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Imaging spectrometry and asphalt road surveys

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Abstract

This study integrates ground spectrometry, imaging spectrometry, and in situ pavement condition surveys for asphalt road assessment. Field spectra showed that asphalt aging and deterioration produce measurable changes in spectra as these surfaces undergo a transition from hydrocarbon dominated new roads to mineral dominated older roads. Several spectral measures derived from field and image spectra correlated well with pavement quality indicators. Spectral confusion between pavement material aging and asphalt mix erosion on the one hand, and structural road damages (e.g. cracking) on the other, poses some limits to remote sensing based mapping. Both the "common practice" methods (Pavement management system-PMS, in situ vehicle inspections), and analysis using imaging spectrometry are effective in identifying roads in good and very good condition. Variance and uncertainty in all survey data (PMS, in situ vehicle inspections, remote sensing) increases for road surfaces in poor condition and clear determination of specific (and expensive) surface treatment decisions remains problematic from these methods.

Keywords: Asphalt road survey; Imaging spectrometry; Pavement management; Spectral library; Remote sensing; Hyperspectral

1. Introduction

Detailed and accurate information about road infrastructure is the foundation for management and planning of transportation assets. Quality standards for the required data have evolved considerably over the last decades as traffic applications and surface treatment practices have become more demanding and include extensive measures of pavement quality. The cost of frequent, comprehensive inspection is high, and many jurisdictions limit their surveys to major roads, while minor roads are surveyed in 3 or 4-year cycles. For this purpose, a number of survey technologies have been applied to road condition mapping. The common

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practice today is extensive field observations by experts who characterize the aggregated measures such as the Pavement Condition Index (PCI) and the Structure Index (SI), based on established physical parameters such as cracking, rutting, raveling, etc. Both are single road performance indicators with a scale usually between 0 and 100 with 100 being perfect conditions. Other technologies are evolving such us the application of Pavement Management Systems (PMS); typically coupled with Global Positioning System (GPS) and Geographic Information System (GIS) technology and semi-automated in situ pavement health surveys. Specially equipped vans capture exhaustive photographic and video logs of pavement quality (and at the same time asset inventory), while recording road geometry with GPS and Distance Measuring Instruments. This produces a detailed and georeferenced condition report, with PCI and SI ratings for every ~10 m of road. Nevertheless, this remains an expensive and troublesome survey, while cost and safety considerations require that it be done at regular intervals.

Recent advances in imaging spectrometry offer the potential of improved road quality mapping over large areas. In this paper we ask the question: Can we map road surface conditions with imaging spectrometry to support current practice in transportation infrastructure management? Imaging spectrometers are able to acquire a large number of spectral bands with narrow bandwidths. Such detailed spectral measurements allow for precise identification of the chemical and physical material properties as well as surface geometry of surfaces (Clark, 1999; Roberts and Herold, 2004). Early remote sensing studies in the 1970s dealt with the visual interpretation of physical surface distresses (e.g. cracks, Stoeckeler, 1971). The results showed that distresses are distinguishable but only in very large-scale aerial photographs. The potential of using imaging spectrometers to map pavement age and condition has been discussed previously (Usher and Truax, 2001; Gomez, 2002; Herold et al., 2004a). However, this potential has only recently been explored by the National Consortium on Remote Sensing in Transportation (NCRST) at UC Santa Barbara (http://www.ncgia.ucsb.edu/ncrst/, Noronha et al., 2002; Herold et al., 2003; Herold et al., 2004b). Central objectives of this research include an improved understanding of the spectral representation of road aging and deterioration processes, optimal spatial/spectral remote sensor configurations to acquire such phenomena, and the assessment of capabilities and limitations of remote sensing technology compared to other road survey techniques.

An experiment in Goleta, California was conducted to explore imaging spectrometry capabilities in mapping asphalt road conditions. The roads were surveyed with "common practice" techniques by Roadware's ARAN survey vehicle and inspected by qualified pavement experts from Iowa State University, and California firms associated with the California Department of Transportation (Caltrans). The Santa Barbara County PMS provided additional spatial information about road conditions. A comprehensive spectral library of road surfaces and distress was acquired using an Analytical Spectral Devices (ASD) full range hand held spectrometer to evaluate the spectral characteristics of road conditions. The roads were sensed by the HyperSpectir submeter hyperspectral sensor of Spectir Inc. Based on this comprehensive database, we investigated the spectral properties of pavement distresses and compared the effectiveness of different survey methods. The ultimate goal was to explore relationships between remotely sensed parameters (i.e. spectral reflectance) and road condition parameters such as PCI and experts' pavement management recommendations. This relationship needs to be established if remote sensing is to support pavement health surveys and to assess the quality of the remote sensing observations in the context of other road survey techniques.

2. Data and methods

2.1. Study area

The study focused on several roads in the Goleta urban area, located 170 km northwest of Los Angeles in the foothills of the California Coast Range (Fig. 1). The study area, located north of US Highway 101, is displayed in a false color composite of 4 m Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data acquired in June, 2000 (Herold et al., 2004b). The main roads of interest are Fairview Avenue and Cathedral Oaks and in particular near their intersection which is shown in the upper middle part of the AVIRIS image (Fig. 1).

Both roads have four lanes with asphalt pavement, two in each traffic direction, and represent major urban arterials. The SB County PCI values for these roads show that they reflect a large variety of conditions. The

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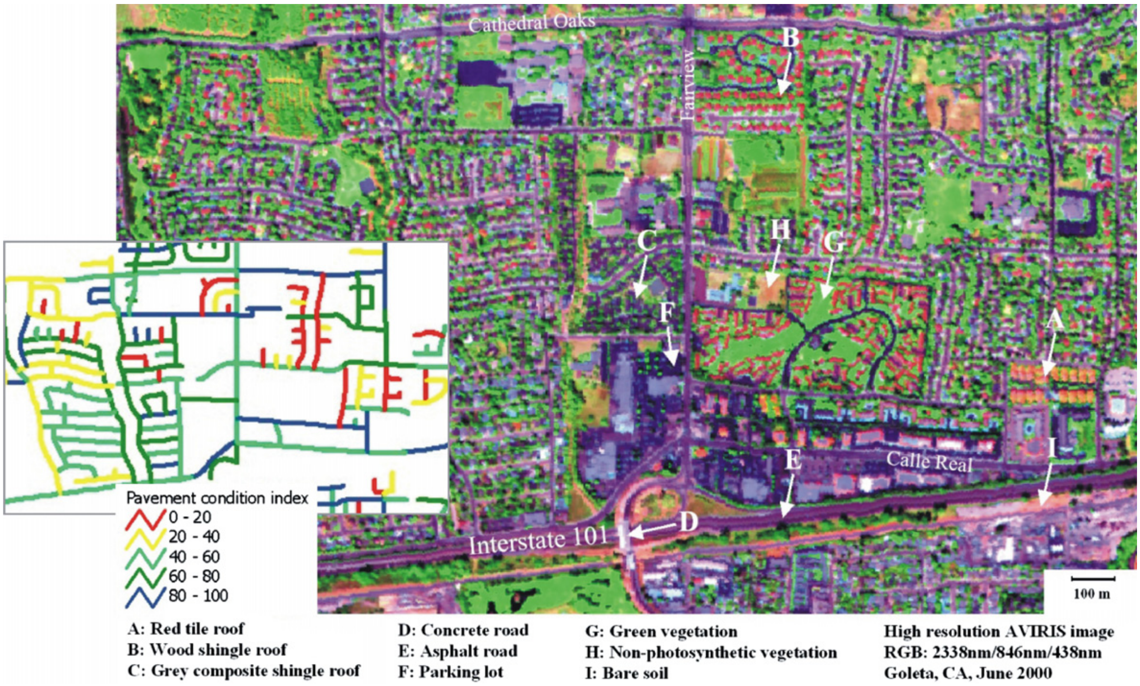

Fig. 1. Hyperspectral AVIRIS image of the Fairview/Cathedral Oaks study area shown with the distribution of the PCI from the Santa Barbara County database and representative land cover types. The roads Cathedral Oaks and Fairview and their intersection in the center top of the study area is the main test site.

eastern part of Cathedral Oaks has a PCI of nearly 100. This road was resurfaced just prior to the start of the study. Fairview and the western part of Cathedral Oaks have fair/poor conditions with PCI values on the order of 40–60. Fairview pavement is in particularly poor condition. The central divider of Fairview is the boundary between two traffic management zones. Rehabilitation efforts have been funded and coordinated by two different transportation agencies. This has resulted in delays and failure of necessary maintenance, and continued deterioration of the road surface is apparent today.

2.2. Road condition data

Road distress surveys are required as part of the planning and design of pavement rehabilitation projects. They provide information on the various distress types, their location, severity and extent (Miller and Bellinger, 2003). Traditionally, these surveys are based on extensive field observations by trained experts. They evaluate the pavement condition in situ considering a variety of distress types, and aggregate the information into a Pavement Condition Index (PCI, Fig. 2). The PCI is a single road performance indicator with a scale usually between 0 and 100. In this study two expert groups surveyed the roads in June and July 2003 (Fairview and Cathedral Oaks). A qualified pavement expert led the first group from the Center for Transportation Research and Education from Iowa State University at Ames. The second expert group included representatives from California firms regularly contracted by the California Department of Transportation: Independent Seals, Western Paving Contractors, Inc (Irwindale, California, www.westernpaving.com) and Vulcan Materials Company (Azusa, California). The experts were asked to place road segments into one of five categories (excellent, good, fair, poor and very poor) and suggest a road management action (do nothing, maintenance, minor rehabilitation, major rehabilitation, and replacement).

The second source of road information was provided by the Santa Barbara (SB) County road database. Since 2001 the County has been using the MicroPaver PMS. This PMS is a decision making tool for cost effective maintenance and repair alternatives for all roads within the County (United States Army Corps of

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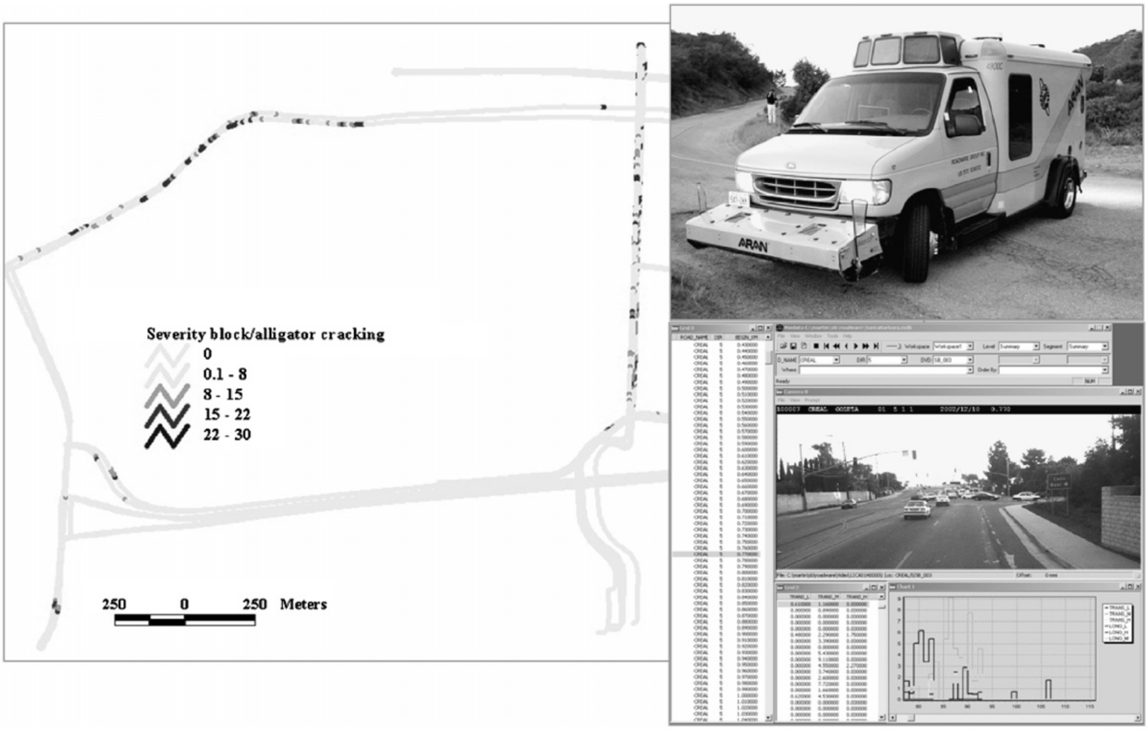

Fig. 2. The Roadware pavement health survey with the ARAN survey vehicle, GPS base station, the video/road distress log and the resulting GIS database.

Engineers, 1982). MicroPaver helps to evaluate present and future pavement conditions, deterioration rates, work history and budget scenarios. The PMS is linked to ArcView® GIS and a digital road database that was available for this study. Fig. 1 shows a subset of this database. The PCI is reported for relatively large road segments and does not discriminate between lanes. The "County PCI" was provided for January 2002. In February 2002 the city of Goleta was incorporated, and the responsibility of road management went to the new city administration, which did not maintain and update the GIS database.

The third survey technique provided detailed information about road distresses. The observations were performed in December 2002 with the Automatic Road Analyzer (ARAN) of the Roadware Corporation (www.roadware.com) of Paris, Ontario, Canada. ARAN is mounted on a specially modified van that houses an extensive set of computers and sensors including lasers, inertial measurement units, accelerometers, ultrasonic transducers, digital cameras and other advanced technology subsystems. GPS on the vehicle and at a base station ensures accurate locational data (Fig. 2). The survey provides geocoded road distress information of over 30 individual parameters aggregated for 10 m road or lane segments. For further analysis the original data were aggregated to 50 m road segments and the individual road distress measures were merged to a PCI and Structure Index (SI) based on the Iowa Pavement Management Program (IPMP) methodology. Similar to the ones for field surveys, the "Roadware PCI" categorizes the majority of distresses in a rating based on 0–100 scale with 100 being the best condition. The PCI calculations are based on deduct values from the actual distress measurements. Each distress has a deduct and threshold value. If the threshold value is reached, the whole amount will be deducted, otherwise, only a portion will be deducted. The deduct and threshold values are different for each pavement type (asphalt, concrete, or composite). The structure index works in a similar manner. The only difference is it only considers distresses that are related to the structure, e.g. only alligator, block, and transverse cracking are used for the SI calculations.

All road condition information was integrated into a GIS database. The Roadware data and the expert evaluations use the road segments (~50 m length) and consider the direction of four lane roads. The County PCI represents much larger road segments on the order of several hundred meters to one kilometer. Furthermore

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there is a difference in time of acquisition; the County data represent the conditions in January 2002, the Roadware data December 2002 and the experts visited in June/July 2003. However, there was no road construction or maintenance within the period of data acquisition that would have affected the validity of this study.

2.3. Spectral library

Spectral libraries contain pure spectral samples of surfaces, including a wide range of materials over a continuous wavelength range with high spectral detail, and additional information and documentation about surface characteristics and the quality of the spectra (i.e. metadata). In May 2001 and February 2004 two ground spectra acquisition campaigns were conducted in the study area. Ground spectra were acquired with an Analytical Spectral Devices (ASD) Full Range (FR) spectrometer (Analytical Spectral Devices, Boulder, CO, USA). The FR spectrometer samples a spectral range of 350–2400 nm. The instrument uses three detectors spanning the visible and near-infrared (VNIR) and short-wave infrared (SWIR1 and SWIR2), with a spectral sampling interval of 1.4 nm for the VNIR detector and 2.0 nm for the SWIR detectors. The measurements were taken within two hours of solar noon and 5–10 road spectra acquisition were bracketed by Spectralon (Labsphere, North Sutton, NH, USA) 100% reflective standard. Spectra of in situ materials were acquired from a height of 1 m using the bare fiber optic, with a field of view of 22° (1474 cm^2 at a height of 1 m equals a measurement circle of about 43 cm in diameter, Fig. 3). A variety of materials were measured in sets of 5 spectra for each field target. All spectra were inspected for quality and suspect spectra were discarded. Each road surface spectrum was divided by its appropriate standard spectrum to calculate the apparent surface reflectance. FR field spectrometer data are widely used and considered to provide high quality spectral

A) ASD spectrometer equipment **B) Field spectra acquisition**

C) Collection of reference/metadata **D) Spectral library/spectroscopic analyses**

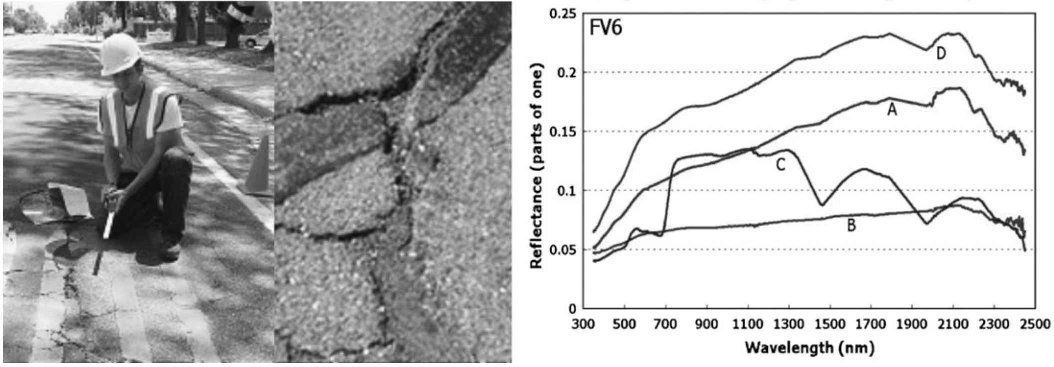

Fig. 3. Steps and resources in the development of the Santa Barbara Asphalt Road Spectral library.

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measurements. All targets were documented and integrated into a spectral library (Fig. 3). The spectral library contains various types of roads (asphalt, concrete, gravel) and asphalt road surfaces in different states of distress. The spectral library was acquired as part of the National Consortium on Remote Sensing in Transportation (NCRST) at the University of California Santa Barbara and is available for research purposes.

2.4. Imaging spectrometry

Imaging spectrometry data were provided by Spectir Inc., located in Goleta, CA (www.spectir.com). The company developed a new sensor "HyperSpectir" with 227 bands over a spectral range of 450–2450 nm. The main advantage of the HyperSpectir is the high spatial resolution. Due to an onboard, integrated stabilization system, the flight altitude can be very low with a Ground Instantaneous Field of View (GIFOV) of about 0.5 m. One tradeoff is the narrow swath of only 40 m. Several roads were missed during the acquisition campaign and the study was limited to specific parts of the test area. Despite its spatial advantages, the spectral calibration of the data was insufficient and only the bands from 450 nm to about 900 nm covered by the first spectrometer sensor could be used for the analysis. The data were experimental from the HyperSpectir I sensor and future sensors provide data products with improved calibration. A standard atmospheric correction (using ENVI/IDL FLAASH) was performed. The geometric correction of the data was performed by the data provider to jointly analyze the remote sensing, GIS and in situ data.

The analysis of the remote sensing only considers unobscured road surfaces. All other land cover types were excluded by using an accurate road curb-line database. Vegetation and shadows obscuring the road surface were excluded in the HyperSpectir data where they were clearly visible. The remote sensing investigations applied a specific reflectance difference that is discussed later.

2.5. Statistical analysis

Statistical analyses were performed to compare the remote sensing signal and the road condition information. The PCI and reflectance are both quantitative measurements and bivariate ordinary least square regressions were applied to explore the correlation between the variables. The PCI values (from Roadware and the County) are reported as averages over road segments. The statistical comparison used the average of the remote sensing signal over the same road area to allow a one-to-one comparison. This segment-based relationship was then used to convert the remote sensing data to PCI values at the pixel level.

A comparison between the quantitative remote sensing signal and the categorical road ratings of the experts requires a different statistical method: Analysis of Variance (ANOVA, Clark and Hosking, 1986). The key statistic in ANOVA is the *F*-test of difference of category means, testing if the means of the category formed by values of the independent variable (remote sensing signal) are different enough not to have occurred by chance. In other words, ANOVA describes if the remote sensing signal is statistically different for the various categories of road conditions.

3. Results

3.1. Contrasting "common practice" road surveys

All three road survey techniques (expert field visit, Roadware vehicle observations, County PMS) applied in this study can be considered as part of the "common practice" in pavement observations. Although the individual surveys have slight differences in time of acquisition and spatial unit (extend of road segments), the data can be compared to explore similarities and differences among them (Fig. 4). Diagram A and B compare the County PCI to the Roadware PCI and structure index. There is a linear relationship between both PCI measures (*R*-squared = 0.74). One large County road segment contains several smaller Roadware segments and the variability in the Roadware PCI emphasizes the road condition variability within the larger County segments. The relationship between County PCI and Roadware structure index is less pronounced with an *R*-squared of 0.54 (Diagram B). This is expected since the SI only reflects structural damage. Early pavement degradation usually does not result in severe structural damage and the structure index remains high. The

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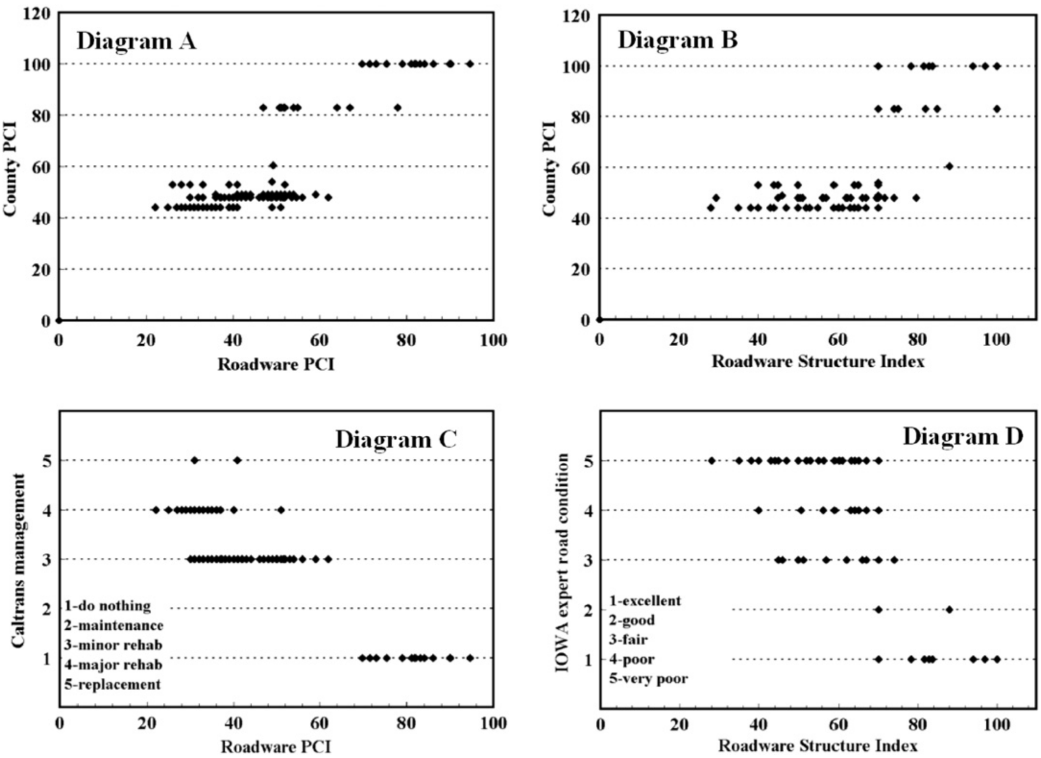

Fig. 4. Comparison of road condition survey data: County PMS, Roadware PCI/SI, Iowa/Caltrans expert ground observations. (*Note*: The *y*-axis of diagrams C and D are categories.)

structure index better describes distresses for roads in poorer conditions with significant structural damage, i.e. there is quite some variability in lower structure index values with the County PCI staying fairly constant. Diagrams C and D in Fig. 4 relate the expert condition inspections and management suggestions to the Roadware pavement quality indicator data. The Roadware PCI clearly reflects the difference between a very good road (“do nothing”) and the roads that need rehabilitation or replacement (Diagram C). A similar distribution is shown in Diagram D. Although the overall relationships between the different survey techniques are obvious, there is a fair amount of variability and disagreement in particular for roads in poorer conditions. Consequently, the “common practice” techniques are not completely congruent and reliable. Every decision based on these will require some kind of compromise especially for approaching expensive rehabilitation or replacement projects with the expert field observations being the most reliable one.

3.2. Spectral characteristics of road aging and deterioration

Asphalt pavements consist of rocky components (minerals) and asphalt mix (or hot mix or bitumen). The chemical nature of asphalt mix essentially is a suite of hydrocarbons that can vary in composition depending on the source of the crude oil and on the refining process. Fig. 5 (Diagram A) presents three spectral samples from the ground spectral library of pure road asphalt with no obvious structural damages or cracks. The age of the pavement, the Pavement Condition Index (PCI) and the Structure Index (SI) are shown with image examples of the surface. Spectrum A reflects a recently paved road. The surface is completely sealed with asphalt mix. The spectral reflectance is generally very low and hydrocarbon constituents determine the absorption processes. The minimum reflectance is near 350 nm with a linear rise towards longer wavelengths. In the visible region, the absorption is broad and there are no individual resolvable absorption bands due to the complex hydrocarbon nature. Overlapping electronic processes and their absorption strengths decrease towards longer wavelength. In the short-wave infrared region (SWIR), Spectrum A exhibits some small scale

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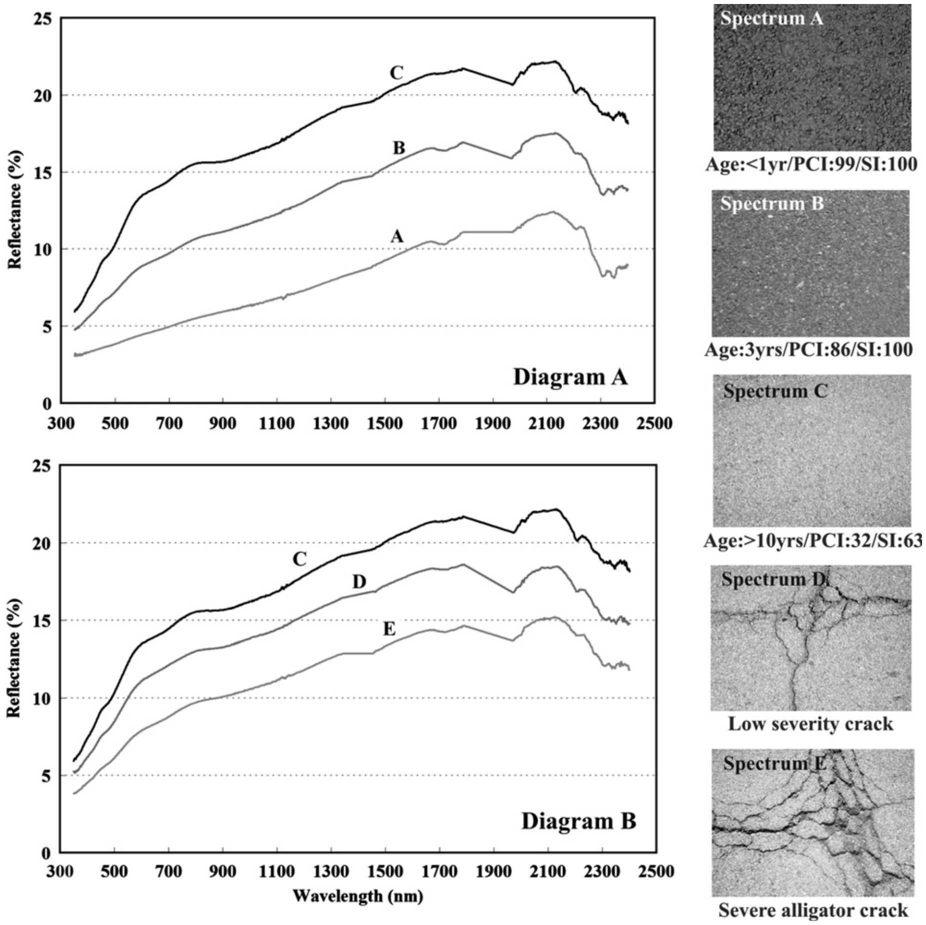

Fig. 5. Spectral effects of asphalt aging and deterioration from the ASD ground spectral measurements. The individual road surfaces of Diagram A reflect different asphalt road surfaces and are labeled with age, Pavement Condition Index (PCI) and the Structure Index (SI) from the Roadware vehicle observations reflecting a transition from a newly paved road surface (Spectrum A) to older road surfaces (Spectra B and C). Diagram B compares Spectrum C (old road surface, no cracking) with surfaces (same PCI and SI) of different severity cracking (the major water vapor absorption bands are interpolated).

absorption features. The most prominent appear near 1700 nm and from 2200 to 2500 nm. If the 1700 nm feature is well developed it is asymmetric hydrocarbon features and reflects a doublet with the strongest absorption at 1720 nm and a second less deep one at 1750 nm (Cloutis, 1989).

The region between 2200 and 2500 nm is affected by numerous overlapping combination and overtone bands. This causes the strong reflectance decrease beyond 2200 nm. The absorption is strong in the 2300 nm region with a well-developed doublet at 2310 and 2350 nm with the 2310 nm feature usually being the stronger one (Cloutis, 1989).

Spectrum C in Fig. 5 shows an old road surface. The image of the surfaces shows that the asphalt seal is mostly eroded and the remaining asphalt mix has undergone an aging process. The natural aging of asphalt is caused by reaction with atmospheric oxygen, photochemical reactions with solar radiation, and the influence of heat, and results in three major processes: the loss of oily components by volatility or absorption, changes of composition by oxidation, and molecular structuring that influences the viscosity of the asphalt mix (Bell, 1989). Spectral effects represent a combination of exposure of rocky components and asphalt aging. The vanishing of the complex hydrocarbon components causes a general increase in reflectance along all parts of the spectrum. This difference is highest in the NIR and SWIR with more than a 10% reflectance increase. The electronic absorption processes in the VIS-region reflect the dominance of minerals and result in a concave shape

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with distinct iron oxide absorption features appearing at 520, 670 and 870 nm. The typical SWIR hydrocarbon absorption features in 1700 and 2300 nm region vanish for older road surfaces and are replaced by mineral absorptions. For example, there is significant change in slope in the transition from hydrocarbon to mineral absorption. For older road surfaces the slope increases between 2120 and 2200 nm as the 2200 nm absorption becomes more prominent. The slope is higher for new pavement materials between 2250 and 2300 nm, which correlates with the strength of the 2300 nm hydrocarbon feature.

Spectrum B in Fig. 5 represents a road pavement of intermediate age. The surface exhibits both asphalt mixtures and exposed minerals. The spectral characteristics reflect this intermediate stage by showing absorption features from hydrocarbons and minerals. The intensity and characteristics of the features is less distinct than for ''pure'' very new and very old road surfaces. Aging and deterioration processes are gradual and there is good spectral evidence that the transition in surface material properties can be mapped using an imaging spectrometer. It should be noted that for a road aging from 1 to 3 years, a change in PCI of 100 to 86, and a constant structure index of 100 the spectral impact is about the same as roads aged from 3 to more than 10 years, in which the PCI decreased from 86 to 32 and the SI decreased from 100 to 63. This suggests that the spectral signal is very sensitive to early stages of aging and deterioration and later, more severe road damages have a lower spectral impact.

The most common road distress and indicator of pavement quality is cracking. Fig. 5 (Diagram B) shows the spectral effects of structural damages or cracks with different severity on the spectral signal. The ''non-crack'' road surface reflectance (Spectrum C) of the pavement is dominated by mineral absorption processes. The main spectral impact of cracking (Spectra D and E) is to modify the brightness of spectra across all wavelengths. An increase in surface roughness and shadows caused reflectance to decrease up to 6–7% in the NIR and SWIR when comparing uncracked to severely cracked pavement. The concave shape in the VIS/NIR is more obvious for brighter, non-cracked road pavement. There is also some indication that the cracked surfaces have more intense hydrocarbon absorption features in 1700 nm and 2300 nm region. Erosion and oxidation of the asphalt mix occurs on the road surface. Cracking exposes deeper layers of the pavement with a higher content of the original asphalt mix, which results in increased expression of hydrocarbon absorption features. This fact highlights the contrary spectral signal between road deterioration of the pavement itself (Fig. 5, Diagram A) and the severity of structural damages (Fig. 5, Diagram B). An aging road surface becomes brighter with decreasing hydrocarbon absorptions while structural distresses lower reflectance but increase the expression of hydrocarbon features. Although the reflectance difference and intensity of the hydrocarbon absorptions is less for cracks than for new asphalt surfaces (compare of spectra A, B and E).

3.3. Analysis of imaging spectrometry data

The spectral interpretations of the asphalt road surfaces (Fig. 5) suggest several features that have utility for spectral identification of road aging and deterioration. A common problem, however, is that the ground spectra and remote sensing observations represent different spatial and spectral scales. Imaging spectrometry data usually have lower spectral resolution with a bandwidth on the order of 10 nm (i.e. for Hyperspectir data) and a lower number of bands respectively, compared to 2 nm bandwidth for the field spectrometer. Small scale spectral characteristics disappear or become less distinct. The spatial resolution of the remote sensing observations causes mixing effects with surrounding surface types; an issue of less prominence for this study since the spatial mapping unit of the field spectrometer (circle with 40 cm diameter) and Hyperspectir data (50 cm spatial resolution) are rather similar. However, remote sensing observations contain larger amounts of spectral noise caused primarily by the sensor system itself, illumination and atmospheric contamination. Although corrections have been applied, poor radiometric calibration of the HyperSpectir data only limited the analysis to the 450–900 nm range.

Given these spectral data limitations the image analysis focused on a band difference in the visible region. The difference describes the spectral difference between the bands at 830 nm and 490 nm (VIS2-difference). The 490 nm band is in the middle of charge transfer iron oxide absorption and the 830 nm band right before the crystal field iron oxide absorption in the NIR at 850–900 nm. The spectral difference between both bands emphasizes the increasing spectral contrast between road surfaces dominated by hydrocarbon absorptions (new roads) and mineral signals (older and deteriorated roads) with increasing brightness and the change

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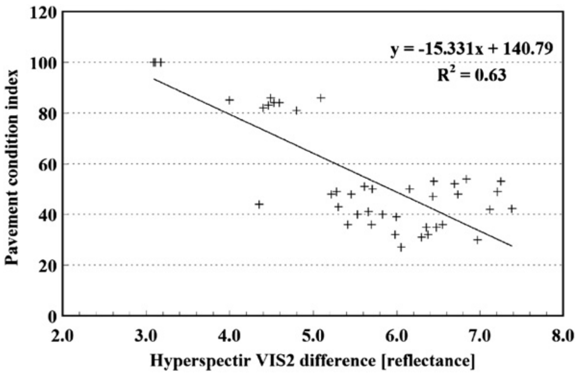

Fig. 6. Comparison between HyperSpectir VIS2 difference values and the Roadware PCI.

towards more concave spectral shape in the VIS for older roads (Fig. 5). This difference is low for new asphalt surfaces and increases with age and level of deterioration, partially caused lower hydrocarbon absorptions and by the iron oxide spectral features.

The HyperSpectir VIS2 difference values show a significant correlation with the Roadware PCI values with an *R*-squared of 0.63 and statistical test confirming the relationship being significant at the 0.0001 probability level (Fig. 6). The relationship is very distinct for roads in good condition since the scatter is quite low. The variability increases for high difference/low PCI values. The spectral signals of the roads in poorer conditions become more complex and the relationship is not as clear. This fact is reinforced by observations from the spectral library interpretations where in situ material aging and asphalt mix erosion processes increase the VIS2-difference (Fig. 5), while, structural road damages darken surfaces decreasing the difference. A decrease in the VIS2-difference due to cracking makes these surfaces look more similar to newly paved ones. However, the statistical relationship shown in Fig. 6 is strong enough to estimate a PCI from the HyperSpectir difference Q1 (Fig. 7). The PCI patterns highlight recently paved roads with high values (blue colors[1]). Road surfaces in poorer condition show lower PCI values (and higher variability yellow–green colors). Specific cracking patterns are revealed in the highlighted area of Fairview. The cracks appear with relatively higher PCI values. This again is due to the contrary spectral contrast of cracks versus aging. Considering scatter in the relationship between the difference and the Roadware PCI for older surfaces, PCI estimates for older surfaces should be viewed with some caution before labeling roads as in poor condition. If the estimated PCI is high it is highly likely that the road is in good or very good condition. Obviously, the current mapping algorithm can clearly identify high quality pavement.

Figs. 6 and 7 emphasize the relationship between the remote sensing signal and descriptive parameters of road condition. However, the remaining question concerns the extent to which remote sensing measures translate into specific management scenarios. An analysis of variance (ANOVA) was applied to determine whether VIS-2 differences between "do nothing" and other management categories were statistically significant. The ANOVA results relating the VIS2 difference values to four categories of possible CALTRANS management actions are shown in Table 1.

The *R*-squared of 46% and the *F*-statistic of 11.24 indicates that there is a significant relationship between both variables. The ANOVA was performed beginning with the first management category: "do nothing". This category has an average VIS2 difference value of 3.13. Compared to this category the management suggestion "maintenance" is significantly different indicated by the mean value of 5.73. The statistical difference between both categories is 2.6% reflectance in the VIS2 difference. Basically this is the expected VIS2 difference between a road that requires no work and a road that requires maintenance. The difference between the categories "maintenance" versus "minor rehab" versus "major rehab" are 0.45 and 0.13 respectively. Both of them are in the range of the standard error and suggest that there is no significant difference between these categories or the difference is far too small to be accurately represented in the remote sensing data. The ANOVA results again

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[1] For interpretation of the references in color in this figure, the reader is referred to the web version of this article.

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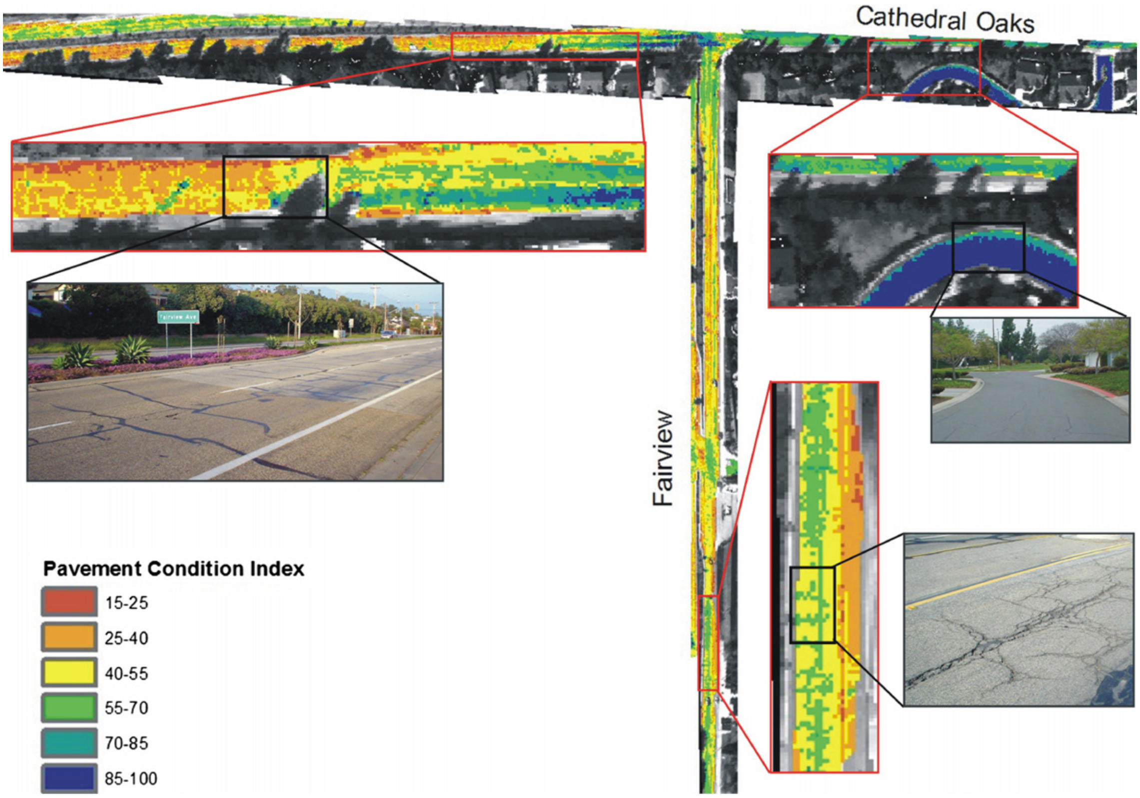

Fig. 7. Spatial distribution of PCI derived from HyperSpectir data.

Table 1
ANOVA results of HyperSpectir VIS2 difference versus CALTRANS management suggestion

Category	Value (%)	Std. error	Difference
Do nothing	3.13	0.44	
Maintenance	5.73	0.16	2.60
Minor Rehab	6.18	0.51	0.45
Major Rehab	6.05	0.36	0.13

Multiple *R*-squared: 0.46.
F-statistic 11.24.

emphasize an observation that was found for several remote sensing analyses during this study. So far, roads in good and very good conditions can be clearly identified by the investigated algorithm.

4. Conclusions and outlook

This study combined ground spectrometry, several in situ road surveys techniques, and imaging spectrometry to explore the potential contribution of remote sensing in road surveys. The aging and degradation of road surfaces are represented by distinct spectral characteristics. The absorptions gradually change from a domination of hydrocarbons to mineral features for aging asphalt surfaces. The specific variations appear in object brightness and small scale absorptions. The presence of structural damages (e.g. cracks) has an inverse effect, leading to surface darkening yet spectral shape preservation. The relationship between the remote sensing signal (image band difference) and the PCI is strong for roads in good conditions but declines for lower quality roads. Roads that required no management action could be discriminated from roads that do. Currently, the algorithm is not able to discriminate between management actions (i.e., maintenance versus rehabilitation).

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However, both the "common practice" methods (PMS, in situ vehicle inspections) and the remote sensing analysis are effective in identifying roads in good and very good condition. The variance and uncertainty in the data significantly increases for road surfaces in poor condition. Only the expert in situ observations can be considered a reliable differentiation between roads that need i.e. rehabilitation versus replacement. The broader issue in this context is that pavement health estimation of low quality road surfaces is a complex science and art. There are about 40 different physical pavement properties listed in the international pavement condition rating manual (ASTM D6433, 2003). Some of these refer to visual characteristics, while others address subsurface conditions (e.g. depths of cracks and small distinct scale variations within cracks) that all surface sensors (Vehicle observations or remote sensing) are currently unable to do.

This investigation only focused on a small study area and on asphalt road surfaces. There were some problems with the spectral calibration of the high resolution HyperSpectir data. With better calibrated data it should be possible to explore other analysis techniques that include the short-wave infrared and small absorption features that were identified in the spectral library analysis. Furthermore, this study utilized a rather simple ratio of two wavelengths in the VNIR. An alternate approach, based on spectral fitting, may better utilize the entire spectrum and discriminate aging effects from surficial cracking, which alters the brightness, but not the spectral shape of older surfaces. Example algorithms that may provide a better estimate of road condition based on spectral shape include spectral fitting (Clark et al., 2003), matched filters (Ben-Dor et al., 2001), and the spectral angle mapper (Kruse et al., 1993).

In summary, road condition mapping from imaging spectrometry has potential. It is not likely that remote sensing will replace field inspection, but the spectral signal is an additional level of information not considered in other pavement assessment methods and it can offer insights into surface conditions and other aspects that the inspector cannot evaluate except with considerable labor. To our knowledge, this is the first time spectroscopic effects of pavement condition and aging has been published and further studies are needed to refine the analysis and develop a map strategy based on existing technology using other sensors. For the remote sensing analysis this study was limited to the visible and near-infrared region. Including additional spectral information from the short-wave infrared (as indicated by the spectral analysis of the study) has potential to further improve the estimation of useful road characteristics. Perhaps, there maybe some limitations for applying this remote technique that have not been a problem for this case but maybe elsewhere. Shadows from buildings and trees obscuring the road surface and dust, dirt or moisture apparent on the road surface can limit the application of the presented approach in other regions. The presented approach should be further tested in experimental designs for different urban and rural conditions to fully explore the operational capabilities.

An emerging technology in this context is the Unmanned Airborne Vehicle (UAV). UAV-based sensors are a new and economic source of remotely sensed information. Fig. 8 shows an example for UAV-based

Fig. 8. UAV-based observation taken from a sensor platform shown in the upper left corner, for interpretations of road distresses over Gilroy, California (©MLB Company, http://www.spyplanes.com/).

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observations for road pavement assessment. Although mapping efforts are only marginally developed, there is great development potential to support transportation infrastructure surveys in many circumstances (Brecher et al., 2004). This technology could support road maintenance efforts and has to be considered in the further exploration of imaging spectrometry; however there are currently significant institutional barriers to the civilian deployment of UAVs.

The use of a simple VNIR difference also suggests another research avenue. Digital videography is a new technology that provides high spatial resolution, georectified imagery that could be used to calculate simple metrics, such as the visible–NIR difference used here at very fine spatial resolutions at low cost (Hess et al., 2002). Digital videography could be used to estimate PCI and SI using methods similar to those used in this paper, without the need of an imaging spectrometer.

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