

## **Using a Ride Quality Index for Construction Quality Control and Acceptance Specifications**

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WORD COUNT: 4,690 + 2 TABLES + 9 FIGURES = 7,440

## **ABSTRACT**

Profilographs have traditionally been the tool of choice for measurement of newly constructed pavement roughness. Although only a modest relationship exists between profilograph output and ride quality, the construction industry has been reluctant to consider other methods of measurement. In part, this is because a well-established method exists for using a profilograph trace to pinpoint locations that require diamond grinding.

In contrast, inertial profilers offer a way to obtain measurements with proven relevance to ride quality and overall pavement performance via analysis by ride quality indexes. A major drawback to using a ride quality index, as cited by the construction industry, is the lack of a method for pinpointing hot spots in the pavement that should be corrected by a diamond grinder.

This paper presents a method for locating isolated rough spots on new pavement and a basis for prioritizing the use of a grinder to improve new pavement smoothness using inertial profiler output. Identification of rough spots is done using an adapted version of the roughness profile called continuous reporting of ride quality. Isolated irregularities are located by reporting a ride quality index on all possible road segments of a given length. The rough spots located by this method provide a direct snapshot of where events occurred on the pavement that penalize the overall ride quality most, which provides feedback to the road builder that can be used to examine the paving process. A Diamond Grinding Simulation is used to ensure that corrective action is only implemented at locations where a grinder would actually improve the ride quality.

## BACKGROUND

During the late 1990s the Ohio Turnpike Commission decided to establish a new means for evaluating the *rideability* of newly constructed pavement. The method in use at that time was a Mays Meter that was installed in a Chrysler K car. Previous methods of road surface analysis measured pavement *smoothness* and included devices such as rolling straightedges and the California Profilograph. The difference in the basic approach behind each of these two methods outlines the schism that has existed in the field of road surface measurement for the past couple of decades. The first approach measures pavement smoothness, defined using a linear accumulation of deviations from a short planar surface traveling over the roadway. The California Profilograph is the most common device used in this approach. The second approach measures pavement rideability and passes a vehicle, real (Mays Meter) or simulated (using a ride quality index), over the road profile to measure vehicle response. (1-3)

There are two main reasons for measuring the *trueness* of a roadway surface. The first reason is to determine what people may feel as they travel over the roadway. The second is to determine the level of dynamic loading on the pavement from heavy vehicles. Both of these items can be reduced to one fundamental property — Vehicle Vibrations. Since measures of rideability, such as the International Roughness Index (IRI), are directly linked to vehicle vibration they serve as a sound basis for road evaluation.

However, each approach has one major advantage and one major disadvantage. Measurements of smoothness that are based on straightedges can not accurately describe vehicle vibration response. This is because their output depends on the geometry of the measurement device, which has no direct connection to vehicle behavior. They can, on the other hand, accurately pinpoint irregularities in the pavement surface. Conversely, measurements of rideability often provide direct estimates of vehicle vibration response but can not be easily used to pinpoint irregularities.

One strategy that has been attempted to overcome these disadvantages is to use an estimate of vehicle response, such as the IRI, to measure ride and use a rolling straightedge to find the irregularities. This combination has proven disastrous for many. The two measurement approaches are rarely sensitive to the same surface deviations and are not compatible. Thus, searching for irregularities with a straightedge-based device often fails to pinpoint aspects of the pavement surface shape that degrade measures of rideability most.

Given these obstacles, a valid specification required that one of two choices had to be made: (1) develop an empirical formula for defining vehicle vibration response from smoothness measurements, or (2) develop a method for locating isolated disturbances from a vehicle response filter. The later was chosen for use on the Ohio Turnpike.

The goal of the Ohio Turnpike rideability measurement program is to summarize the rideability of new construction on a scale that is repeatable, reproducible, and consistently correlated with the satisfaction of the riding public. In order to satisfy these needs the new measure of rideability had to produce the desired summary information that was selected for describing the pavement surface. First, this information included the reporting of numerical values that best conveyed a summary rideability score to engineers. Second, localized ride disturbances must be easy to locate and the magnitude of their effects on ride displayed using the same scale as the summary values. Third, a method for analyzing these disturbances for determining the required type of corrective action was needed. This paper describes the procedures used to meet all of these needs. The paper also outlines the rationale used to select a ride quality scale, a reporting system customized to simultaneously provide an overall rideability score and isolate hot spots, and a new method for determining a strategy for corrective action.

Although many of the methods described here already existed, they were not commonly used in this application. The method for determining a corrective action strategy is based on new analyses that includes a grinder simulation. The profile analyses described in the paper are demonstrated using a profile for the first mile of an eight-mile long resurfacing project recently completed as part of the Ohio Turnpike Third Lane Project.

## RIDE QUALITY INDEX SELECTION

A cornerstone of the effort to improve the rideability measurement program on the Ohio Turnpike was the replacement of the Mays Meter with inertial profiling. Inertial profiling, when used correctly, provides repeatable and reproducible measurements of the pavement surface. (4) An important aspect of the move to profiling was the

selection of a ride quality index. One requirement for the scaling of the index was that it produce low values for good ride, and increase as ride degrades. This convention was the same as previously used methods, such as the Mays Meter and profilograph, and would simplify the transition to the new measurement system.

A requirement for a ride quality index was that it must have a well-established relationship to vehicle vibration response to the road. There are several models of ride quality index that estimate vehicle response, such as the IRI, Half-Car Roughness Index (HRI), and Ride Number (RN). (5, 6) The IRI and HRI use the numerical convention mentioned above, in which a value of zero signifies a perfectly smooth pavement, and values increase as ride quality decreases. The RN, on the other hand, is cast onto a scale from 0 to 5, where 5 indicates a perfectly smooth road and the value decreases toward 0 as ride quality degrades. This is achieved using an exponential transformation of a ride quality index with a scaling that increases with roughness. (7) This index, dubbed Pre-Transform Ride Number (PTRN), is used for reporting RN for the Turnpike Commission because of its conventional scaling.

The HRI, which is the half car version of the IRI, was the ride quality index chosen for the Ohio Turnpike. There were several reasons for this choice:

1. The half car model reported one statistic per lane. Since acceptance is determined on a lane by lane basis, having multiple outputs per lane only made the process cumbersome and inefficient. HRI streamlined the analytical process.
2. The half car model produces less variation across repeat measurements than IRI or RN and therefore provides a more consistent means of measure.
3. It was the general opinion that a half car model was a better representation of how a real vehicle suspension would react to the profile. The transition to HRI would also be easier to accept, because the HRI more closely models an idealized Mays Meter than the other indexes. (8)
4. The quarter car version of this filter, IRI, is the most widely acceptable ride quality index for measuring roughness.

Although the PTRN was not officially selected for use in the Turnpike's rideability measurement program, it is often calculated and examined side by side with HRI. This is because PTRN has demonstrated a strong relationship to user opinion. (7, 9, 10) The HRI differs from the PTRN in that it is sensitive to features longer than PTRN and the PTRN is sensitive to features shorter than HRI. By reporting both of these indexes a crude categorization of ride quality can be developed. Short disturbances that only affect RN, middle range disturbances that affect both RN and HRI, and long disturbances that only affect HRI. The same type of information can be obtained using spectrum analysis of road profile. (11) However, spectrum analysis does not lend itself to use for locating isolated disturbances.

## **FIXED INTERVAL REPORTING**

Fixed interval reporting is currently the most common format for summarizing ride quality data. In fixed interval reporting a single value of a ride quality index, or perhaps one value for each wheel path, is reported for each consecutive road segment of equal length. The most common interval in use for this purpose is one tenth of a mile. (1, 3, 12) In an attempt to help isolate the roughest segments of road, the Ohio Turnpike experimented with a shorter fixed interval of one twentieth of a mile. With this interval, the ride quality of each lane mile of roadway would be summarized by 20 values of HRI. Each value represents the average ride quality score of a segment 264 feet long with a specific starting and ending point. Table 1 shows the output produced by reporting the ride quality of a half-mile of a newly resurfaced lane on the Turnpike using this interval.

Although fixed interval reporting does provide a simple way to specify and quantify pavement roughness, when used alone it greatly reduces the information available about the road condition. Consider the 10 values listed for a half-mile of Turnpike in table 1. These summary ride quality values can only serve as pass/fail criteria for the overall quality of a segment of road. On the Turnpike an HRI value higher than 45 in/mi is considered unacceptable for a segment of pavement one twentieth of a mile long. For the half-mile covered by table 1, only the first of ten segments violates the criteria. Without further analysis, no clues are available to reveal the cause of the unacceptable

ride quality value. Since this segment violated the limit by a slim margin, diagnostic information may be very important. In addition, there is no way to know for sure if the fifth segment, which was just as close to the threshold, but below it, is any less annoying to the traveling public.

### **Consistency**

Ride quality values reported at a fixed interval depend heavily on the starting point selected for the measurement. To illustrate this, consider the theoretical case of a perfectly flat road with a single isolated disturbance. Figure 1 shows two extreme scenarios of the way fixed interval reporting may treat this disturbance. In one extreme scenario this disturbance happens to fall completely within one interval and contributes 80 in/mi to its ride quality value. In the other extreme scenario half of this disturbance falls within one interval and half falls in the next interval and two intervals are reported at 40 in/mi. Even though the road was exactly the same, the two summaries appear very different simply because of the arbitrary selection of a starting point.

The example above is extreme, but it illustrates that reporting ride quality at a fixed interval may lead to inconsistent results. This reporting system is in common use by engineers who seek to monitor the overall condition of a road network. In monitoring a large pavement network enough distance is covered to allow these inconsistencies to average out, so reporting ride quality at a fixed interval is likely to provide a reasonably accurate overall view of the ride quality of the road system. Evaluation of new construction, however, usually involves measurement of only a few miles of road at a time. Further, smoothness incentive payments are normally based on a discrete and rather coarse set of cut-off values. In such a case the way a new pavement surface is split into intervals, which has nothing to do with the quality of the road, can influence the way it is classified. Therefore a more precise method for conveying the index summary information is required.

The new pavement surface examined in table 1 provides a practical example of this weakness in fixed interval reporting. Table 2 reports the HRI at a fixed interval of 264 feet covering the first mile of the same pavement. In table 2, the pavement is split into segments four times, each with the starting point for the entire job shifted by 66 feet. Each column lists 20 ride quality values for a distinct shift in starting point. Thus, each value in the table covers a segment that overlaps parts of two segments in the other columns, except for the first and last values. For example, the values of ride quality listed for an offset in starting point of 132 feet represent a segment that covers half of the first two segments in the column with no offset.

Values over 45 in/mi, which are considered unacceptable for a 264-foot segment on the Turnpike, are shown in bold in table 2. Note that 6 of the segments are over the threshold when the starting point of the first segment is not offset from the starting point of the new pavement. (This is marked no offset.) Offsetting the starting point of the first segment just slightly decreases the ride quality value of the first segment significantly, because an irregularity in the pavement surface appears right at the start of the interval. The other three values of offset examined in the table show acceptable ride quality in the first segment, because they do not include this localized roughness. A more important observation is that offsetting the starting point by 66 feet, 132 feet, or 198 feet lowers the number of segments over the threshold to just 4. The decrease in defective segments in the second half of the table is strictly a consequence of the way road features that degrade ride quality are split into segments. Such variation can occur even if the starting point is only shifted by a few of feet, depending on the type of disturbances within the segment.

A value of 60 in/mi has been recommended as a threshold value for incentive bonus payments for pavement jobs managed by state departments of transportation. (12) Table 2 shows two cases where a value over 60 in/mi is reported and two cases with none. Bear in mind that these diverse ride quality values represent no change in the actual pavement surface.

### **Detail**

In fixed interval reporting, isolated rough spots in the pavement are difficult to find, because their influence can be hidden in an otherwise smooth segment of road. Some studies of human ride perception have concluded that a few instances of harsh vehicle vibration in an otherwise smooth ride can be much more annoying than a steady, consistent vibration. (13, 14) Therefore, it is reasonable to expect, although never verified directly, that two road segments with the same overall ride score may be perceived quite differently if one of them contains a few large

pavement irregularities and the other has many small pavement irregularities. Reporting ride quality only at a fixed interval of one twentieth of a mile or longer does not provide a means to distinguish between these two cases.

With the lack of detail provided using a long reporting interval, it is difficult to develop a strategy for correcting unacceptable rough features. It is also difficult to improve paving practices, because there is no way to relate short, rough features to paving problems and provide useful feedback to a paving crew. One potential method of capturing some of the details about short rough features is to report ride quality at a fixed interval that is very short. For example, when ride quality is reported at an interval of 528 feet, the data can be supplemented by another listing of ride quality reported at an interval that is at least 10 times shorter. When shorter intervals are used the average ride quality stays the same, but more extreme values are observed.

Overall, reporting at a fixed interval provides inconsistent results in that the same pavement could pass or fail depending on the starting point, and lacks the detail needed to make good engineering decisions. Reporting ride quality at a short interval is a useful way to solve some of these problems. However, ride quality reported at a short interval is even more vulnerable to the phenomenon demonstrated in figure 1. Continuous reporting, described below, solves these problems.

## CONTINUOUS REPORTING

The Turnpike Commission selected a method of *continuous reporting* as a way to analyze the rideability of new pavement in a consistent, detailed manner. The concept of continuous reporting is based on the *roughness profile*, first proposed by Sayers for detailed examination of the way features that contribute to the IRI are spatially distributed. (15) For the Turnpike, the method is applied to the HRI.

In continuous reporting, as in fixed interval reporting, a standard segment length is chosen. Rather than report a ride quality value for a small number of consecutive segments of that length, a ride quality value is displayed for all possible segments.

Displaying ride quality using continuous reporting requires three basic steps. In the first step, the profile is filtered, as it normally would be for computing the desired index. In the case of the HRI, this involves averaging the left and right profile point by point, then passing the result through the IRI filter. (6) Figure 2 shows the profile of a small segment of new pavement after the HRI filters have been applied. In the second step, taking the absolute value of every point rectifies the filtered profile. (See figure 3.) Each point in the resulting signal represents a contribution to the HRI of a small patch of road near the corresponding location. (Since the original profile was sampled at 10 points per foot, the output a mile of road is represented by 52,800 points.) Within any given segment, the average of all points within the corresponding limits is the HRI. Thus, the HRI of the 500-foot long segment represented in figure 3 is the average of all of the points displayed in it, which is 42 in/mi. Note that values much more extreme than that appear in the figure.

The final step required for a continuous report of ride quality is to apply a moving average to the rectified filter output. Once the moving average is applied, every point in the continuous (graphical) report represents the ride quality of a segment whose length is equal to the baselength of the moving average. The continuous reporting graph for a baselength of 100 feet is shown in figure 4. This is a continuous report of the ride quality of all possible 100-foot long segments within the range of the display. Since the sample interval was 0.1 feet, figure 4 shows 5000 individual ride quality values. Calculating them is actually rather efficient. The first value is the average of all of the rectified filter output values within the first 100 feet. The next value, for a segment shifted forward only 0.1 feet, is calculated by subtracting the influence of the point that passed out of the range (at the start) and adding the influence of the next point that passed into the range (at the end). The segment limits are then shifted as many times as are needed to reach the end of the profile.

Continuous reporting displays all the information that is provided by the ride quality index. When using continuous reporting of the HRI of 264-foot long segments, collected using a sample interval of 0.1 feet, there are 50,161 ride quality values reported (graphically) for every mile of roadway. In contrast, fixed interval reporting only provides 20 values, which represents only a fraction of the useful information in a continuous report.

A continuous display of ride quality has two major advantages. First, areas of poor ride quality are not missed as a consequence of using discrete segments. Major contributors to roughness, such as the one described in

figure 1, are always captured in a continuous report. In the example shown in figure 1, the disturbance will *always* be reported as 80 in/mi. Second, isolated rough spots on the pavement can be found by searching the continuous report for peaks. In addition, the degree to which they degrade the overall ride quality can be quantified directly. Both of these advantages depend on wise choices of baselength for the moving average filter.

The Ohio Turnpike analyzes two versions of the continuous ride quality report. One version uses a baselength of 264 feet for general pavement acceptance. Another version uses a baselength of 25 feet to search for isolated rough spots and candidates for correction.

Figure 5 shows the continuous report for a baselength of 264 feet. A threshold of 45 in/mi has been set for acceptance. That means that every possible segment 264 feet long must have an HRI of less than 45 in/mi. With the continuous reporting graph, areas of concern can be located at a glance. In figure 5, four areas of concern appear: at the start of the job, about 3250 feet from the start, 4000 feet from the start, and 4550 feet from the start. As a means of automating the search for road segments of unacceptable ride quality the ranges that violate ride quality threshold in the plot, and their peak HRI values, could certainly be tabulated.

Note that the continuous report contains all of the information provided by a fixed-interval report. Figure 6 shows the continuous report for a baselength of 264 feet again, with markers (vertical lines) every 264 feet. These markers appear in the center of each consecutive 264-foot segment. Each intersection of the continuous reporting graph with a marker represents the HRI value that would have been reported in a fixed interval for the segment of pavement starting 132 feet right and ending 132 feet left of the intersection point. Fixed interval summary information for comparison is included to the right of figure 6. The potential inconsistency in fixed interval reporting can be predicted by shifting the set of markers to the left or right. Wherever the new intersection points occur will be the corresponding numbers that are reported for the fixed interval. For someone trying to get incentive bonus for smoothness under a fixed interval reporting specification, this is an indispensable tool.

For locations that fail to meet the ride quality specification a detailed investigation of the pavement and its profile is undertaken. To determine the exact location of individual disturbances, the analysis baselength is shortened to 25 feet so only small segments of roadway are analyzed. Figure 7 shows the continuous report for the section of pavement containing the last three disturbances, mentioned above, for a baselength of 25 feet. The values are much more extreme than they are for a baselength of 264 feet. The peak value in a continuous reporting graph will always increase as baselength decreases. Thus, a unique set of ride quality threshold values is needed for each value of baselength. The Turnpike has not set an explicit threshold value that corresponds to a baselength of 25 feet. (It is anticipated that threshold values will be set after more experience with this procedure.) Nevertheless, the continuous ride quality report for this short baselength provides an excellent tool for isolating hot spots in the pavement. Peak values in figure 7 occur at locations that contribute most to the overall HRI. Three locations that need attention are immediately apparent from the figure: at 3975, 4075, and 4525 feet. These locations, and any others that penalize the ride quality most are then examined for possible corrections.

With the appropriate set of baselength and threshold values, a continuous reporting graph is also a useful tool for specifying ride quality on and near bridges.

## **SIMULATED DIAMOND GRINDING**

Now that rough areas could be identified, a strategy for correction had to be developed. Generally speaking there are two alternatives, removal/replacement and diamond grinding. Grinding is the least expensive option but it is not an effective solution for all poor riding pavement areas. For example, dips can not be ground out of the pavement surface. To determine which areas of pavement would benefit most from diamond grinding, a diamond grinding simulation was developed. Since a grinding simulation can only be used for the machine that it models, several different grinding simulations were actually developed. A patent is pending on the grinding simulation, and the procedure for using it described here.

To examine the road surface using this technique the measured profile is modified by a diamond grinding simulation and then is reanalyzed and summarized using the same type of continuous ride quality report described above. By examining the effect of the simulated diamond grinding, it is a simple task to determine which areas will benefit sufficiently from grinding to merit the expense.

Figure 8 shows the potential benefit of grinding the three rough spots isolated in figure 7 with a Target Grinder Model 3804. The figure shows a continuous report of ride quality that can be expected if grinding is applied using the starting and stopping locations used in the simulation. The results are very sensitive to the range covered by the grinder and the vertical position of the grinding head. These variables were optimized using several runs of the grinding simulation. The results in figure 8 depict the improvement in ride quality expected using the optimal starting and stopping points for the grinder. The vertical position of the grinding head were set by moving the grinder to each starting location, and computing the position the grinding head would take if it were set down there and frozen.

According to the simulation, the rough spot near 4520 feet would be corrected sufficiently after grinding to decrease the ride quality value below the threshold of 45 in/mi. The two other rough spots would not improve enough to meet the threshold, but they were improved enough that it was worthwhile to grind there anyhow.

A Target Grinder Model 3804 was applied to the pavement as recommended by the simulation. Afterward, a new profile was collected to verify the results. Figure 9 shows the continuous report of ride quality produced by the grinding simulation in black, and obtained after the actual grinding in gray. A thin black line shows the original plot (before grinding). Note that the original plot only differs from the grinding simulation near the ranges where the grinder was applied. These ranges extend from about 3900-4150 feet, 4430-4640 feet. In these two ranges, the results of the grinding simulation did an excellent job of predicting the ride quality of the road after grinding.

Some large ranges are presented in figure 9 where no grinding was done. In these ranges, the measurements taken before and after the actual grinding should agree. They agree quite well, due in part to the fact that the measurements were only two days apart, and in part to the excellent repeatability of the profiler.

The grinding simulation is a powerful engineering tool. Pavement deficiencies can be prioritized based on the predicted outcome of diamond grinding. This provides a means to maximize grinding efficiency by targeting the largest improvements in ride quality. This is very important for projects that have incentive/disincentive specifications. Diamond grinding is a costly process. The simulation provides a basis for maximizing the benefits of its use, and avoiding situations where grinding may not improve the ride quality enough to justify the expense.

## **SUMMARY**

The techniques described herewith provide the Ohio Turnpike Commission with a unique methodology for measuring, reporting, and specifying ride quality of new pavement. The HRI serves as the central index in the ride quality program. Its selection was the result of the subjective judgment of the professionals involved in creating this new system. However, the analysis techniques described can be applied to other ride quality indexes as well as smoothness measuring systems such as the California Profilograph. The system outlined in this paper, to date, has proven to be an effective and efficient method for determining ride quality on construction projects. It has also correlated well with the subjective opinion of the construction engineering staff.

The concept of a continuous roughness report was suggested as a helpful tool for studying ride quality over a decade ago. (15) This paper demonstrates that a continuous report of ride quality provides a wealth of information as compared to ride quality reported at fixed intervals. The method was demonstrated as a way to specify overall ride quality, and search for localized ride disturbances that are candidates for correction. A grinder simulation is also demonstrated for optimizing correction of localized roughness.

## **ACKNOWLEDGEMENTS**

The transition to this new system of rideability measurement was made possible with the help of two individuals. Brian Schleppe, of the Ohio Department of Transportation, provided guidance for index selection and section averaging lengths. Dennis Albrecht P.E., previously of the Ohio Turnpike Commission, developed the benchmark criteria for all new construction and rehabilitation projects.

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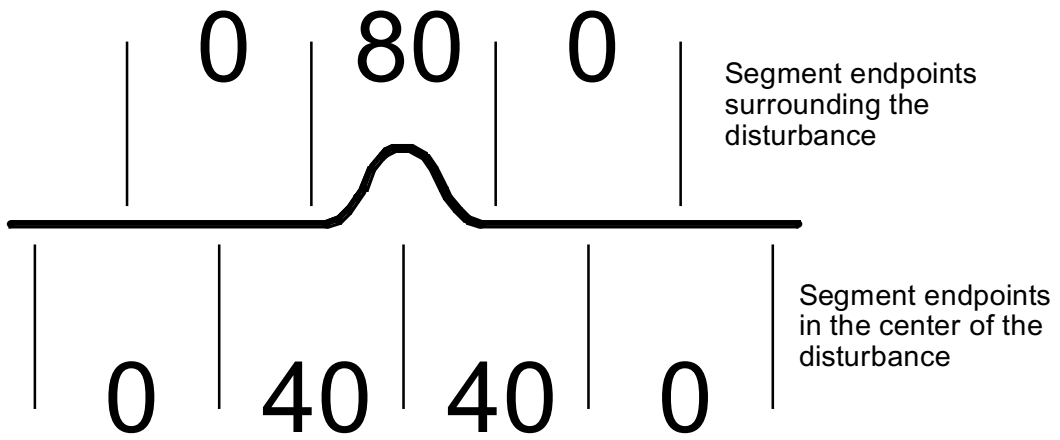
Figure 9 Validation of simulated grinding.

**Table 1. HRI reported at a fixed interval.**

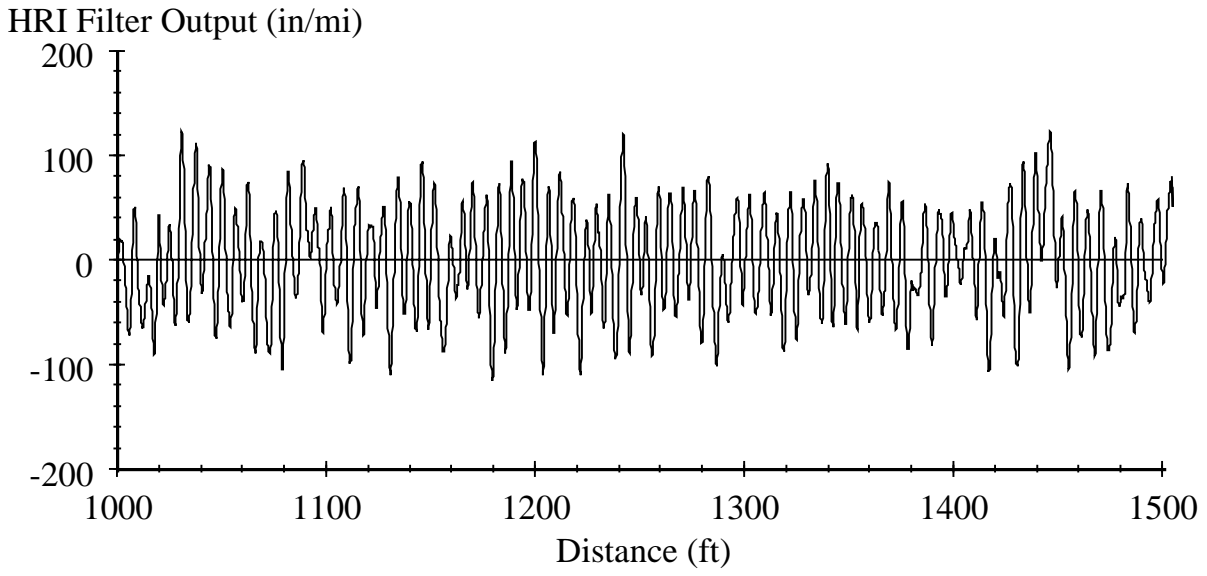
Segment Starting Point (ft)	Segment Ending Point (ft)	Half-Car Roughness Index (in/mi)
0	264	47.3
264	528	31.2
528	792	29.8
792	1056	32.1
1056	1320	42.9
1320	1584	40.4
1584	1848	40.6
1848	2112	39.6
2112	2376	33.0
2376	2640	38.1

**Table 2. Changes in HRI with starting point.**

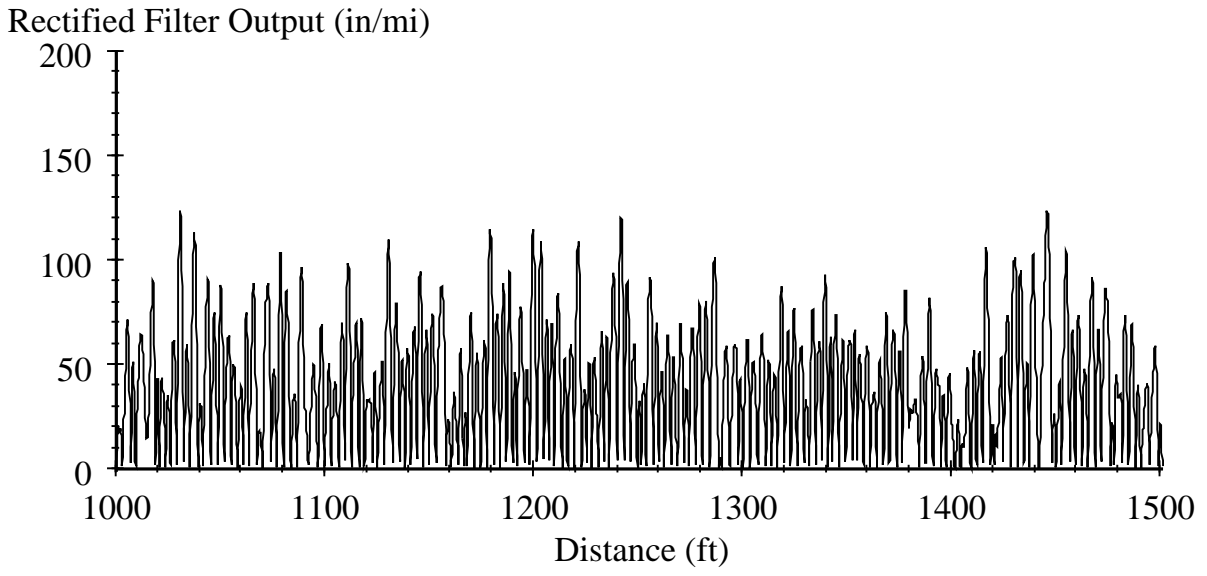
Segment Number	Half-Car Roughness Index (in/mi)			
	No Offset	Job Offset by 66 feet	Job Offset by 132 feet	Job Offset by 198 feet
1	<b>47.3</b>	32.4	30.8	29.6
2	31.2	31.1	29.0	29.2
3	29.8	28.7	28.7	29.5
4	32.1	35.7	39.5	43.1
5	42.9	42.7	42.1	40.0
6	40.4	39.8	42.7	42.6
7	40.6	43.3	38.1	39.3
8	39.6	34.0	34.4	32.6
9	33.0	37.4	37.8	38.0
10	38.1	38.4	40.1	38.9
11	38.8	43.8	42.4	43.7
12	<b>46.6</b>	44.2	<b>51.7</b>	<b>52.2</b>
13	<b>55.1</b>	<b>51.0</b>	<b>48.8</b>	<b>48.4</b>
14	42.6	42.6	41.6	44.4
15	<b>48.4</b>	<b>59.1</b>	<b>64.4</b>	<b>65.0</b>
16	<b>58.4</b>	<b>46.9</b>	40.1	36.6
17	39.1	<b>50.8</b>	<b>54.3</b>	<b>53.0</b>
18	<b>53.2</b>	41.9	34.6	37.2
19	36.3	36.7	38.3	38.7
20	38.6	40.3	38.5	35.7



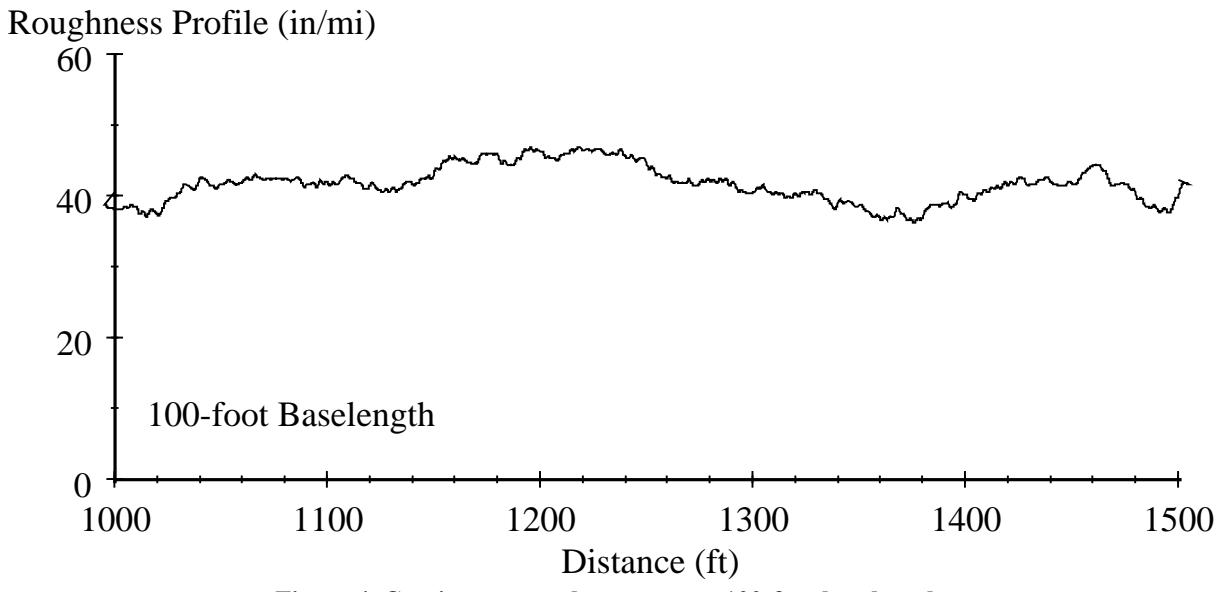
**Figure 1. Ride quality values divided between segments.**



**Figure 2. HRI filter sample output.**



**Figure 3. HRI filter, rectified sample output.**



**Figure 4. Continuous roughness report, 100-foot baselength.**

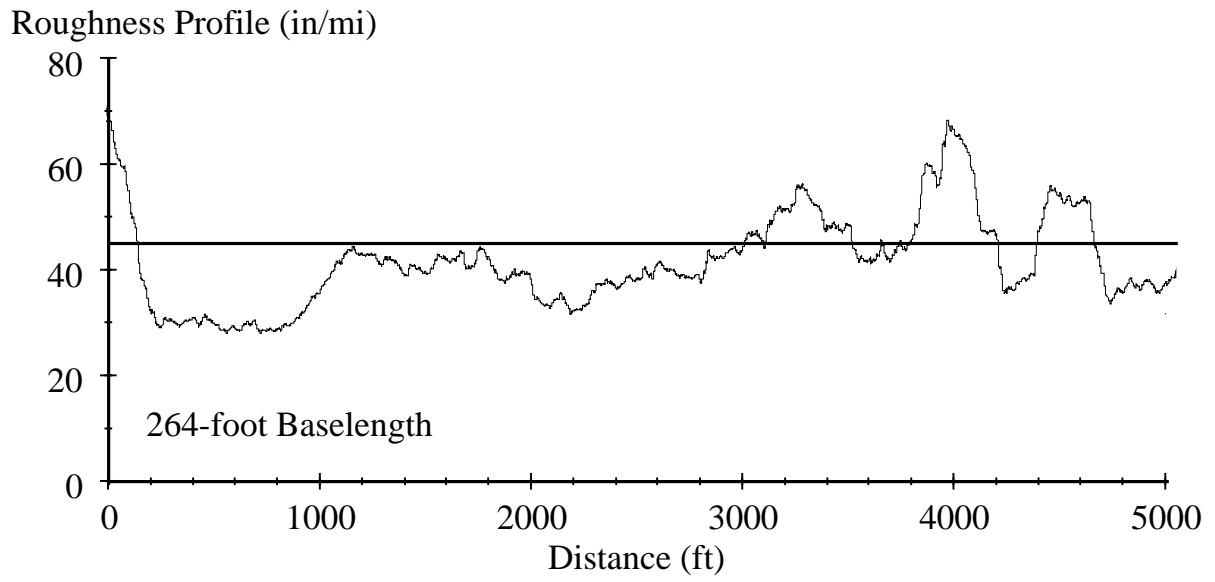


Figure 5. Continuous roughness report, 264-foot baselength.

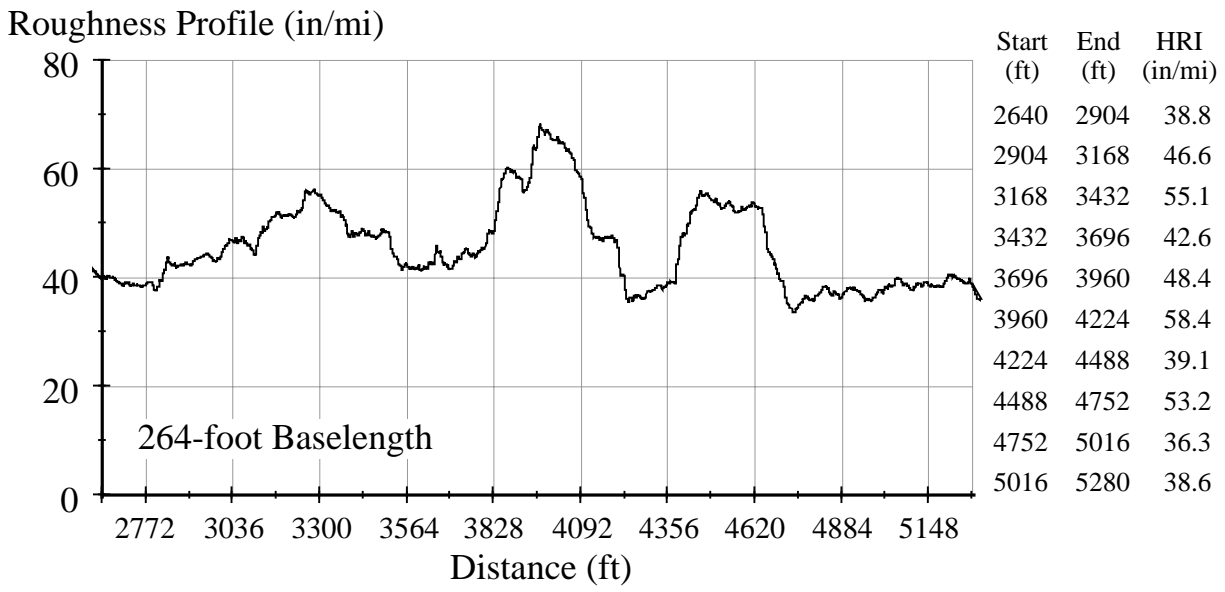
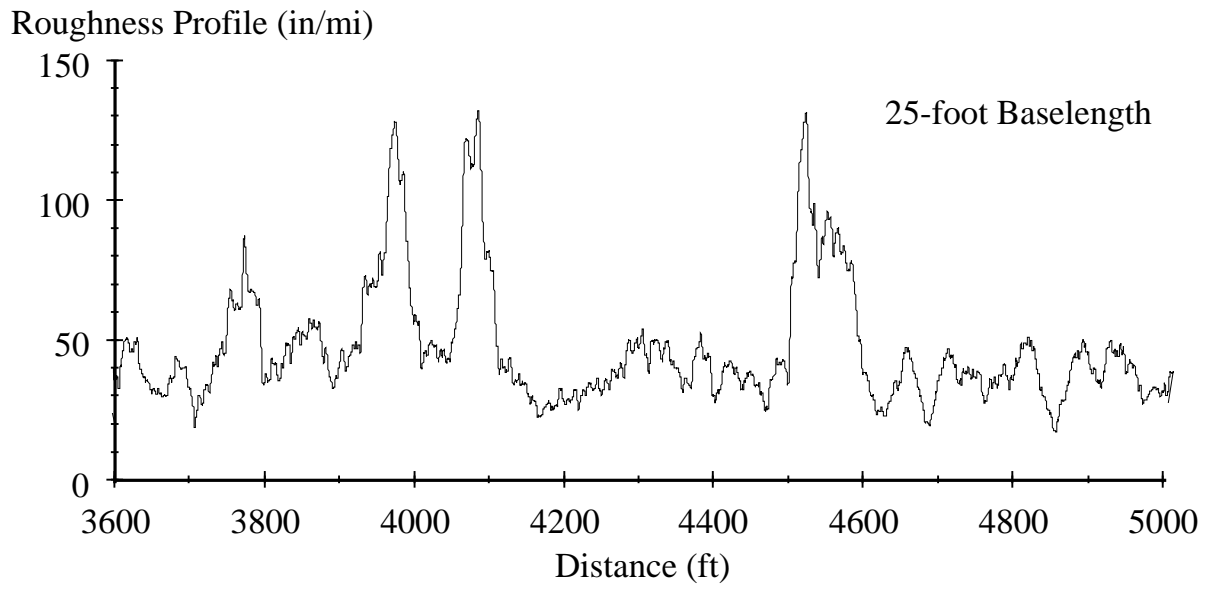
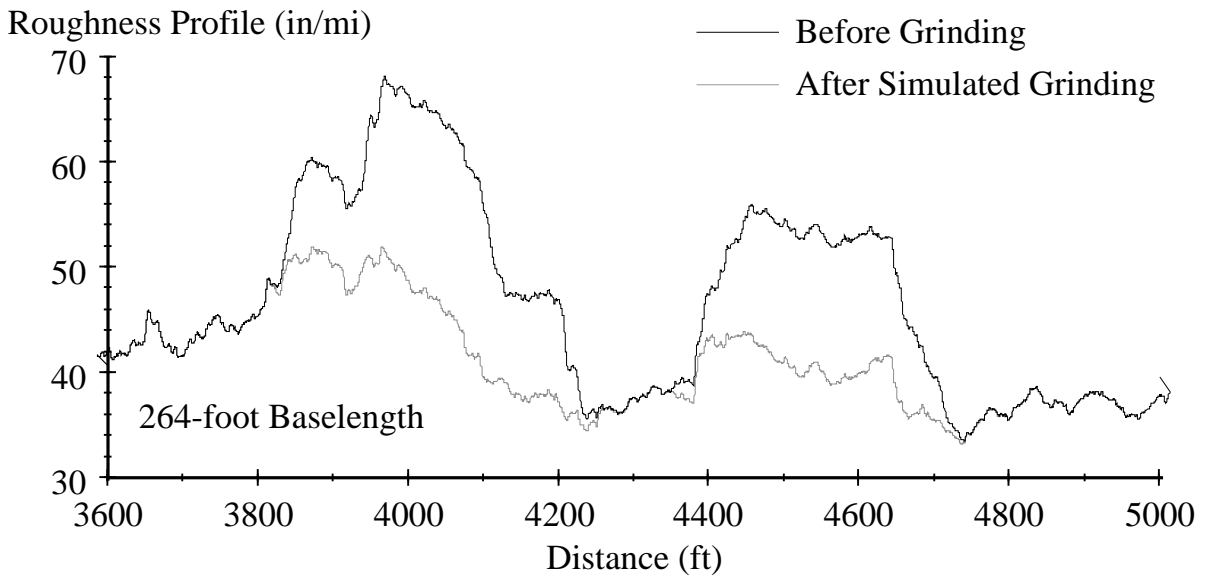


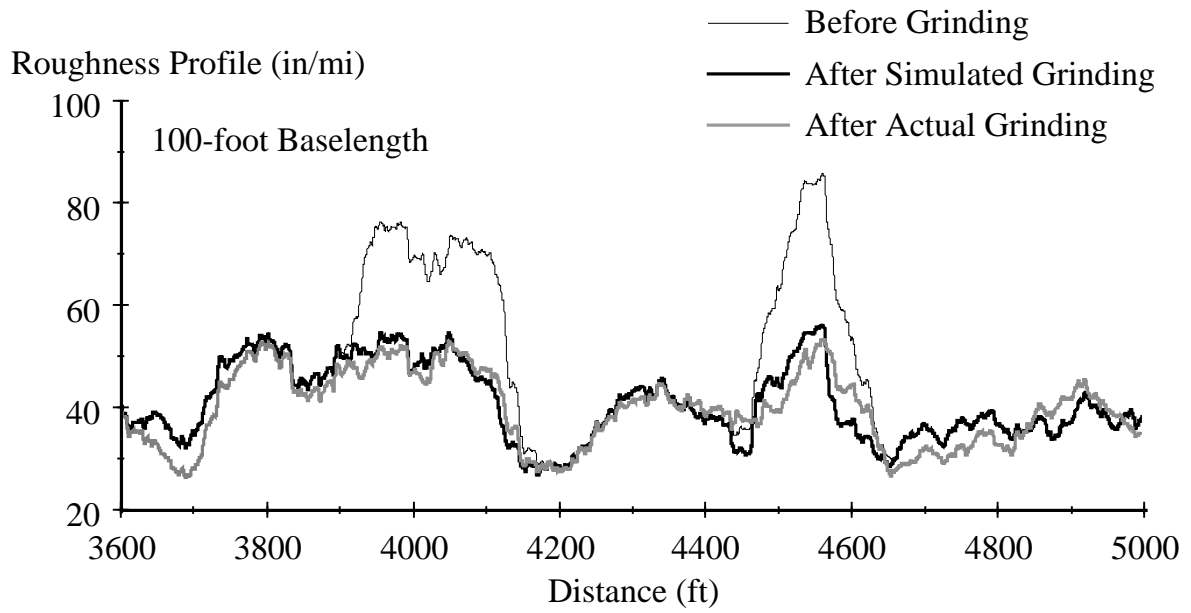
Figure 6. Comparison of continuous and fixed interval reporting.



**Figure 7. Continuous roughness report, 25-foot baselength.**



**Figure 8. Simulated grinding.**



**Figure 9. Validation of simulated grinding.**