Moving to International Roughness Index Measured by Inertial Profilers in an End Result Specification for New Asphalt Construction in Ontario

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ABSTRACT

The smoothness of new pavements constructed for the Ontario Ministry of Transportation (MTO) is accepted on the basis of Profile Index (PI), as measured by California Profilographs. Since these 7.6 m long devices are difficult to handle, operated at walking speeds (3-5 km/hr) and can only measure one wheelpath at a time, the MTO and the hot mix industry have been looking for an alternative device that would be easier and safer to operate.

This paper summarizes the results of two field studies which were conducted using laser inertial profilers consisting of "lightweight" profilers, operated at speeds of 15 to 20 km/hr and "high speed" profilers which can be operated at highway speeds. Both kinds of devices can also measure both wheelpaths simultaneously in units of both Profile Index (PI) and International Roughness Index (IRI). Since inertial profilers take measurements much faster than California Profilographs, they cause less disruption to traffic and are inherently much safer to operate. The objectives of this study were to determine if:

I. Inertial profilers can replace California Profilographs,
II. IRI can be used as an acceptance attribute for new construction to replace PI, and
III. IRI measurements produced by inertial profilers could be integrated into a network data base for the long term monitoring of Ontario's pavements.

During the fall of 2003, three lightweight profilers, three California Profilographs and a high speed Automated Road Analyzer (ARAN) measured 15 pavement sections in Eastern Ontario. In addition, a 2007 study compared a single profilograph with three high speed profilers on two asphalt sections in Central Ontario. The correlation between PI (by the California Profilographs) and IRI (by inertial profilers) were excellent and the results can be used to develop IRI-based acceptance criteria "equivalent" to the PI-based ones.

Based on the results of these studies, inertial profilers can be used to replace California Profilographs for the acceptance of new pavement construction and IRI measurements can also be integrated into the long term monitoring of Ontario's new pavements.

As Ontario moves toward implementing inertial profilers for the smoothness acceptance of new construction, much faster measurements, less disruption to traffic and improved operator safety are expected to be realized.

Key words: Flexible Pavement, Inertial, Lightweight Profilers, Roughness, Smoothness

INTRODUCTION

The Ontario Ministry of Transportation (MTO) implemented a smoothness specification for hot mix paving in 1997. Monitoring of smoothness data for the past seven years, show that the riding comfort of Ontario highways has improved by some 25 percent.

In Ontario, the smoothness of new asphaltic and Portland cement concrete pavements is accepted on the basis of Profile Index (PI) measurements by California Profilographs.

A California Profilograph consists of a 7.6 m long aluminum truss supported by bogey wheels with a centrally-located, pneumatic measuring wheel which is secured to a moveable arm that moves up and down as the device is pushed down the road. Since California Profilographs can only measure one wheelpath at a time and the measurements are taken at a relatively slow pace (at about 4 km per hour), MTO and the hot mix industry has been looking for an alternative device that is quicker and safer to operate.

However, MTO has been using International Roughness Index (or IRI), as measured by the Automated Road Analyzer (ARAN) to monitor the highway network. IRI is a roughness statistic that is calculated from the "true profile" of the road. The ARAN can measure pavement smoothness in both wheelpaths at highway speed using laser sensors and devices called accelerometers.

This means that the smoothness of pavements in Ontario have been measured using two different kinds of indices (i.e. both PI and IRI) during their lives. Therefore, there is a need to harmonize the measurements for all pavements based on IRI.

PURPOSE AND PLAN OF INVESTIGATION

A project was undertaken to investigate if:

i) Faster profilers can be used to replace California Profilographs,
ii) The emerging use of IRI can be used as an acceptance attribute for new construction to replace PI,
iii) IRI measurements taken on MTO's new pavements can be integrated into future network level monitoring of those same pavements; and
iv) A new acceptance attribute can be developed to replace scallops.

With these objectives in mind, the study was divided into the following tasks:

1) First, a literature review was carried out to determine which type of available IRI-based devices, could most suitably replace and be faster than a California Profilograph [i.e. the devices should be able to measure IRI (and possibly PI) in both wheelpaths simultaneously].
2) In the second part of the project, two field studies (i.e. Phase I and II) were undertaken to compare the types of devices chosen with California Profilographs and the ARAN. The results were used to develop correlations between the devices that were investigated.
3) In the final part of the project, the data generated from the field studies was used to develop:
    a. Acceptance criteria that could be used in a specification for new construction and;
    b. A method of integrating the data into MTO's network level measurements.

LITERATURE REVIEW

A literature search was carried out to investigate the various types of IRI-based road profilers that could be used to replace the California Profilograph (Karamihas and Gillespie [8], Sayers and Karamihas [11], etc.). There were several different criteria that MTO was looking for in a profiler, including the ability to:

- Measure IRI (and possibly RS and PI as well);
- Take measurements at a faster rate than a California Profilograph (i.e. inherently, the less time a device is spent on the road, the safer it is to operate it).

- Take measurements in both wheelpaths simultaneously (i.e. inherently safer, as above); and
- To create profile traces similar to those produced by a California Profilographs and to identify individual bumps or dips to replace the “scallops” (i.e. local roughness or “must-grinds” - as most jurisdictions describe them).

Inertial Profilers were found to meet the criteria mentioned above. All inertial profilers are equipped with lasers or infrared sensors to measure the distance to the pavement from a fixed reference point. Accelerometers, which sit on top of the sensors, are used to maintain a fixed vertical reference by cancelling out any bouncing of the vehicle, as it is driven down the road. All of the inertial profilers that were investigated can be equipped with two sensors so that both wheelpaths can be measured simultaneously. The data produced can be used to calculate both IRI and PI and most can print out an identical PI-based profile trace to the one produced by a California Profilograph. They include:

1) Lightweight Profilers
2) High Speed Profilers

Lightweight profilers consist of golf carts or other vehicles (Figure 1), which travel at speeds of 20 to 40 km/hr while high speed profilers such as the ARAN (Figure 2), can travel close to highway speed.

Although, inertial profilers appeared suitable, there were several concerns that needed to be investigated such as:

- How the devices measure very smooth or very rough pavements, when compared with California Profilographs. This will determine how IRI-based acceptance limits equate to the PI-based ones that are currently being used;
- How reproducible/repeatable the results are;
- How weather and other environmental conditions affect the equipment and results; and
- The speed and accuracy of the data acquired.

Two field studies were carried out using similar approaches to the ones used by Karamihas and Gillespie [8] and FHWA (7), during their investigations.

PHASE I – LIGHTWEIGHT PROFILER STUDY (Single Dot Lasers)

Phase I of the work was carried out in 2003. Several different pavement sections were measured using lightweight profilers, California Profilographs and the ARAN. All of these devices were equipped with single dot laser sensors, which was the technology that existed at the time. The procedures and sequence of operation are described as follows:

Selection of Pavement Sections

At the time of the Lightweight Profiler Study, MTO was also participating in a fuel consumption study, which was being co-ordinated by the Federal Government. It was decided to include the five sites that were involved in that study (i.e. Sites 1, 2, 4, 5 and 8 shown on Figure 3), in MTO’s Lightweight Profiler Study. In addition, approximately 20 other candidate sites representing a wide range of surface smoothness were also identified. By March 2003, the ride quality of each of these candidate sites was assessed. Surface deficiencies of the sections were also noted and photographed. After evaluating the smoothness of all of the proposed sites, three of the 20 other candidate sites were eventually selected to add to the five fuel study sites that were already established. These sites were selected to cover the widest possible range of surface smoothness.

Two pavement sections, from 1.2 to 2.1 km long, were chosen at seven of the eight sites and a single 3.0 km pavement section was chosen at the remaining one (Site 2) for smoothness testing. A total of 15 pavement sections (or 284 - 100 m sublots)- five of which were concrete (or 72 - 100 m sublots) with the rest being asphalt, are summarized in Table 1.

Immediately prior to beginning the smoothness measurements, the limits of each pavement section were marked with paint onto the pavement surface. Wooden stakes were also driven into the shoulder at both ends of each section and at 500 m intervals.

The surface of most of the pavement sections was generally in good to excellent condition with the following exceptions:

- Concrete sections 5A and 5B exhibited numerous moderate to severe cracking (several with spalled edges) throughout.
- Concrete section 8B exhibited slight to moderate cracking.
- Asphalt section 8A exhibited slight to moderate transverse cracking at 5 to 12 m spacings.
- Asphalt sections 7A and 7B exhibited a few short patches.

The concrete pavement at sections 1A, 1B and 8B were transversely tined but no tining was found at sections 5A and 5B.

Field Measurements and Collection of Data

Three lightweight profilers, from different manufacturers, and two California Profilographs (a McCracken and a Cox Bros.) were chosen through a competitive selection process. MTO provided a third California Profilograph (a McCracken).

The asphalt sections were tested by each profilograph running once in both wheelpaths using a zero (0) blanking band. However, the concrete sections were measured twice so that the data for those sections could be generated for both 0 and 5 mm blanking bands (Figure 4). The profilographs were tested according to ASTM E 1274-88 (5) and MTO's smoothness specification for asphaltic concrete pavement that was in place at the time (13).

The measurements took place between October and November 2003. Since the profilographs were known to take measurements at a much slower pace than the lightweight profilers, the work was arranged so that the two types of devices would be measuring different sites on the same days. During the fieldwork, the temperature was generally below freezing (particularly at the beginning of the day). However, on a couple of days, the temperatures rose as high as 10 degrees celcius during the latter part of the day. The work was extended by three or four days because of rain.

Each lightweight profiler ran all of the pavement sections a minimum of three times (see Figure 5). Their operators were required to report RS (and PI) using both 0 and 5 mm blanking bands (i.e. only a 0 blanking band on the asphalt sections) and International Roughness Index (IRI) as well as the locations and heights of all scallops from each run in both wheelpaths. The lightweight profilers were tested according to ASTM E950 (1) and the most recent versions of the AASHTO protocols (2, 3, 4).

To avoid scheduling conflicts with the other two types of devices, the ARAN (see Figure 2) measured all 15 pavement sections somewhat later (i.e. between November and December 2003). As with the lightweight profilers, the ARAN operator measured each pavement section three times and reported IRI for both wheelpaths.

®Excel data templates were distributed to each operator of the three different devices. The operators were required to create separate data files for each pavement section. All of the accumulated data was sent to the MTO's Bituminous Section on either a floppy disk or CD as ®Excel and ERD files. The ®Excel templates were used to assemble a global ®Excel file which facilitated the data analysis and lead to the establishment of a separate ®Kaleidagraph plotting file.

Data Analyses

The data obtained from the various measuring devices, was used to:

1) Develop a series of correlations of PI and IRI between the lightweight profilers, the California profilographs and the ARAN;
2) Investigate the accuracy and reproducibility of the IRI data; and
3) Investigate if lightweight profilers could adequately simulate scallops measured by California Profilographs.

Note that the analyses presented here will only be based on the measurements taken on the asphalt sections.

Correlations between the average PI's and IRI's for Profilographs, Lightweight Profilers and the ARAN

The data was used to determine a number of different correlations. The most important of these included:

- PI by Lightweight Profilers Versus PI by California Profilographs.
- IRI by Lightweight Profilers Versus PI by California Profilographs.
- IRI by Lightweight Profilers Versus IRI by the ARAN.

The correlations which are presented here are based on the:

- Average PI's which have been determined from a single run of both wheelpaths by the three different profilographs (labelled P1, P2 and P3);
- Average PI's and IRI's which have been determined from the three runs of both wheelpaths (i.e. wheelpaths measured simultaneously) by the three different lightweight profilers (labelled L1, L2 and L3); and
- Average IRI's which have been determined from three runs of both wheelpaths (i.e. wheelpaths measured simultaneously) by the ARAN.

It should be noted that the correlations involving PI, which are presented graphically, have been based solely on the zero blanking band. Although several correlations based on the 5 mm blanking band have also been developed for the concrete pavements, they will only be presented in tabular form (Table 2).

PI by Lightweight Profilers Versus PI by California Profilographs

The objective of this comparison was to investigate how well a lightweight profiler is able to emulate the PI measurements taken by a California Profilograph.

Figure 6 shows a plot of the combined average PI's simulated by each of the three lightweight profilers, in their 3 runs, versus the combined average PI's measured by the three California Profilographs, in their single runs, for each 100 m sublot in the ten asphalt pavement sections that were tested. It is quite clear from this figure that there is an excellent linear relationship for PI(0) between the two types of devices (R = 0.993) which is given by the following equation:

$$PI_{Light} = -36.554 + 1.0214 \times PI_{Prof} \quad \text{(0 blanking band)} \qquad \text{(i)}$$

In addition, the correlation equations developed between each of the lightweight profilers shows that, there are also excellent linear relationships between the averages of each of the three devices, when compared with the overall averages for the profilographs, with Lightweight Profiler #2 slightly outperforming the other two (R = 0.9909, Table 2).

Figure 7 shows a similar plot, but also includes the results from the five concrete pavement sections. The results for this plot as well as similar equations for the concrete sections only, which are summarized in Table 2, (i.e. R between 0.981 and 0.996), show that all of the correlation equations have excellent linear relationships when comparing PI measurements taken by lightweight profilers to those taken by the California Profilographs. Lightweight Profiler #2, again slightly outperformed the other two.

IRI by Lightweight Profilers Versus PI by California Profilographs

One of the objectives of this study was to determine if IRI could be used to replace PI as an attribute for smoothness acceptance. Therefore, the relationship between the IRI's measured by the Lightweight Profilers and the PI's measured by the California Profilographs was investigated.

Figure 8 shows a plot of the average IRI's measured by the three lightweight profilers in their 3 runs versus the combined average PI's measured by the California Profilographs (using a zero blanking band) in their single runs for the 10 asphalt pavement sections. As this figure shows, there is a good linear relationship between the measurements taken by both types of devices (R = 0.926), although there was somewhat greater variation when the PI's were greater than about 430 mm/km. Also, more variation was found here than when the PI's were compared between the two devices. This greater variation is to be expected, since the devices used and methods of obtaining their respective indices are very different. The correlation equation for the best-fit line representing the overall averages of the IRI's measured by the lightweight profilers versus the PI's measured by the profilographs is given by the following equation:

$$IRI_{Light} = 0.1998 + 0.002088 \times PI_{Prof} \text{ (0 blanking band)} \quad \text{(ii)}$$

Good linear relationships (Figure 9) were also found when all of the pavement sections were tested (0.960) or when the concrete sections were tested alone using either 0 or 5 mm blanking bands (R = 0.938 to 0.970). Again slightly more variation was measured than in the comparable PI versus PI plots.

IRI by Lightweight Profilers Versus IRI by the ARAN

The last group of correlations were carried out to determine the feasibility of using IRI measurements taken by the lightweight profilers for new construction as a basis for future network level smoothness monitoring of the same pavements by the ARAN. The relationship between the average IRI's measured by the three lightweight profilers in their three runs and the average IRI's measured by the ARAN in its three runs (Figure 10) was determined. An excellent linear correlation was found between the two variables (R = 0.99), as given by the following equation:

$$IRI_{Light} = 0.02705 + 0.9358 \times IRI_{ARAN} \qquad \text{(iii)}$$

Excellent linear correlations were also found when the 5 concrete sections were added to the results (see Figure 11) or when the concrete pavement sections were tested alone.

Correlation Simulations and IRI Variability for the Lightweight Profilers

In order to enable Lightweight Profilers to be used for acceptance in current contract specifications, simulations were needed to evaluate the variability of the IRI measurements. Currently, MTO conducts RS(0) correlations between all of the profilographs that will be used on MTO contracts, prior to the beginning of each construction season. During those correlations, each profilograph is required to run a continuous 300 m section of a single wheelpath (i.e. 3 profile sections of 100 m each) three times. Using the data that is generated, the acceptability of each of the profilographs is determined on the basis of the following acceptance criteria:

1) Reproducability: The average RS(0) for the 300 m section of a single wheelpath run three times, must be within 4 percent of its overall mean established by all of the participating devices.
2) Repeatability: The average coefficient of variation (i.e. the ratio of standard deviation to the mean) of RS(0), for all 3, 100 m sections within that 300 m, expressed as a percentage, must be less than or equal to 5 percent in accordance with the following equation.

$$\left[\frac{\sum_{i=1}^{3} \frac{s_i}{\overline{X}_i}}{3}\right] \times 100 \quad \leq 5\,\% \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(iv)}$$

Where: s_i and $\overline{X}_i$ are the standard deviation and average of the three rate of smoothness measurements taken for each independent 100 m section.

In order to determine how each of the lightweight profilers would perform under similar conditions, discrete comparisons of reproducibility and repeatability were conducted on IRI data measured by each profiler on 420 simulated 300 m asphalt profile sections. These comparisons were then used to plot curves indicating the probability that each of the three lightweight profilers would meet similar requirements. For these purposes, it was assumed that a lightweight profiler would be acceptable if it met both acceptance criteria at least 70 percent of the time.

<u>Reproducibility</u>:

Simulated correlations were conducted by comparing the average IRI measurements taken by each of the lightweight profilers with the overall average established by all 3 of them.

Figure 12 shows the probability that the average IRI for each lightweight profiler is likely to deviate from of the overall mean established by all three lightweights. If it is assumed that a deviation limit of 4 percent would be considered acceptable [as MTO currently accepts for RS(0)], then it appears that all three Lightweight Profilers would meet MTO's reproducibility requirement more than 85 percent of the time.

<u>Repeatability</u>:

Figure 13 shows the probability that the average coefficient of variation for the 3, 100 sections within any 300 m section of a single wheelpath would meet MTO's repeatability requirement for IRI. If it is assumed that a limit of 5 percent would be considered acceptable [as MTO currently accepts for RS(0)], then it appears that all three of the lightweight profilers would meet MTO's repeatability requirement more than 90 percent of the time, with Lightweight #2 performing the best of the three.

Scallops Measured by Lightweight Profilers and California Profilographs

Currently, the issue that most effects the financial impacts of smoothness on MTO contracts in Ontario is the number and the amplitudes of the scallops that are recorded. Therefore, as part of this investigation, each lightweight profiler produced a PI-based profile trace for each run and then the operator was required to report the amplitudes of each of the scallops that were identified, in accordance with MTO's current acceptance categories which are given in the middle column of Table 3.

Table 4 shows the average number of scallops that were reported by the operators of each lightweight profiler in their three runs, in comparison to the average number of scallops that were reported by the operators of the three California Profilographs in their single runs for each of the 10 asphalt pavement sections that were tested.

The results show that, Lightweight Profiler #1 best emulated the California Profilographs for the scallops that were up to 14.5 mm in amplitude but produced somewhat more scallops than the profilographs when their amplitudes were greater than that. Lightweight Profiler #3 best emulated the California Profilographs for the scallops with amplitudes greater than 14.5 mm but did poorly when comparing the bulk of the scallops that had amplitudes less than that. Although, on balance, it appears that Lightweight Profiler #2 best emulated the California Profilographs in terms of the combined total number of scallops that were recorded in all three categories, it produced somewhat less scallops than the profilographs in the 10 to 11.5 mm category and somewhat more for the ones with amplitudes greater than 14.5 mm.

Based on these results, it appears that generally lightweight profilers do not simulate California Profilographs very well, in the determination of scallops.

PHASE II – INERTIAL PROFILERS (Using Multiple Laser Arrays) AND ®ProVAL

Introduction

After Phase I was completed, the following two technological changes were introduced:

1) Laser Sensors: The inertial profilers that were used during the Phase I study were equipped with single dot lasers. However, subsequent work appears to show that single dot lasers do not measure pavements with surface voids very well and they sometimes suffer from repeatability/reproducibility problems, particularly when measuring open-graded mixes and diamond ground surfaces Karamihas [9]. As a result, newer, multiple laser arrays were developed to average the results over a much wider area.
2) ®ProVAL: Since every manufacturer of inertial profilers has software that handles (i.e. filters) the raw data files from the laser sensors/accelerometers differently, a new software program was developed by the Transtec Group in Texas, to provide consistency in the way that the data is being analyzed and additional security. This software is widely used by other jurisdictions, and MTO has decided that Ontario will also be using it for both the approval of inertial profilers and for contract acceptance.

In view of these changes, MTO decided to conduct a second (i.e. Phase II) study with the following objectives:

1) Measure additional pavements using inertial profilers equipped with laser arrays;
2) Process all of the data files from the Phase I and Phase II studies through the ®ProVAL software; and finally
3) Determine "Equivalent" acceptance limits for IRI and what is now being termed "Localized Roughness" (see note given below) to respectively replace PI and Scallops, in MTO's specifications.

Note: Localized roughness occurs where the deviation between the average profile (i.e. for the left and right wheelpaths) and the same profile after a 7.62 m long moving average filter (i.e the length of a profilograph) has been applied to it , is greater than certain user-defined threshold limits (i.e. either positive or negative).

Field Measurements and Collection of Data

Three inertial profilers and a McCracken California Profilograph measured a 2 km long, one-lane section of Stone Mastic Asphalt (or SMA) at Hamilton, Ontario's New Red Hill Creek Expressway. The devices also measured a 500 m, one-lane section of somewhat older Dense Friction Course (or DFC) at MTO's profilograph Correlation Site, located at a weigh scale on the Eastbound Lanes of Highway 407 just east of Appleby Line, in Oakville, Ontario.

The inertial profilers that participated in the fieldwork included a vehicle with trailer-mounted Selcon ®Roline (i.e. 100 laser dot) sensors, a van equipped with ®Roline and Ames' ®Triod (i.e. 3 laser dot) sensor (which were switched back and forth to cover both wheelpaths) and an ARAN (i.e. the same one used in the Phase I study) which is equipped with single dot lasers.

The profilograph completed 2 runs at the Red Hill Creek Site for each wheelpath and 3 runs at MTO's profilograph Correlation Site. Both the trailer and the ARAN completed 5 runs at both sites measuring both wheelpaths simultaneously. However, since the operator of the van only provided one ®Roline and one ®Triod sensor array, their inertial profiler had to switch the sensors from left to right and re-run each sublot, in order to measure both wheelpaths. As a result, due to time constraints, the van only completed 3 runs (i.e. X 2 for each wheelpath) on the last 3 of 4 sections, at the Red Hill Creek Site.

It should also be noted that, although the averaging effect of the 1 kHz ®Roline sensor is generally known to give excellent results on open-graded mixes, recent information indicates that problems are sometimes created "at high vehicle speeds due to their processing capability. To investigate this, measurements at different vehicle speeds were conducted on the SMA at the Red Hill Creek Site by one of the inertial profilers. Although the IRI appeared to be consistent, some additional "Localized Roughness" was detected at highway speed. As a result of this, all of the "high speed" inertial profilers that participated were asked to conduct the measurements at only 30 km/hour for the purposes of this study. It should be noted that the manufacturer of these sensors is currently developing a much faster 3 kHz version which is expected to completely alleviate this problem.

Development of Acceptance Limits for a Smoothness Specification Based on Inertial Profilers

All of the data files that were generated by the Inertial Profilers were imported into the ®ProVAL software and then a 91.46 m (or 300') "Butterworth" filter was applied to each of them. The pre-filtered files were saved and then imported back into ®ProVAL to determine both IRI for the individual 100 m sublots and "Localized Roughness". The data files that were generated by the Lightweight Profilers in the Phase I study were also treated the same way.

IRI by Inertial Profilers Versus PI by California Profilographs for 100 m Sublots on Asphalt

To determine the IRI's, all of the pre-filtered data files that were generated for the measurements taken on asphalt in both the 2003 and 2007 studies were run through the ®ProVAL software using it's "Ride Stats at Intervals" option and by applying a 250 mm averaging filter. For the Phase I study, the IRI's that were generated by the single dot lasers from the three lightweight profilers were compared to the PI's generated by the 3 profilographs that participated in that study. For the Phase II study, the IRI's for the two "high speed" inertial profilers (measured at 30 km/hr) that used laser arrays and the one profiler (the ARAN) that used the single dot lasers were compared with the PI's from the profilograph.

Figure 14 shows the results of all of this work. Line "A", represents the "best-fit" line for the combined average IRI's generated from the measurements taken by the lightweight profilers and the ARAN compared to the combined average PI's reported by the operators of the 3 profilographs that participated in the 2003 Phase I study. Line "B", which is also given on Figure 14, shows the combined average IRI's generated from the measurements taken by the two inertial profilers equipped with Roline or Triod sensor arrays compared with the combined average PI's reported by the operators of the profilograph(s). Line "C", shows a similar graph based on measurements by the ARAN's single dot laser sensors.

Based on the limited data provided by the 2007 study, it appears that the "best-fit" (i.e. Line "B") line, representing the ®Roline/®triod sensor arrays is flatter and represents a "smoothing out" of the data when compared to Line "A" for the single dot lasers. The correlation line for the Roline/Triod sensors versus the PI's (i.e. Line "B") for the profilograph is given by the following equation:

$$IRI_{LaserArrays} = 0.1916 + 0.0019013 \times PI_{Prof} \text{ (0 blanking band)} \qquad \text{(v)}$$

It also appears that the data points for the ARAN's Line "C" appear to follow Line "A" for the smoother pavement sections but Line "B" for the rougher ones. It turns out that the data points for the rougher sections actually represent the dense-graded DFC at the Profilograph Correlation Site while the data points for the smoother sections represent the open-graded SMA at the Red Hill creek Site. Therefore, although there is limited data here, it appears to confirm previous studies by others that single dot lasers do not correlate well with the Roline/Triod sensors on the more open-graded mixes like SMA. Since MTO is now using more of these mixes and diamond grinding (which creates a rough texture that single dot lasers also have difficulty measuring consistently) is allowed as one of our repair options, it was decided that smoothness acceptance for new asphalt pavements would be based on laser arrays rather than single dot lasers.

As mentioned previously, the smoothness acceptance of new asphaltic concrete pavements constructed for MTO is now being measured in terms of Profile Index (PI) by California profilographs. The current limits, to the nearest mm/km (and based on a zero (0) blanking band), are shown in the middle column of Table 5. These limits and equation (v) for the laser arrays were used to calculate the proposed "equivalent" IRI-based limits in m/km. They are presented below and shown in the right column of Table 5.

	IRI in m/km		
Maximum Bonus:	< 0.50	rounded	
Bonus:	0.50 to < 0.65	to the	
Full Pay:	0.65 to 1.00	nearest	(vi)
Price Reduction:	> 1.00 to 1.25	0.05 m/km	
Rejectable:	> 1.25		

IRI by Inertial Profilers Versus IRI by MTO's ARAN for 100 m Sublots on Asphalt

As was previously mentioned, MTO's network level measurements for smoothness are based on IRI measurements taken by the ARAN. Therefore, as part of this work, it was desired to find a relationship between the IRI measurements taken by the ARAN and the IRI measurements taken by other inertial profilers using either single dot lasers or laser arrays. Once again, analyses were conducted using the data files from measurements taken by the ARAN and the lightweight profilers from the Phase I study (all of which used single dot lasers), as well as the high speed profilers from the Phase II study (which used laser arrays) run through the ®ProVAL software. Lines "A" and "B", shown on Figure 15, represent the average IRI's that were generated from measurements taken by the ARAN versus those generated from measurements taken by the single dot lasers from the lightweight profilers and the laser arrays from the other inertial profilers, respectively. The equations for Lines "A" and "B" given by the following can be used to convert measurements taken from lightweight profilers equipped with single dot lasers and laser arrays to those measured by the ARAN:

$$IRI_{ARAN} = -0.002286 + 1.0475 \times IRI_{LightweightProfilers} \qquad \text{(vii)}$$

$$IRI_{ARAN} = 0.17245 + 0.88441 \times IRI_{LaserArrays} \qquad \text{(viii)}$$

It is interesting to note that the rejectable limit for MTO's new warranty-based contracts is currently being set at 1.32 m/km based on 500 m intervals. When the rejectable limit, based on laser arrays shown in equation (vi) is substituted in equation (viii), the equivalent rejectable limit, if measured by the ARAN, would be about 1.28 m/km. Although this number is based on 100 m intervals and it has been arrived at through a very different method than the acceptance limit for the warranty-based contracts, the two appear to be very comparable to one another.

Localized Roughness by Inertial Profilers Versus Scallops by California Profilographs

As in the previous section, all of the pre-filtered data files that were generated from both the 2003 and 2007 measurements were run through the ®ProVAL software. However, this time, ® ProVAL's "Localized Roughness" option, a 7.62 m (25 ft) averaging filter and an assumed "Threshold Limit" were used to determine the areas of individual roughness. In order to decide what threshold limit should be used, an iterative process was conducted using different assumed limits. Each time the analysis was conducted, the magnitude and frequency of the areas of Localized Roughness were compared with the magnitude and frequency of the scallops that were determined using the current acceptance limits for scallops (shown in the left column of Table 3) by the profilograph(s). The results of that work lead to the "equivalent" limits for Localized Roughness shown below (and in the right column of Table 3).

	Threshold Limit in mm		
Acceptable:	< 3.3	rounded to the nearest 0.1 mm	(ix)
Category 1 Price Reduction:	3.3 to 3.7		
Category 2 Price Reduction:	3.8 to 4.7		
Rejectable:	> 4.7		

The average number of scallops that were detected by the three profilographs in the 2003 Lightweight Profiler Study (based on the current acceptance limits) were compared with the average number of "Localized Roughness" events that were detected by the three lightweight profilers using the proposed limits given in equation (ix). Similar analyses were also conducted with the 2007 data files obtained from the high speed profilers equipped with laser arrays and the profilograph. The results of these comparisons are given in Table 6.

Table 6 shows the average number of incidents of localized roughness determined from measurements taken by the lightweight's and the ARAN's single dot lasers using the 2003 data files for each of the measured locations. It also includes the results from the ARAN's single dot lasers and the combined results from the inertial profilers using the ®Roline/®Triod sensors from the 2007 data files. Based on these results, the overall average totals for localized roughness in the various acceptance categories were found to be generally quite close to the overall average totals for the scallops, regardless of the kinds of sensors being used. However, it should be noted that slightly more incidents of localized roughness were determined when the ARAN's 2003 data was used. Interestingly, when looking at the 2007 results, for acceptance categories 1 and 2, the laser arrays were slightly closer to the profilograph on the open-graded mixes at the Red Hill Creek Site than the ARAN but the ARAN performed better than the laser arrays at the rougher, dense-graded correlation site. However, at both sites, the ARAN produced more incidents of localized roughness than the laser arrays in the rejectable category 3.

In any case, although there are some differences between the various individual categories, acceptance limits based on localized roughness using files that are run through ProVAL produced much more consistent results than when we attempted to have inertial profilers (i.e. the lightweight profilers) simulate scallops in the Phase I study.

SUMMARY OF FINDINGS

The measurements that have been taken in Phases I and II have lead to the following findings:

Correlations Between Average PI's and IRI's Measured Using Lightweight Profilers, High Speed Profilers and California Profilographs on Asphalt Pavements:

- Excellent linear relationships (correlation coefficients ≥ 0.99) were found between the PI's measured by the lightweight profilers (with single dot lasers) versus the PI's measured by the California profilographs.
- Excellent linear relationships (correlation coefficients ≥ 0.99) were found between the IRI's measured by the lightweight profilers and the IRI's measured by MTO's ARAN (all with single dot lasers).
- Very good linear relationships (correlation coefficients between 0.93 and 0.97) were found between the IRI's measured by the inertial profilers (with single dot lasers or multiple laser arrays) versus the PI's measured by the California Profilograph(s).
- Excellent linear correlations of IRI were generally found between MTO's ARAN (with single dot lasers) and the other inertial profilers when either single dot lasers or laser arrays (correlation coefficients .98 to .99) were used.
- Limited data indicates that the single dot laser sensors do not correlate well with laser arrays on open-graded mixes like SMA.

Reproducibilty/Repeatabilty of IRI Measured By Lightweight Profilers Equipped With Single Dot Lasers:

- All three lightweight profilers exhibited excellent reproducibility and repeatability when measuring IRI (and limited data with laser arrays during the Phase II study also shows that this is very likely to be the case).

Determination of equivalent Acceptance Limits for IRI, Scallops and Equivalent Acceptance Limits Based on Localized Roughness:

- Comparable IRI-based acceptance limits can be established to replace the current PI-based ones.
- Inertial profilers do not adequately simulate scallops identified by California Profilographs.
- Comparable acceptance limits can be established for localized roughness to replace scallops.

Additional Findings and Observations Made During These Studies:

In order to consider inertial profilers for smoothness acceptance on MTO contracts, the following additional findings and observations were made during these studies that should be considered:

- Inertial Profilers can only be operated when the pavement is completely dry.
- Inertial profilers are more sensitive to leaves and other debris on the road (i.e. the sensors measure and include them as part of the roughness calculation) than the profilographs (i.e. the measuring wheel for a profilograph simply can depress leaves or small debris or it produces a spike that's usually not counted as part of the roughness measurement).
- The beams from single dot laser sensors can penetrate pavement cracks and joints, whereas a profilograph's measuring wheel will simply bridge over it. Laser arrays average the results over a much wider area and seem to produce more consistent results on open-graded mixes.
- Inertial profilers have difficulty in maintaining a proper offset without additional aids (e.g. laser spot or another type of lane tracking guide).

CONCLUSIONS

The following conclusions can be drawn for this study:

1) Faster, Inertial profilers can replace California Profilographs. However ,

- Some hardware and/or software changes will be required to meet MTO's current administrative requirements (i.e. maintaining a proper offset and security of the data); and
- There would be slightly more restrictions on when such measurements can be taken (i.e. the pavement would have to be completely dry).

2) The emerging use of IRI can be used as an acceptable attribute to replace PI by,

- Importing the raw data files from the inertial profiler into the ®ProVAL software and using ®ProVAL's "Ride Stats at Intervals" option to determine IRI; and then
- Using the proposed acceptance limits given in Table 5.

3) IRI measurements taken on new construction by inertial profilers can form the basis for future network level monitoring of the same pavements by the ARAN, by using:

- Equation (vii) to convert the IRI measurements taken by lightweight profilers equipped with single dot lasers to equivalent measurements taken by the ARAN; or
- Equation (viii) to convert IRI measurements taken by inertial profilers equipped with laser arrays to equivalent measurements taken by the ARAN.

4) Localized Roughness can be used to replace scallops, by:

- Importing the raw data files from the inertial profiler into the ®ProVAL software and using ®ProVAL's "Localized Roughness" option to determine all incidents of localized roughness; and then
- Using the proposed acceptance limits given in Table 3.

FUTURE WORK

The Ministry will continue to move forward in its investigation of inertial profilers for IRI-based smoothness acceptance on Ministry contracts by:

1) Continuing to investigate the use of ®ProVal, for the acceptance of inertial profilers and to calculate IRI and Localized Roughness from raw data files generated by inertial profilers.
2) Conducting, side-by-side IRI measurements taken by Inertial Profilers (and running the raw data files through ®ProVal) with PI measurements taken by California Profilographs on additional pavement sections, in order to further validate the acceptance limits established during this investigation for IRI and Localized Roughness and to compare PI and IRI-based price-adjustments and scallops/Localized Roughness under simulated contract situations.

These further steps will allow MTO to continue its movement towards IRI-based acceptance for newly-constructed pavements, and to integrate this information into the data base used for network level monitoring in Ontario.

FIGURES

Figure 1 – A “Lightweight” Profiler

Figure 2 - MTO’s Automated Road Analyzer

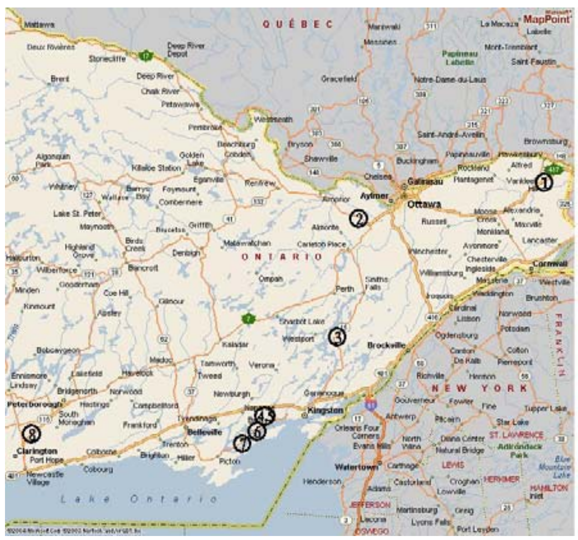

Figure 3 - Locations of Pavement Sections (Phase I)

Figure 4 - The Three California Profilographs

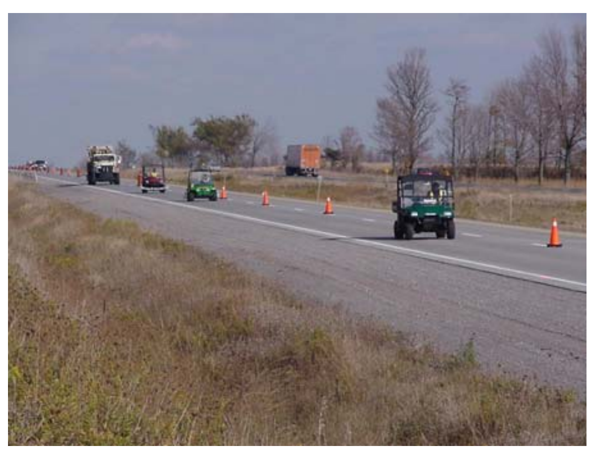

Figure 5 – The Three Lightweight Profilers

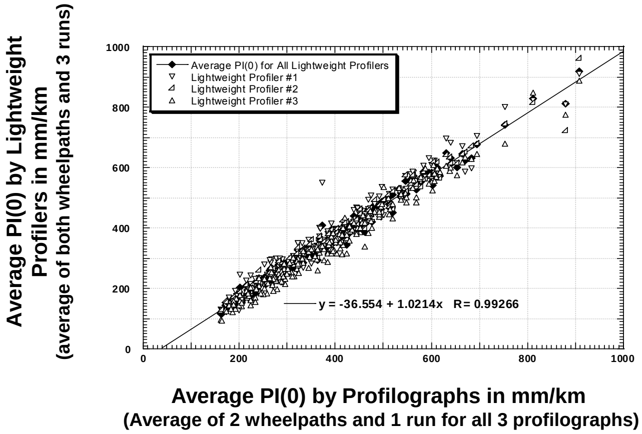

Figure 6 - PI(0) by Lightweight Profilers Versus PI(0) by Profilographs (Asphalt Sections Only)

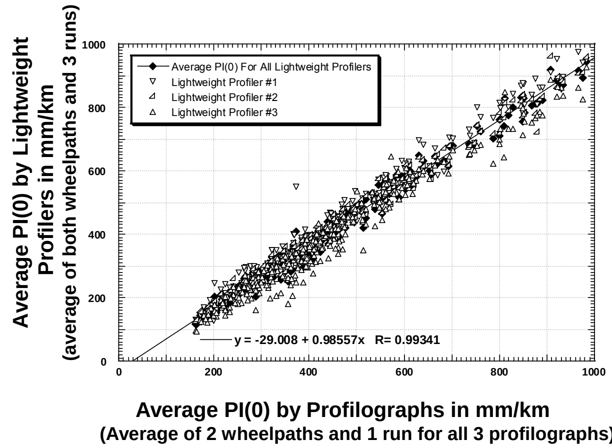

Figure 7 - PI(0) by Lightweight Profilers Versus PI(0) by Profilographs (All Pavement Sections)

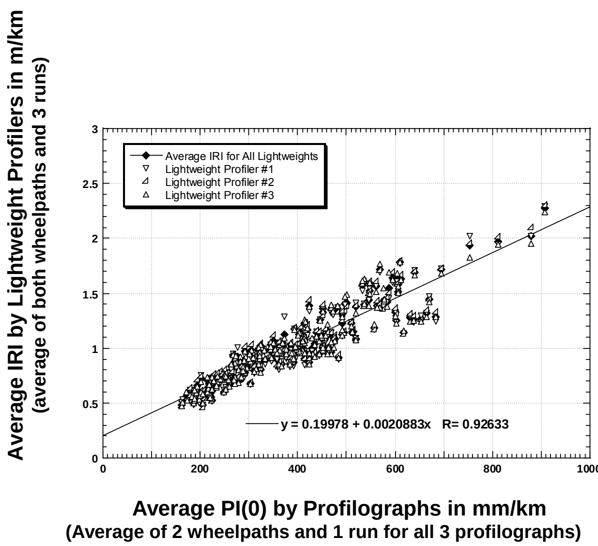

Figure 8 - IRI by Lightweight Profilers Versus PI(0) by Profilographs (Asphalt Sections Only)

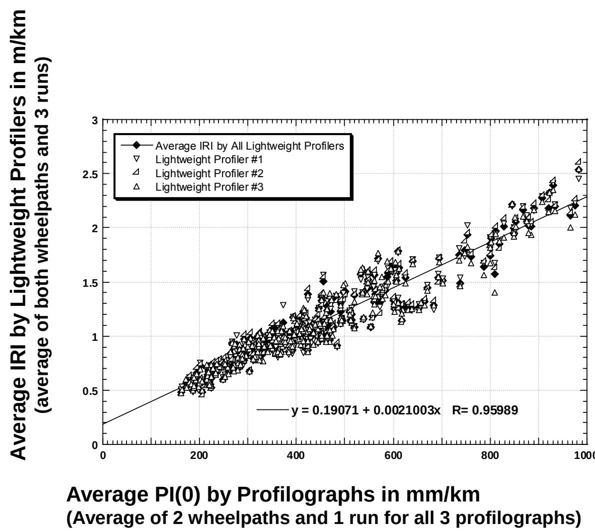

Figure 9 - IRI by Lightweight Profilers Versus PI(0) by Profilographs (All Pavement Sections)

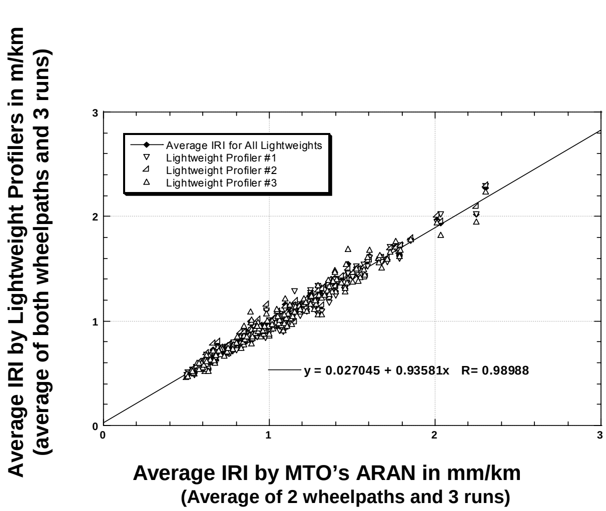

Figure 10 - IRI by Lightweight Profilers Versus IRI by MTO's ARAN (Asphalt Sections Only)

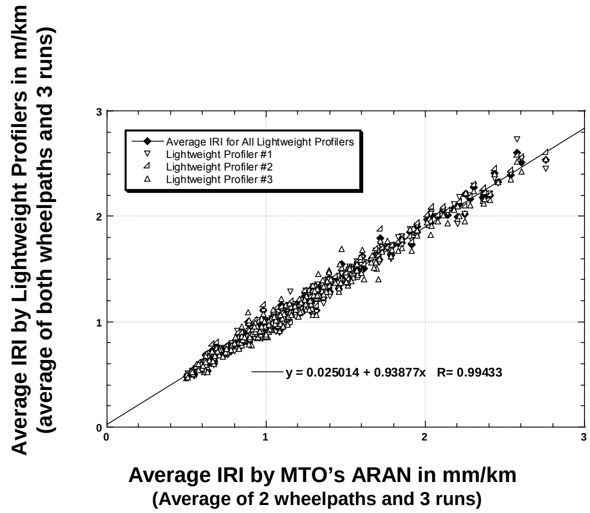

Figure 11 - IRI by Lightweight Profilers Versus IRI by MTO's ARAN (All Pavement Sections)

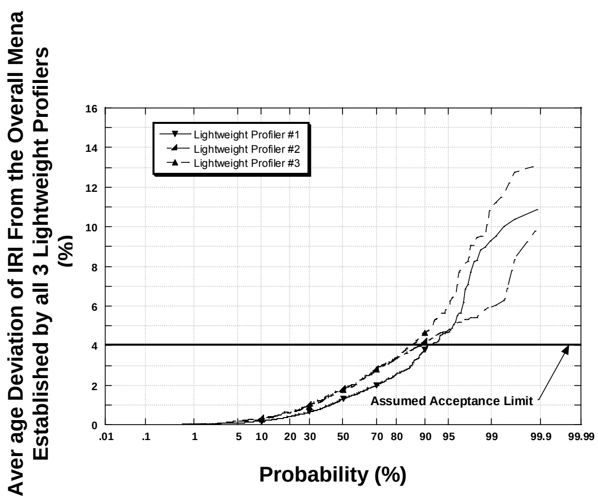

Figure 12 - Probability that Each Lightweight Profiler Would Meet MTO's Proprosed Reproducability Requirement for IRI (420, 300 m sections)

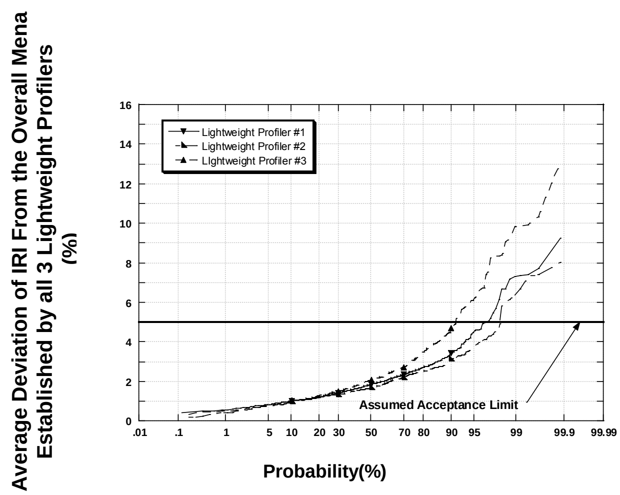

Figure 13 - Probability that Each Lightweight Profiler Would Meet MTO's Proprosed Repeatability Requirement for IRI (420, 300 m sections)

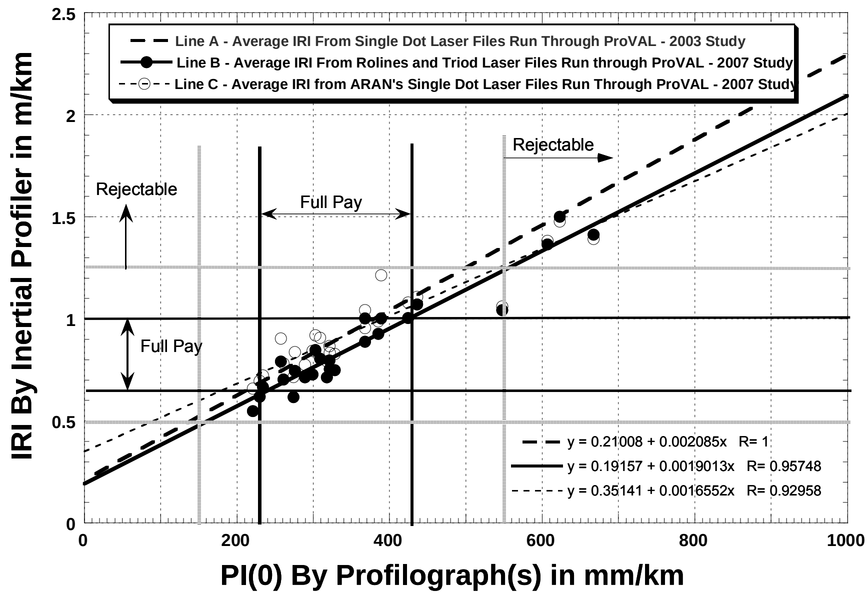

Figure 14 – **IRI Measured by Laser Arrays and Single Dot Lasers Versus PI Measured by California Profilographs (2003 and 2007 Studies)**

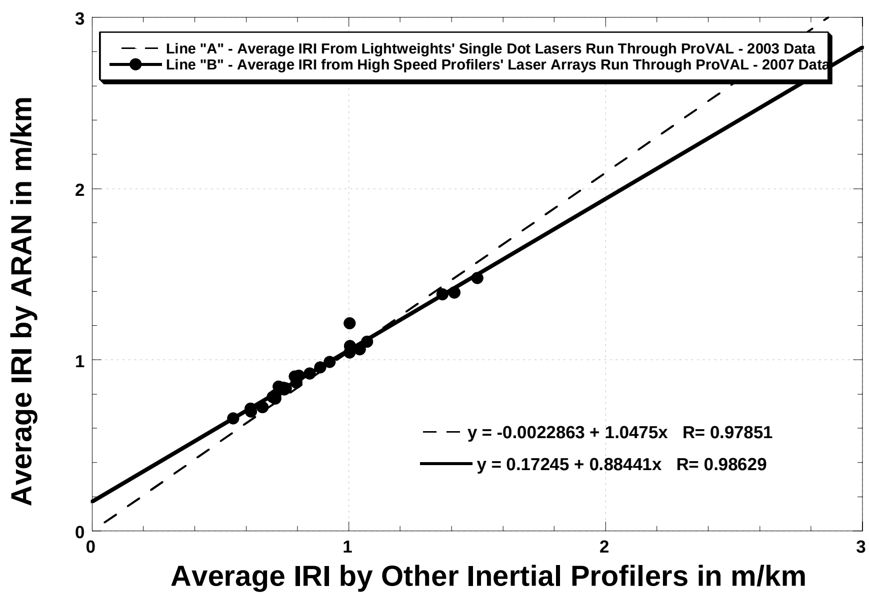

Figure 15 – **IRI Measured by the ARAN Versus Other Profilers Using Single Dot Lasers and Laser Arrays (2003 and 2007 Studies)**

TABLES

Table 1 - Summary of Pavement Sections (Phase I)

Site	Hwy	Location	Surface	Approximate Year(s) Since Paved	Length of Test Section
1A	417	km 22 to km 20.5 EB (East of Ottawa)	200mm of JPCP (concrete) and transversely tined	2002	1500
1B	417	km 19.5 to km 18 EB (East of Ottawa)	200mm of JPCP (concrete) and transversely tined	2002	1500
2	417	West of Ottawa	HL1	1999	3000
3A	15	North of CtyRd 42	HL1	2001	2100
3B	15	North of CtyRd 42	HL1	2001	2100
4A	L&A* CtyRd 2	W of Site4 at CtyRd 7	HL3	1997	2000
4B	L&A* CtyRd 2	W of Site4 at CtyRd 7	HL3	1997	2000
5A	L&A* CtyRd 4	between CtyRd 2 and Millhaven (southerly direction)	225mm of JPCP (concrete) no tining	1963	1200
5B	L&A* CtyRd 4	between CtyRd 2 and Hwy 401 (southerly direction)	225mm of JPCP (concrete) no tining	1963	1500
6A	33	East of Conway	HL4	1998	2000
6B	33	East of Conway	HL4	1998	2000
7A	33	Between Adolphustown and Conway	30/70 Recycled Hot Mix	2000/01	2000
7B	33	Between Adolphustown and Conway	30/70 Recycled Hot Mix	2000/01	2000
8A	115	at CtyRd 12 EB	HL1	1991/2	2000
8B	115	At CtyRd 12 WB	200 mm JPCP w Dowels and transversely tined	1991/2	1500

* Lennex and Addington County Roads

Table 2 - Summary of Correlation Equations Between Lightweight Profilers,California Profilographs and MTO's ARAN (Phase I)

Linear Correlations for 100 m sublots	Linear Constants and Correlation Coefficients											
	Lightweight Profiler #1			Lightweight Profiler #2			Lightweight Profiler #3			All Lightweight Profilers Combined		
	A	**B**	**R**	**A**	**B**	**R**	**A**	**B**	**R**	**A**	**B**	**R**
1) $PI_{Light} = A + B \times PI_{Prof}$												
a) 0 mm BB, Asphalt Sections Only	-27.16	1.025	.9800	-26.90	1.009	0.991	-50.33	1.015	0.986	-36.55	1.021	0.993
b) 0 mm BB, All Pavement Sections	-24.20	1.010	0.9900	-21.93	0.981	0.993	-39.16	0.961	0.984	-29.01	0.986	0.993
c) 0 mm BB, Concrete Sections Only	-47.03	1.033	0.994	-71.00	1.031	0.995	-115.2	1.035	0.988	-78.08	1.033	0.996
d) 5 mm BB, Concrete Sections Only	-9.795	1.017	0.983	-3.623	0.983	0.992	-8.526	0.894	0.981	-7.496	0.963	0.992
2) $IRI_{Light} = A + B \times PI_{Prof}$												
a) 0 mm BB, Asphalt Sections Only	0.184	0.002	0.926	0.205	0.002	0.924	0.210	0.002	0.918	0.200	0.002	0.926
b) 0 mm BB, All Pavement Sections	0.172	0.002	0.961	0.196	0.002	0.958	0.204	0.002	0.953	0.191	0.002	0.960
c) 0 mm BB, Concrete Sections Only	0.159	0.003	0.969	0.147	0.003	0.965	0.083	0.003	0.968	0.129	0.002	0.970
d) 5 mm BB, Concrete Sections Only	1.016	0.003	0.932	1.009	0.003	0.933	0.945	0.003	0.942	0.900	0.003	0.938
3) $IRI_{Light} = A + B \times IRI_{ARAN}$												
a) Asphalt Sections Only	0.012	0.940	0.990	0.030	0.944	0.990	0.350	0.924	0.981	0.027	0.936	0.990
b) All Pavement Sections	0.007	0.951	0.992	0.265	0.949	0.994	0.041	0.912	0.989	0.025	0.939	0.994
c) Concrete Sections Only	0.065	0.928	0.993	0.043	0.942	0.994	-0.012	0.940	0.991	0.032	0.923	0.993

Note: A, B = Constants, BB=blanking band, IRI=International Roughness Index, IRI_{ARAN} = Average IRI determined by MTO's ARAN, IRI_L = Average IRI determined by an individual lightweight profiler (or by all three combined), PI_{light}=Average Profile Index determined by an individual lightweight profiler (or by all three combined), PI_{Prof}=Average Profile Index determined by all three profilographs, R=Correlation Coefficient

Table 3 - Current Acceptance Limits For Scallops and Proposed Limits for Localized Roughness.

Acceptance Categories for Asphaltic Concrete	Current Limits for Scallops in mm (Rounded to the Nearest 0.5 mm)	Equivalent IRI-Based Limits in mm (Based on "Localized Roughness Option" in ®ProVAL and Rounded to the Nearest 0.1 mm)
Acceptable	≤ 10	≤ 3.3
Category 1 Price Reduction	11.5 to 12.0	3.3 to 3.7
Category 2 Price Reduction	12.0 to 14.5	3.8 to 4.7
Category 3 Rejectable	> 14.5	> 4.7

Table 4 - Comparison of the Average Number of Scallops that the Operator of Each Individual Lightweight Profiler Reported Versus the Number Reported by the Operators of the Three Profilographs.

Pavement Section	*Number of Scallops											
	Amplitude Range for Each Lightweight Profiler									Amplitude Range For Average of all 3 Profilographs		
	Lightweight Profiler #1			Lightweight Profiler #2			Lightweight Profiler #3					
	10-11.5	12.0-14.5	>14.5	10-11.5	12.0-14.5	>14.5	10-11.5	12.0-14.5	>14.5	10-11.5	12.0-14.5	>14.5
2	5.7	5	1.7	2.7	4	1.3	3.3	2.7	0	5.3	2	1
3A	5.7	1.3	0	3	3.3	0	0	2	0	4.7	3	0
3B	3	2.3	1.7	2.3	1.7	1	0	2	1.3	3.3	3	0
4A	7.7	1.7	0.3	4	1.3	0	0	1.3	0	5.3	1	0
4B	6.7	1.7	3	4	1	2	2	1	2	7.7	1	2
6A	10.7	12.7	8.7	10	9.7	8	4.3	8	5.3	13.3	13	4.7
6B	7	2	0.3	7.7	2	0	2.3	1.7	0.3	5.3	2.7	0
7A	0	0	0	0	0	0	0	0	0	0	0	0
7B	0	1	0	2.7	2	0	0	1	0	1.7	2	0
8A	2	2.7	3.3	2.7	0	0	0.7	0.7	0.3	1.7	0	0
Totals For Asphalt Pavements	48.5	30.4	19	39.1	25	12.3	12.6	20.4	9.2	48.3	27.7	7.7
	97.9			**76.4**			**42.2**			**83.7**		
	72.2											

*Note: The numbers are based on the number of times that a Lightweight profiler recorded each scallop in its three runs (e.g. 1=3 of 3 runs or 0.66=2 of 3 runs). For the profilographs, the number of scallops is based on the average number of times that each scallop was recorded by the three profilographs combined in their single runs.

Table 5 - Current Acceptance Limits For 100 m Sublots Based on PI and Equivalent Limits Based on IRI.

Asphaltic Concrete Surface Courses Pay Categories	Current Limits for PI in mm/km (Based on a 0 Blanking Band)	Equivalent IRI-Based Limits in m/km (Based on in "Ride Stats At Intervals Option" in ®ProVAL)
Maximum Bonus	< 150	< 0. 5
Bonus	150 to <230	0.50 to < 0.65
Full Payment	230 to 430	0.65 to 1.00
Price Reduction	>430 to 550	> 1.00 to 1.25
Rejectable	> 550	> 1.25

Table 6 - Summary of Scallops By Profilograph Versus Localized Roughness By Inertial Profilers (All Results Based on Files Run Through ®ProVAL)

STUDY PHASE	Pavement Section Designation (# of 100 m sublots)	Scallop/ Localized Roughness Acceptance Categories (see Note 1)	Scallops by Profilograph(s) (see Note 2)	Localized Roughness by Inertial Profilers: ARAN Using Single Dot Lasers (See Note 3)	Localized Roughness by Inertial Profilers: Lightweight Profilers Using Single Dot Lasers (see Note 4)	Localized Roughness by Inertial Profilers: High Speed Profilers Using Laser Arrays (see Note 5)
Phase I 2003 Lightweight Profiler Study	2 (30)	1	4.30	4.67	2.89	N/A
		2	2.00	0.67	2.33	
		3	0.00	2.33	2.67	
	3 (42)	1	6.67	3.00	3.89	
		2	6.00	3.33	1.56	
		3	0.00	0.00	0.11	
	4 (40)	1	11.67	15.33	14.33	
		2	1.33	6.00	3.78	
		3	2.00	1.67	1.56	
	6 (40)	1	18.33	24.00	17.44	
		2	12.00	13.67	10.33	
		3	4.33	5.33	5.66	
	Averages of All Sections (152)	1	40.97	47.00	38.55	
		2	21.33	23.67	18.00	
		3	6.33	9.33	10.00	
	Totals	**All Categories**	**68.63**	**80.00**	**66.55**	
Phase II 2007 Study	Red Hill Creek (20, 100 m sublots)	1	1.00	0.00	N/A	0.00
		2	2.00	1.00		2.00
		3	0.00	1.00		0.33
	Correlation Site (5, 100 m sublots)	1	6.00	7.00		3.00
		2	1.00	0.00		2.00
		3	0.00	1.00		1.00
	Averages of All Sections (25, 100 m sublots)	1	7.00	7.00		3.00
		2	2.00	1.00		4.00
		3	0.00	2.00		1.33
	Totals	**All Categories**	**9.00**	**10.00**		**8.33**

Notes:
1 - Limits for scallop and localized roughness categories are given in Tables 5 and 6, respectively.
2 - In Phase I, the number of scallops are the averages for three profilographs making a single run in each wheelpath.
In Phase II, the number of scallops are only for one profilograph making a single run in each wheelpath.
3 - In Phase I, the numbers of localized roughness locations are the averages for 2 runs using the ARAN's single dot lasers.
In Phase II, the numbers of localized roughness locations are the averages for the first 3 runs using the ARAN's single dot lasers.
4 - In Phase I, the numbers of localized roughness locations represent the averages for 3 runs using three lightweight profilers' single dot lasers.
5 - In Phase II, the numbers of localized roughness locations represent the averages for Trow's high speed profiler using it's two Roline sensors, Ames high speed profiler and it's single Roline sensor (which was switched from the left to the right side) and Ames high speed profiler and it's single Triod sensor (which was switched from the left to the right side). All of the results are based on the first 3 runs made by both devices, except for all but the first 5, 100 m sections at the Red Hill Creek Site where Ames' profiler made only 2 runs with each sensor.

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REFERENCES

1. American Society for Testing and Materials (ASTM), Vol. 04.03 Designation: E 950-98" Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces with an Accelerometer Established Inertial Profiling Reference".

2. American Association of State Highway and Transportation Officials (AASHTO), PP 50-02, "*Draft* Standard Equipment Specification for An Inertial Profiler".

3. American Association of State Highway and Transportation Officials (AASHTO), PP 51-02, "*Draft* Standard Practice for Certification of Inertial Profiling Systems".

4. American Association of State Highway and Transportation Officials (AASHTO), PP 52-02, "*Draft* Standard Practice for Operating Inertial Profilers and Evaluating Pavement Profiles".

5. American Society for Testing of Materials (ASTM), "Standard E 1274-88 - Standard Test Method for Measuring Pavement Roughness Using a Profilograph".

6. Emmanuel Fernando and Carl Bertrand, Transportation Research Board, 81st Annual Meeting, TRB#02-4050, "Application of Profile Data to Detect Localized Roughness", Washington D.C. (2002).

7. Federal Highway Administration (FHWA), FHWA-RD-02-057, "Pavement Smoothness Index Relationships", Washington, D.C. (2002).

8. Steven M. Karamihas and Thomas D. Gillespie, University of Michigan Transportation Research Institute (UMTRI), "Assessment of Profiler Performance for Construction Quality Control", Ann Arbor, MI., (2002).

9. Steven M. Karamihas, University of Michigan Transportation Research Institute (UMTRI), "2005 ACPA Profiler Repeatability Tests", Ann Arbor, MI., (2005)

10. National Cooperative Highway Research Program (NCHRP). "Smoothness Specifications for Pavements - Final Report (NCHRP Project 1-31) (1997).

11. Michael W. Sayers and Steven M. Karamihas, UMTRI 96-19, "Interpretation of Road Roughness Profile Data – Final Report, June 1996

12. Michael W. Sayers and Steven M. Karamihas, The University of Michigan, "The Little Book of Profiling", Ann Arbor, MI., (1998).

13. Ministry of Transportation, Ontario (MTO), Special Provision SP103 F34, "Asphaltic Concrete Surface Tolerance and Payment Adjustment for Surface Smoothness", 2004

14. Hao Wang, Thesis Submitted to the Faculty of Virginia Polytechnic Institute and State University, "Road Profiler Performance Evaluation and Accuracy Criteria Analysis", Blacksburg, Virginia, July 2006.