway design drawings (plan and profile drawings, typical section drawings, etc.) and pavement structural design (with layer thickness, material, Equivalent Single Axle Load (ESAL), and other design parameters). The detailed traffic data, including vehicle type, number of axles, and loads measured using Weight-in-Motion (WIM) devices at each entry point, are also recorded. Table 1 shows the example of the recorded traffic data, including vehicle ID, entering and exiting toll plaza IDs, vehicle type, number of axles,

Table 1. Traffic Data Collected at the Toll Plaza.

Vehicle ID	1	2	3
Entering			
Toll plaza ID	701	1103	1103
Vehicle type	4	1	2
Passenger/Truck	2	1	2
Time	2008-6-4 5:18:29	2008-6-3 14:22:48	2008-6-4 10:11:35
Exiting			
Toll plaza ID	1105	1105	1105
Vehicle type	5	1	2
Passenger/Truck	2	1	2
Time	2008-6-4 10:33:45	2008-6-3 14:34:49	2008-6-4 10:35:10
Total weight (kg)	51840	2160	21660
Number of axles	6	2	2

total weight, etc. The traffic data can provide a detailed traffic spectrum. Some roadway asset data (e.g. bridges) is also stored, but their condition assessments are performed in separate systems.

To support spatial and temporal analysis of the collected data, the Chuning PMS was designed with GIS technology to integrate the data spatially. Most transportation agencies, such as the Georgia Department of Transportation (GDOT), use a centerline-based LRS in their PMS to represent a location with route number and station [9]. The Chuning PMS uses a lane-based LRS to manage the pavement condition data in the detailed level. The direction, lane number, and station are used to identify a location on the highway. With the GIS function, the spatial interrelationships among the different activities (e.g. pavement distress and the corresponding preservation performance at a specific location and traffic lane) can be examined**.** The following subsections briefly describe the data collected to evaluate pavement condition.

Pavement Distress Measurement

Pavement distress data is essential to any PMS. A pavement condition evaluation procedure was developed to provide a consistent knowledge base for instructing surveyors on standardizing the identification, measurement, and recording of different distresses. Engineers can easily access the definitions of different pavement distress types and their severity levels, measurement methods, and pavement distress images through the web anytime and anywhere. The text on the left-hand side of Fig. 3 lists the twelve distress types specified in the pavement condition evaluation. For each distress type, the definition and measurement method are described along with distress images. For example, the right side of Fig. 3 describes the definitions of different severity levels of transverse and longitudinal cracks in text (Chinese) along with images to facilitate learning of different distress types, severity levels, and their measurements. It first describes that a transverse and longitudinal crack is typically caused by weathering of an asphalt-concrete surface or shrinkage of cement-treated base materials or the reflective cracking from the semi-rigid pavement base [10, 11]. Longitudinal cracks typically occur parallel to the driving direction and are not located in the wheel paths. Sometimes, longitudinal cracks can be caused by the non-uniform settlement of an embankment. Longitudinal cracks in the wheel path are related to traffic loading. This on-line knowledge base also describes the distress measurement method. For example, there are two severity levels. Severity Level 1 is crack width less than or equal to 3 mm; Severity Level 2 is crack width greater than 3 mm. The images in this knowledge base are continuously updated with actual distress images collected on the Chuning Highway as shown in Fig. 3.

Although the procedure described is a manual data collection method, the automatic data collection methods, such as different pavement distress segmentation methods critically assessed by Tsai *et al*. [12], can be added in the future. In addition, the system can store, upload, and analyze the pavement condition evaluation data collected using both manual and automatic methods.

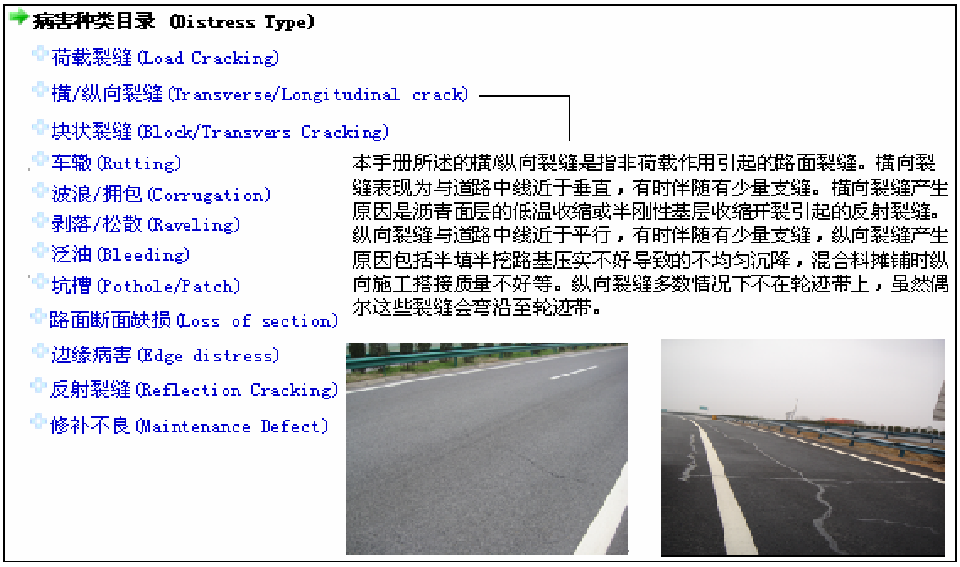

Fig. 3. On-line Training Guideline Showing the Definition and Measurement of Transverse and Longitudinal Cracks.

Falling Weight Deflectometer (FWD) Measurement

FWD is used for the structural analysis to determine the bearing capacity, estimate of the expected life, and design of a rehabilitation plan. According to "Highway Performance Assessment Standards" [11], a FWD survey is required upon the construction completion and recommended every 2 to 4 years thereafter. Two years of FWD, collected in October 2007 and in August 2008, are stored in the system. With the measurement of every 100 meters of each lane, there are more than 6,400 readings in the Chuning PMS.

IRI Measurement

The IRI developed by the World Bank is used to quantify roughness or ride quality. An IRI survey is required upon construction completion and is recommended every 2 to 4 years for every 50 meters thereafter, according to China's "Highway Performance Assessment Standards" [11]. Two years of IRI data, collected in 2007 and 2008, are stored in the Chuning PMS. The IRI was reported for every 100 meters on each lane, and there are more than 6,400 readings in the system.

Images

Traditionally, images have not been incorporated into or utilized in PMSs. With the advances in sensing and information technology, roadway images, including pavement deficiencies, can be taken easily using regular cameras or cell phones. The use of images can provide good visual interpretation of the asset condition and can assist in performing before-and-after comparisons. It is especially important to provide visual feedback on special events, such as natural hazards or roadway accidents. The Chuning PMS emphasizes the use of these images, which are stored with a time stamp, location information, and the particular asset it is associated with.

Chunig PMS Application Cases

Three cases are presented in this section to demonstrate the benefits of using the developed lane-based, image-tracking, GIS-enabled, and life-cycle activity integrated Chuning PMS to enhance pavement preservation and management. Case 1 highlights the enhanced pavement preservation and management and communication among different pavement management parties using the developed system. Case 2 shows the developed system can be used to analyze historical pavement condition data, such as IRI, at different detail levels (e.g. entire roadway or a selected section). Case 3 presents the comprehensive roadway and pavement data that can be visualized and analyzed spatially using the developed lane-based LRS along with the GIS function. The following cases have demonstrated the feasibility of implementing such a detailed level of PMS.

Case 1: Enhance Pavement Preservation and Management, and Communications among Different Parties

This case highlights the benefits of using the Chuning PMS to enhance the communication among different parties and to improve the decision-making process of pavement preservation and management.

The Chuning Company has a contractor performing a quarterly distress survey. The survey results, including distress type, location, and corresponding images, are uploaded to the system remotely via web access. The following shows an actual example. A longitudinal crack at station 27+482 km was observed and reported to the system upon the completion of the survey. The images taken in the field showing the roadway condition and the observed longitudinal crack at station 27+482 km, as shown in Fig. 4(a) and 4(b), were uploaded to the Chuning PMS. The engineers at the Chuning Company can review the distress data and the corresponding images to determine if a site visit for issuing a maintenance order is needed. Therefore, the maintenance order, such as a crack sealing in this case, can be issued promptly to the maintenance contractor. The maintenance contractor can perform the work and report the completion of the work with corresponding images. Fig. 4(c) shows an image taken by the contractor after a crack sealing was applied and uploaded to the Chuning PMS. The Chuning Company engineers can then review the completion of the maintenance work, as shown in Fig. 4(c), from a remote site to determine if the maintenance work is acceptable. If it is not satisfied, the Chuning Company can take necessary actions promptly. Note that the developed Chuning PMS is not to replace the existing quality control procedures; instead, it is to strengthen existing procedures by easily accessing comprehensive information, such as images, through web access. The developed system provides an effective platform for managing pavement condition assessment and preservation activities and facilitates the communication among different parties so the pavements can be monitored and maintained promptly. These maintenance histories, along with images are stored in the system. This enables the Chuning Company to track the distress and maintenance history and monitor the performance of the maintenance work, such as crack sealing. For example, the company can access the images taken at different times at the station of 27+482 km to evaluate the pavement distress history. In addition, by comparing the images taken at the crack seal location at different times after the crack sealing was applied, the performance of the crack seal can be evaluated to determine its performance. Annual pavement condition evaluations are conducted by a consulting company or the Chuning Company and stored in the system. They are used to determine the adequate maintenance and rehabilitation (M&R) methods. The M&R information, including the treatment method, cost, and time of the treatment applied, is also recorded in the system to support subsequent life-cycle cost analysis. If a new treatment was demonstrated to be effective, it can be added into the treatment criteria knowledge base.

As demonstrated in this case, the Chuning PMS uses images effectively and supports efficient communication among different parties (e.g. the pavement engineer, manager, condition evaluation contractor, maintenance contractor, and third parties – consultants and experts) using these images and web technology and enables timely decision-making on pavement preservation and management. The function presented in this case is also very useful to support a timely decision-support making process during an emergency or special event, such as unexpected weather damage to the roads. With the web capability, the manager can remotely access the on-site pavement condition information (e.g. images) and make informed

Fig. 4. Reporting and tracking a longitudinal crack using the web-based Chuning PMS.

decisions efficiently during special events.

The Global Positioning System (GPS) can be used to acquire exact location of an image taken with pavement distresses. In the future, a mobile device (e.g. cell phone or PDA) coupled with GPS can be used to collect roadway image data in the field and submit these images to the system via a wireless connection.

Case 2: Perform Historical Pavement Condition Analysis

The developed system enables lane-based analysis to evaluate the pavement condition of a lane for identifying abnormal spots. Pavement condition data, such as measurements of IRI, FWD, and surface distresses (load cracking, rutting, etc.), can be visualized based on its lane-based LRS. In addition, the historical data can be compared based on the common LRS to visualize the pavement condition change over time.

As shown in Fig. 5, pavement data (e.g. IRI) can be analyzed based on each lane or average of all lanes at different years. The blue dots in Fig. 5 represent the individual measurements on each lane. Each blue dot represents a 100-meter IRI measurement on each lane. The pink lines in Fig. 5 represent the average value of the IRI measurements at every 1 km on all lanes in both directions. Fig. 5(a) and 5(b) show the IRI data collected in 2007 that are an indication of the as-built pavement ride quality. Fig. 5(a) shows the IRI measurements on the inside lanes, while Fig. 5(b) shows the IRI measurements on the outside lanes collected in 2007. Fig. 5(c) and 5(d) show the results in 2008 after being open to traffic for one year. A couple of findings were observed by analyzing the historical data from 2007 to 2008. By looking at Fig. 5(a) to 5(d), we find the differences of IRI readings between outside lanes and inside lanes are smaller in 2007 (right after the construction) than those in 2008 after one year in operation. It can be found that the IRI measurements on the outside lanes are higher than the inside lanes. This could be caused by the heavy trucks running on the outside lanes. Instead of visualizing the 84.5 km of the roadway, users can zoom in and have a close look at the IRI data from station 35k to 43k, as shown in Fig. 6. The high IRI spots/locations can be easily identified from Fig. 6. This will allow engineers to conduct focused studies, such as conducting field trips to the spots/locations with high IRI values to study the corresponding reasons. In addition, engineers can trace the changes of IRI data for different years.

As demonstrated in this case, the developed system stores the as-built pavement condition data, including IRI and FWD, which can be used to compare with the IRI data collected in subsequent years. This is extremely valuable for establishing a reliable pavement performance model, as well as identifying the locations with abnormal deterioration rate throughout the year, so timely pavement preservation can be applied.

Case 3: Integrate Spatially-referenced Roadway and Pavement Condition Data to Support Comprehensive Roadway Condition Analysis

With the incorporation of the GIS technology, the developed system can integrate all spatially-referenced data, including IRI, FWD, pavement distress survey data, images, pavement design data, roadway design documents, etc., to correlate causal factors (e.g. traffic volume) to their consequences (e.g. pavement distresses) spatially for diagnosing the causes of pavement deficiencies. This is very important for determining the adequate M&R method. In the developed system, the pavement data are integrated on a lane-based LRS using dynamic segmentation. The maps, such as pavement rating and IRI, are automatically generated from the survey data. The LRS represents a route with a unique route number and station and is widely used by DOTs as a location referencing system. A lane-based LRS is developed to track the detailed information on

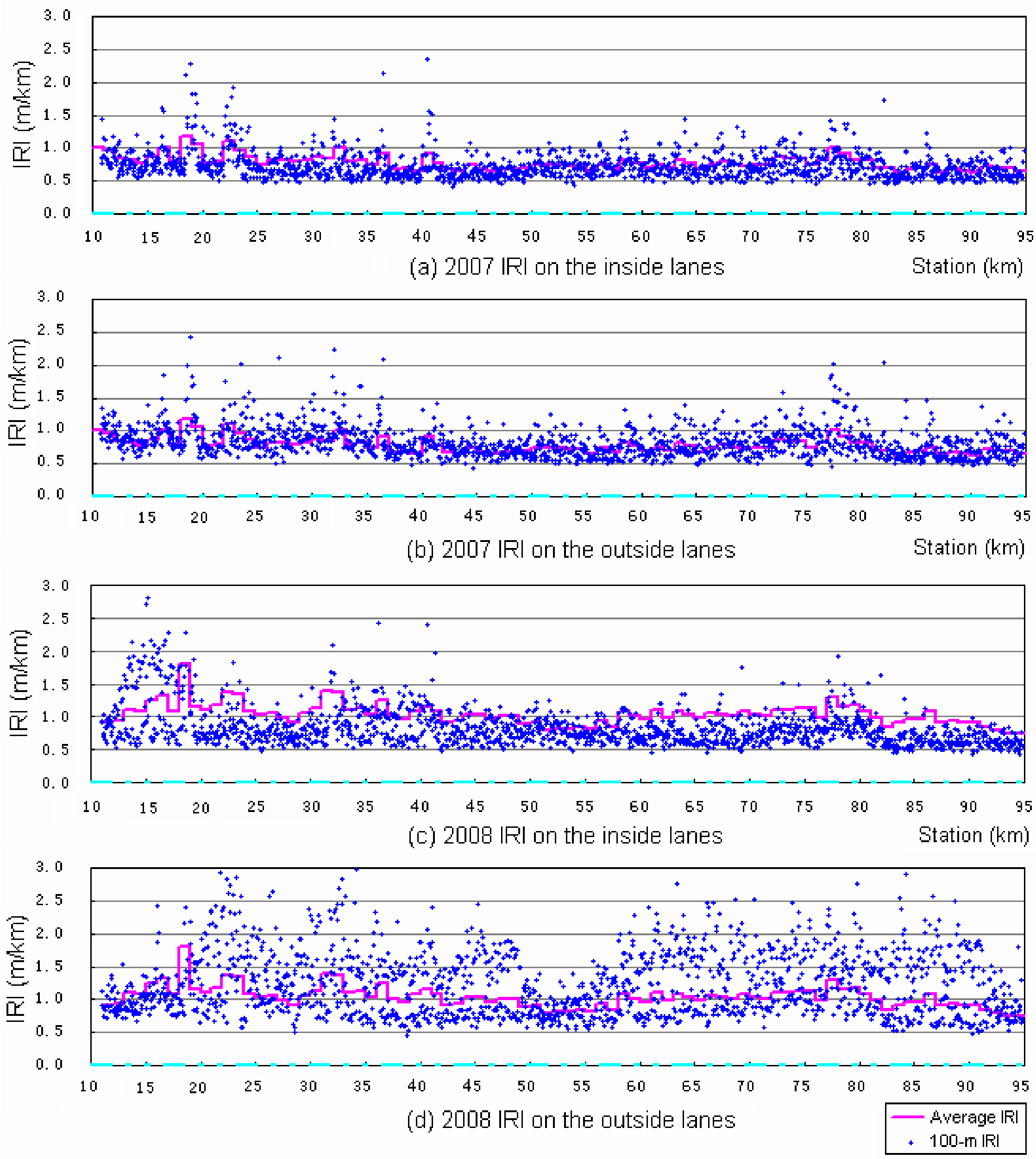

Fig. 5. Analysis of Historical IRI Data.

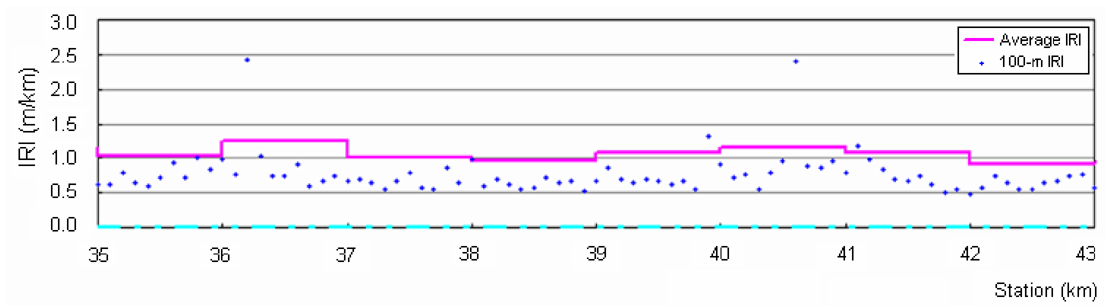

Fig. 6. A Close Look on 2008 IRI Data in the Outside Lane (Negative Direction).

each lane, while the majority of the PMSs use only centerline-based LRS. Because of the unique characteristics (e.g. a single project around 100km) of the Chuning Highway, a lane-based LRS has been designed and developed to support detailed data analysis.

With the GIS function, the developed system can visualize and analyze the spatial distribution of pavement distresses on the Chuning Highway by accessing the spatially-correlated information at different levels of details. Fig. 7 shows an example of analyzing

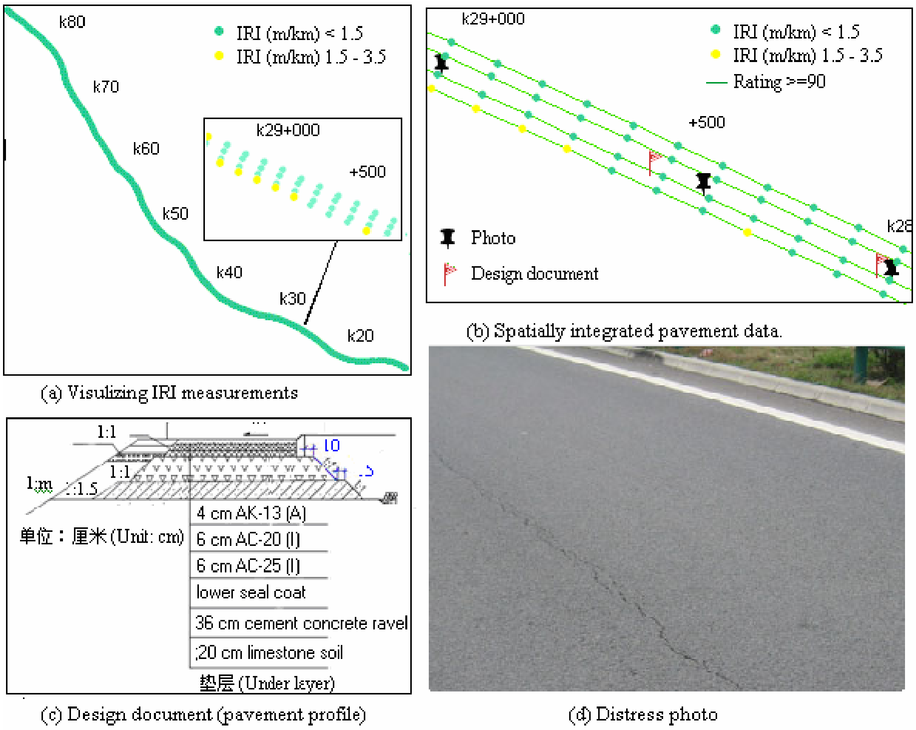

Fig. 7. Integrated and visualized spatially-referenced roadway and pavement data using GIS.

IRI information using the developed GIS function. First, engineers can specify IRI ranges of interest to visualize spatial distribution of the IRI measurements. For example, engineers can specify and analyze IRI ranges of less than 1.5 mm/km and between 1.5 mm/km and 3 mm/km, as shown in Fig. 7(a). The green and yellow dots represent the IRI measurements in different ranges. Engineers can then zoom into the detailed level to see the IRI at each measurement point, as shown in Fig. 7(b). The corresponding pavement distress rating is also displayed. The green lines in Fig. 7(b) represent the pavement rating greater than 90. In addition, engineers can access the corresponding pavement design (e.g. pavement profile) as shown in Fig. 7(c) by clicking the pavement design flag. The corresponding images can also be visualized by clicking the image label on the map. Fig. 7(d) shows a longitudinal crack was observed at station 28+420 km. The spatially-referenced information can be visualized and analyzed by engineers from different parties.

As demonstrated in this case, the developed GIS function in the Chuning PMS will enable experts to easily review the spatially-referenced roadway and pavement inventory, including IRI, FWD, pavement distress survey data, pavement design, maintenance records, traffic data, and images, to conduct pavement condition evaluations and to provide treatment recommendations. Effective communication with experts is important to the Chuning Company because, with limited pavement engineering expertise, the company relies on experts' opinions to make the cost effective M&R decisions. For cases in which the pavement deficiencies are not complicated, the M&R recommendations can be made directly. For a complicated problem, understanding the problem before the field visit will help. Therefore, the developed system can effectively support comprehensive roadway condition assessment. The system does not replace the traditional field trip but makes the field trip more effective.

Conclusions and Recommendations

While it is still technically challenging to develop and implement a detailed level PMS, a lane-based, image-tracking, GIS-enabled, and life-cycle activity integrated Chuning PMS is proposed in this paper to evaluate the feasibility of implementing such a PMS on the Chuning Highway, a typical PPP highway project in China. The developed Chuning PMS has been successfully implemented to store and manage more than two years of pavement condition survey data (e.g. FWD, IRI, and surface distress), detailed axle-load traffic data, pavement structure design, roadway plan drawings, etc., for enhancing the pavement condition assessment, preservation, and management of the Chuning Highway. Cases have demonstrated the benefits and the feasibility of implementing the proposed PMS. It provides important guidance for developing a detailed level PMS on a large-scale roadway network.

The following summarize the findings in developing the Chuning PMS:

1. The unique characteristics of the Chuning Highway are identified. They are (a) the significance of the highway on connecting different provinces, (b) a single 84.5 km 4-lane project, which is typically not very long and is operated by a single organization (the Chuning Company), (c) a toll-collection operation focus, (d) a strong investment return incentive, (e) limited personnel and expertise in pavement preservation and management, and, thus, needing a platform to effectively store and mange pavement preservation and management activity data, (f) contracting out all pavement maintenance and rehabilitation activities, and, thus, needing a platform to effectively communicate among different parties, including pavement engineers, managers, condition evaluation

contractors, maintenance contractors, and third parties (consultants and experts).

2. The system serves as a knowledge base to store pavement condition evaluation practices and maintenance methods, and new knowledge can be added. For example, distress classification, measurement methods, and maintenance methods are available. They can be used as a training guide on how to conduct a consistent pavement condition assessment and to conduct maintenance work. Also, cost-effective pavement preservation strategies specifically useful for the Chuning Highway can be identified and added into the maintenance criteria of the Chuning PMS.
3. The system serves as a data and document repository. The document module is an electronic and web-based library that can store and to retrieve roadway design documents. Different parties can easily access the documents based on the location of interest.
4. The system enhances the communication among different parties involved in pavement condition evaluation and pavement preservation for making timely pavement preservation decision. This is especially important when there are limited personnel resources, such as the Chuning Company has. The Chuning PMS actively uses images to track pavement preservation activity and enables effective routine pavement deficiency monitoring, work order issue, application of maintenance activities, and maintenance quality checking. Routine pavement deficiency survey contractors can upload pavement deficiency data and images. The engineers in the company can review them before issuing work orders. The completed maintenance work, along with images, can then be uploaded to the system. The engineers can track and verify the routine maintenance works performed by the contractor.
5. Cases have demonstrated it is feasible to integrate all levels of life-cycle activities, including lane-based pavement condition evaluations, pavement design, axle-load traffic data, actual maintenance activities, and costs, into a PMS system to support future life-cycle cost analysis.
6. GIS is used to integrate spatially-referenced data for supporting pavement condition evaluation. In addition, we have designed a lane-based LRS instead of a typical centerline-based LRS to provide GIS spatial data visualization and analysis at detailed traffic lane levels.

The following is a list of future enhancements for the developed Chuning PMS:

1. Training and certification of the personnel performing the pavement condition data collection to ensure the data quality.
2. Analysis of the detailed axle-load traffic spectrum, including lane distribution to take advantage of using the detailed traffic data on pavement performance forecasting.
3. Development of a pavement performance forecasting model, and refined treatment criteria after the historical pavement condition evaluation data are accumulated.
4. Incorporation of methods to automatically inventory other roadway assets, such as bridges, signs [13, 14], roadway geometry [15], pavement markings, etc. for developing a comprehensive asset management system.

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