ROAD CONDITION MAPPING WITH HYPERSPECTRAL REMOTE SENSING

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1. Introduction

The quality standards for transportation infrastructure have evolved considerably over the last three decades. The data accuracy requirements to support road management have decreased from tens of meters to a few decimeters with annual update rates. Roads are prioritized for maintenance and treatment as a result of pavement inspections. The cost of frequent, comprehensive inspection is high, and many jurisdictions limit their surveys to major roads, while minor roads are surveyed in 3-year cycles. For this purpose, a number of survey technologies have been applied to road condition mapping. The common practice today is extensive field observations by experts who characterize the Pavement Condition Index (PCI), based on established physical parameters such as cracking, rutting, raveling, etc. Other technologies are evolving such us the application of Pavement Management Systems (PMS); typically coupled with GPS/GIS technology and semi-automated in-situ pavement health surveys facilitated by vans. They 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 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 hyperspectral remote sensing technology have shown capabilities to derive physical and chemical material properties on a very detailed level (Clark, 1999). Consequently one would raise the questions: Can we map road surface conditions with hyperspectral remote sensing to support current practice in transportation infrastructure management? Previous studies on pavement condition mapping with remote sensing are rare. Early studies in the 1970s dealt with the visual interpretation of physical surface distresses (e.g. cracks, see Figure 1). The results showed that distresses are distinguishable but only in very large-scale aerial photographs. Currently emerging technologies in this context are observations from Unmanned Airborne Vehicles (UAV). Although mapping efforts are only marginally developed, they have potential to support transportation infrastructure
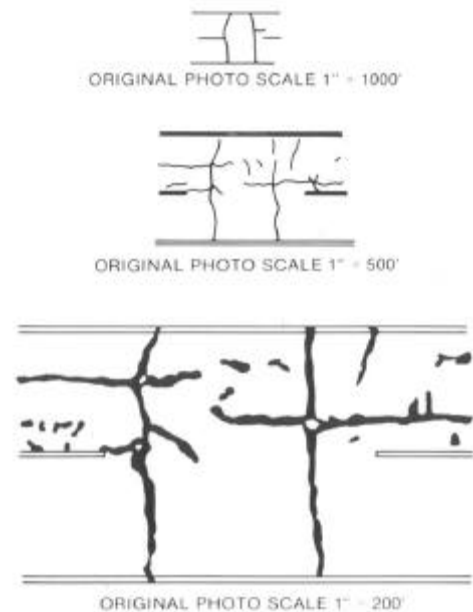

Figure 1: Pavement surface defects mapped from aerial photographs on different scales (Stoeckeler, 1970)

surveys (Brecher et al., 2004). Figure 2 shows an example for UAV based observations for road pavement assessment. UAV based sensors are another new and economic source of remotely sensed information that could support road maintenance efforts and have to be considered in the exploration of hyperspectral imaging.

Figure 2: UAV based observation for visual interpretations of road distresses over Gilroy/CA (©MLB http://www.spyplanes.com/).

The potential of hyperspectral remote sensing is mentioned on several occasions (Usher and Truax, 2001, Gomez, 2002). However, this potential has only recently been explored by the National Center for Remote Sensing in Transportation (NCRST) at UC Santa Barbara (http://www.ncgia.ucsb.edu/ncrst/, Noronha et al., 2002, Herold et al., 2003). An experiment in Santa Barbara and Goleta, CA was conducted to explore the hyperspectral capabilities in mapping road conditions. The investigated 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 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 ASD hand held spectrometer to study generic spectral characteristics of road conditions. The roads were sensed by NASA-JPL's low altitude AVIRIS and by the HyperSpecTIR sub-meter hyperspectral sensor of Spectir Inc. Based on this comprehensive database, we investigated the spectral properties of road surface distresses and compared different of survey methods. The ultimate goal was to explore relationships between remotely sensed parameters (i.e. spectral reflectance) and road condition parameters such as PCI. This relationship needs to be established if remote sensing is to support pavement health surveys.

2. Data and Methods

2.1 Study area
The study focused on several roads in the Goleta urban area, located 170 kilometers northwest of Los Angeles in the foothills of the California Coast Range. Figure 3 shows the study area north

of Interstate 101. The main roads of interest are Fairview Avenue and Cathedral Oaks and in particular near the intersection of both which is shown in the upper middle part of the AVIRIS image (Figure 3). Both roads have four lanes, two in each traffic direction, and represent major urban roads. The SB County PCI values for these roads show that the roads reflect a large variety of conditions (Figure 3). The eastern part of Cathedral Oaks has a PCI of nearly 100. This road was resurfaced just before the study started. 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 particular poor conditions. The central divider of Fairview was the boundary between two traffic management zones. Every rehabilitation effort had to funded and coordinated by to different institutions. This resulted in delays and failure of necessary maintenance and continued deterioration of the road surface is apparent today.
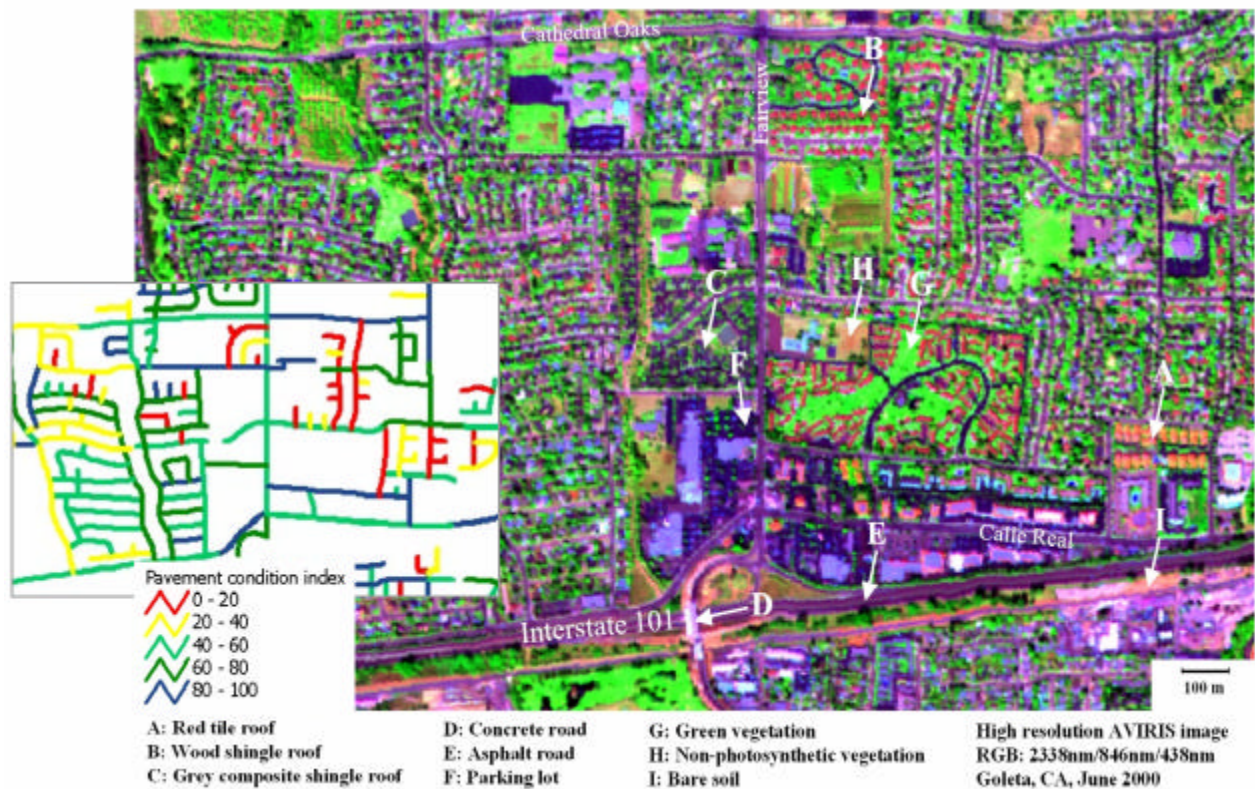

Figure 3: AVIRIS image of the Fairview/Cathedral Oaks study area shown with the distribution of the PCI from the Santa Barbara County database.

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, Figure 4). 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 the Iowa State University at Ames. The second

expert group included representatives from California firms associated with CALTRANS: Independent Seals, Western Paving and Vulcan Paving. The experts were asked to categorize the road condition in five categories (excellent, good, fair, poor and very poor) and suggest a road management action (do nothing, maintenance, minor rehabilitation, major rehabilitation, and re-placement).
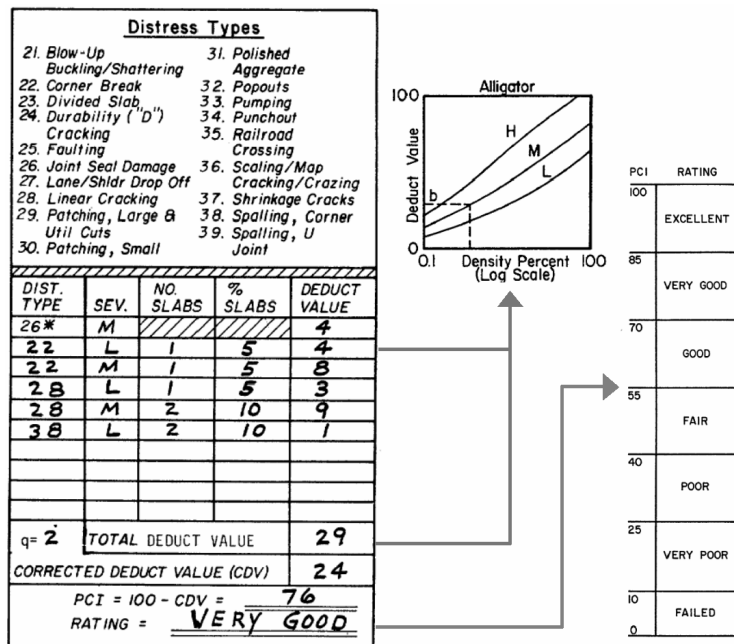

Figure 4: Road condition survey sheet outlined by the US Army Corps of Engineers (1982)

The second source of road information was provided the Santa Barbara (SB) County road database. Since 2001 the County has been using the MicroPaver Pavement Management System (PMS). This PMS is a decision making tool for cost effective maintenance and repair alternatives for all roads within the County. 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. Figure 3 shows a subset of this database. The PCI is reported for relatively large road segments and does not discriminate between different 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 very detailed information about road distresses. The observations were performed in December 2002 with the Automatic Road Analyzer (ARAN) of the Roadware cooperation (www.roadware.com). ARAN is mounted on a specially modified vehicle that houses an extensive set of computers and sensors including: lasers, inertial measurement units, accelerometers, ultrasonic transducers, digital cameras and other advanced technology subsystems (Figure 5). GPS on the vehicle and at a base station ensures accurate locational data. The survey provides geocoded road distresses 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. Similar to the ones for field surveys, the "Roadware PCI" categorizes the majority of distresses in a rating based on 0 to 100 scale with 100 being the best condition. The PCI calculations are based on deduct values (Figure 4) that come from the actual Roadware observations (see also Figure 4). 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.

Figure 5: The Roadware pavement health survey with the ARAN survey vehicle, GPS base station, the video/road distress log and the resulting GIS database.

All road condition information was integrated into a GIS database. The Roadware data and the Expert evaluations use similar 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 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 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 shortwave infrared (SWIR1 and SWIR2), with a spectral

Figure 6: Acquisition of spectral samples of road surface distresses.

sampling interval of 1.4 nm for the VNIR detector and 2.0 nm for the SWIR detectors. FR field spectrometer data are widely used and considered to provide high quality spectral measurements. All targets were documented and integrated into a spectral library (Figure 6). The spectra library contains various types of roads (asphalt, concrete, gravel) and different distresses of asphalt road surfaces.

2.4 Remote sensing data

Two hyperspectral datasets were acquired in the study area. The AVIRIS sensor flew on June 9th, 2000. The data were acquired at a spatial resolution of approximately 4 meters. The AVIRIS sensor acquires 224 individual bands with a nominal bandwidth of 8-11 nm, covering a spectral range from 370 to 2510 nm (Green et al., 1998). The Jet Propulsion Laboratory (JPL) and the University of California, Santa Barbara (UCSB) preprocessed the data for motion compensation and reduction of geometric distortions due to topography. The data were processed to apparent surface reflectance using modified Modtran radiative transfer code and further adjusted using a ground reflectance target from the spectral library (Green et al., 1993). In general, the spatial and spectral quality of the AVIRIS data were excellent (see Figure 3).

As second set of hyperspectral remote sensing observations was provided from the Spectir Inc. located in Goleta, CA (www.spectir.com). The company developed a new sensor "HyperSpecTIR" (HST) with 227 bands over a range of 450-2450 nm. The main advantage of this HST is the high spatial resolution. Due to an onboard, integrated stabilization system the flight altitude can be very low with a GIFOV of about 0.5 m. This is quite an advantage over AVIRIS for detailed mapping of road conditions (Figure 7). 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 Spectir data were experimental from the HST I sensor. The recently completed HST II and III sensors, along with improved spectral calibration will hopefully enhance the spectral quality of future datasets.

Figure 7: Comparison of spatial detail provided by the AVIRIS and HyperSpecTIR sensor.

The analysis of the remote sensing only considers the actual visible road surfaces. All other land cover types were excluded by using an accurate road outline available in digital format. Vegetation and shadows obscuring the road surface were excluded in HST data where they were clearly visible. The remote sensing investigations applied specific reflectance ratios that are discussed later. The local variance in the 3x3 neighborhood of these ratios was also calculated and included in the analysis.

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 on 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). 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.
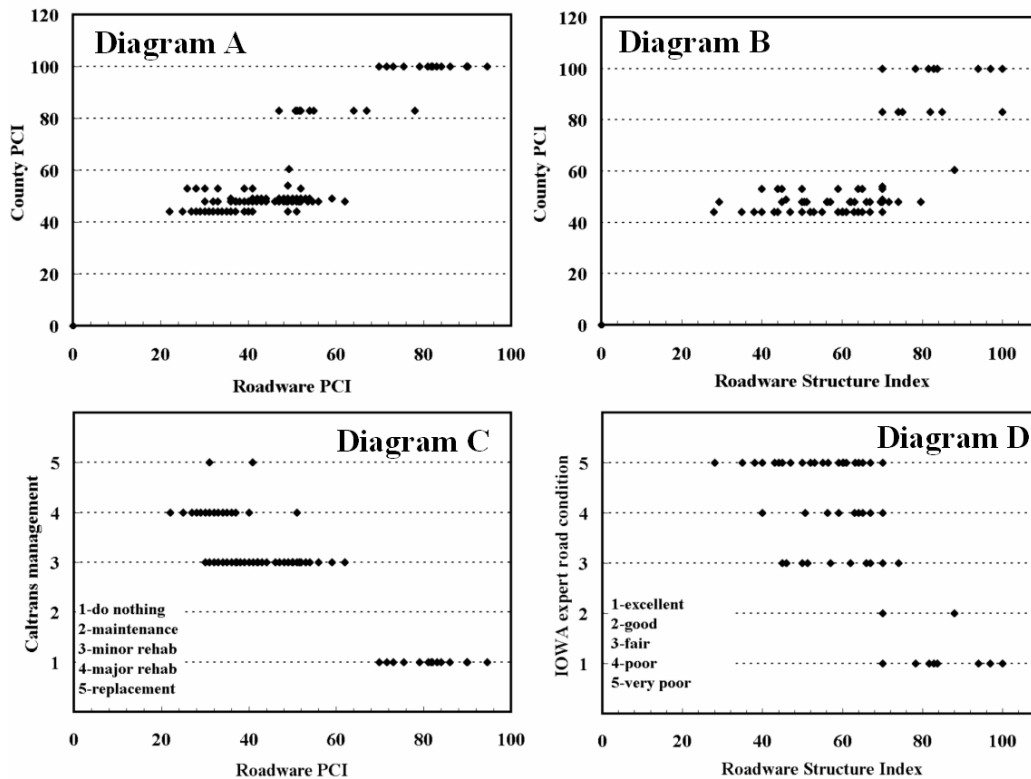

Figure 8: Comparison of road condition survey data (Note: The y-axis of diagrams C and D are categories.)

3. Comparison of road surveys

All three road survey techniques (expert visit, Roadware, County PMS) applied in this study can be considered part of the "common practice" in pavement management. 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 (Figure 8). Diagram A and B compare the County PCI to the Roadware PCI and structure index. There is a good linear relationship between both PCI measures. 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 non-linear (Diagram B). This is expected since the structure index only contains the structural damages. Early pavement degradation usually does not result in severe structural damages and the structure index remains high. The structure index better describes distresses for roads in poorer conditions with significant structural damages, i.e. there is quite some variability in lower structure index values with the County PCI staying fairly constant. Diagrams C and B in Figure 8 relate the expert opinions to the Roadware data. Both show good relationships. The Roadware PCI clearly reflects the difference between a very good road ("do nothing") and the roads that need rehabilitation or replacement. A similar distribution is shown in Diagram D. Although the overall relationships between the different survey techniques is 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.

4. Spectral characteristics of road conditions

The spectral signal from different types of road materials such as concrete and asphalt are different and hyperspectral sensing can easily distinguish between them (Herold et al., 2004). This study focuses on the variability within asphalt road surfaces i.e. the spectral effects of aging and deterioration of asphalt pavement (Figure 9).
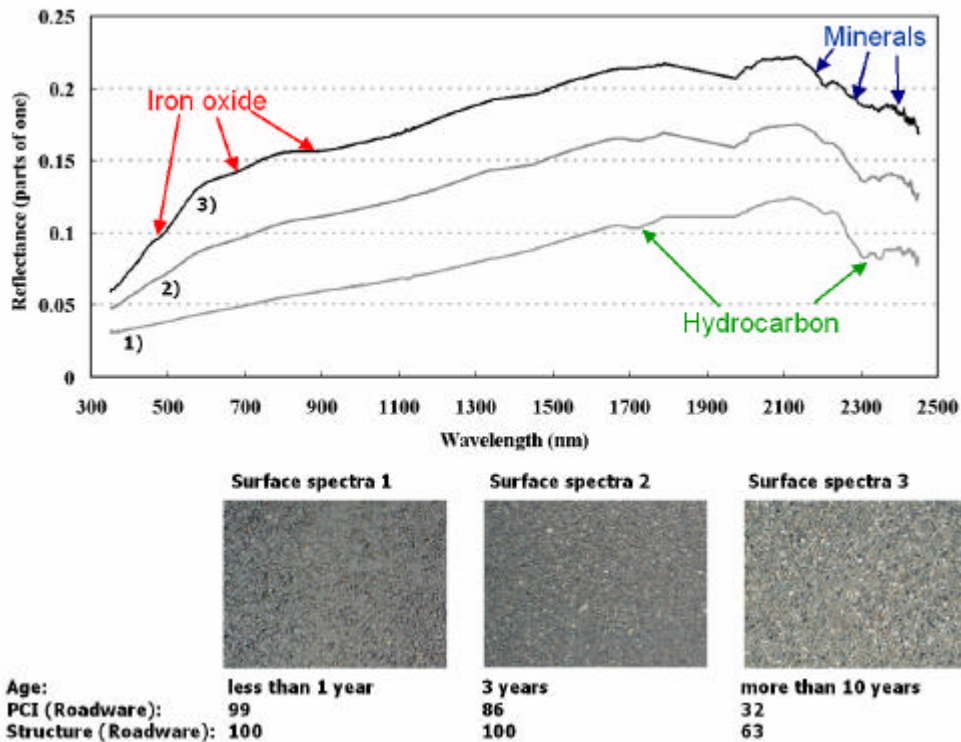

Figure 9: Spectral effects of asphalt aging and deterioration from the ASD ground spectral measurements (the major water vapor absorption bands are interpolated).

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 (Bell, 1989): 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 (steric hardening). The loss of oily components is relatively short-term; the other two are more long-term processes. The results of these processes are represented in the spectra. New asphalt surfaces have the lowest reflectance with a linear increase in reflectance towards 2100 nm. The surface is nearly completely covered with asphalt mix (spectrum 1). Hydrocarbon absorptions are evident at ~1750 nm and above 2100 nm with a significant doublet at 2310 and 2350 nm (Cloutis, 1989). As the pavement ages and its condition deteriorates, reflectance increases in all parts of the spectrum. The asphalt mix seal starts eroding exposing the rocky components of the pavement (spectrum 2). This process continues until the rocky components dominate the asphalt surface. With the erosion of the asphalt mix the road surface is less viscous and more prone to structural damages like cracking. This decreases asphalt mix absorptions resulting in a significant increase in object brightness. This difference is highest in the NIR and SWIR with more than 10% reflectance. The spectral shape in NIR and SWIR changes from slightly concave for new asphalt to more concave for older surfaces. The oxidation process and exposing of rocky components is clearly shown by the appearance of iron-oxide absorption features at 520, 670 and 870 nm in spectra 2 and 3. The hydrocarbon features are only distinct for new asphalt surfaces and vanish with age and poorer surface conditions. Furthermore there is significant change in slope in the transition from hydrocarbon to mineral absorption. For older roads the slope increases between 2100-2200 nm and decreases between 2250-2300 nm.
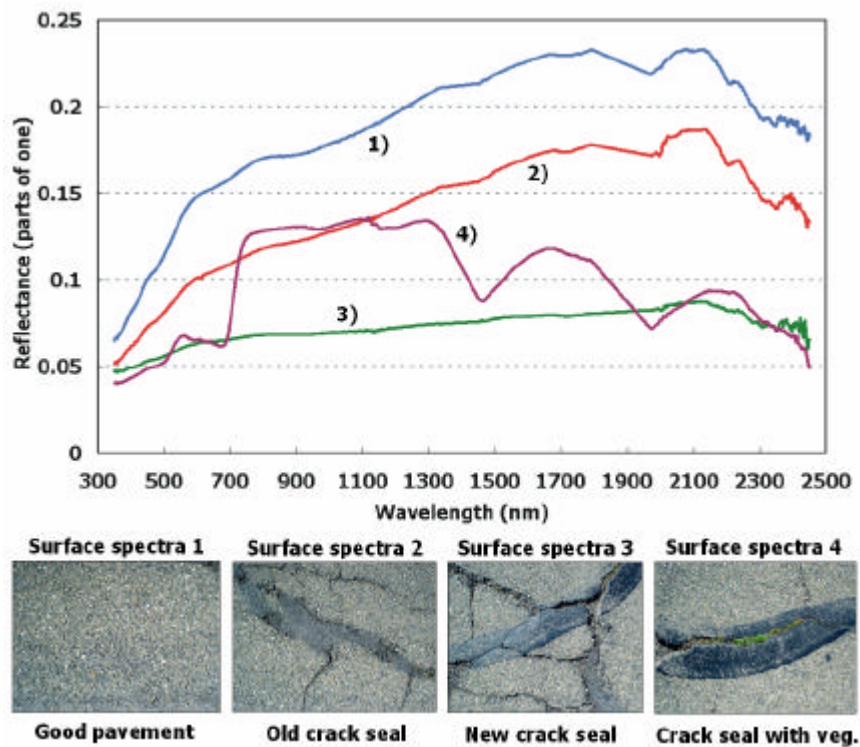

Figure 10: Spectral effects of different structural road damages from the ASD ground spectral measurements (the major water vapor absorption bands are interpolated).

Spectral characteristics of specific road damages are presented in Figure 10. The spectra show that cracks and old crack seals produce decreasing brightness. For new crack sealing, this effect is more dominant and results in near constant low reflectance similar to the ones found for parking lot surfaces (Herold et al., 2004). Some older cracks contain green vegetation, which again has a strong impact on the spectral response exposing typical spectral features from chlorophyll, water content and lingo-cellulose.
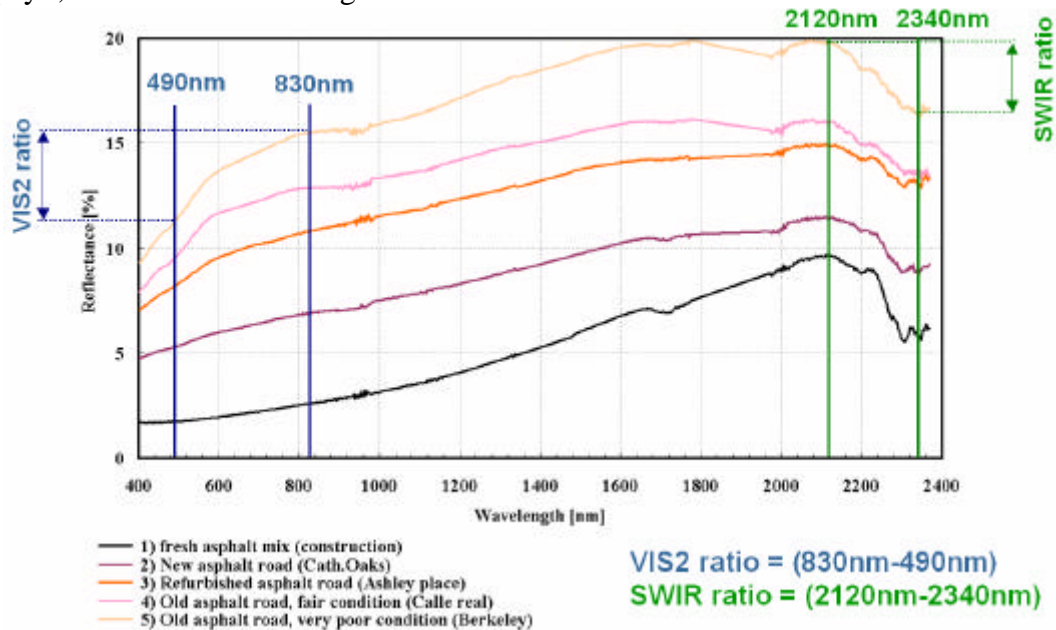

Figure 11: Two image ratios used for the hyperspectral data analysis shown with ASD ground spectra of different asphalt road surfaces.

5. AVIRIS data analysis

Spectral analyses of road surfaces suggest several features that have utility for spectral identification of road aging and deterioration. The coarse spatial resolution of the AVIRIS data and the spectral quality of the HST data, however, only allowed for the use of very general spectral features, i.e. small absorption features were excluded from the hyperspectral data analysis. The investigations were based on two image ratios (Figure 11).
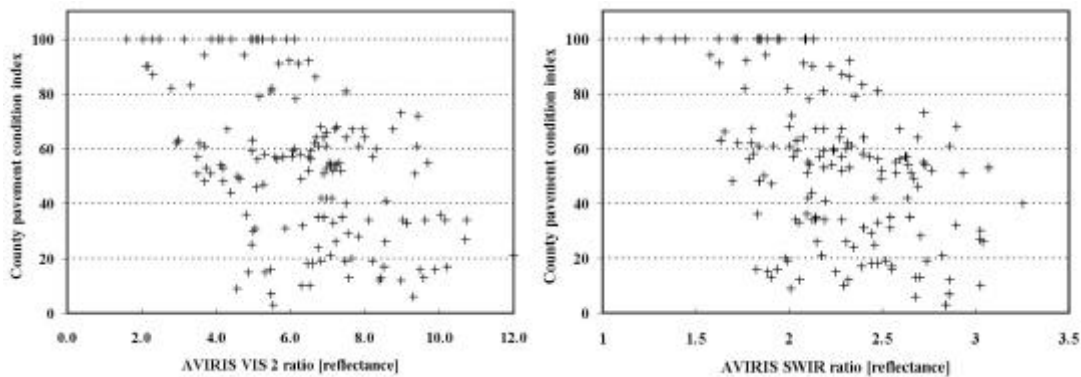

Figure 12: Comparison of two AVIRIS based image ratios versus the County PCI.

These ratios emphasize the increasing brightness and the change towards more concave spectral shape in the VIS for older roads. The first ratio (VIS2) represents the reflectance difference between 830 nm and 490 nm. This ratio is low for new asphalt surfaces and increases with age and level of deterioration, partially caused by the iron oxide absorptions. The SWIR ratio reflects the spectral contrast between ~2120 nm and ~2340 nm, which decreases for older asphalt surfaces (Figure 9 and 11). The AVIRIS based image ratios were compared to the County PCI values (Figure 12). The graphs show a large amount of variation in the ratios versus the PCI values. There is some indication of the expected decrease in image ratios for higher PCI values. The variability of the ratios seems to increase for roads with lower PCI. However, the relationship is very weak (R-squared values in the order of 0.1-0.2) and it can be concluded that AVIRIS data did not allow for mapping of road conditions in this study. This limitation can be related to the spatial resolution. Figure 7 emphasizes the spatial detail provided by the AVIRIS sensors. Pure road surface pixels are rare and surrounding land cover types (vegetation, gravel, buildings etc.) affect the spectral signal and add significant variability and uncertainty to analysis of road conditions (Figure 12).
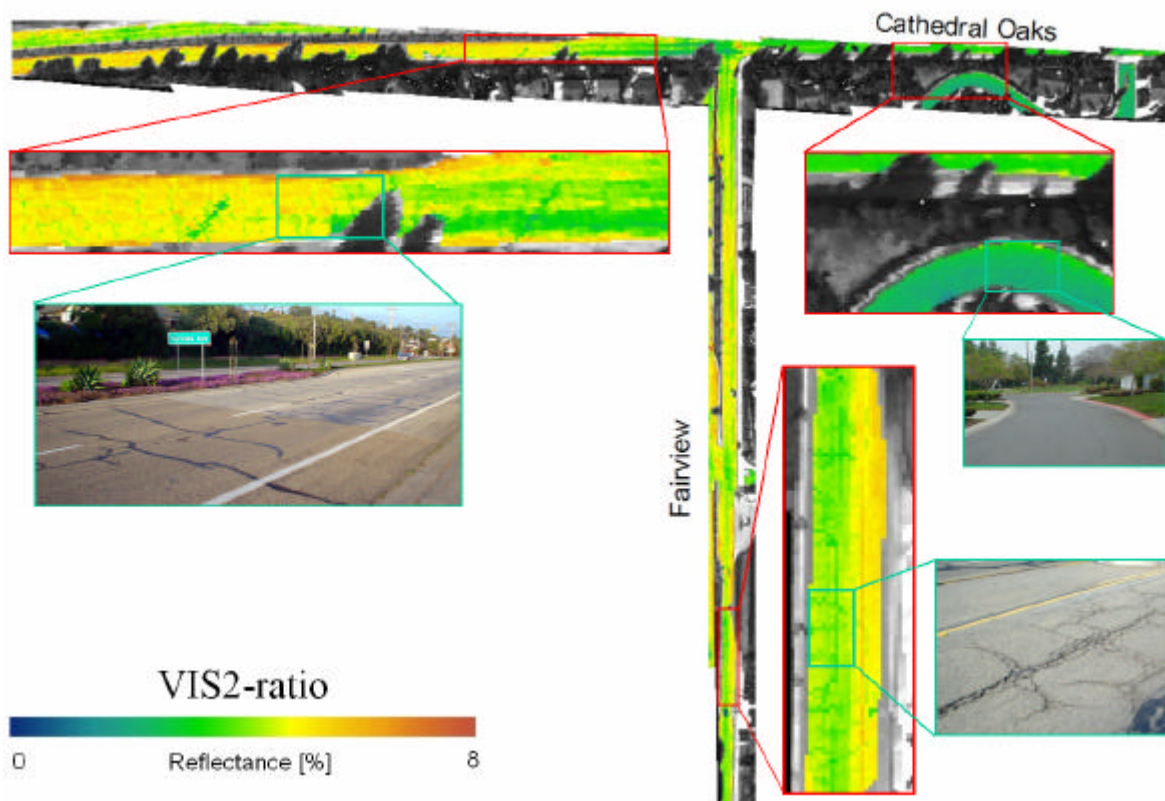

Figure 13: Spatial distribution of the VIS2 ratio derived from the HST data.

6. Hyperspectir data analysis

The HST analysis only focused on the VIS2 ratio since the spectral quality of the data limited the investigations on the VIS-NIR region. The spatial resolution was very beneficial since road surface features and distresses are represented in the HST data (Figure 13). The spatial distribution of the VIS2 ratio showed expected general road surface pattern. Roads with recently paved surfaces (upper left part of Figure 13, east Cathedral Oaks) show low ratio values on the

order of 2-4 % reflectance difference (dark green and blue) between 830 and 490 nm. The highlighted part of west Cathedral Oaks presents the transition between a newer split-seal refurbished road (green-yellow) and an older part with several sealed transverse cracks (yellow-orange). The southern part of Fairview shows an area with severe alligator and block cracking. The crack patterns are visible in the VIS2 distribution with lower ratio values (see Figure 10). This adds spatial variance to the ratio values and appears for roads with structural damages.
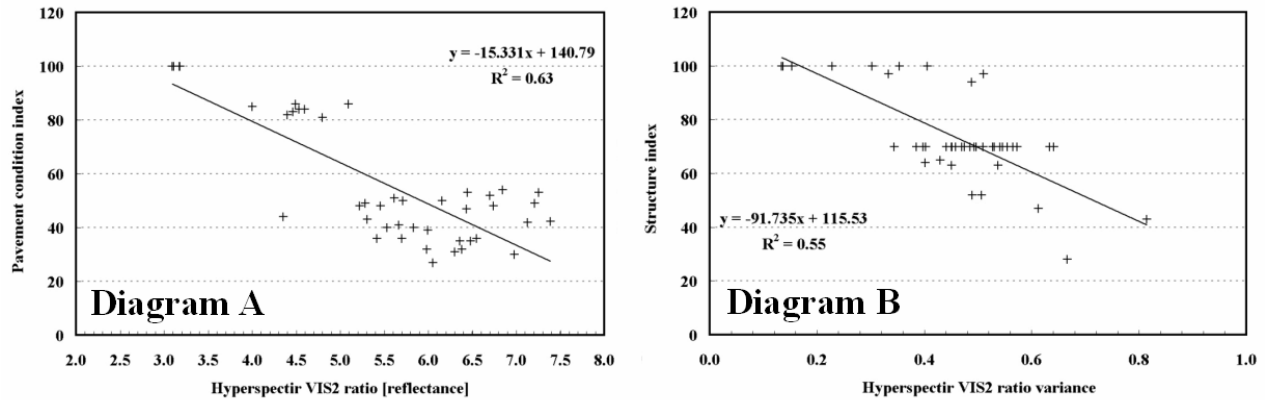

Figure 14: Comparison between HST VIS2 ration and Roadware PCI and structure index.

The HST VIS2 values show a significant correlation with the Roadware PCI values (Figure 14, Diagram A). For roads in good condition the relationship is very distinct. The variability increases for high ratio/low PCI values, hence to spectral signal of the roads get more complex and the relationship is not as obvious. Diagram B shows the spatial variance in the VIS2 ratio versus the Roadware structure index. This relationship represents the fact that structural road damages add complexity to the spectral signal. There is, however, significant variability for very high PCI values. They are false positives, basically other features that add variability to the spectral signal and do not represent road damages such as shadows from light poles, cars etc.

The statistical relationships in Figure 14 are strong enough to convert the remote sensing signal (VIS2 ratio, VIS2 ratio variance) to road condition parameters (PCI, structure index). The spatial distributions are shown in Figure 15. The PCI patterns highlight recently paved roads with high values (see Figure 13). Road surfaces in poorer condition show lower PCI values and higher variability. Specific cracking patterns are revealed in the highlighted area of Fairview. The structure index was derived from the local VIS2 ratio variance. The spatial distribution emphasizes local pattern of road surface variability caused by structural damages. In the areas of newly paved roads in the upper left on the bottom map, there are some small high-variance features near the edges of the roads that are not road distresses representing false positives. Cracking patterns and other distresses are reflected in the other highlighted areas on Fairview and west Cathedral Oaks which show high variance.
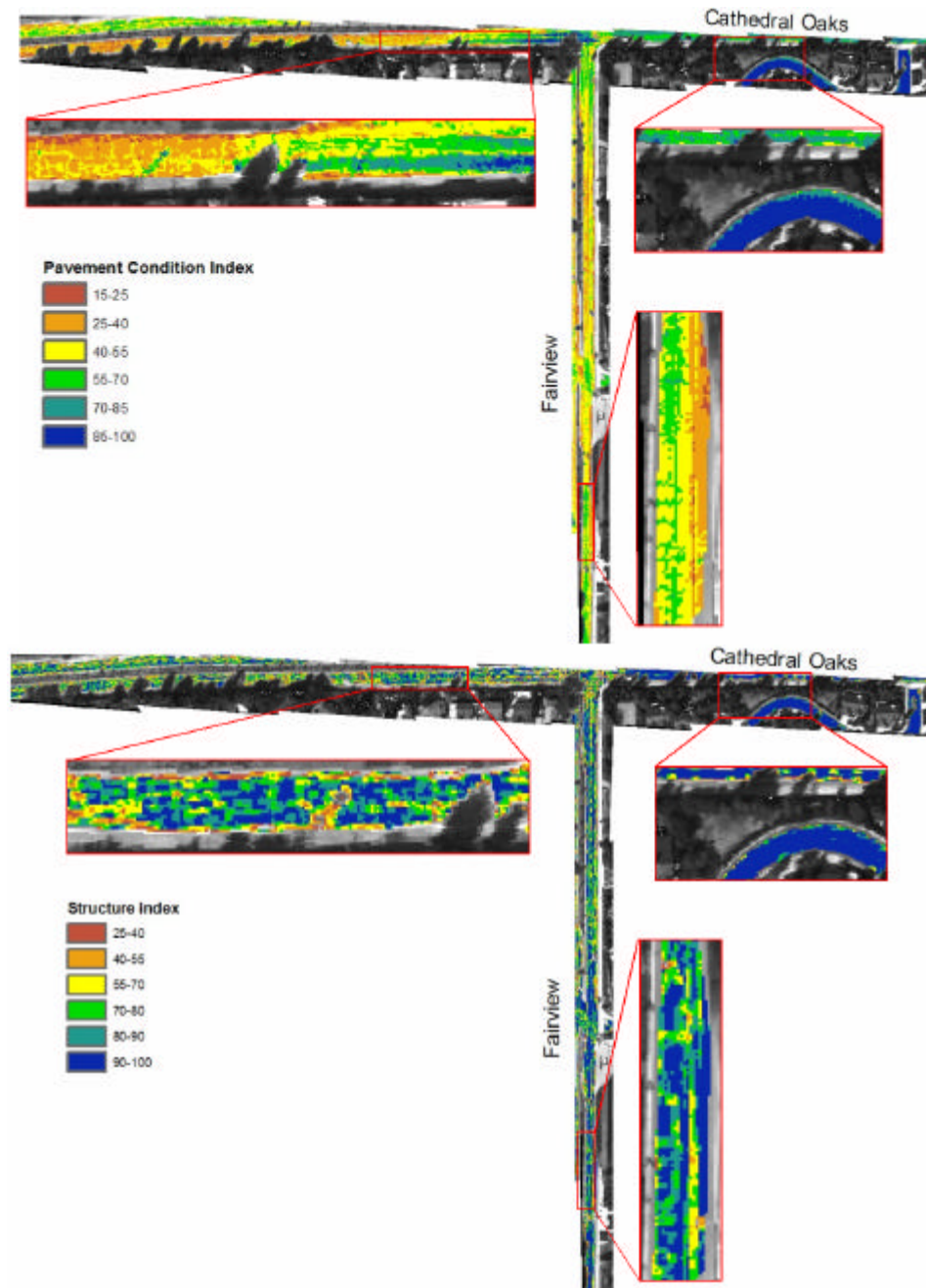
Figure 15: Spatial distribution of PCI and structure index derived from HST data.

Figures 14 and 15 show the relationship between the remote sensing signal and descriptive parameters of road condition. However, the remaining question is to what extent can remote sensing signals be translated into specific management suggestions. An analysis of variance (ANOVA) was applied to show if the remote sensing signal is statistically different for the various categories of management. The ANOVA results relating the VIS2 ratio values to four categories of possible CALTRANS management actions are shown in Table 1.

Table 1: ANOVA results of HST VIS2 ratio versus CALTRANS management suggestion.

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


Multiple R-Squared: 0.46
F-statistic: 11.24
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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 HST ratio 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 ratio. Basically this is the expected VIS2 ratio 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. They 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 emphasize an observation that was found for several analyses during this study. Obviously, both the "common practice" methods 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 not able to acquire and it is doubtful that this detailed level of information can ever be acquired with these methods.

Conclusions
This study combined field spectrometry, in-situ road surveys and hyperspectral remote sensing to explore the potential in mapping road conditions from remote sensing. The aging and degradation of road surfaces are represented by distinct spectral characteristics. This study used image ratios and the spatial variance measures to relate the remote sensing signal to pavement condition indices. Image ratios showed the best correlation with the PCI, and variance correlated with an index describing structural road damages (e.g. cracks). Essential for the mapping of road deterioration are the spatial sensor resolutions. The GIFOV should be at least on the order of 0.5 m for detailed road condition observations. The mapping results are most accurate for roads in good conditions. Older roads are more complex and their condition evaluation is more uncertain, in both remote sensing data vehicle-based in-situ observations. There are some limitations to this study. The 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 hyperspectral mapping techniques including the short-wave infrared and small absorption features that were identified in the spectral library analysis. In summary, road condition mapping from hyperspectral remote sensing has some potential. It is not likely that remote sensing will take the part of an expert field inspector, but it can offer insights into surface conditions and other aspects that the inspector cannot evaluate except with laborious and destructive testing and field surveys can be limited and optimized. However, this is the first time this issues was presented in this context and further studies are needed to refine to analysis and develop a mapping strategy based on existing technology and in comparison to sensor developments (UAV-based).

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