Automated Pavement Condition Assessment Using Laser Crack Measurement System (LCMS) on Airfield Pavements in Ireland.

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ABSTRACT

Pavement condition surveys which identify pavement distress types, severities and quantities and provide a condition index or rating are an essential part of any pavement management system and an invaluable tool in the evaluation of a pavement's performance. Traditionally, distress data has been collected manually on foot, where the pavement is examined by eye, and the distress data is measured by hand. For airfield pavements, this often involves significant disruption to or closure of runways which can be very inconvenient and costly. Further modifications in Ireland have led to the development of more rapid visual inspection methods using a driven windshield survey procedure and more recently, using forward view digital video. This paper describes a case study where automated data collection and processing using Laser Crack Measurement System (LCMS) technology was used to establish and graphically report the pavement condition on two major runways at Dublin and Cork Airports, Ireland. The runways at both airports were constructed with asphalt-surfaced pavements.

The data collection for the study included manual walking surveys, visual surveys from forward view digital video, and the collection of intensity and range three-dimensional (3D) imagery using an LCMS mounted on a high speed vehicle. The type, severity and extent of the pavement distress data were identified from the manual survey, the digital video, and using automated extraction from the LCMS 3D imagery. The data were processed and evaluated using the Micro PAVER pavement management system and the condition reported using the US Army Corps of Engineers Pavement Condition Index (PCI). The imagery and distress data from the LCMS survey were graphically reported using colour-coded thematics in ArcGIS and Google Earth GIS formats, and the detailed distress data was also mapped in AutoCAD layers.

The paper examines and compares the pavement condition results obtained from the manual, video and LCMS data collection methods, and outlines the findings in using LCMS technology to automatically identify, geo-locate and graphically report pavement condition and distress data for airfield pavements.

2. INTRODUCTION

Collection of regular pavement condition information can be one of the most costly elements of the implementation and operation of a pavement management system. There are many different methods to collect pavement distress data. In Ireland, distress data has been collected using manual surveys, a driven windshield survey procedure and more recently, using visual assessment from high definition forward view digital video. These survey methods are based on human observation which can produce subjective results and can be labour intensive, time consuming and involve safety risks. With the rapid development in automated data acquisition and image recognition techniques, automated pavement condition surveys have improved significantly over recent years and provide some clear advantages in terms of the limitations of manual visual surveys.

The Laser Crack Measurement System (LCMS) has been in use in Ireland since 2012. It is used to provide totally automated data collection on the entire 5300 kilometres (3300 miles) of the National Road network annually since 2013. In addition, the LCMS has been used by Airport authorities in Ireland to provide high speed pavement distress data and imagery for runways, taxiways and aprons. In the study, the LCMS was used to establish the pavement condition on Runway 16/34 at Dublin airport and Runway 17/35 at Cork airport. The automated distress data were compared against visual distress data identified from manual walking surveys and forward view digital video. The data were processed using Micro PAVER (Version 6.1.2, 2009) and the surveys compared using the Pavement Condition Index (PCI) in the analysis (1).

3. AIRPORT DESCRIPTION

The value to Ireland from air transportation is approximately €4.1 billion ($5.5 billion) of which €1.9 billion ($2.5 billion) comes directly from aviation. On average, 90% of people who travel by air to or from Ireland use Dublin and Cork airports (2).

Dublin Airport is the largest airport in Ireland, and is one of the ten busiest airports in Europe, handling on average 20 million passengers annually. The airport has two runways, the main Runway 10/28, and a secondary Runway 16/34 which is operationally critical to the airport as a secondary cross-wind runway and back-up to the main runway. Dublin Airport manages an average of 60,000 passengers per day, rising to 80,000 during the peak season, and has more than 600 aircraft movements every day.

Cork Airport is Ireland's second busiest airport after Dublin and handles on average 2.4 million passengers annually. The main runway is Runway 17/35. Cork Airport manages an average 7,000 passengers per day, rising to 15,000 during the peak season and has about 60 commercial aircraft movements a day.

4. THE MICRO PAVER SYSTEM AND PCI

The Micro PAVER system, developed by the U.S. Army Corps of Engineers, uses the Pavement Condition Index (PCI) to establish pavement condition (3). The PCI scale ranges from 0 for a failed pavement to 100 for a pavement in perfect condition with no visible distress. It is calculated from information collected during a pavement condition survey in which distress types, severities and quantities are identified. A breakdown of pavement latest classification by PCI scale from American Society for Testing and Materials (ASTM) Standard D5340 is as follows (4):

PCI Range	Pavement Condition
85 to 100	Good
70 to 85	Satisfactory
55 to 70	Fair
40 to 55	Poor
25 to 40	Very Poor
10 to 25	Serious
0 to 10	Failed

Micro PAVER uses deduct value curves based on expert opinion to calculate the PCI from the measured distress data. For each distress measured, there are deduct values depending on the nature of the distress, its severity and quantity. The deduct values, which range from 0 to 100, indicate the impact that each distress has on pavement condition. The individual deduct values are summed, adjusted to account for the interaction of multiple distresses, and subtracted from a "perfect" PCI of 100 to give the actual PCI. In order to store and retrieve the pavement distress data, the pavement network is divided into a hierarchy of smaller components known as branches, sections and sample units.

5. DISTRESS SURVEY METHODS USED

The pavement distress data were collected using visual assessment from manual walking surveys and high definition digital video, and using automated data collection with LCMS.

5.1 Visual Distress Surveys

For consistency with surveys done prior to 2012, the manual and video surveys in this study were conducted using the PCI methodology in accordance with the 2003 edition of the ASTM Standard D5340 "Standard Test Method for Airport Pavement Condition Index Surveys" (5). The manual survey is based on a sampling procedure and detailed measurement is carried out only on the selected sample units. For asphalt-surfaced airfield pavements, 16 possible distress types can be identified using the 2003 edition of ASTM D5340 and a detailed survey manual is used by the survey team (6). In the 2012 edition of the D5340, there are 17 distress types listed with weathering and ravelling treated as separate defects. In this study, weathering and ravelling were evaluated as a single distress type using the 2003 standard (5).The pavement distress data are assessed manually by detailed measurement and recording of distress quantities on each sample unit using a hand odometer, a tape, a straightedge and a ruler. The sample unit PCI results are extrapolated to represent the pavement section as a whole.

More recently, the pavement condition has been assessed using a high definition digital video camera system to record a forward view/pavement-orientated video of the pavement surface. The video camera used is a broadcast quality Canon XH-A1 camera which has three 1/3" 16:9 interlaced charge couple devices (CCDs) that capture images at 1080i resolution. The camera is mounted on the dash of the survey vehicle and the digital video is recorded by an onboard computer. The digital video is recorded as individual georeferenced JPEG images taken every 5 metres.

A very accurate DMI (Distance Measuring Instrument) is attached to the vehicle and connected to the hardware interface. The video camera outputs a high definition digital video stream to the hardware interface and the frames are compressed using state-of-the-art compression algorithms to retain maximum definition at minimum storage space. The video data collection can be carried out at normal driving speeds, and the video is recorded using both chainage and GPS referenced coordinate systems. For this study, the runway data was collected at c. 50 km/hr (about 31 mph).

The digital video can be subsequently post-processed in the office to carry out a visual condition survey and record pavement distress data. The distress data is identified from the digital video using a desktop computer and a specially designed software programme. The software programme presents the forward view video as a windshield survey on the left of the screen, and a list of the defect types and severities on the right side of the screen that allows the observer to record the distress data as per a live survey. As one relies totally on visual assessment to identify the type, severity and quantity of the defects, the observer has the alternatives of quantifying the defects using the programme by either ranges of magnitude (<1, 1-5, 5-10, 10-20 or 20-40 m, m^2), the estimated quantities or the estimated percentage areas of the distresses (7). The distress data is recorded for each 100 metre length of pavement. The software is capable of pause/fast forward/fast rewind and will allow the observer to set the speed of the video as per driving for a live survey. The distress data is used to produce the Video PCI (VPCI) on each 100 metre sample unit.

The use of video for condition evaluation has some advantages over manual walking inspection methods. The video can be collected quickly in the field allowing much higher data collection outputs with less disruption. Inspection and identification is carried out in the office in safe and comfortable surroundings, and the video can be played at different speeds, paused, reversed etc. by the inspector to ensure that the distress identification is correct. Multiple inspectors can be used in the post-processing phase to expedite the duration of processing, and auditing of the distress identification process is much less costly than field auditing. In addition, the video provides a permanent record of the pavement surface at the time of testing, and can be used for other pavement management purposes or linking images to pavement data in GIS.

5.2 Laser Crack Measurement System (LCMS)

The LCMS, developed by Pavemetrics Systems Inc., Canada, is a 3D laser-based, high-speed and high-resolution transverse profiling system. The LCMS consists of two downward facing high-speed line scan cameras and high power laser line projectors to acquire both 2D images and high-resolution 3D profiles of the pavement surface. Lasers are projected on to the pavement surface to be inspected and its image is captured by the cameras. Figure 1 shows the LCMS in operation at Dublin Airport.

The LCMS acquires 3D data by measuring the distance from the sensor to the surface for every sampled point on the pavement. The sensors simultaneously acquire both 3D "Range" (height of each pixel) and "Intensity" (the intensity of the reflected light for each pixel) images of the scanned surface (8). The two fully synchronized 3D laser profiles can capture a continuous image of the pavement profile with 1 millimetre/pixel resolution. Each profile consists of up to 4160 data points giving full 4-metre width 3D profiles of the pavement. The system can be operated in full daylight or in night time conditions. The LCMS can be driven at speeds of up to 120 km/hr (about 75 mph), but is typically operated in Ireland at 70 to 80 km/hr (about 45 to 50 mph).

The LCMS is mounted on the rear of a Road Surface Profiler (RSP) survey vehicle. In addition to the LCMS imagery, the RSP provides a multi-purpose data collection system for continuous high-speed measurement of a variety of other pavement performance data including longitudinal profile (including IRI, International Roughness Index), transverse profile (rut depths), surface macrotexture (expressed as MPD, Mean Profile Depth), geometrics, forward-view imaging and positioning data. The data is chainage-referenced using a highly accurate DMI, and geo-referenced using a high-specification GPS device and Inertial Navigation System (INS).

The LCMS range and intensity data are processed using automated image/data algorithms that analyse each data profile to determine the extent and severity of distress data in the pavement surface including cracking, patching, ravelling and rutting. This analysis is done in Pavemetrics LcmsRoadInspect software (Version 3.4.1.4, 2014) (9). Following the LCMS processing, the data is then analysed using the automated 'Dynatest Explorer' software (Version 1.6.5.0, 2013) (10), to classify and output the type, severity and quantity of pavement distress data for input into the Micro PAVER database (1). Figure 2 shows an image created using LcmsRoadInspect and the same image with the distress type overlay in the Dynatest Explorer.

Automated pavement surveys are more objective, faster and safer than manual surveys. The most difficult part of an automated LCMS survey is in detecting and classifying pavement distresses, with an inability in some instances to identify some defects and severity levels. However, to overcome these limitations significant improvements to processing power and to automated image/data algorithms have been made in recent years. In this study, the automated software has some difficulty with the identification of short lengths of hairline longitudinal and transverse cracking, short lengths of low severity sealed cracks and with the initial misdiagnosis of transverse and diagonal tining as linear cracking. The automated data algorithms were successfully improved during the study to prevent misdiagnosis due to tining and to better identify short lengths of low severity sealed cracks.

FIGURE 1 High-Speed LCMS Survey Vehicle at Dublin Airport.

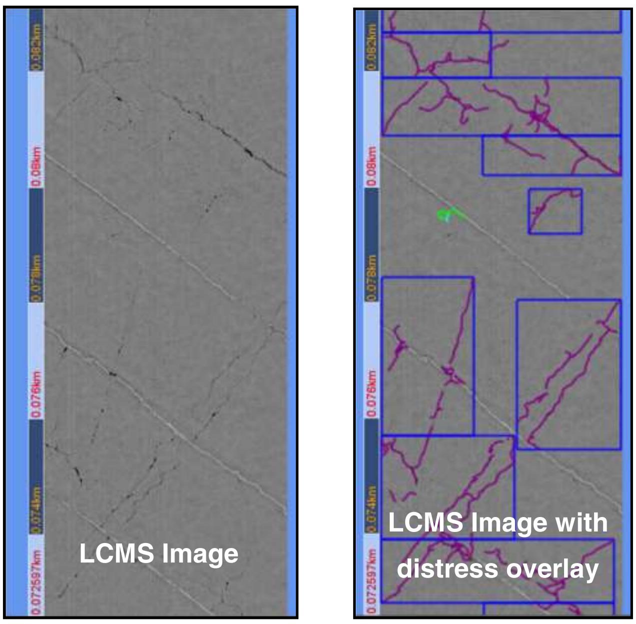

FIGURE 2 LCMS and Dynatest Explorer Images.

6. DATA COLLECTION

The scope of the study comprised two runways, with surveys conducted on Runway 16/34 at Dublin Airport and Runway 17/35 at Cork Airport. The distress data on the runways was collected using the three pavement data collection methods of manual walking, digital video and automated LCMS. All data was both chainage and GPS referenced.

The runways were delineated into 3 metre (about 10ft) wide sections which were sub-divided into 100 metre (about 328ft) long sample units. The pavement condition data was collected on both runways during daylight hours in between flights. The runways at both airports were constructed with asphalt-surfaced pavements.

6.1 Surveys on Runway 17/35 at Cork Airport

Runway 17/35 at Cork Airport was 2130 metres long and 45 metres wide. The runway was divided into fifteen 3-metre wide rips (or lanes) across the runway, which are identified by letters A to O starting from the north edge to the south. Each rip had twenty one sample units with a total of 315 sample units over the whole runway. The LCMS survey including the collection of the forward view video of the pavement surface in each of the fifteen rips were collected in March 2014. The accuracy of the rips along the runway were tracked using a high-sensitivity GPS/SBAS Trimble GPS receiver and antenna enabled tablet which allowed the operator to select the offset by which to move the vehicle parallel to the previous test rip.

The LCMS data was processed for all fifteen rips to determine the LCMS-PCI and to graphically report the pavement condition and distress data in GIS. While the LCMS collected 3D laser profiles over the full 4 metre width, the data was only processed for the required 3 metre rip.

To establish a reference value to compare with the automated LCMS pavement distress measurement and video distress data, a manual walking survey was carried out to establish ground truth. The manual PCI distress survey was carried out by personnel with long experience on condition surveys using the PCI methodology (ASTM Standard D5340) to determine the distress data. Due to access restrictions in March, the manual distress survey on the ground was conducted over one day in June 2014. As the manual survey is a time consuming task and the runway was in live operation, a sampling procedure was adopted. In total, 42 sample units (13% coverage) were manually surveyed comprising 7 sample units randomly selected in rips B, D, F, I, K and M. The pavement distress was assessed by detailed measurement of distress quantities on each sample unit by hand.

The pavement distress was also recorded using visual assessment from the forward view video to determine the Video-PCI for the same 42 sample units in rips B, D, F, I, K and M. The sample unit and section PCI values from the LCMS, video and manual surveys were compared in the analysis.

6.2 Surveys on Runway 16/34, Dublin Airport

Runway 16/34 was 2072 metres long and 60 metres wide. The runway was divided into twenty rips across the runway, which are identified by letters A to T starting from the east edge to the west. Each rip had 19 sample units with a total of 380 sample units over the whole runway. The high speed LCMS survey and forward view video in each of the twenty rips was carried out on Runway 16/34 in June 2013. The data collection was carried out in each of the twenty rips with 100% coverage over the full length of the runway. Due to traffic restrictions, it was not possible to obtain sufficient daylight access to carry out a manual survey on this runway.

The LCMS data was processed for all twenty rips to determine the LCMS-PCI. The Video-PCI survey was carried out for each 100 metre sample units on the full length of rips D, H, I, J, K, L, M, P and S (180 sample units in total). The PCI values from the LCMS and video were compared in the analysis.

7. SURVEY RESULTS AND ANALYSIS

The distress data from the manual, video and LCMS surveys were processed and evaluated using Micro PAVER (Version 6.1.2, 2009) to determine the PCI results for the three survey methods. There was very good agreement between the overall average PCI from the manual, video and LCMS methods. For Runway 17/35, the Manual PCI was 89, Video PCI was 90 and LCMS PCI was 94, all indicating a runway in excellent condition. For Runway 16/34, the Video PCI was 69 and LCMS PCI was 74, both indicating a very good condition rating.

The results indicated that there was generally good consistency between the type, quantity and severity of distress data identified from the manual, video and LCMS methods. The most common defects observed were longitudinal and transverse cracking, weathering and ravelling, and alligator cracking. In general, there was little need to intervene with the automated distress data outputs from the LCMS. Where intervention was required, this involved some manual verification and adjustment for short lengths of hairline longitudinal and transverse cracking. The runway at Dublin Airport had transverse tining throughout. In Cork airport, the runway had transverse tining throughout, with combined transverse and diagonal (multi-directional) tining over a 700 metre stretch of the runway from chainage 300 to 1000. As part of the processing, the LCMS automated image/data algorithms were modified to prevent the transverse tining being diagnosed as linear cracking. In the areas with multi-directional tining, the automated algorithms had a tendency to misdiagnose these areas as ravelling requiring some manual adjustment in these areas. The algorithms were also improved to help in the identification of short lengths of low severity sealed cracks.

Figure 3 shows the profile of sample unit PCI from the manual, video and LCMS for rips B, D, F, I, K and M on Runway 17/35 at Cork. The sample unit PCI values ranged from 68 to 100. Generally, there is very good agreement between the three surveys across all the sample units with the automated LCMS being marginally higher. Based on the sample unit PCI's, the average absolute difference between the manual and LCMS was 5 PCI points, manual and video was 2 PCI points, and video and LCMS was 4 PCI points. The following average PCI values for each rip indicate the three survey techniques give very similar section PCI values.

17/35 Test Rip	Manual-PCI	Video-PCI	LCMS-PCI
Test Rip B	96	96	99
Test Rip D	93	92	97
Test Rip F	88	88	91
Test Rip I	83	86	87
Test Rip K	92	92	96
Test Rip M	85	86	92
Average	89	90	94

A comparison of the video and LCMS sample unit PCI data for rips D, H, I, J, K, L, M, P and S on Runway 16/34 at Dublin airport are shown in Figure 4. For this runway, the sample PCI values ranged from 0 to 100, with very good correlation between the Video and LCMS PCI outputs. The average PCI values for each rip shown below indicate the two survey techniques result in similar values.

16/34 Test Rip	Video - PCI	LCMS - PCI
Test Rip D	75	82
Test Rip H	71	77
Test Rip I	66	65
Test Rip J	67	69
Test Rip K	69	74
Test Rip L	60	69
Test Rip M	69	67
Test Rip P	68	77
Test Rip S	81	86
Average	69	74

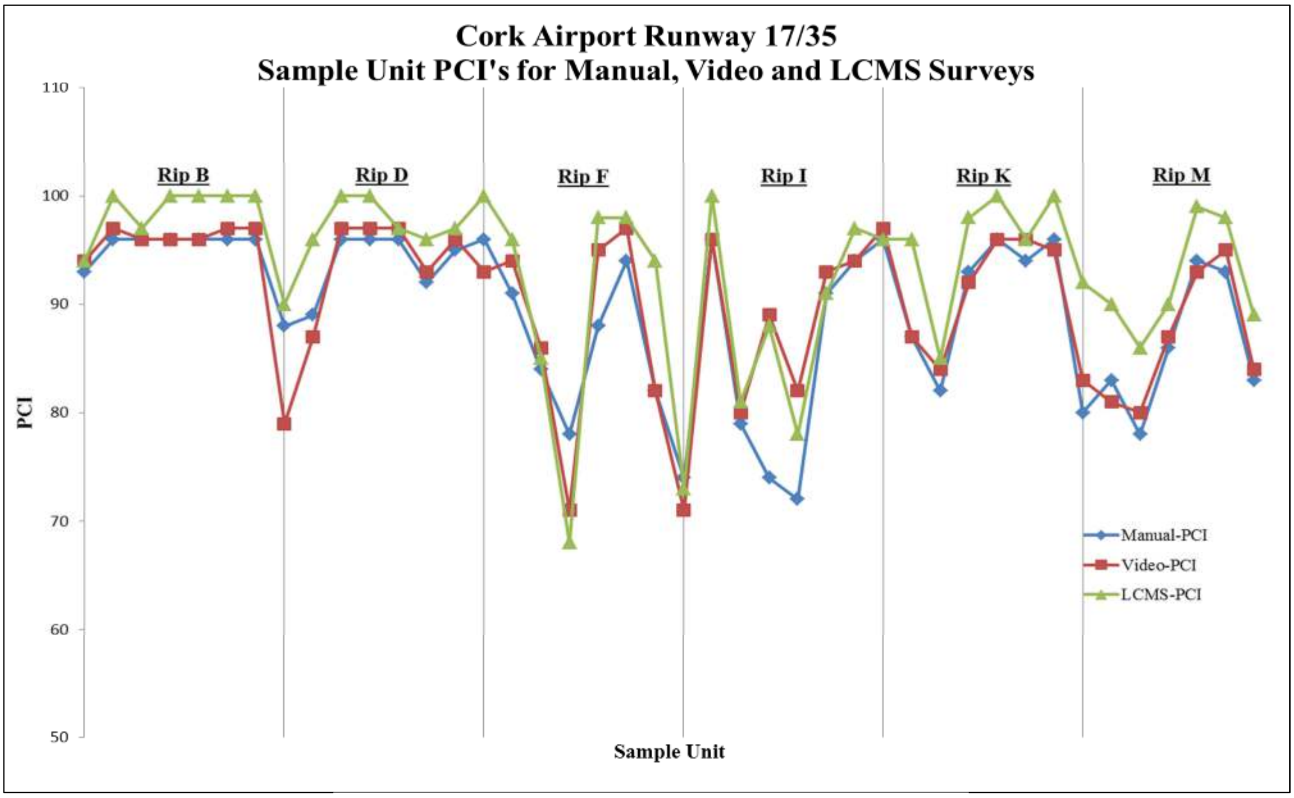

FIGURE 3 Runway 17/35 Sample Unit PCI

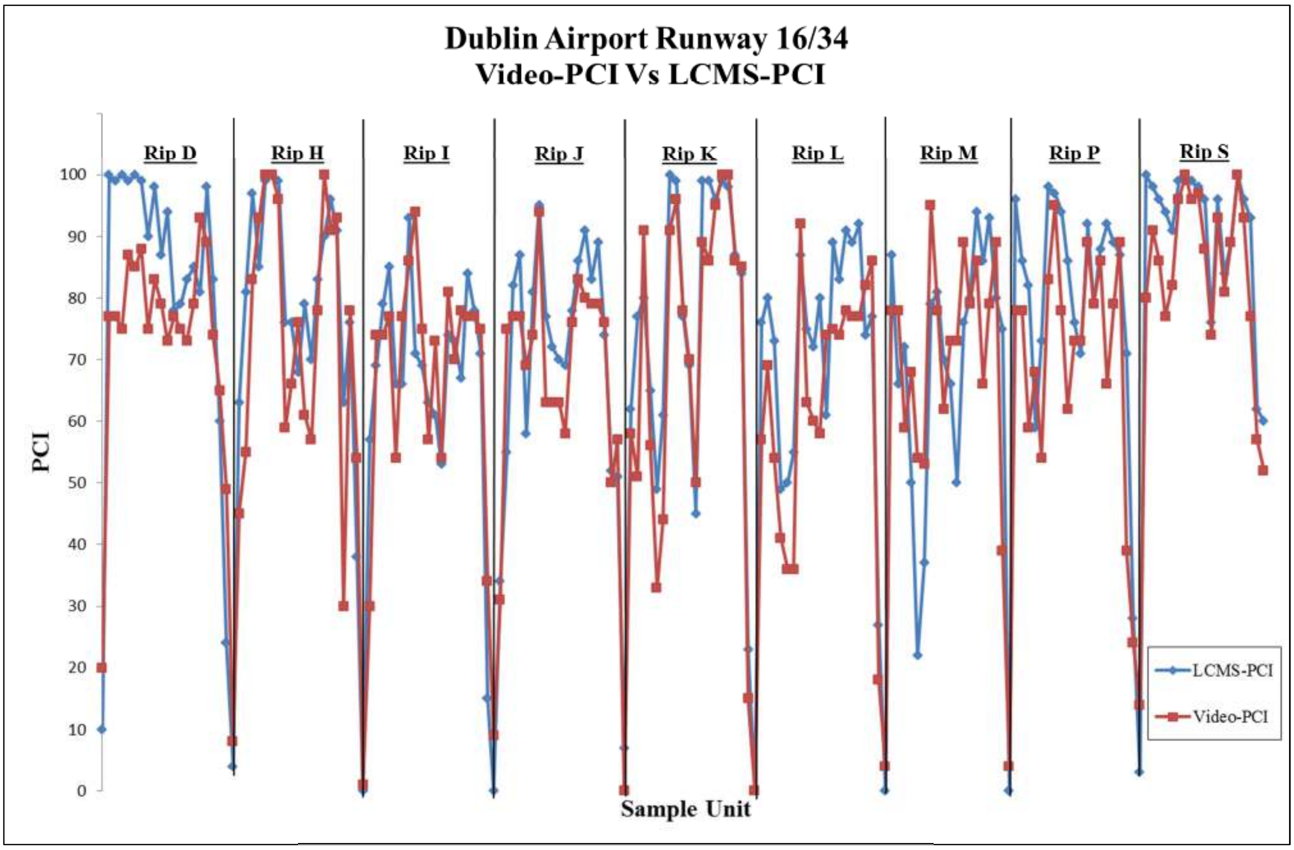

FIGURE 4 Runway 16/34 Sample Unit PCI.

8. STATISTICAL ANALYSIS

The levels of agreement between the PCI results obtained using the manual, video and LCMS methods were established using linear regression analysis. The process consisted of comparing the PCI values calculated from the distress data from the pavement surface area that was common to the three survey methods, and establishing the correlation between each set of data. The degree of determination, R^2, was used as a measure of the 'goodness of fit' to report the percentage of variation in the data of the response variable that can be explained by the regression equation fitted to the data.

The following statistical regression models were run to test the consistency of the patterns between the three survey methods.

- LCMS versus Manual
- Video versus Manual
- LCMS versus Video

8.1 Runway 17/35 at Cork Airport

The regression models were developed using the 42 sample units surveyed using the manual, video and LCMS survey methods on Runway 17/35. In the regression, the distress survey results from the manual survey were taken as the ground truth for comparison against the LCMS and video results. The correlation between the LCMS PCI and the Manual PCI is shown in Figure 5. The R^2 value is 0.746 indicating a very good level of agreement between the LCMS and manually measured PCI.

Figure 6 shows the correlation between the Video PCI and the Manual PCI. The R^2 value is 0.764 indicating a very good correlation between the video and manual methods. The correlation between the LCMS PCI and Video PCI is shown in Figure 7. There is also very good agreement between the LCMS and Video with an R^2 value of 0.780. Hypotheses testing using the F-Test showed there was no significant difference between the variances of the three samples for a 95% confidence level. The R^2 values indicate that the regression models for the automated LCMS is a good model for predicting the manual/ground truth PCI and video PCI.

Regression models were also developed using the PCI values from the six sections (rips B, D, F, I, K and M) from each survey. Figure 8 shows the correlation of the section PCI values between the LCMS and the manual surveys. The R^2 is 0.940 indicating a very good level of agreement between the automated and the manual survey methods. There was also a very good correlation between the section PCI's for the video versus manual, and LCMS versus video, which gave R^2 of 0.941 and 0.825, respectively.

8.2 Runway 16/34 at Dublin Airport

The regression model was developed using the nine rips (D, H, I, J, K, L, M, P and S) comprising 180 sample units common to both the video and LCMS survey methods on Runway 16/34. The correlation between the sample unit PCI's from the video and LCMS on this runway is shown in Figure 9. There is a very good correlation between both survey methods with an R^2 of 0.769.

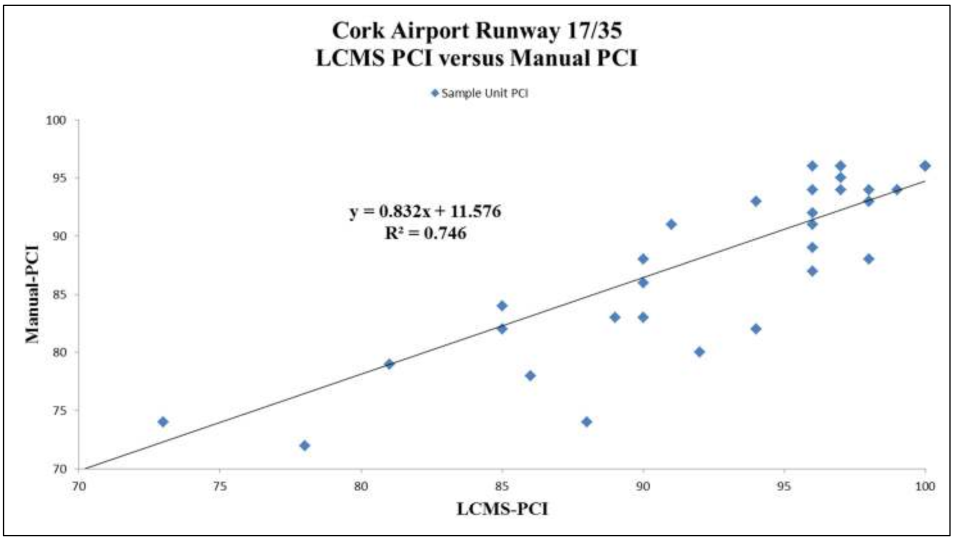

FIGURE 5 Plot of LCMS PCI versus Manual PCI for Runway 17/35.

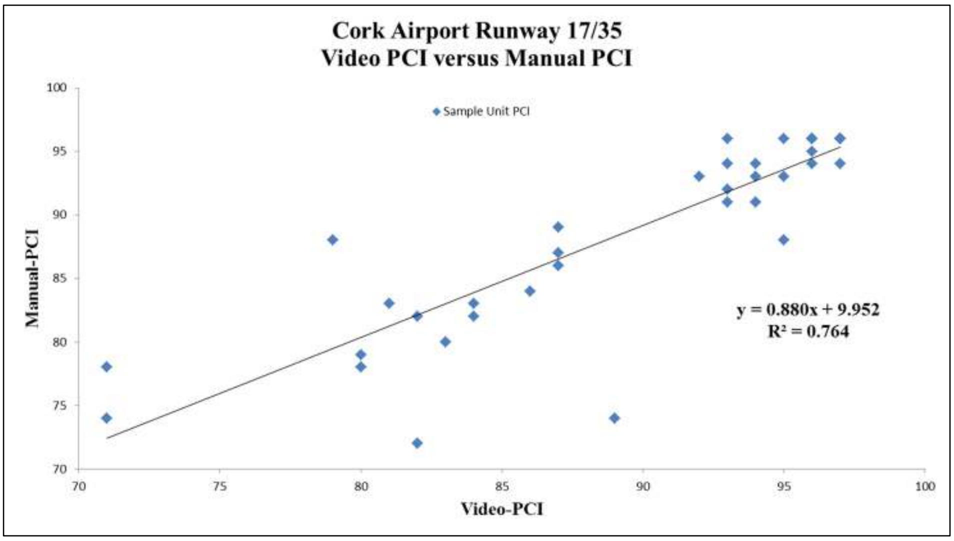

FIGURE 6 Plot of Video PCI versus Manual PCI for Runway 17/35.

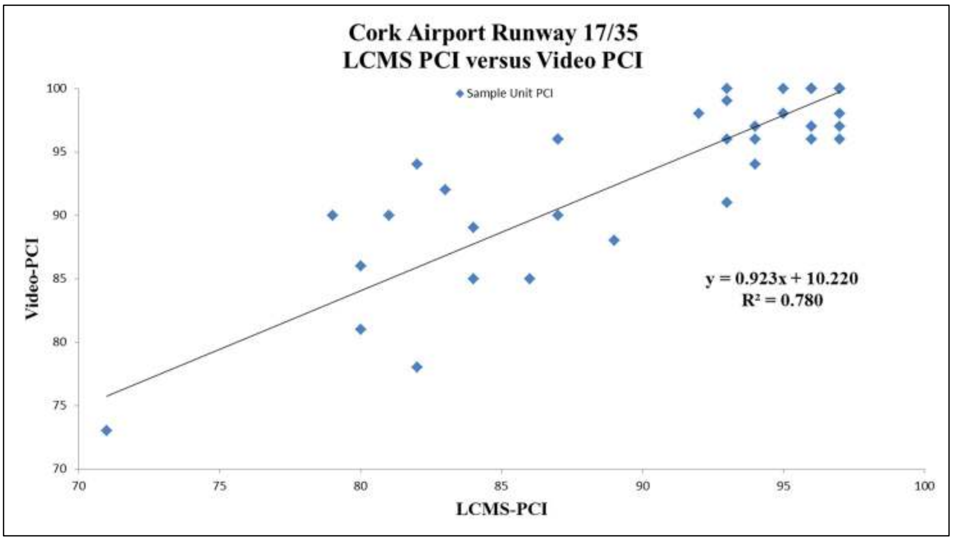

FIGURE 7 Plot of LCMS PCI versus Video PCI for Runway 17/35.

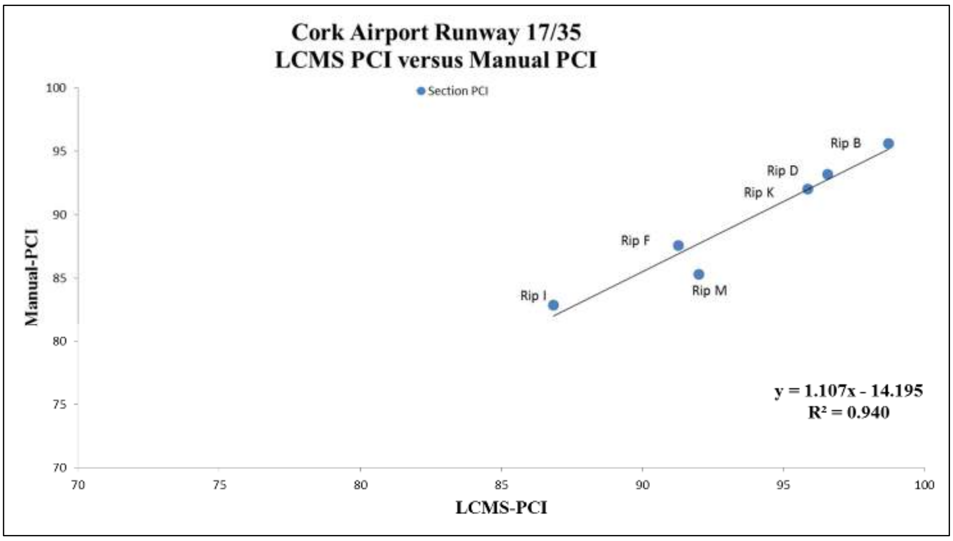

FIGURE 8 Plot of LCMS versus Manual Section PCI for Runway 17/35.

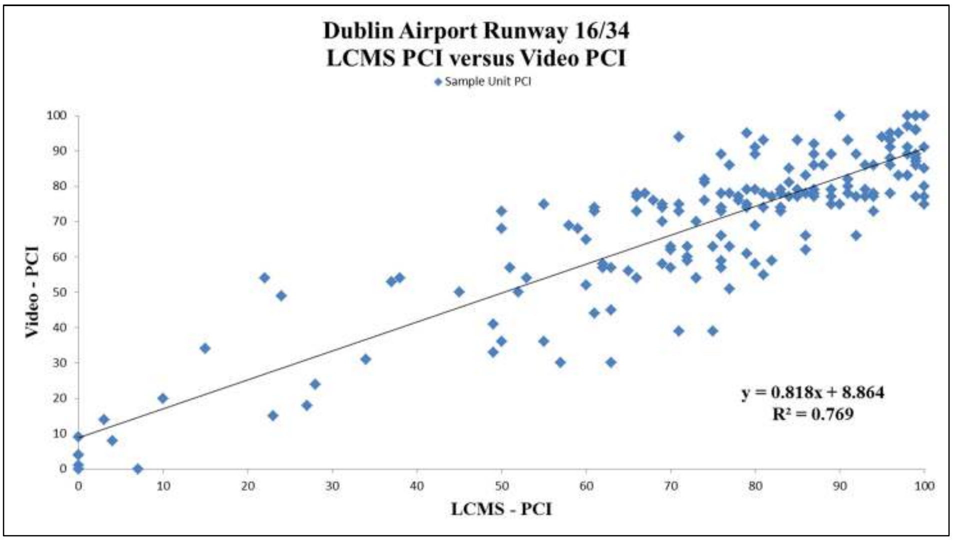

FIGURE 9 Plot of LCMS versus Manual Sample Unit PCI for Runway 16/34.

9. GRAPHICAL REPORT OF THE LCMS DATA

The forward-view, range and intensity images were output as JPEG images from the LCMS survey for use in the graphical reporting of the data. The imagery, distress data and PCI from the automated LCMS survey were graphically reported using colour-coded thematics in ArcGIS and Google Earth GIS formats, and the detailed distress data was also mapped in AutoCAD layers. The ArcGIS was reported using a .shp (shapefile) format. The Google Earth output was reported using a .kmz file, and the AutoCAD data was reported in layers using a .dwg file format. The data was reported for each 100m x 3m sample unit on both runways. The colour-coded thematics in ArcGIS and Google Earth reported the area and linear distresses in separate layers using a RAG (red, amber, green) colour coding depending on the level of severity. By clicking on individual sample units, the PCI data, detailed distress data, and the forward view and LCMS imagery is displayed using pop up links. Figure 10 shows a sample of the graphical output in Google Earth.

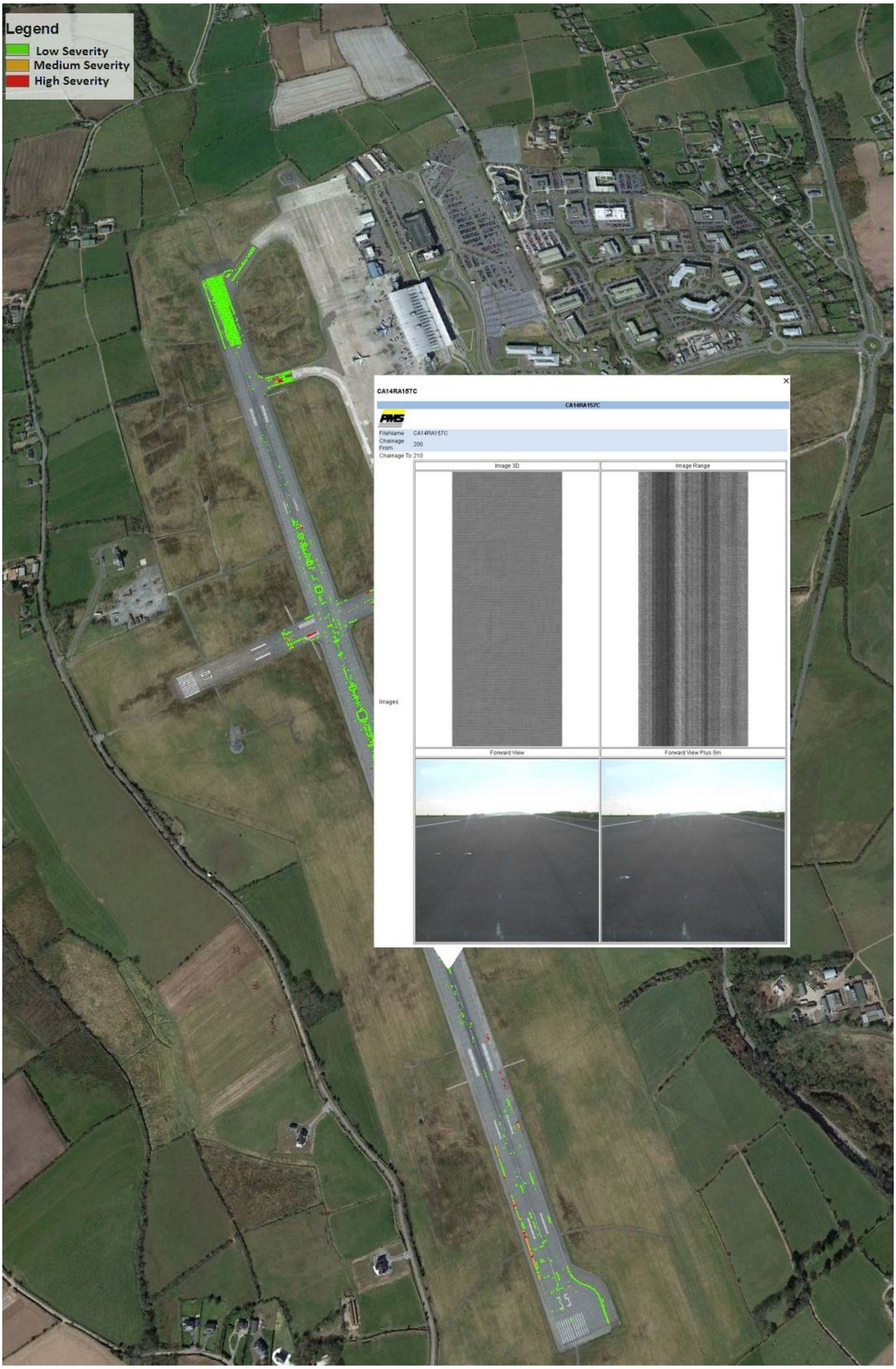

FIGURE 10 Google Earth Thematic for Runway 17/35, Cork Airport.

10. SUMMARY AND CONCLUSIONS

In this study, pavement distress data was collected using manual walking, high definition digital video and automated LCMS survey methods on two runways with asphalt-surfaced pavements. The runways used in the study were Runway 16/34 at Dublin Airport and Runway 17/35 at Cork Airport, Ireland. The overall average condition of both runways was in very good to excellent condition. The section PCI values in the study ranged from 60 to 97, and the individual 100 metre sample unit PCI values covered the full PCI spectrum of 0 to 100. For consistency with surveys done prior to 2012, the manual and video PCI surveys were carried out in accordance with the ASTM D5340 (2003 edition). The data was processed using Micro PAVER and the PCI determined from each survey method for the same pavement area. Regression analysis was used to examine the correlation between the PCI values from the manual, video and LCMS survey techniques. The PCI, distress data and imagery from the LCMS survey were graphically reported using colour-coded thematics in ArcGIS and Google Earth GIS formats, and the detailed distress data was also mapped in AutoCAD.

The results indicate that in general there is very good consistency between the type, quantity and severity of distress data identified from the manual, video and LCMS techniques. The most common defects observed were longitudinal and transverse cracking, weathering and ravelling, and alligator cracking.

The comparison of LCMS versus Manual, Video versus Manual, and LCMS versus Video indicated that the three techniques provided similar PCI values. In the comparison of the sample unit PCI's for the automated LCMS versus the manual walking, the R^2 value was 0.746 indicating a very good level of agreement between the LCMS and manual survey methods. Comparing the section PCI values, the R^2 was 0.940, indicating a very high level of correlation between the LCMS and manual measured PCI. The Video PCI also provided very similar measurement when compared to the manual and LCMS methods with an R^2 of 0.941 and 0.825, respectively, based on the section PCI values.

Manual surveys can be subjective, slow, labour intensive, and involve safety risks. This study has shown that there is a very good level of agreement between the automated LCMS, video and manually measured PCI. The LCMS allows for full pavement condition surveys to be carried out in narrow time slots in daytime or night time conditions. In addition, the automated LCMS survey provides more efficient and objective distress data interpretation, reduced time and labour costs, and provides increased safety for survey personnel. These findings indicate that the automated LCMS technique provides a viable alternative to manual surveys for airport authorities to assess and report pavement condition.

11. ACKNOWLEDGEMENTS

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