



STATE OF CALIFORNIA
DEPARTMENT of TRANSPORTATION

**DIVISION OF
ENGINEERING SERVICES**

**MATERIALS ENGINEERING
AND TESTING SERVICES**

**OFFICE OF RIGID PAVEMENT
AND STRUCTURAL CONCRETE**

**5900 Folsom Boulevard
Sacramento, California 95819**



**THE EFFECTIVENESS OF DIAMOND GRINDING
CONCRETE PAVEMENTS IN CALIFORNIA**

May 2005

REPORT ON THE EFFECTIVENESS OF DIAMOND GRINDING CONCRETE PAVEMENTS IN CALIFORNIA

This report does not constitute a standard, specification, or regulation. The Caltrans Office of Rigid Pavement and Structural Concrete and their consultants, Applied Research Associates, Inc., are responsible for the accuracy of the information and data presented in this report.

Report Prepared by.....Richard Stubstad
Michael Darter
Chetana Rao
Tom Pyle
Walid Tabet



RICHARD N. STUBSTAD, P.E.
Principal Engineer
Applied Research Associates – ERES Division



TOM PYLE, Chief
Office of Rigid Pavement and Structural Concrete
Materials Engineering and Testing Services

ACKNOWLEDGEMENTS

The Office of Rigid Pavement and Structural Concrete would like to express their gratitude to the following for their participation, assistance, and support:

APPLIED RESEARCH ASSOCIATES, INC. – ERES CONSULTANTS DIVISION

**Ventura, CA Office
Sacramento, CA Office
Champaign, IL Office**

HEADQUARTERS

Materials Engineering and Testing Services

**District 4
District 5
District 6
District 7
District 8
District 11
District 12**

OFFICE OF ROADWAY REHABILITATION, DEPARTMENT OF MAINTENANCE

Caltrans Headquarters – Sacramento, CA

WESTERN STATES CHAPTER – AMERICAN CONCRETE PAVEMENT ASSOCIATION

Newport Beach, CA

Cover Photo: Courtesy of Western States Chapter – American Concrete Paving Association

TABLE OF CONTENTS

EXECUTIVE SUMMARY	1
INTRODUCTION.....	3
EXPERIENCE OF OTHER STATES.....	3
THE CALTRANS PMS DATABASE.....	5
RIDE SCORE IMPROVEMENT DUE TO GRINDING	8
LONGEVITY OF CALIFORNIA GRINDING PROJECTS	9
OTHER BENEFITS OF DIAMOND GRINDING	12
CRITERIA FOR USING GRINDING AS A REHABILITATION	
TECHNIQUE	14
APPENDIX A	17-32
POINTS OF CONTACT	BACK PAGE

LIST OF FIGURES

FIGURE 1 – SURVIVAL CURVES FOR 76 NATIONWIDE DIAMOND GROUND PAVEMENTS	4
FIGURE 2 – MEASURED IRI VALUES AFTER GRINDING A SECTION OF I-710 IN 1997	6
FIGURE 3 – MEASURED IRI VALUES BEFORE AND AFTER GRINDING A SECTION OF I-5 IN 2000.....	7
FIGURE 4 – IMPROVEMENT IN RIDE QUALITY DUE TO DIAMOND GRINDING FROM 26 CALIFORNIA PROJECTS	8
FIGURE 5 – CHANGE IN THE RATIO OF IRI OVER TIME AS A FUNCTION OF THE INITIAL IRI AFTER GRINDING	10
FIGURE 6 – RELIABILITY LEVELS FOR THE EXPECTED SURVIVABILITY OF CALIFORNIA DIAMOND GRINDING PROJECTS	11

LIST OF TABLES

TABLE 1 – TYPICAL NOISE LEVELS OF ARIZONA PCCP	12
TABLE 2 – CPX TEST RESULTS FOR VARIOUS DIAMOND GROUND SURFACES (DBA).....	13
TABLE 3 – FRICTION VALUES AND PERCENT CHANGES DUE TO DIAMOND GRINDING	14

EXECUTIVE SUMMARY

Diamond grinding has been used in California since 1965 to provide a smooth surface on old Portland Cement Concrete (PCC) pavement. Given the large amount of PCC pavement needing rehabilitation today, increased knowledge of its effectiveness is very much needed. The present study is intended to better quantify the expected longevity or “survival” of a diamond ground PCC pavement, and its overall effectiveness under California conditions and construction practices.

Nationwide, studies have shown that the average longevity of a diamond ground project is around 14 years, or about 11 years at an 80% certainty (reliability) level. The 76 test sections involved in a recent nationwide study included freeze-thaw zones and other adverse conditions not normally encountered in California. It was expected that the dry-no freeze zone of California would yield even better results, due to the milder climate.

For the present study, data were obtained from several projects on the performance of diamond grinding in California. Based on this historical data, Figure ES-1, below, shows the average expected longevity of diamond ground projects in California, along with the corresponding curves for the 70th, 80th and 90th percentile reliability levels.

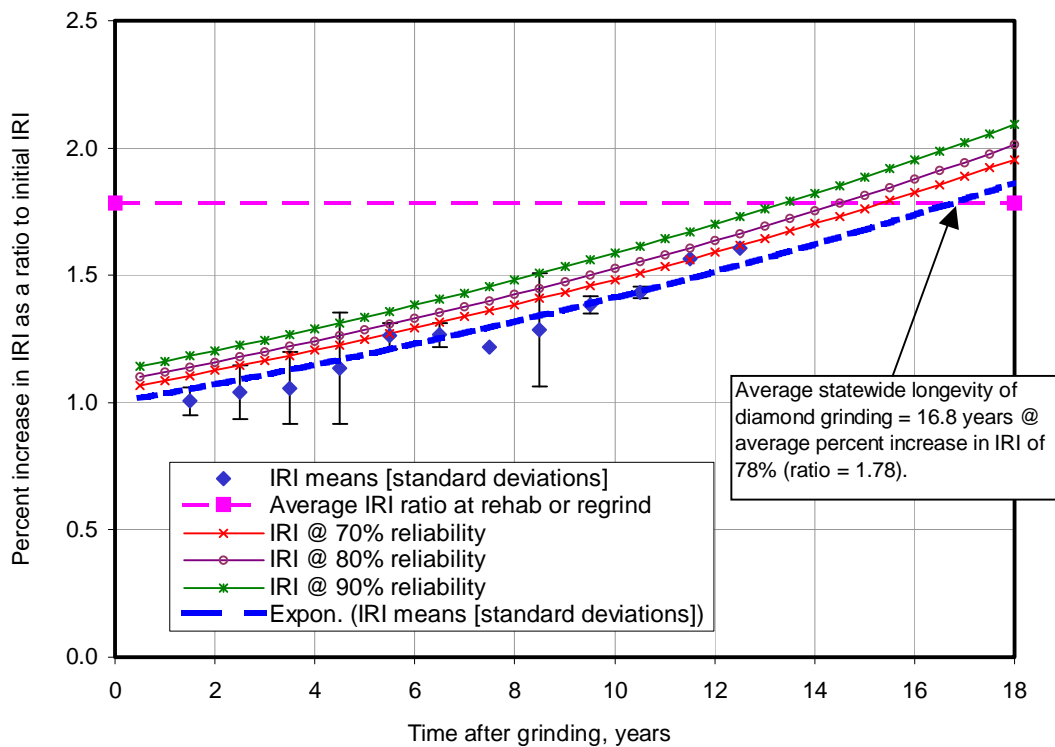


Figure ES-1 – Expected survivability of diamond ground PCC pavements in California

In the preceding figure, the expected percent increase in the International Roughness Index (IRI) is expressed as the average IRI for 26 statewide diamond ground projects within one year after grinding divided into the average expected IRI for the same 26 projects at the end of their design lives using a 78% increase over this entire period of time. In other words, if the IRI just after grinding on any given project is, say, 100 in/mi, then (on average) it is expected to be 178 in/mi at the end of its design life when further rehabilitation is likely to be applied. This second rehabilitation may be another grinding project (up to three successive grinds have been performed on Route 10 in San Bernardino County) or any other form of rehabilitation.

The upshot of Figure ES-1 is that, on average, a diamond ground PCC pavement should maintain its smoothness for between 16 and 17 years in California, or better than 14 years if, for example, an 80th percentile reliability level is applied. Compared to the corresponding national average values of 14 and 11 years, respectively, these results are quite reasonable, since the climatic conditions in California are comparatively favorable for longer lasting PCC pavement performance.

The above results have been achieved by Caltrans without a formal project selection and design procedure for a grinding project. Currently, there are no objective criteria (such as maximum joint faulting, maximum percent cracked slabs, or a maximum roughness value) that could be used as a trigger for the selection of any given concrete pavement as a candidate for diamond grinding. Nevertheless, many factors are currently considered and the process is working reasonably well, especially considering the excellent results obtained to-date.

Currently, the specification for pavement smoothness after grinding is based on a California Profilograph measurement using California Test Method #526, which is not particularly stringent. Even though it is certainly possible for contractors to achieve a very smooth surface as a result of grinding (combined with slab leveling for major settlements or properly constructed dowel bar retrofits, if needed), this capability has not yet been utilized to its fullest.

Two other major advantages to diamond grinding are also achieved: improved texturing and skid resistance, and reduced tire/pavement interface noise levels. Based on current experience, it is possible to diamond grind candidate concrete pavements up to three times before major reconstruction is needed. This could extend the service life of a new concrete pavement to, say, twice its normal design life by adding only these two or three diamond grinding projects and continuing normal routine maintenance—none of which should disrupt the traffic flow during “peak” hours.

THE EFFECTIVENESS OF DIAMOND GRINDING CONCRETE PAVEMENTS IN CALIFORNIA

INTRODUCTION

With the rising costs of both pavement construction and user delays during construction or rehabilitation, more attention is being given to effective and simpler measures of pavement rehabilitation that can be carried out on our California freeway system while minimizing the impact of rehabilitation on road users. One rehabilitation alternative that is now commanding nationwide attention on concrete pavements is diamond grinding. In fact, the technique was first used in 1965 on a 19-year old section of I-10 in Southern California to eliminate excessive faulting. This pavement was again ground in 1984 and again in 1997 and is still amazingly carrying heavy traffic today—nearly 60 years after it was first constructed!

Through diamond grinding, it is possible to extend the service life of many of our aging concrete pavements at a relatively low cost and with minimal disruption to traffic flow. In the past, many states have employed diamond grinding as a viable rehabilitation technique with excellent results. The question is: Exactly *how* effective is diamond grinding, as opposed to other rehabilitation alternatives, and how much does it cost relative to other alternatives?

In this report, it will be shown that diamond grinding is in fact a viable and cost-effective rehabilitation measure when properly applied. Diamond grinding not only extends the service life of a concrete pavement, but it also reduces tire-pavement interface noise and improves texture and skid resistance. Because the pavement is much smoother after grinding, highway user costs are also reduced through improved fuel efficiency and lower vehicle maintenance costs.

EXPERIENCE OF OTHER STATES

A 1999 TRB paper by Rao, Yu, Khazanovich and Darter entitled “Longevity of Diamond Ground Concrete Pavements” is a thorough study on many nationwide grinding projects available through 1999. This study can be summarized as follows:

- 1) The study included 76 projects from 9 states, including California and Arizona but also including pavements in the more hostile climatic zones, such as freeze-thaw areas where PCC material durability issues may have contributed to a shorter life cycle.
- 2) The performance of diamond ground PCC pavements differed somewhat, depending on the amount of CPR performed (e.g., dowel retrofit, slab repairs) and the extent of structural and environmental damage prior to grinding.
- 3) 50% of the study’s diamond ground sections lasted some 14 years or more prior to a second regrinding or other rehab. These sections carried 13.5 million heavy axles (ESALs) on average. Similarly, 80% of the sections lasted at least 11

years. Twenty-one percent of the projects carried more than 20 million ESALs. Accordingly, the performance of diamond ground sections located in the dry-no freeze zone of California is better than the nationwide findings indicate.

- 4) Some PCC pavements have been reground up to three times without a significant loss in structural integrity (one of these being the I-10 in Southern California). Many of these pavements are fairly thin by today's standards, less than 250-mm (10-in). Thicker slabs—especially with dowels—should perform even better after regrinding.
- 5) In all cases, the texture and skid resistance of ground PCC surfaces improves considerably, followed by a gradual decline over the succeeding 8-15 years of longevity after a grinding project is carried out, depending on the hardness of the aggregate and spacing of the saw blades.
- 6) Noise characteristics were not measured or considered in the nationwide study.

Survival curves for the 76 test sections included in the nationwide diamond grinding study report are reproduced in Figure 1.

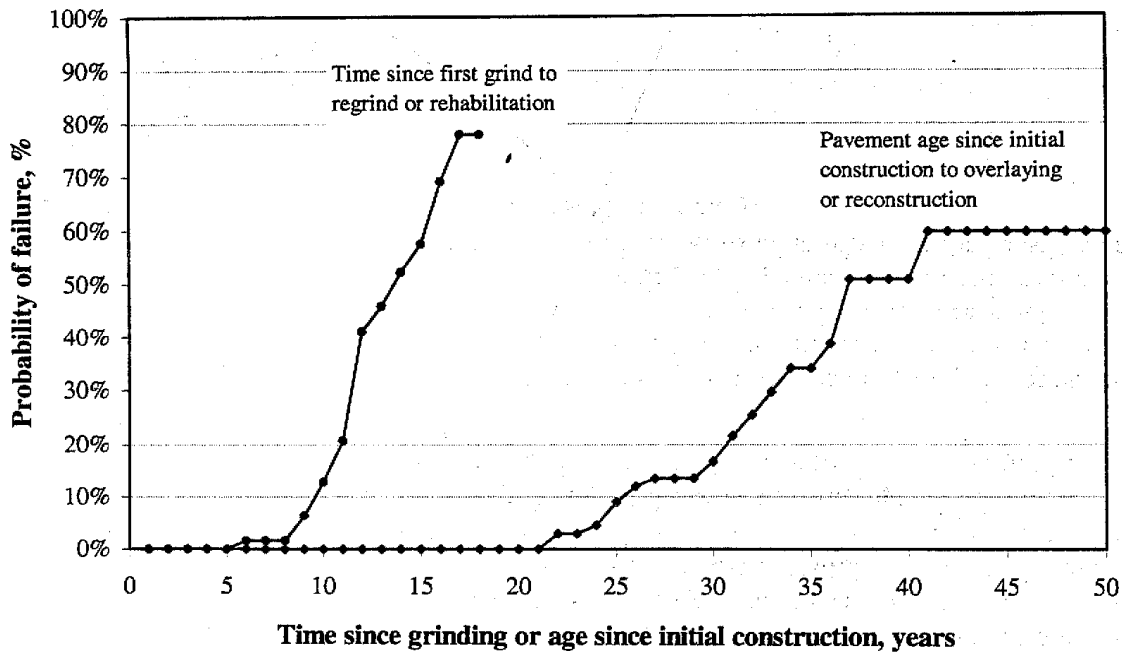


Figure 1 – Survival curves for 76 nationwide diamond ground pavements

Note that the left-hand curve represents the length of time a diamond ground pavement lasted until regrind or other rehabilitation was needed, in terms of probability of failure. In other words, since 50% of the study sections lasted 14 years or more, then the nationwide average longevity of any arbitrary diamond ground section is approximately 14 years. Similarly, if one would like to know the design life of a diamond ground section at a 90% probability of survival, then this value is read across the Y-axis at a probability of failure of 10%, thus arriving at a 10-year design life.

It is also interesting to note from Figure 1 that the nationwide average life of a newly constructed concrete pavement to rehabilitation or reconstruction (with one intermediate grinding project) is between 35 and 40 years, an excellent track record that is exceeded by over three-quarters of California's rigid pavements.

To confirm the above nationwide findings and adjust these findings to California conditions specifically, a review of the Caltrans Pavement Management System database was carried out.

THE CALTRANS PMS DATABASE

A list of most of the recorded diamond ground sections statewide, meaning those associated with and included in the current Caltrans PMS database, was obtained from the Office of Pavement Management at Caltrans Headquarters in Sacramento. This database primarily consists of concrete sections ground after 1997. In addition, a handful of older diamond ground sections were also included. The Office of Pavement Management identified more than 60 diamond ground sections statewide in California.

From the provided list, 30 sections were selected for further analysis, mainly based on the apparent use in these cases of diamond grinding as the primary rehabilitation technique, with only minimal (secondary) CPR activities or adjacent asphalt overlays, etc., in some areas. This was done in order to focus the present study on the effect of diamond grinding as a primary rehabilitation option when it is not used in combination with other rehabilitation techniques in the same project.

The object was to determine, if possible, how much joint (step) faulting or other measured distresses triggered the action of diamond grinding. However, the Caltrans PMS does not track joint faulting specifically. Rather, it only mentions faulting as a "seat of the pants" noticeable defect as the smoothness survey vehicle is driving over a section. Accordingly, if faulting is mentioned as a distress, its magnitude is unknown.

On the other hand, the International Roughness Index (IRI) has been carefully monitored by Caltrans since 1998 using a high-speed profiler. Since faulting will strongly affect a section's IRI, this parameter can be used as a surrogate to ascertain the short- and long-term effects of diamond grinding.

An example of a diamond ground section along the I-710 freeway in District 7, Los Angeles County, is shown in Figure 2.

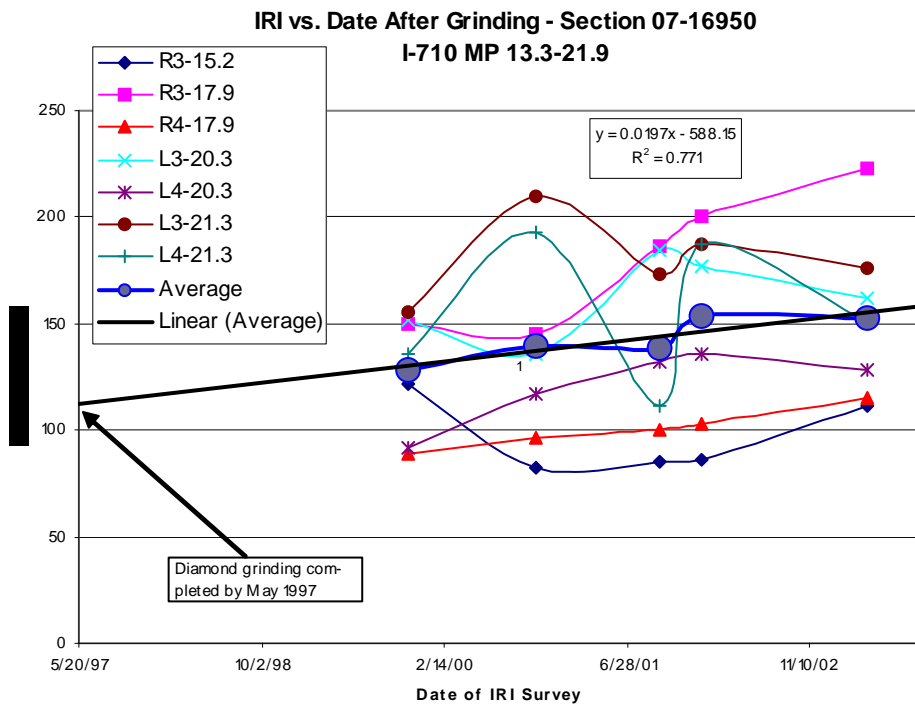


Figure 2 – Measured IRI values after grinding a section of I-710 in 1997

This section—Caltrans Project Number 07-16950 shown in Figure 2—was diamond ground in May of 1997 (lanes and starting mileposts noted in the legend). The reported date of completion is indicated by the left-hand date, which forms the Y-axis. No direct IRI values were available prior to this date. However, for several of the approx. 1-mile lane segments of Project No. 07-16950, IRI values were available for 5 consecutive years (except 1998 when no IRI data were present in the database).

Although there is obviously a great deal of scatter shown along the individual lane-segments shown in the figure, the overall IRI for this project has not changed much during the reported five years of profile measurements. On average, in 1999 the IRI was approximately 130 in/mi, while in 2003 it was evidently around 150 in/mi. If one extrapolates back to the year of grinding, the after-ground average IRI was likely between 110 and 120 in/mi, depending on whether a linear or exponential extrapolation function is utilized.

In other words, through extrapolation and using a terminal IRI of, say, 200 in/mi, this section should survive a total of some 11-13 years from the date of grinding before requiring further grinding or other rehabilitation. It should be added as well that this section is under very high traffic loadings.

Another extremely high-trafficked diamond ground section of freeway from the I-5 in District 7, also in Los Angeles County, is shown in Figure 3.

**IRI Tracking - Before & After Grinding - Section 07-17530
I-5 NB: MP 73.6-88.6**

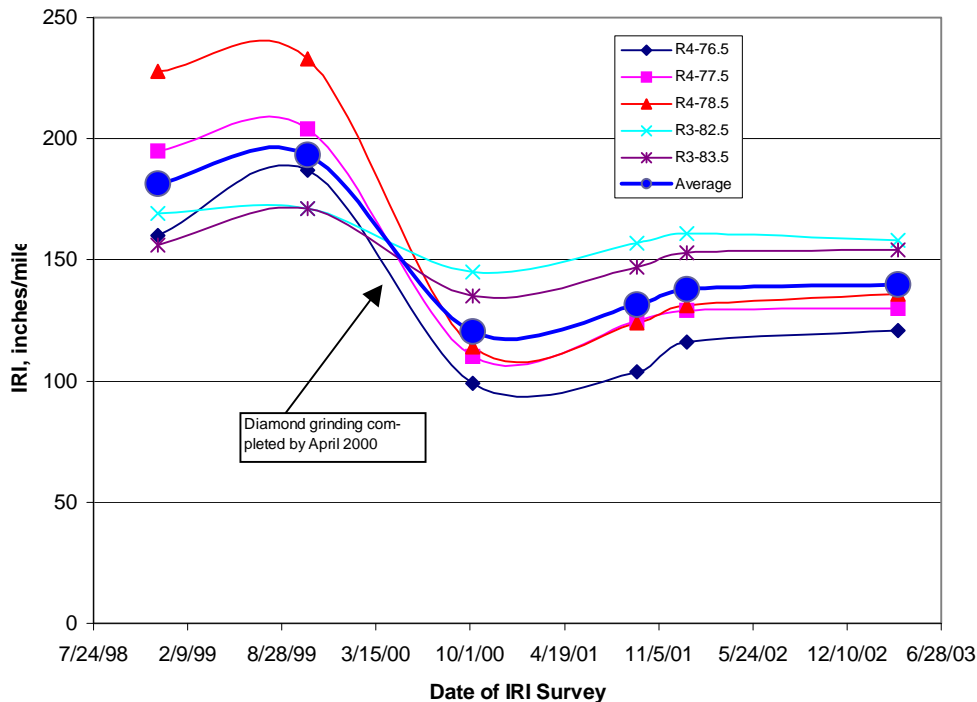


Figure 3 – Measured IRI values before and after grinding a section of I-5 in 2000

In the case of Section 07-17530 as shown in Figure 3, since the pavement was ground around April of 2000, it was possible to ascertain both the before and after IRI levels for some of the approximately 1-mile lane segments that were involved in the grinding project (lanes and starting mileposts noted in the legend).

The average pre-grind IRI was evidently around 190 in/mi. After grinding, the average IRI was reduced to about 120 in/mi, which has in turn increased through 2003 to around 140 in/mi, with a leveling trend possibly indicated over the past 2-3 years. If a “terminal” IRI of 180-200 in/mi before any further major rehab is assumed, this section may well survive some 10 years or more, depending on how joint faulting and slab cracking develop which may cause the IRI-values to increase as time passes.

The above examples are but two of the 30 statewide diamond grinding projects analyzed, 26 of which were usable for a further regression analysis of the effect of diamond grinding in California. Graphs of all 30 individual projects are included in *Appendix A*.

Based on all sections analyzed, it would appear that most of Caltrans’ diamond ground sections have an acceptable but not an excellent level of smoothness after grinding, expressed in IRI smoothness units using the Caltrans high-speed profiler. In general, one would hope that diamond grinding would typically result in IRI values less than 100 in/mi. Some long wavelength profile settlements or heaves are impossible to remove through grinding such a thin layer from the surface of the PCC. This level is dependent in

part on any major settlements or heaves that may exist along the project and to what extent they are leveled out using slab leveling or other techniques. It is also possible that one high-speed profiler will not exactly match another manufacturer's device, for example due to laser spot size or longitudinal sampling distance.

The two above examples indicate an initial IRI of somewhat over 100 in/mi, which is certainly acceptable—especially if the rate of increase in IRI post-grinding is slow and gradual. The average statewide post-grind IRI was 94 in/mi, while the average pre-grind IRI was 165 in/mi.

RIDE SCORE IMPROVEMENT DUE TO GRINDING

All IRI data from the selected grinding projects were downloaded from the Caltrans PMS database and put into spreadsheet format for further analysis. Two essential quantities were sought: What is the average improvement in IRI due to any given project, and what is the expected life cycle (number of years to next rehabilitation) of any given grinding project?

The average improvement in IRI due to diamond grinding can be quantified as the ratio between the average pre-grind IRI and the average post-grind IRI. Figure 4 shows the ratio of pre-grind IRI to post-grind IRI as a function of IRI prior to grinding based on 26 statewide projects where both pre- and post-grind IRIs were available.

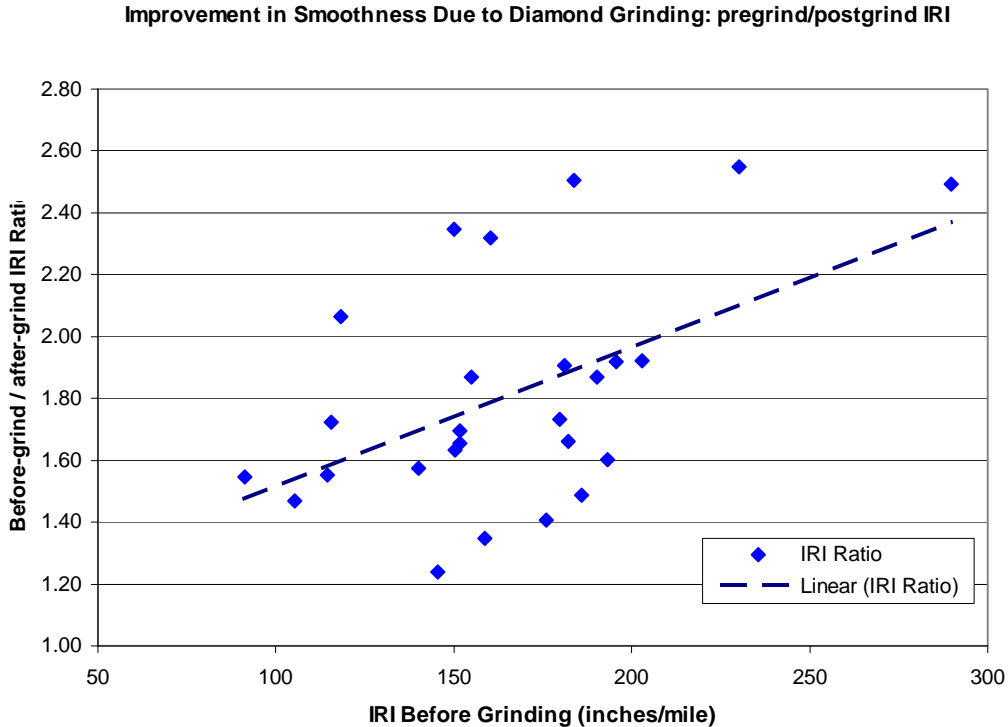


Figure 4 – Improvement in ride quality due to diamond grinding from 26 California projects

In Figure 4 it can be seen that there is a tendency for the pre- vs. post-grind IRI ratio to increase as a function of the magnitude of the pre-grind IRI. In other words, if there is an exceptionally rough, and most likely faulted, JCP pavement, the immediate improvement through grinding tends to be greater than if the pre-grind IRI is relatively smooth and, probably, less faulted.

However it can also be seen from Figure 4 that there is a great deal of scatter in the data, indicating that the improvement in IRI through grinding may well be a function of the quality of the work carried out by the grinding contractor or other site-specific factors such as excessive foundation settlements or heaves from swelling soils. In fact, the correlation R-squared for the best-fit line in Figure 4 is only 0.26. It was therefore deemed more appropriate to work with an average improvement in terms of IRI when evaluating the overall effectiveness of JCP grinding in California. The average pre- vs. post-grind IRI ratio for these 26 projects was 1.78, which was also used in the overall survival analysis as outlined in the following sections.

LONGEVITY OF CALIFORNIA GRINDING PROJECTS

Compared to the national average of 14 years (see Figure 1), the important question for Caltrans is: How long is the average grinding project expected to last (i.e. until further rehabilitation is needed) in California specifically?

Using all available data, the average improvement in IRI from the year of grinding onwards was calculated for the entire database. Although most of the data were from projects carried out within the last five years, a few projects (5 out of 26) were older, ranging up to a project carried out 12½ years ago. The improvement in IRI for the year of grinding was assumed to be 1, of course (no change in IRI was assumed for the year the grinding project was carried out), followed by a gradual increase in IRI through subsequent years.

A plot of these data, showing both a linear and an exponential regression curve, is shown in Figure 5.

The IRI before a grinding operation was calculated based on the ratio of the average IRI prior to the first grind divided by the average IRI after grinding. These results showed that the average IRI just prior to grinding was 1.7835 times the IRI soon after grinding. For lack of a better terminal criterion to indicate when further rehabilitation will be needed, it was assumed that the average IRI before the next rehabilitation (including a grinding option, if applicable) would be approximately the same as the IRI was before the previous rehabilitation (which was diamond grinding for all examples used in the analysis).

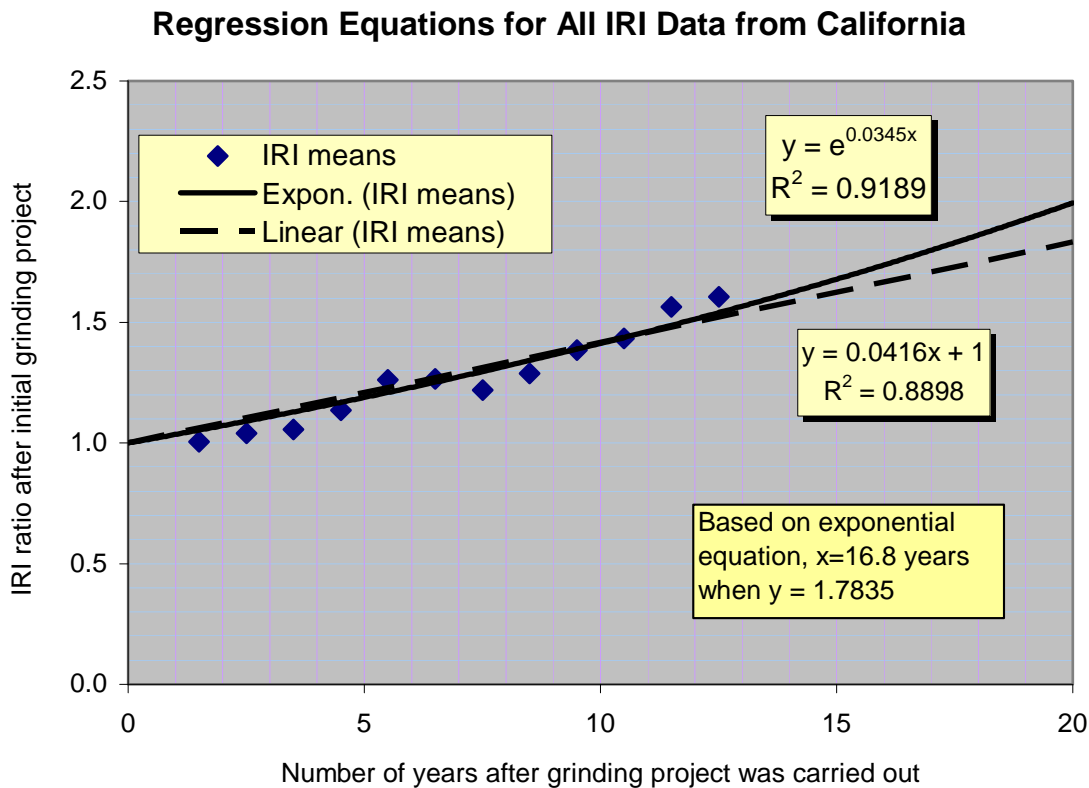


Figure 5 – Change in the ratio of IRI over time as a function of the initial IRI after grinding

Figure 5 reveals that the trend of the increase in IRI is probably exponential as opposed to linear based on the R-squared values of both regressions (0.92 for exponential and 0.89 for linear). The most conservative of the two regression equations shown in Figure 5 is the exponential relationship, where the average diamond ground PCC pavement in California will last 16.8 years (i.e. when the IRI ratio equals 1.7835). This criteria utilizes the average percentage change in IRI due to grinding as an ad-hoc, “terminal” increase in IRI until further rehabilitation is needed after first grind.

If one instead had used the linear regression shown in Figure 5, the expected life of the average California diamond ground project would increase to nearly 19 years. While this is possible, it is unlikely that the rate of increase in IRI towards the end of the life of a diamond ground project would be the same as it was towards the beginning of its design life, as a linear extrapolation would indicate.

Therefore, to be conservative, a statewide average design life of 16 to 17 years should be used, assuming Caltrans continues to use the same criteria to “trigger” an actual grinding project as previously. It is to be noted that the data available for the analysis only spanned over 12½ years and therefore includes an extrapolation of the model beyond the data range to predict the number of years to achieve an average terminal IRI ratio of 1.78.

Another important consideration is: What certainty or reliability levels are associated with the above 16.8-year average life cycle prediction?

Since the data primarily consisted of relatively recent projects, it was not possible to calculate reliable standard deviations or coefficients of variation for all seventeen years of average expected pavement life. In the event, only 12 years of annual data were available, with the greatest number of observations occurring during the first four or five years after grinding.

Accordingly, it was assumed that the weighted average standard deviation (weighted by the number of observations for any given year after grinding) was valid as an overall average standard deviation. The influence of the standard deviation in the confidence level of the prediction was incorporated by means of a reliability factor. Suitable adjustments are made to the mean predicted IRI ratio, i.e. the IRI ratios are “inflated” to correspond to the predictions at different reliability levels. This adjustment at different ages is based on the weighted average standard deviation.

Four different design life curves are shown in Figure 6, representing the average life of ground JCP pavements as was shown in Figure 5, along with the 70th, 80th, and 90th percentile reliability levels associated with a wide variety of California statewide projects.

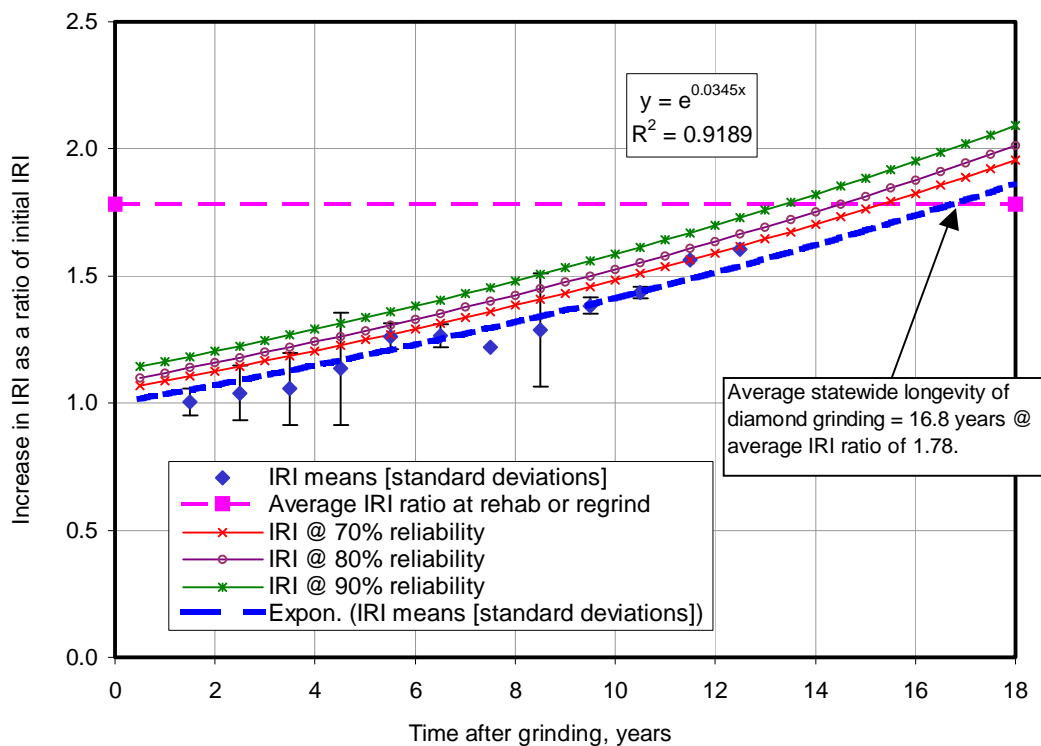


Figure 6 – Reliability levels for the expected survivability of California diamond grinding projects

Figure 6 reveals that even at a very conservative certainty level of 90% (meaning 9 out of 10 diamond grinding projects should last at least that long), the design life in California is expected to be around 13½ years. This figure is nearly the same as the national average of 14 years, which is by definition based on a 50% certainty level.

Please note however that the analysis conducted did not consider the many other effects that may confound the accumulation of pavement roughness. For example, traffic load (very high in most of the projects selected), extent of faulting, slab cracking, soil type, drainage, properly placed dowel bars, and workmanship (the overall quality of grinding project) were not considered as independent causal factors. Due to the lack of data and the limited number of projects available for analysis, it was not possible to consider more than one indicator (IRI) to arrive at the above conclusions. Accordingly, the results of this study represent an overall picture of many causal factors.

OTHER BENEFITS OF DIAMOND GRINDING

In the foregoing, it was shown that diamond grinding of jointed PCC pavement results in a long service life in California when it is properly applied under the right conditions. The actual lifespan of such a project is expected to compare well with most other rehabilitation options, probably better than most. From a cost standpoint, the cost of diamond grinding is typically about one-half that of a conventional HMA overlay. Thus, when applied under appropriate existing pavement conditions (e.g., no highly progressive structural cracking), diamond grinding is a very cost-effective rehabilitation technique for PCC pavements in California.

There are two other potential benefits to diamond grinding that were not measured or recorded in the Caltrans PMS database. One of these benefits is to achieve an appreciable noise reduction in tire-pavement interface sound emissions, while the other is to improve the safety of the freeway by virtue of an immediate and long-lasting increase in the skid resistance of a diamond ground concrete surface.

It is commonly experienced that diamond ground pavements are much quieter after grinding than before grinding. To quantify this well-known phenomenon, the Arizona DOT (ADOT) ran a series of grinding and texturing tests along the SR-202 Freeway in the Phoenix area. The test areas, with the grinder using differing blade spacings and grinder configurations for several adjacent test areas, were called “whisper grind” sections, since the primary objective of ADOT’s study was not smoothness but rather noise mitigation. A summary table from ADOT’s Construction Report, “SR202 PCCP Whisper Grinding Test Sections” (Scofield, October 2003) is reproduced in Table 1.

Table 1 – Typical noise levels of Arizona PCCP

Surface Texture Type	CPX Noise Level Measured at Tire (dBA)
Whisper Grind Test Section – Test Area #4	95.5 (As-Constructed)
ADOT Uniform Longitudinal Tined (3/4”)	99.1
ADOT Uniform Transverse Tined (3/4”)	102.5

As can be seen in Table 1, compared to other common PCCP surface textures of transverse tined or longitudinal tined, diamond ground surfaces are considerably quieter. For new construction, Caltrans typically utilizes uniform longitudinal tining—which tested out in Arizona at around 99 dBA using the close proximity method (CPX) of noise measurement. As can be seen, considerable improvement is obtained, with noise levels as low as 95.5 dBA attainable through whisper grinding.

As mentioned, several different grinder configurations were included in the experimental design of the whisper grind test sections. Table 2 shows the results to-date of all CPX tests conducted on two different dates after grinding.

Table 2 – CPX test results for various diamond ground surfaces (dBA)

Test Area	6/6/03	6/6/03	6/6/03	9/8/03	9/8/03	9/8/03
	Lane 1	Lane 2	Lane 3	Lane 1	Lane 2	Lane 3
1	96.6	96.4	NA	NA	97.5	NA
2	NA	NA	98.1	NA	NA	98.0
3	98.5	95.6	NA	NA	97.0	NA
4	NA	NA	95.5	NA	NA	95.5

There was some variability between the different test areas as a function of the configuration of the grinder. The lowest CPX noise level recorded was 95.5 dBA in Test Area 4. Most noise levels were less than 98 dBA, still somewhat better than newly constructed, longitudinally tined surface textures (which were ~99 dBA – see Table 1).

In terms of improved texturing and skid resistance, many documented studies have shown considerable improvement in the skid resistance of diamond ground concrete pavements. The degree of improvement naturally depends on the skid resistance of the facility before grinding, from new construction (in the case of California, with longitudinal tining) to older, polished surfaces that may have lost much of their macrotexture. The hardness of the aggregate in the PCC is also critical to longevity of diamond ground surfaces with respect to skid resistance. Softer aggregates, such as limestone, are more prone to polishing, causing a loss of texture depth on diamond ground surfaces. Most aggregates in California are much harder and thus maintain their texture over longer time periods.

The same ADOT study for noise mitigation mentioned above also monitored the changes in skid resistance for the same whisper grind test sections. Table 3 depicts the before and after skid numbers, together with the percent improvements, due to diamond grinding with various blade spacings and grinder configurations. The percent improvement for any given test section due to grinding is shown in parentheses.

Table 3 – Friction values and percent changes due to diamond grinding

Test Area	Before Grinding	Before Grinding	Before Grinding	After Grinding	After Grinding	After Grinding
	Lane 1	Lane 2	Lane 3	Lane 1	Lane 2	Lane 3
1	0.52	0.55	NA	0.65 (25%)	0.63 (15%)	NA
2	NA	NA	0.56	NA	NA	0.66 (18%)
3	0.49	0.51	NA	0.69 (41%)	0.69 (35%)	NA
4	NA	NA	0.53	NA	NA	0.67 (26%)

The pavements shown in Tables 1, 2 and 3 were all new (with longitudinal tining) before grinding. Therefore, the improvement in skid resistance due to diamond grinding is likely to be even better for older PCC pavements with, for example, polished and exposed aggregate.

As indicated in Table 3, the increase in friction values varied between 15% and 41%, with an overall average improvement of 27%.

CRITERIA FOR USING GRINDING AS A REHABILITATION TECHNIQUE

Currently in California, the criteria for selecting diamond grinding for candidate projects to rehabilitate a JCP section in need of rehabilitation (while still structurally sound) are not formally defined.

Firstly, the pavement needs to be rough enough such that the pavement needs a smoother ride for the traveling public. Secondly, the cost of a grinding project to restore ride quality has to be within the District’s current budgetary means and this option should result in a lower life cycle cost than other effective alternatives.

Some considerations in setting the above criteria include:

- Currently, there are no objective criteria for what constitutes a “rough” pavement. It would be good if either an IRI level of roughness or a PI (from the California Profilograph), or a specific degree of joint (step) faulting was specified in order to qualify for a grinding project for the purpose of PCC pavement rehabilitation. If Caltrans eventually adopts the new Mechanistic-Empirical Design Guide, such input quantities will be required.
- One of the main reasons for diamond grinding—step faulting—is not currently measured or quantitatively recorded by the Caltrans PMS data collection system. If faulting is severe enough to be noticed by the high-speed profiler operator, it is

merely noted as “faulting” but it is not quantified. It may in fact be possible to quantify step faulting using the longitudinal pavement profile measured by the Caltrans or other high-speed profilers, by subtracting the vertical elevation just after a joint or crack from the elevation measured immediately before the same joint or crack.

- The speed of grinding operation is a function of aggregate hardness and the depth of removal. Whisper grinding operations therefore have a relatively smaller production time. Similarly, surface longevity is also a function of aggregate hardness and therefore the performance can vary across different projects.
- Until now, the longevity of a diamond ground project was not quantified so it was difficult to carry out a reasonable and objective life cycle cost/benefit analysis for the grinding alternative. Based on the present study, an average lifespan for a diamond ground project is between 16 and 17 years. If a given certainty or reliability level in lieu of an average value is required (e.g., an 80% probability that a given project will last a certain number of years), the probability curves in Figure 6 may be used, thus obtaining an effective design life of about 14 years at an 80% certainty level, for example.

Another potential shortcoming to the present practice is that the smoothness achieved after grinding is not always as good as could be achieved by most contractors, unless the project has significant settlements or heaves. Currently, IRI is measured both before and after grinding, while the grinding contract itself utilizes the California Profilograph with California Test Method #526. It may be useful to “tighten up” the current smoothness specification that contractors have to meet, or to change the spec for diamond grinding projects to an IRI-based one using a high-speed profiler. Additionally, if significant settlements exist, these could be leveled through slab jacking operations prior to grinding. If the load transfer efficiency is poor, dowel bar retrofits, if properly constructed, may help rectify this structural problem prior to grinding.

The use of a more stringent smoothness criteria, whether measured in terms of IRI from a high-speed profiler or the PI in terms of the California Profilograph, may well extend the design life of a diamond ground project even further than the present average of nearly 17 years, because the rate of increase in roughness is relatively constant from project to project, regardless of the starting or ending point as measured by IRI. For example, if an average IRI percentage improvement ratio of 2.0 instead of the assumed statewide average of 1.78 could be used, the average design life for a diamond ground project may result in a 20-plus year average survivability. Using an 80% reliability level, as another example, the corresponding figure for an average IRI ratio of 2.0 would be around 18 years (see Figure 6).

On the other hand, there are certain pavement distresses or conditions that should preclude the use of diamond grinding as a rehabilitation alternative. These include:

1. Lack of structural integrity (e.g., voids under joints from pumping, excessive slab cracking and progressive cracking over time).
2. Very poor load transfer at transverse joints as indicted by excessive faulting and voids.
3. Spalling or other damage due to ASR.
4. Freeze-thaw damage, including D-cracking.

5. Soft aggregates in the PCC slab, such as limestone, that are prone to polish (this may be overcome by widening the spacing of the grinding blades).

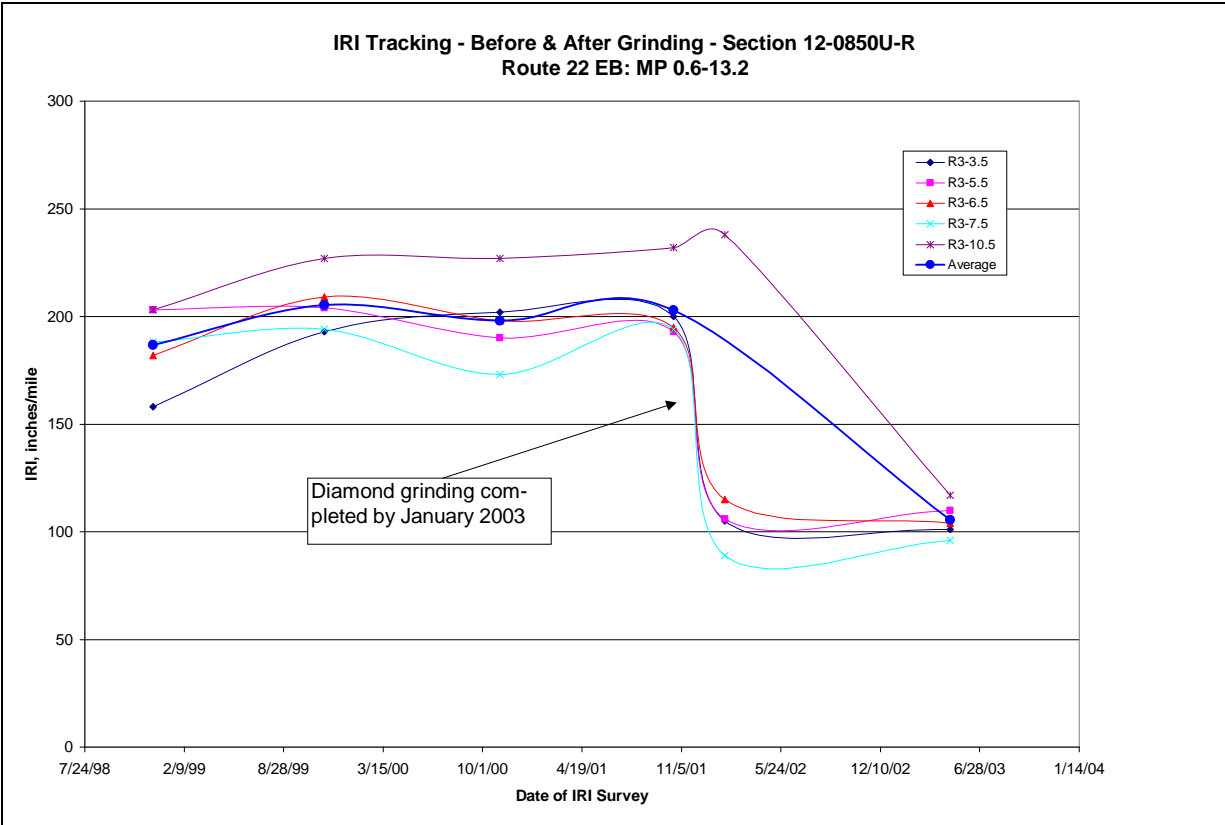
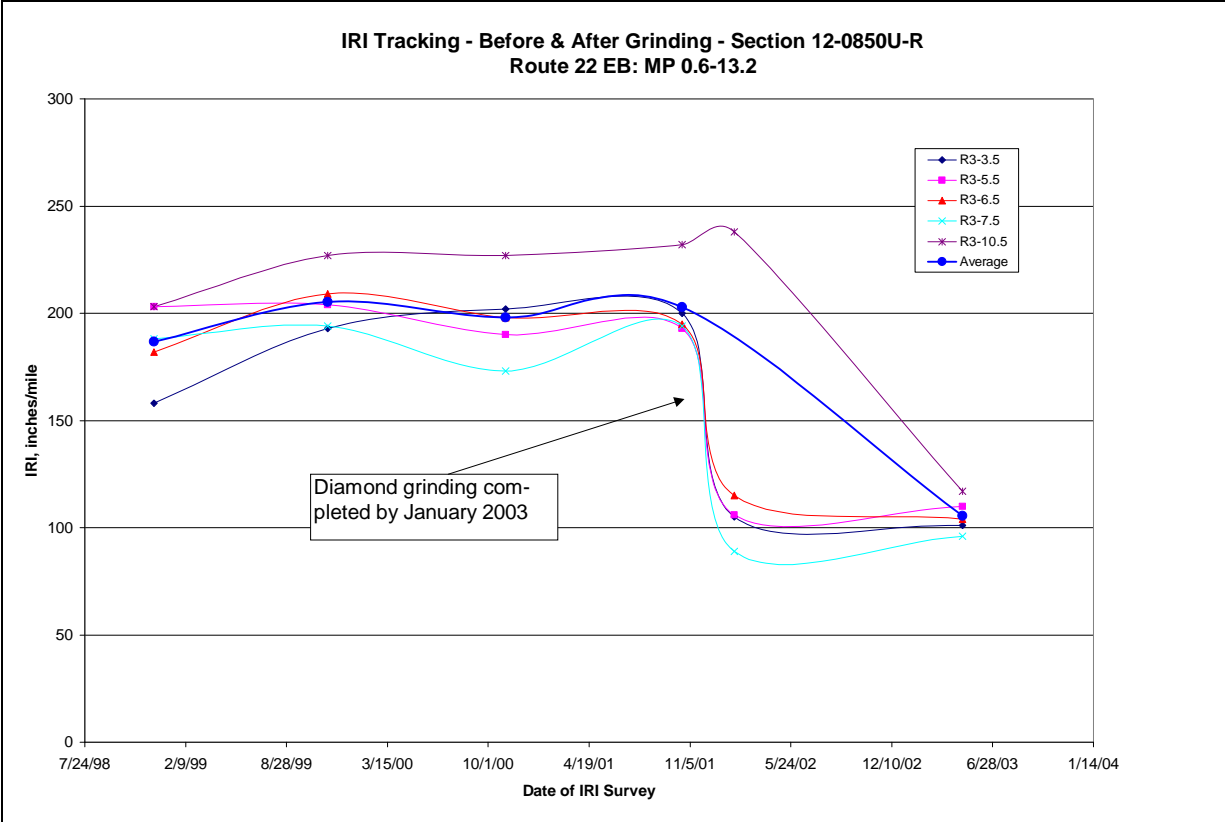
None of these distresses would be remedied by diamond grinding alone, and the problem would likely continue to cause pavement failure a short time after grinding. Such precluding factors are probably considered under present Caltrans guidelines, albeit without any truly objective criteria or measurable threshold values.

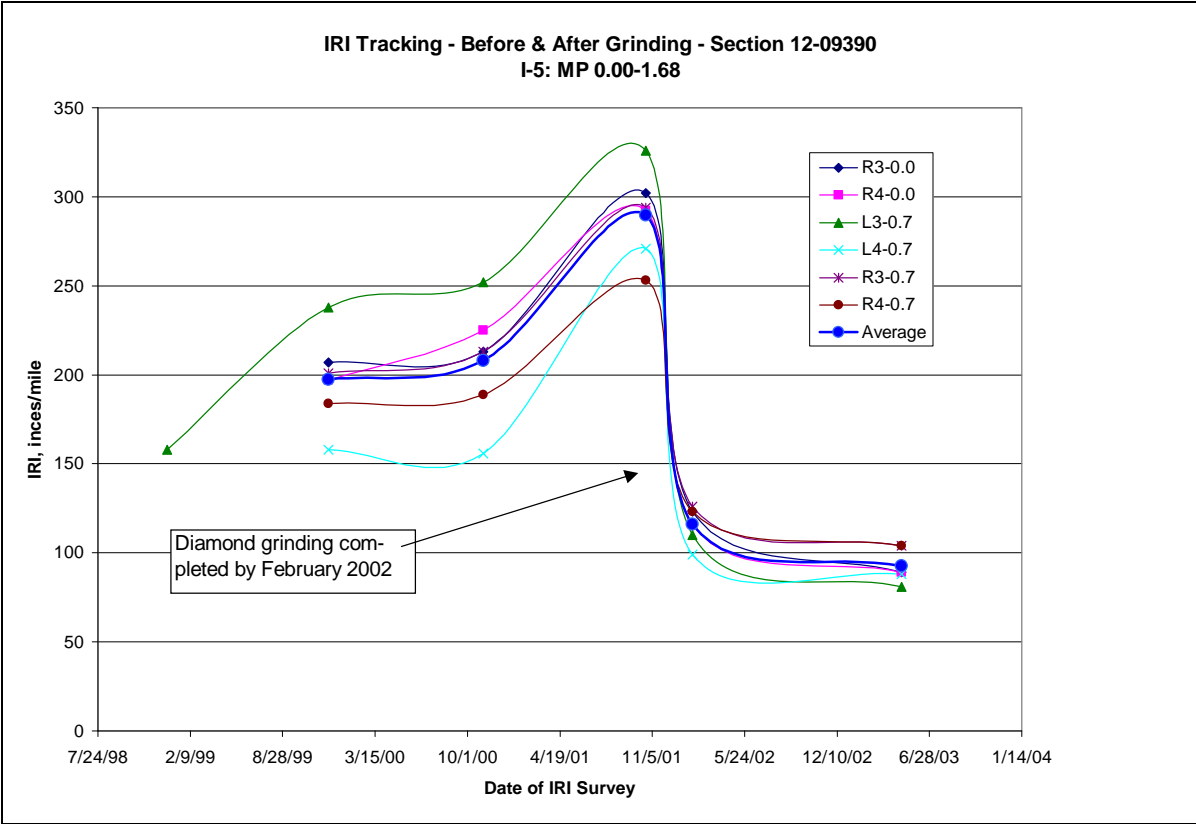
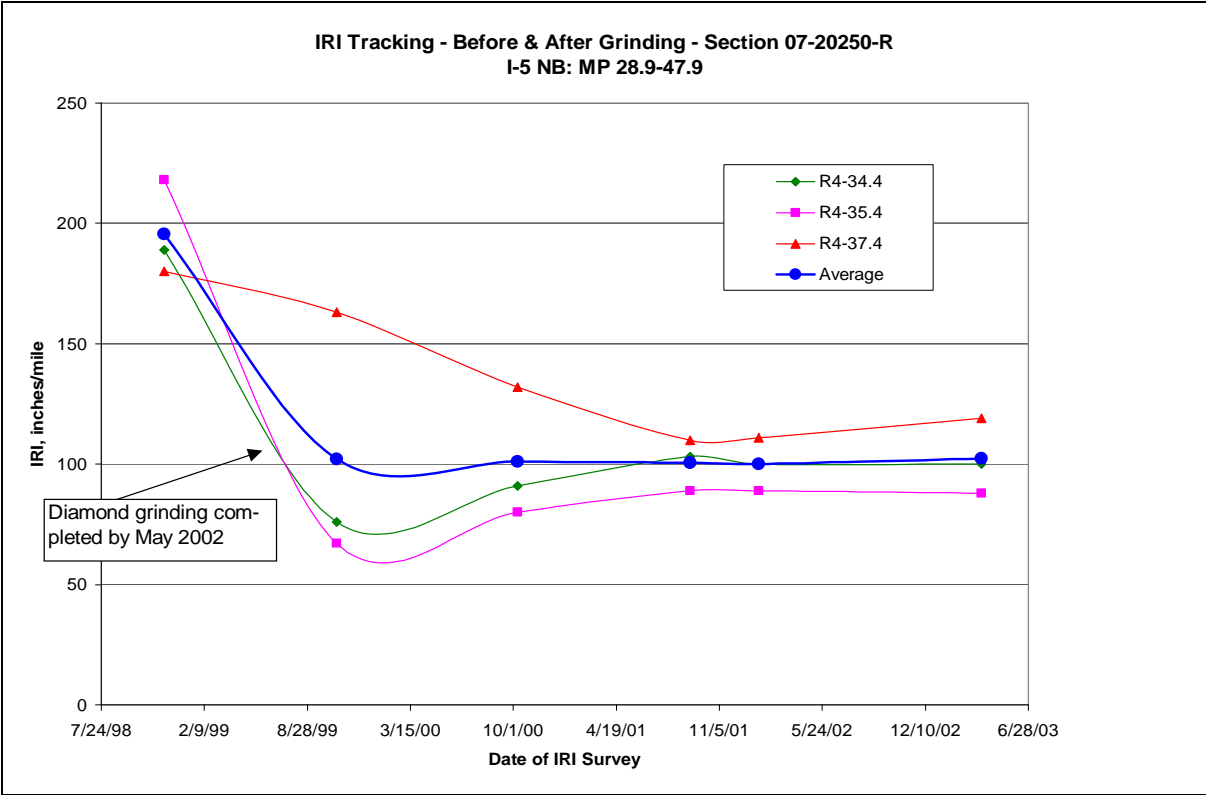
It has been shown that it is possible in California to diamond grind candidate PCC pavements up to three times during the lifespan of the pavement. In other words, if the service life of a well-designed concrete pavement can be extended by 16-17 years, on average, with diamond grinding, and this technique could be applied two or three times, then we can effectively utilize a concrete pavement, without major reconstruction, over a very long time span with only routine maintenance—provided the pavement remains structurally adequate. This magnitude of pavement life is associated with very good ride quality and safety (skid) properties, and it makes diamond grinding a very competitive option for rehabilitation of PCC pavement in California.

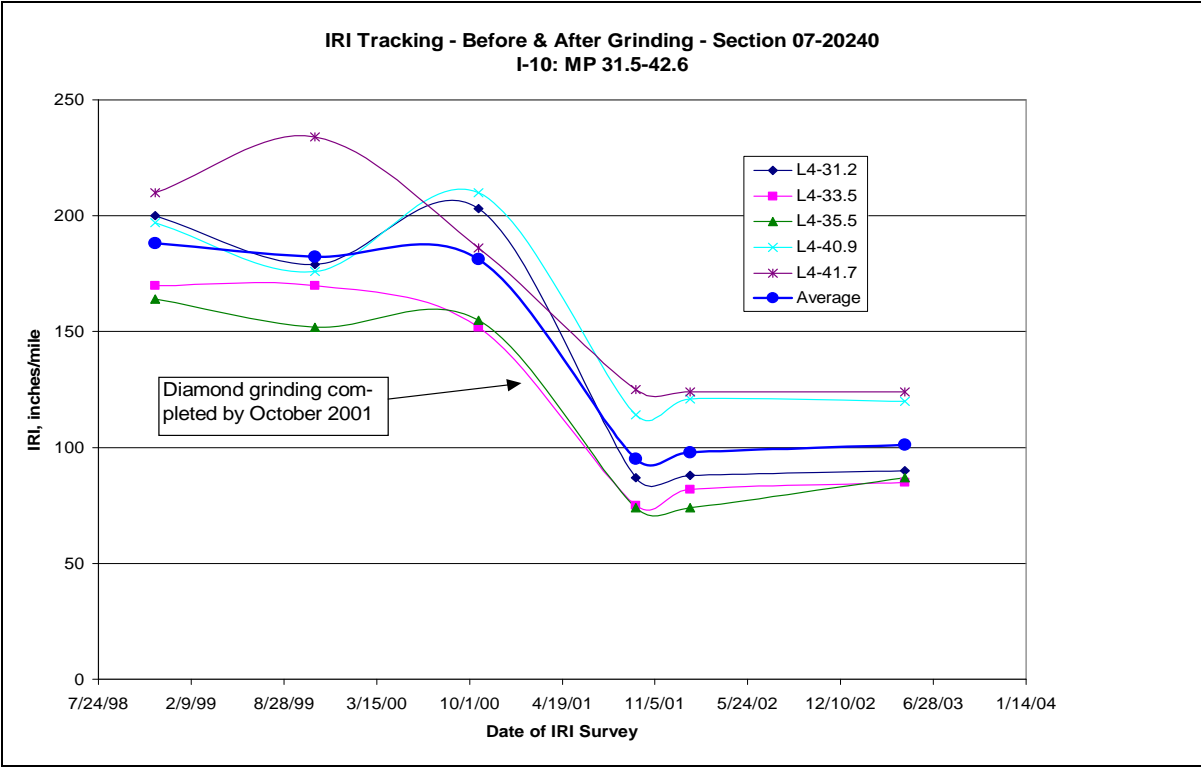
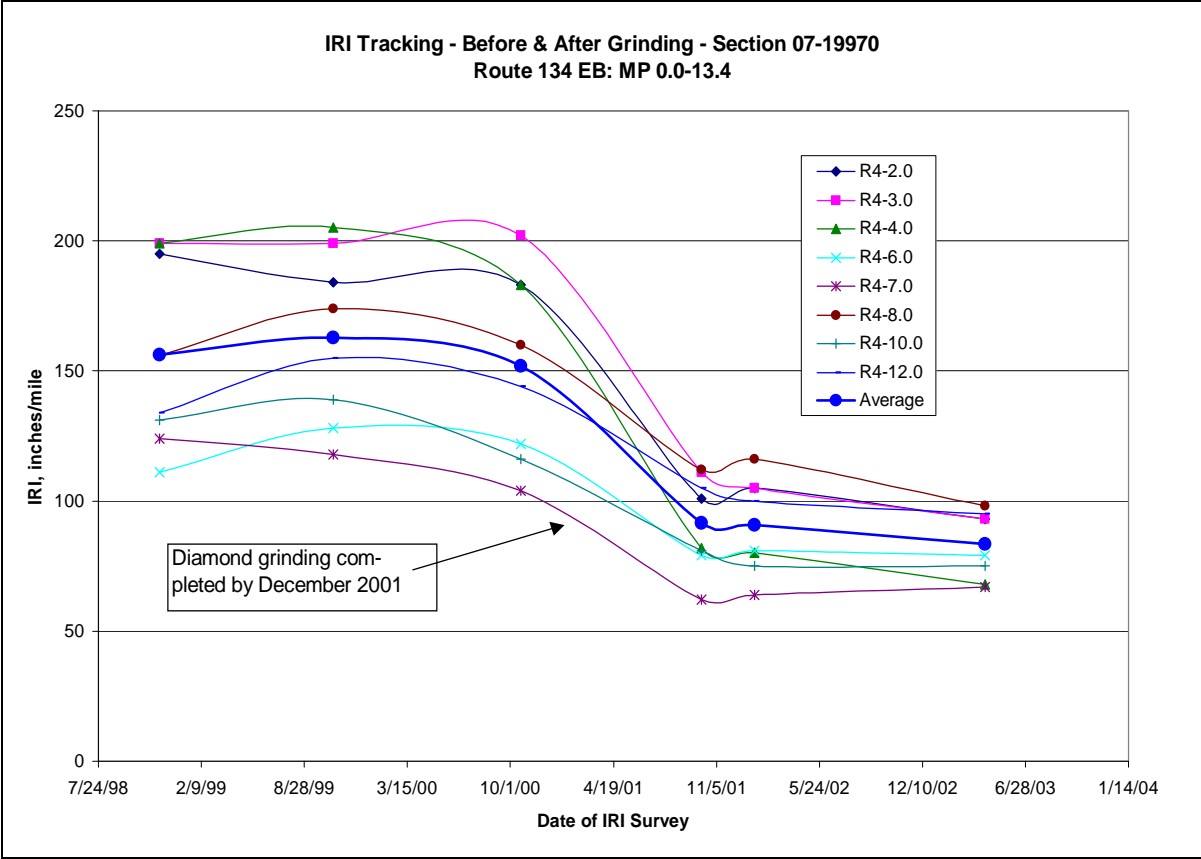
APPENDIX A

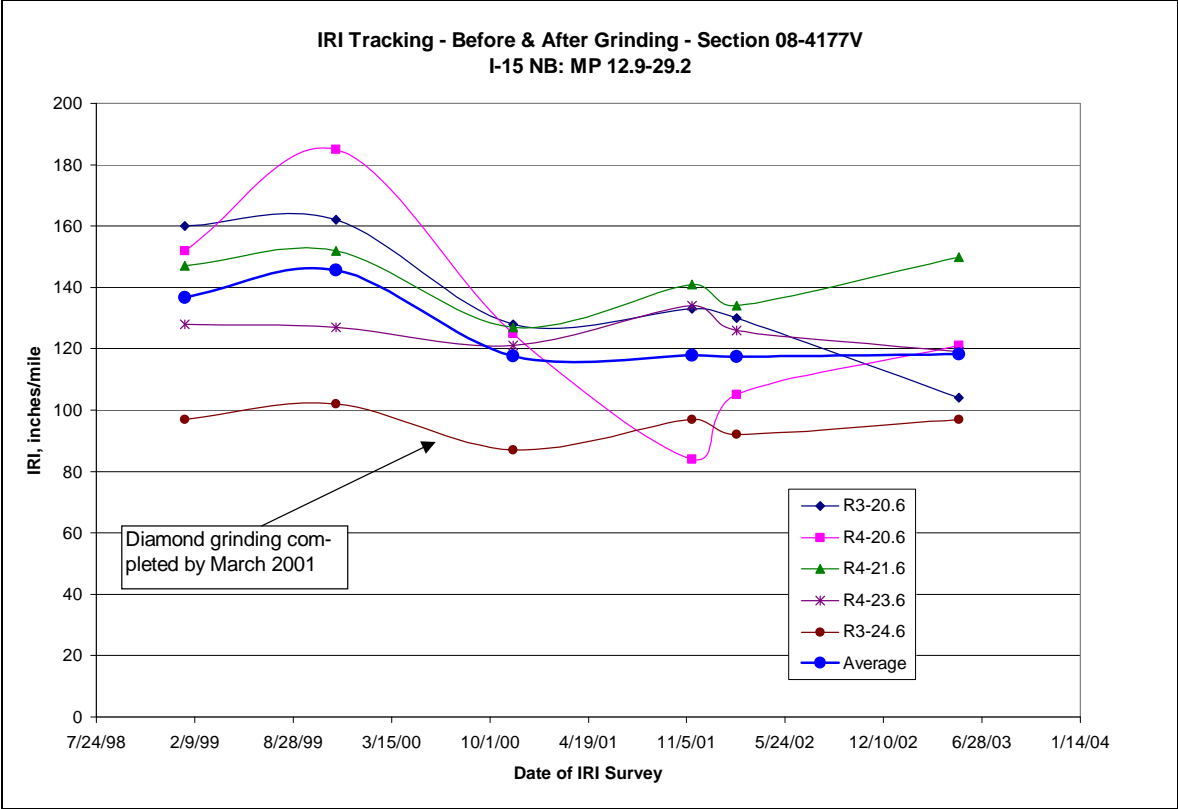
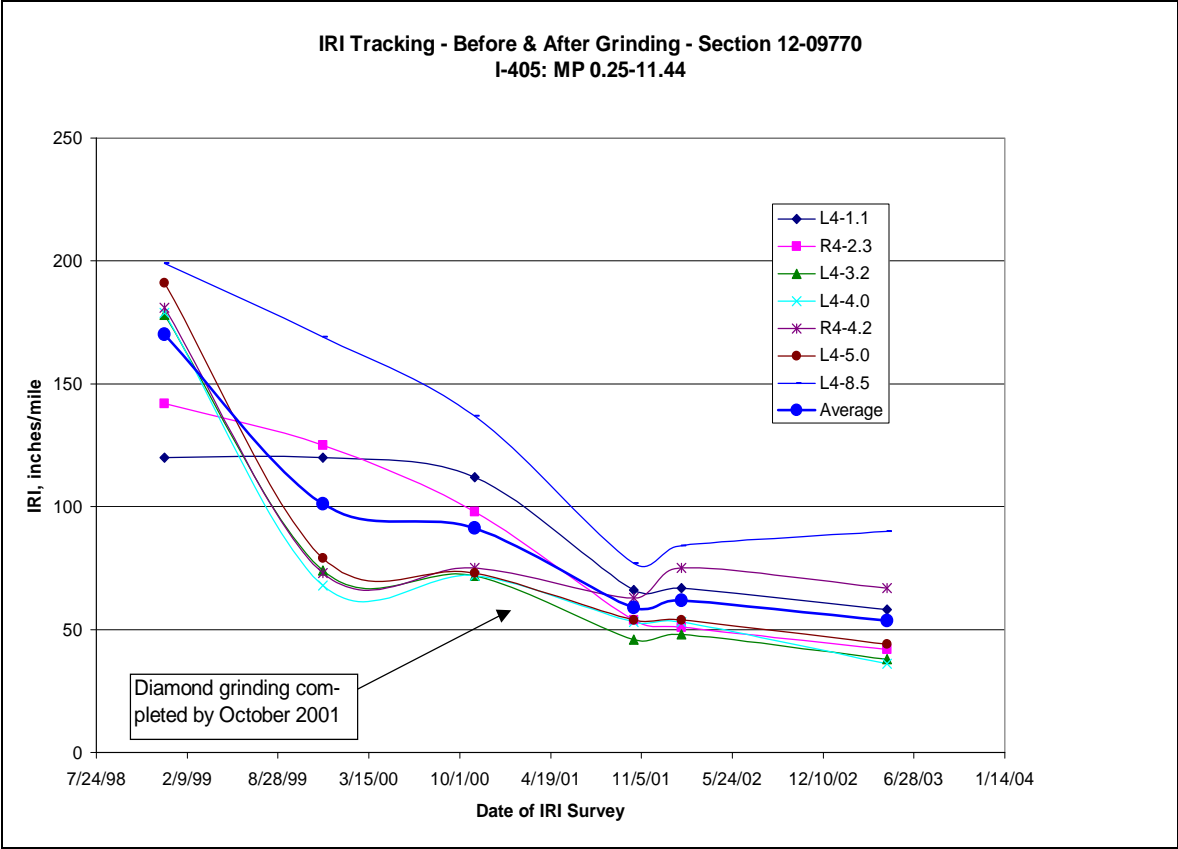
Diamond grinding projects (denoted by District Number – Project Number) analyzed and presented in this appendix, in the following order.

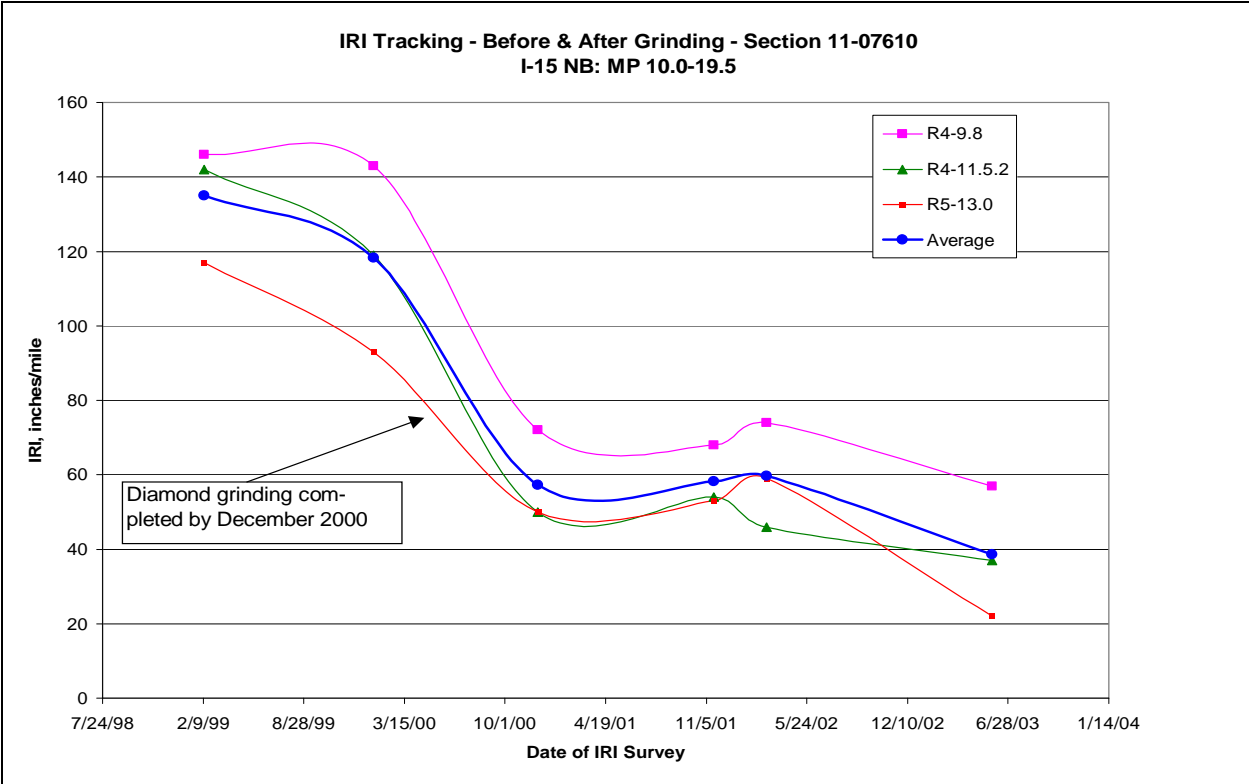
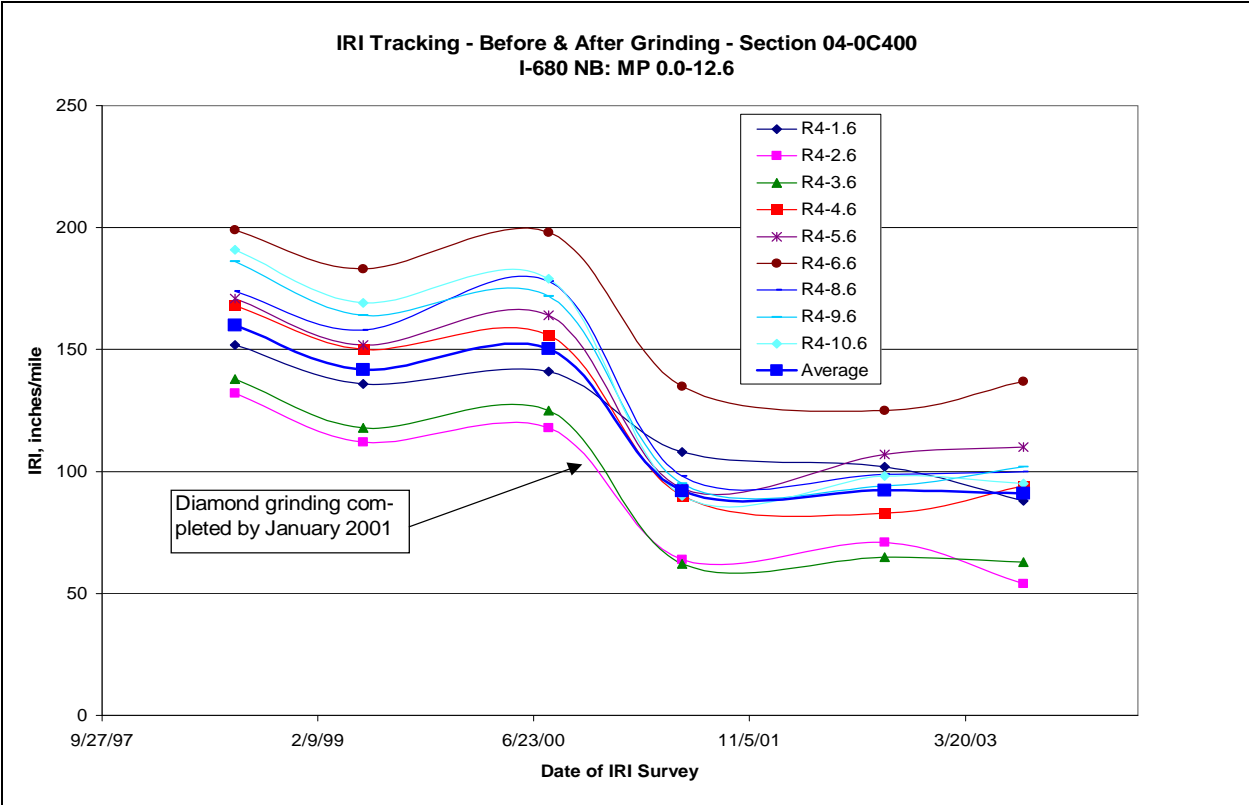
12-085UR
11-07620
07-20250
12-09390
07-19970
07-20240
12-09770
08-4177V
04-0C400
11-07610
04-0C510
04-0C360
04-0C600
07-18130
04-0C410
06-42170
04-0C370
07-17530
08-48890
08-36762
12-0A110
11-22300
08-43950
08-43960
07-16940
07-17200
07-16950
08-34800
05-23250
04-Dixon I-80

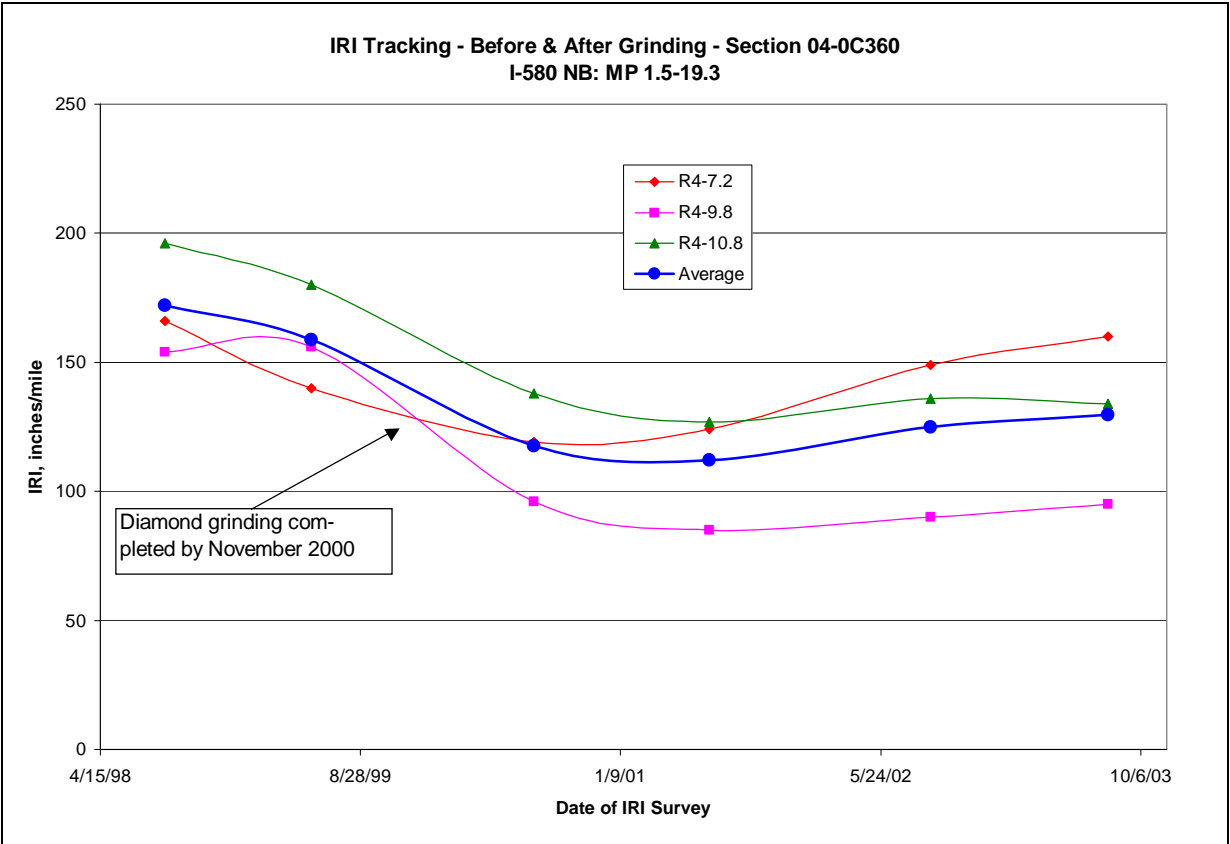
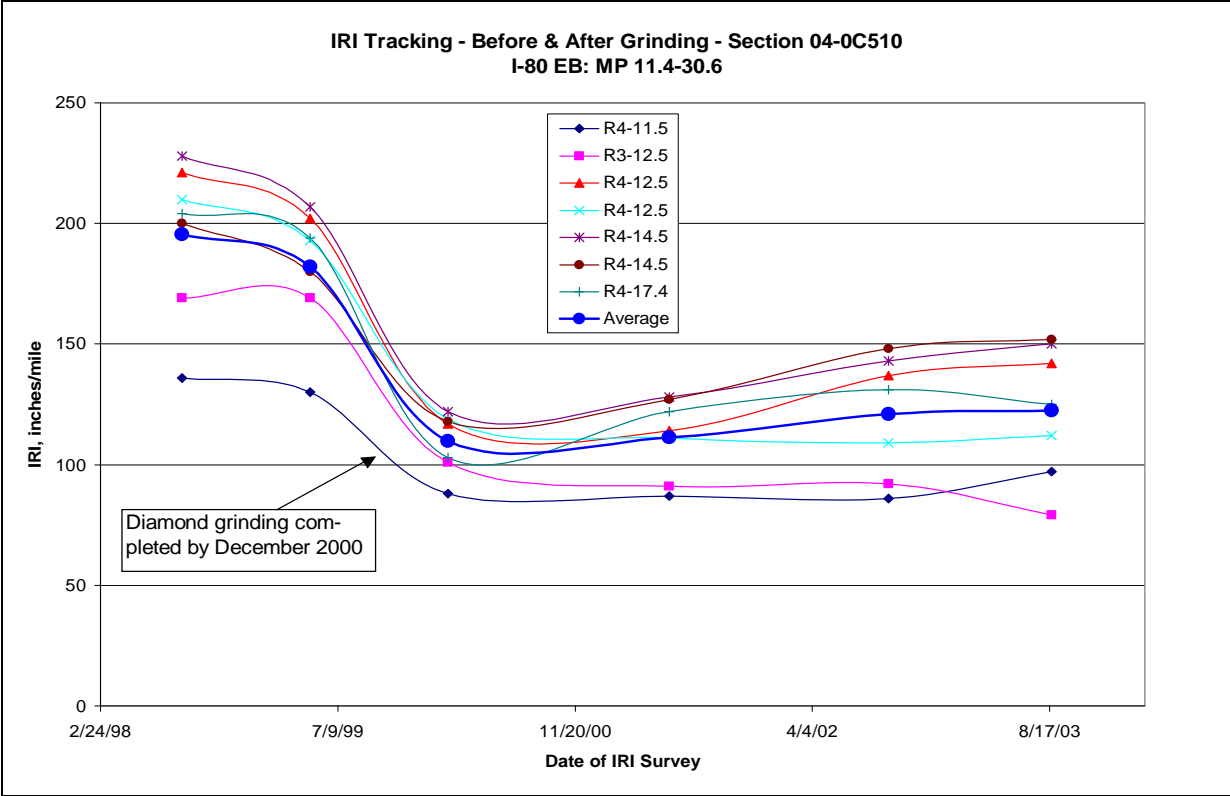


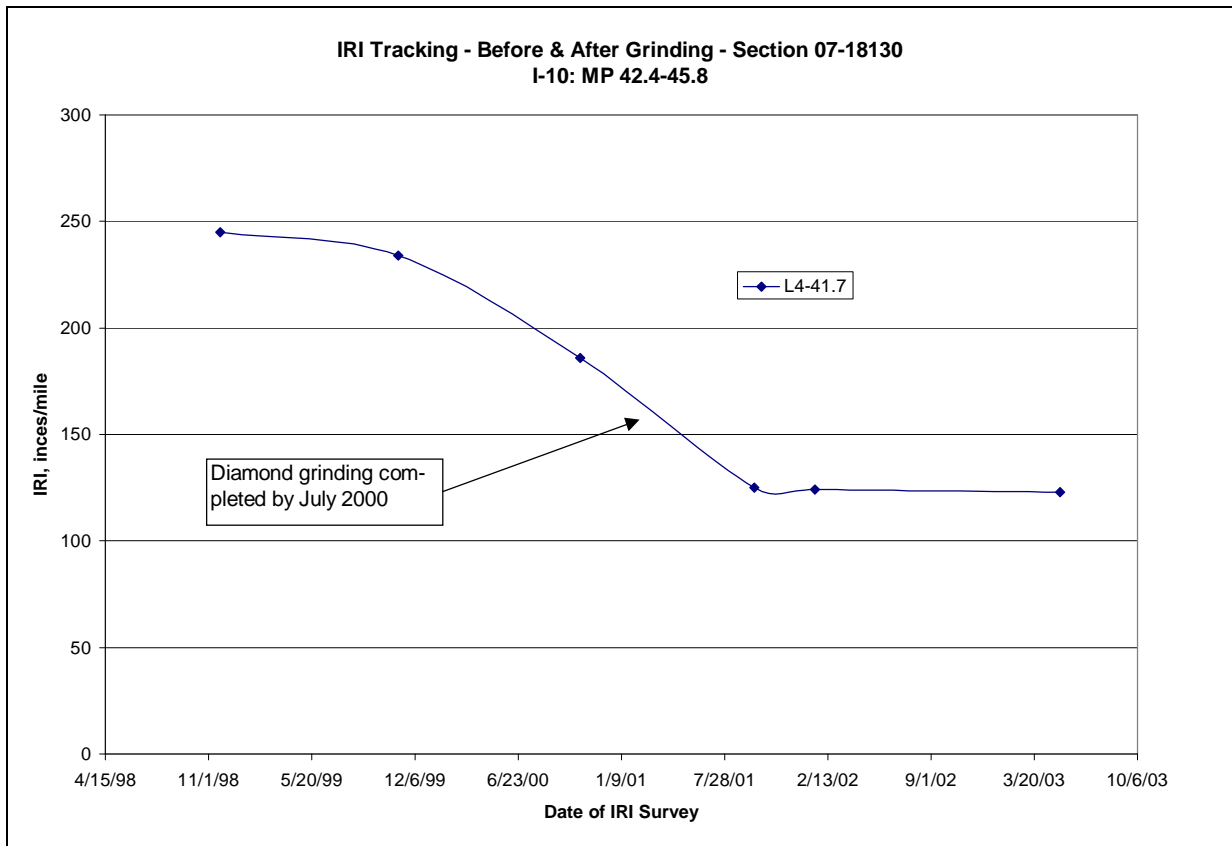
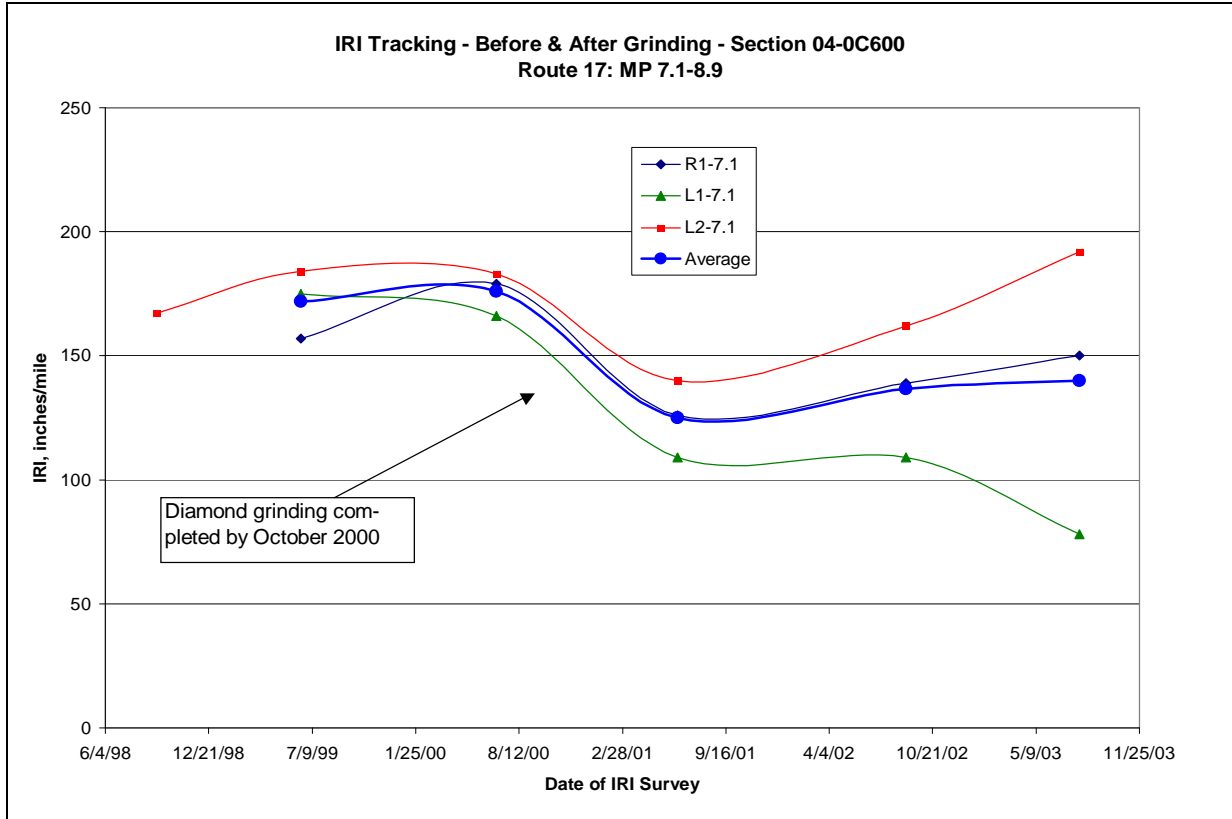


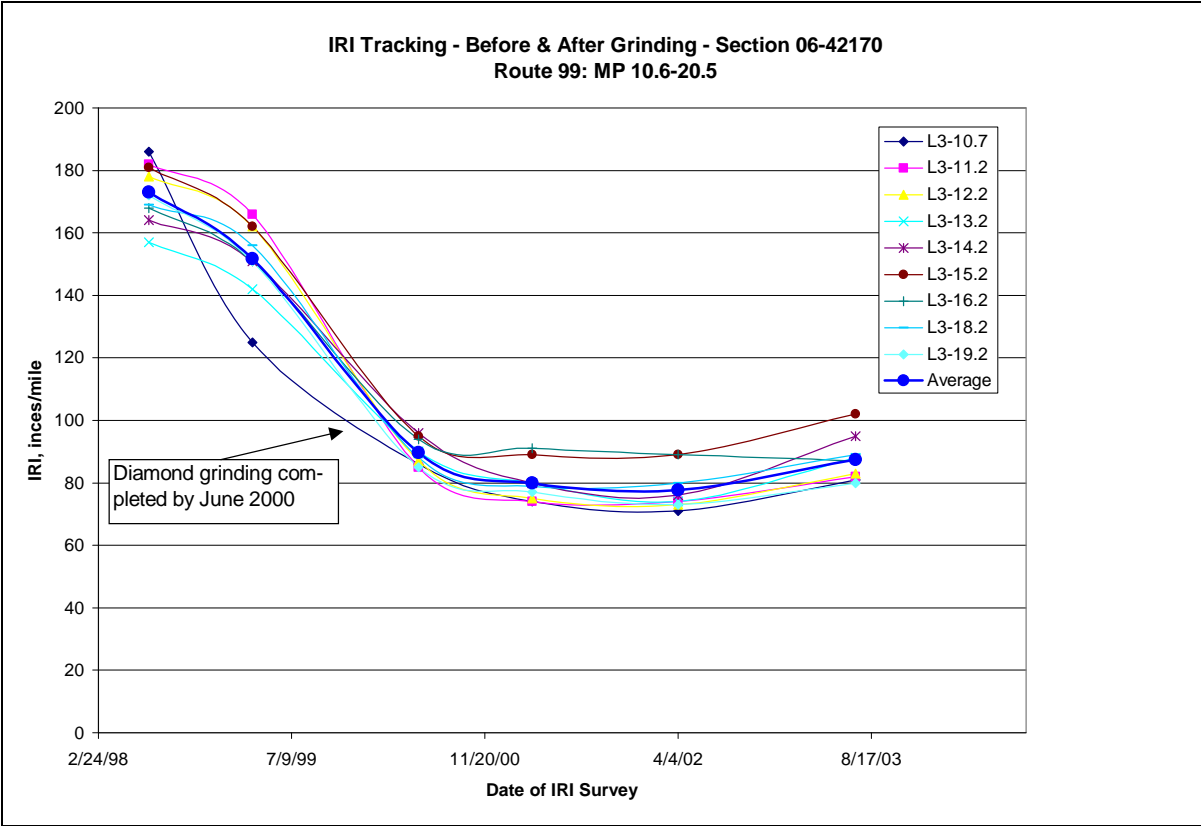
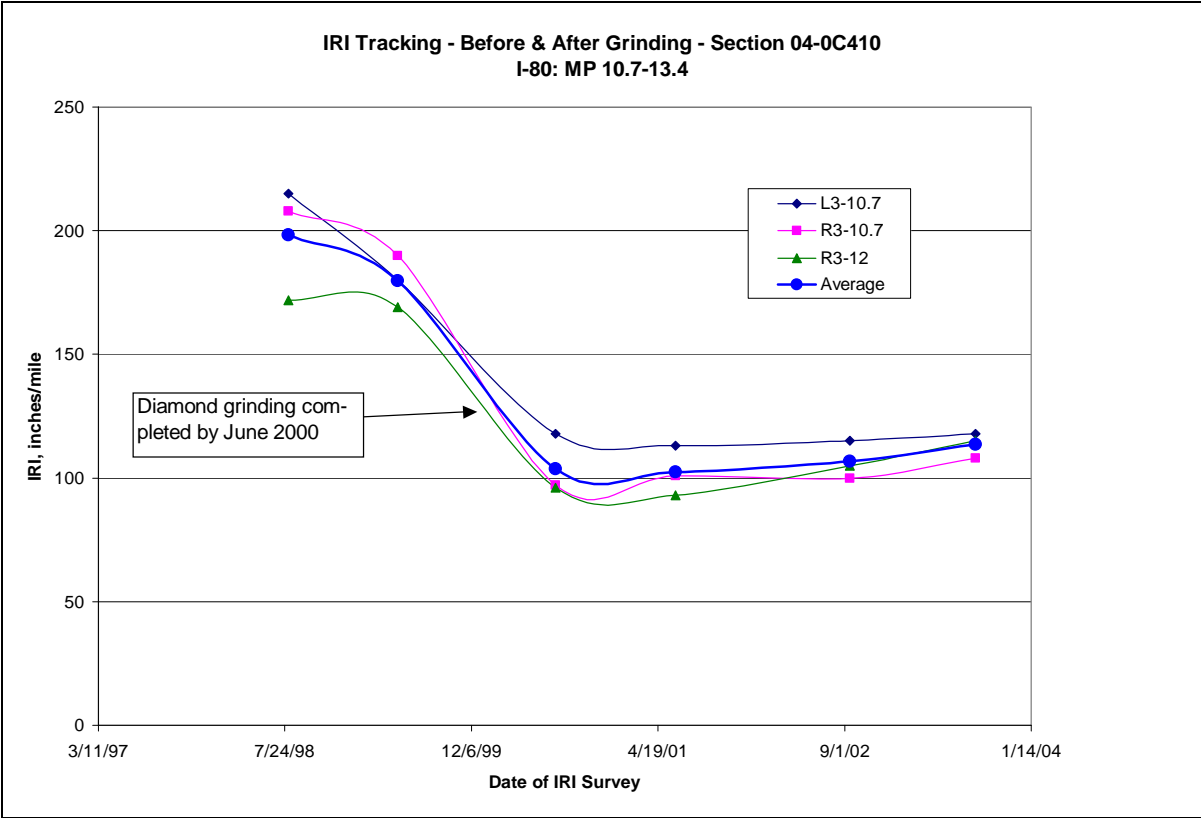


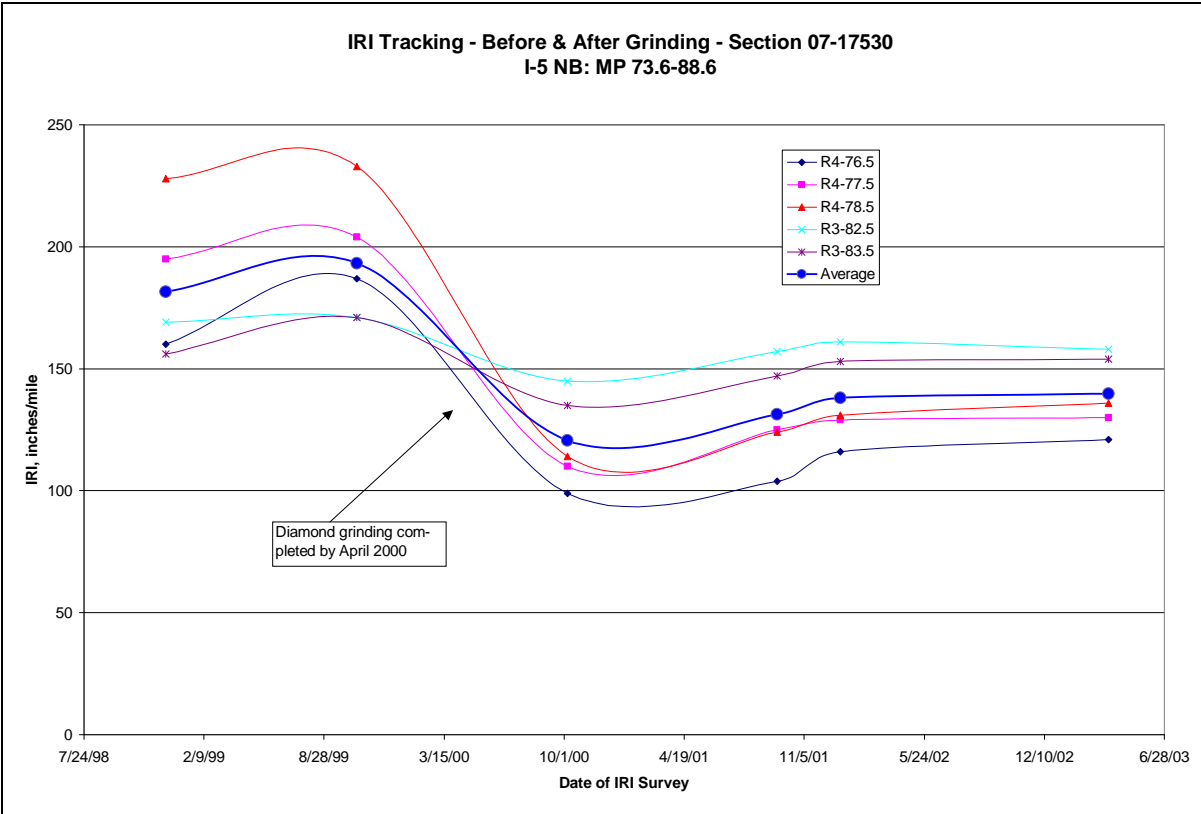
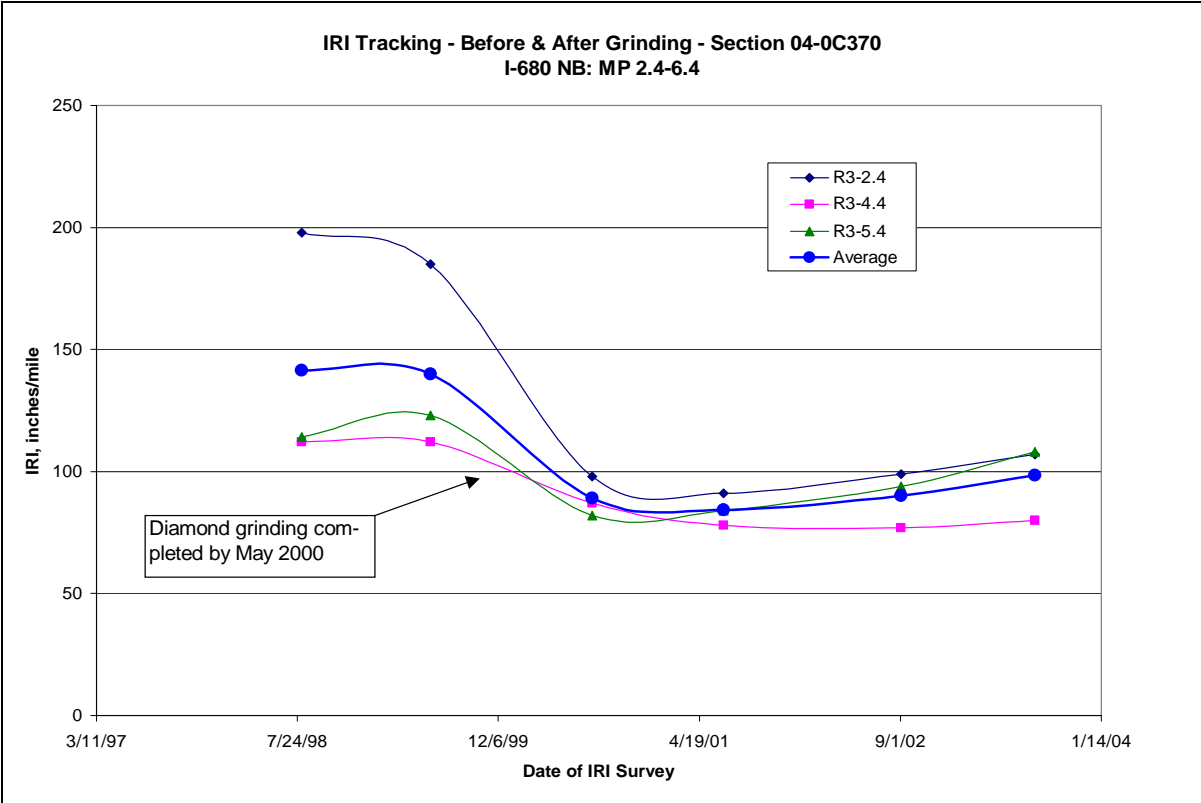


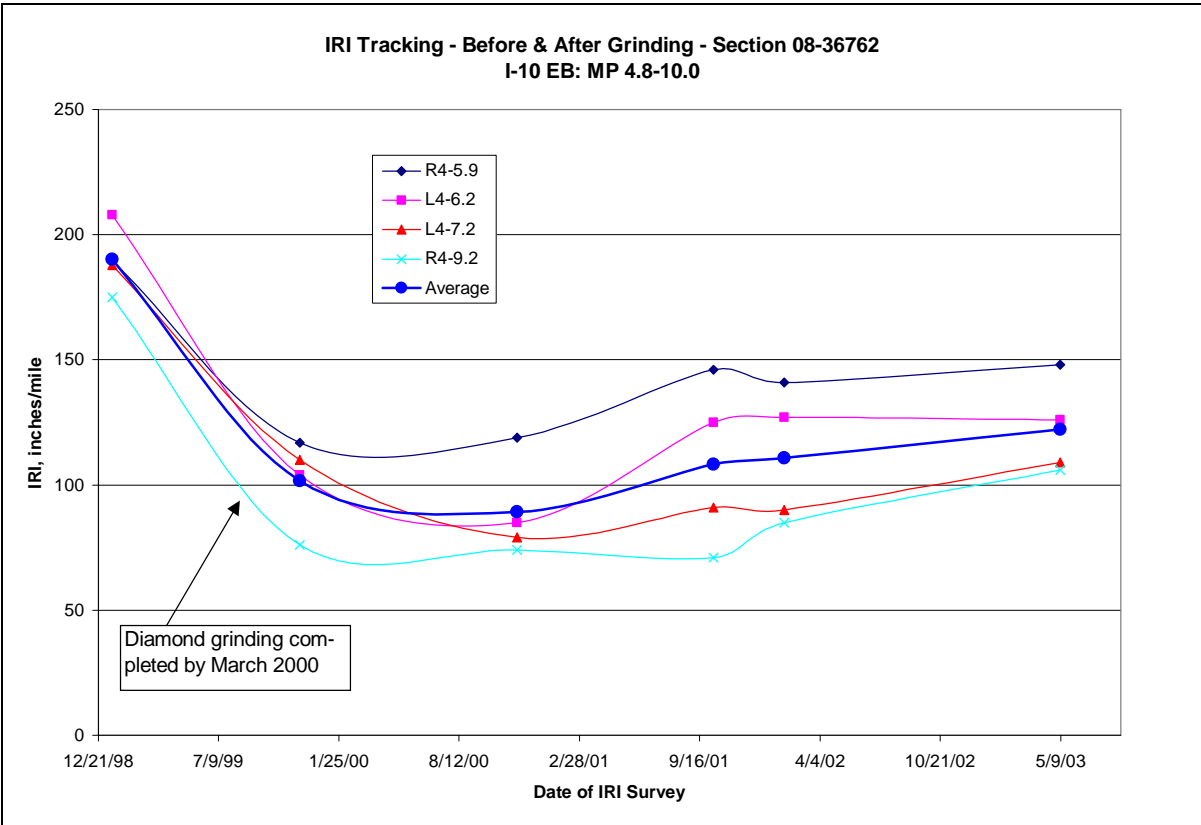
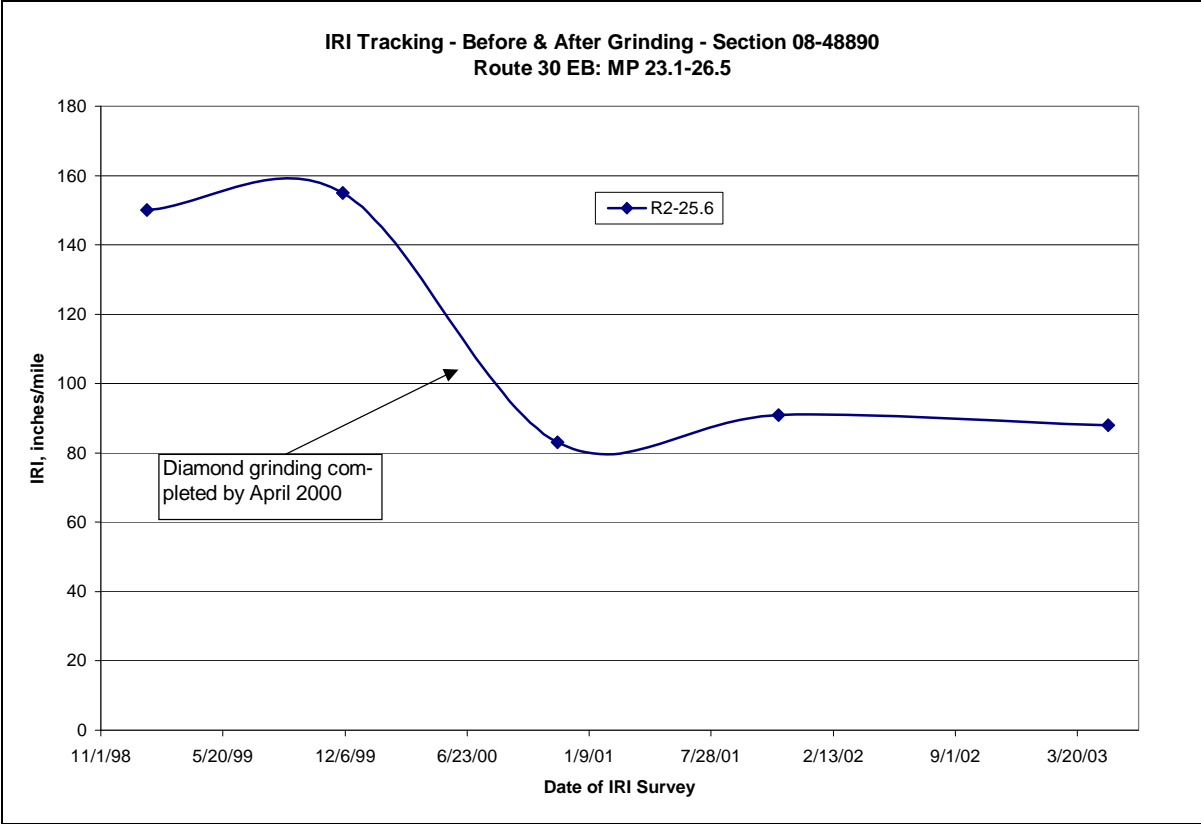


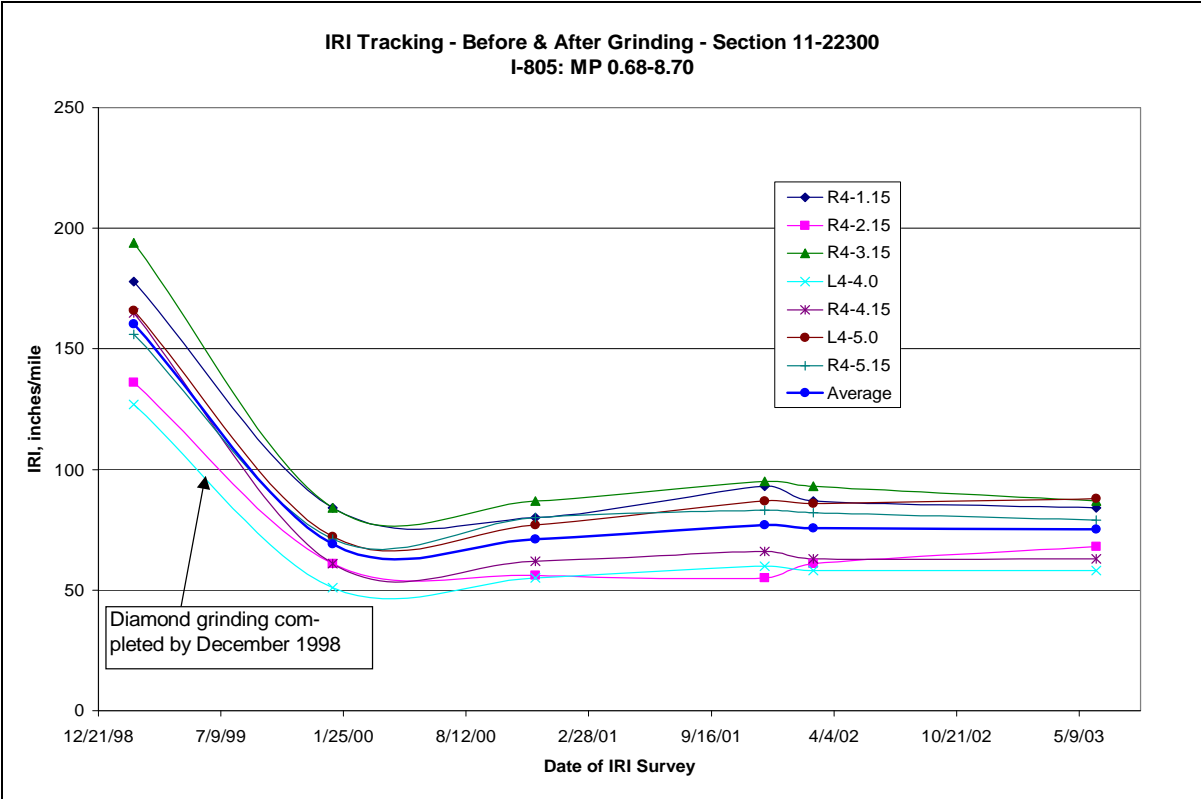
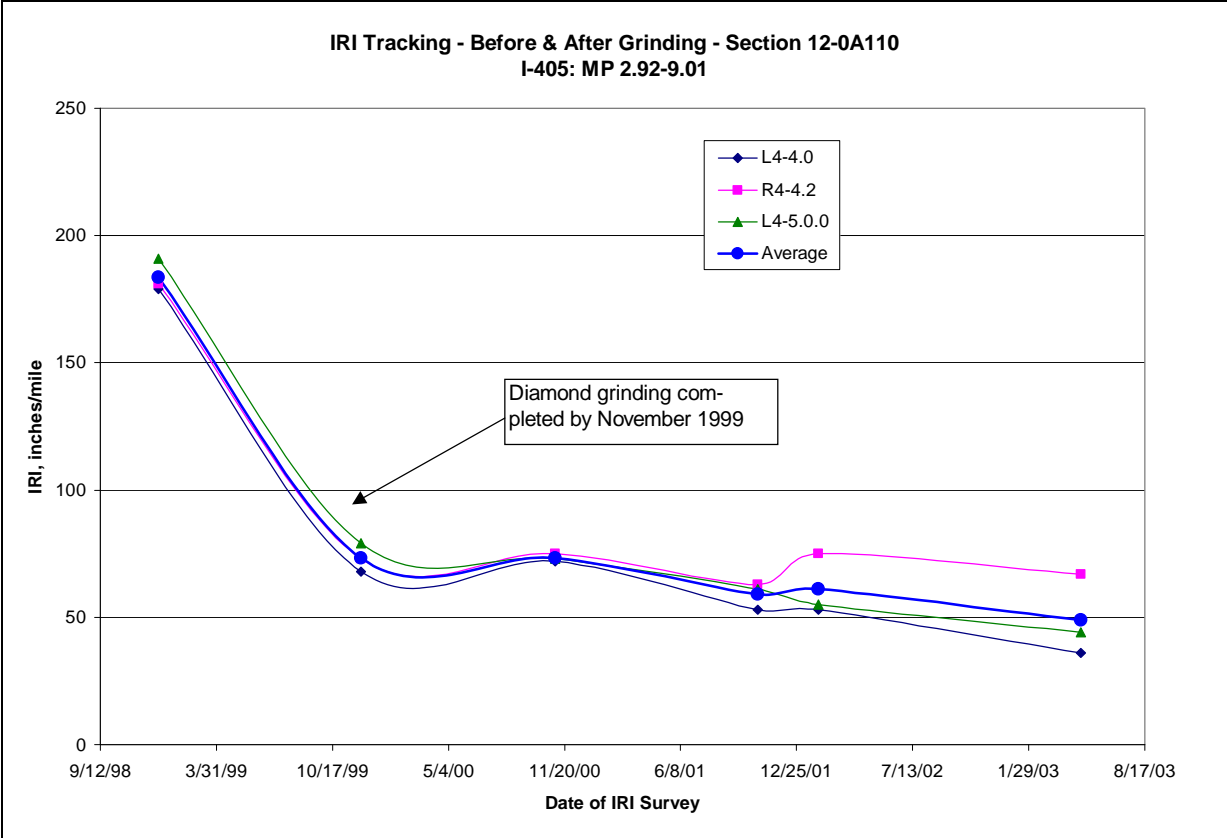


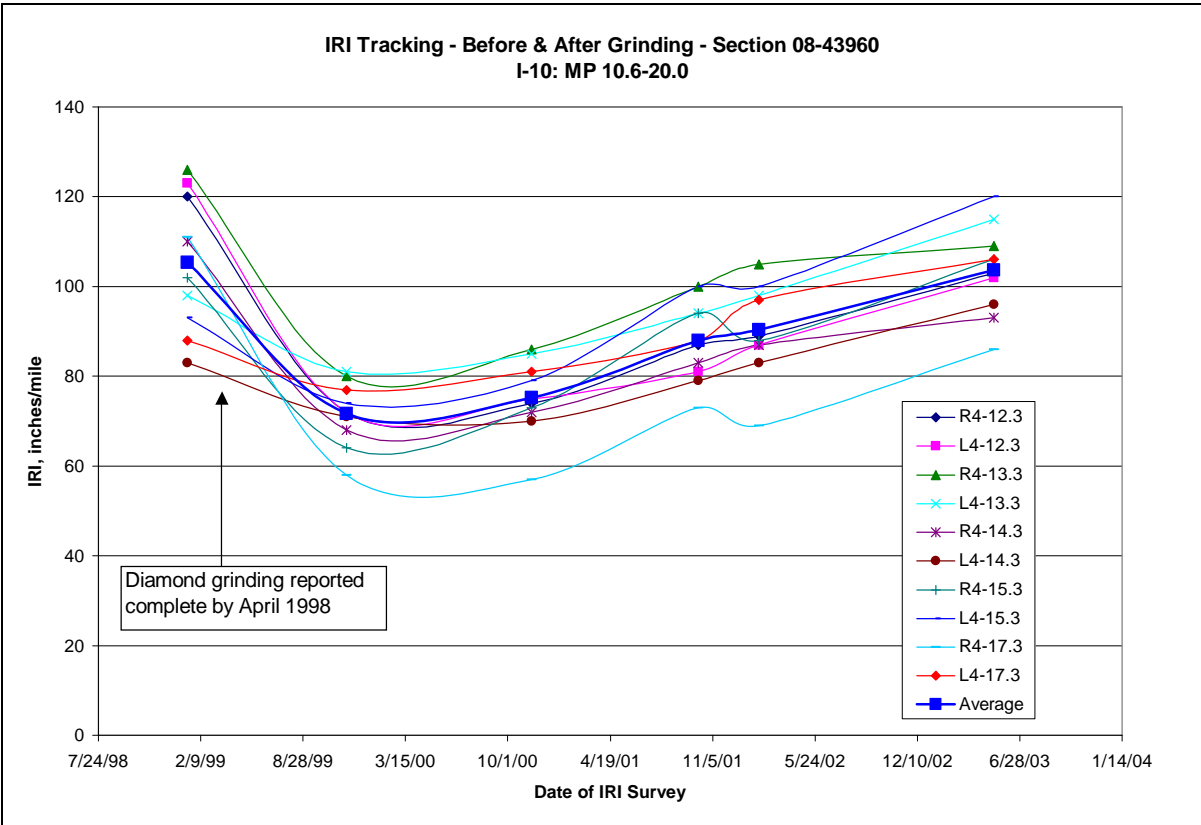
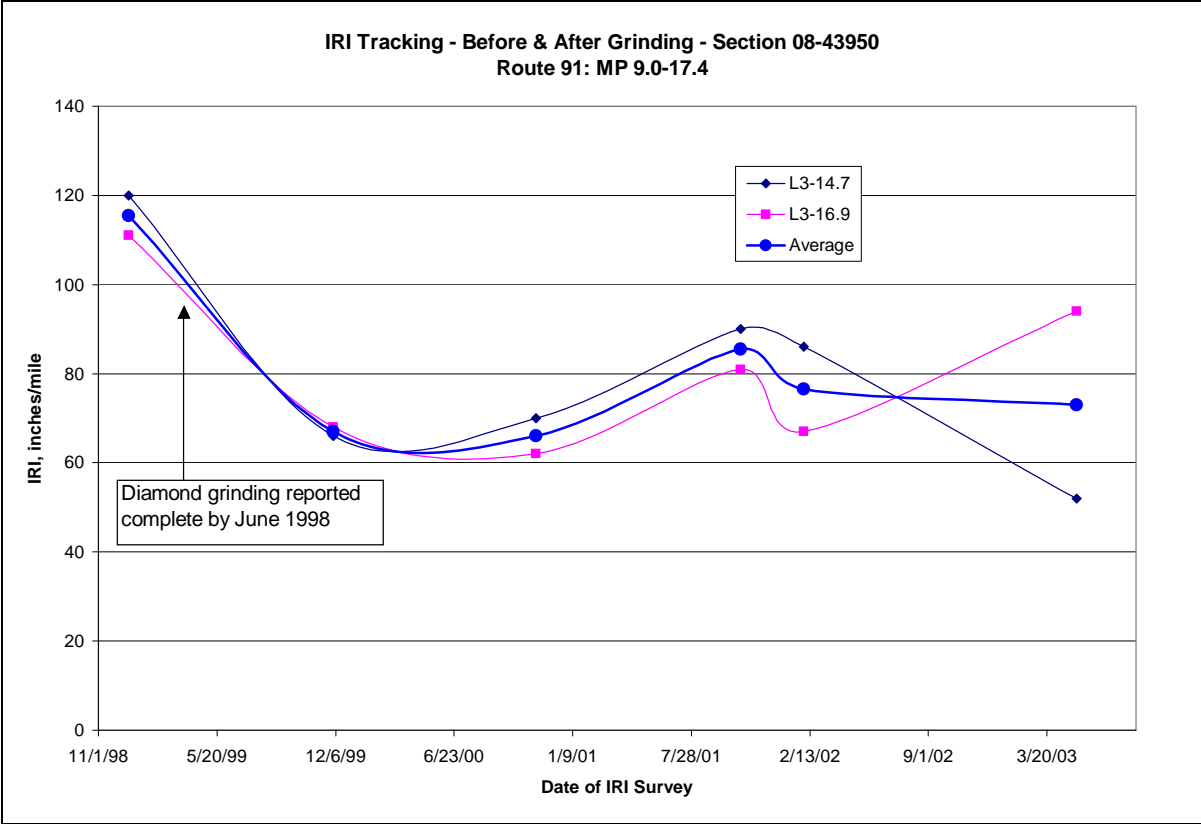


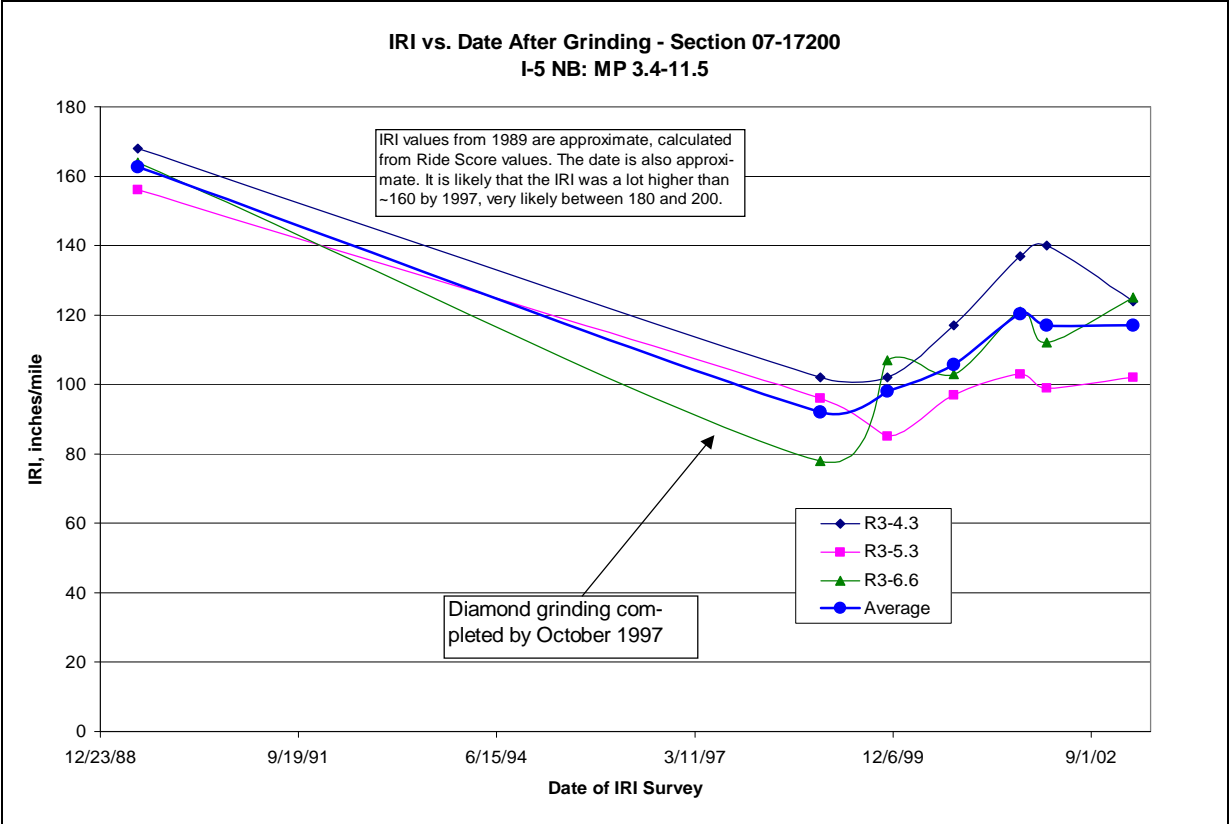
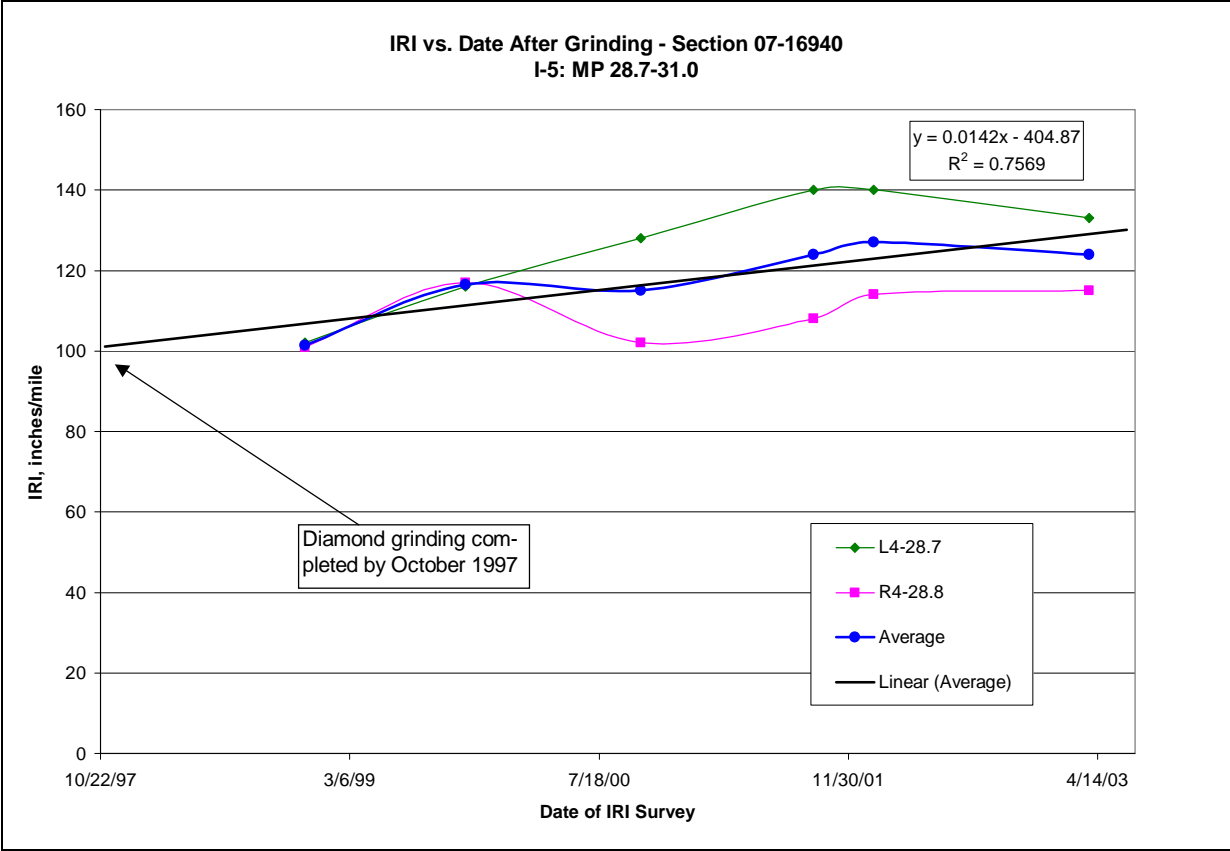


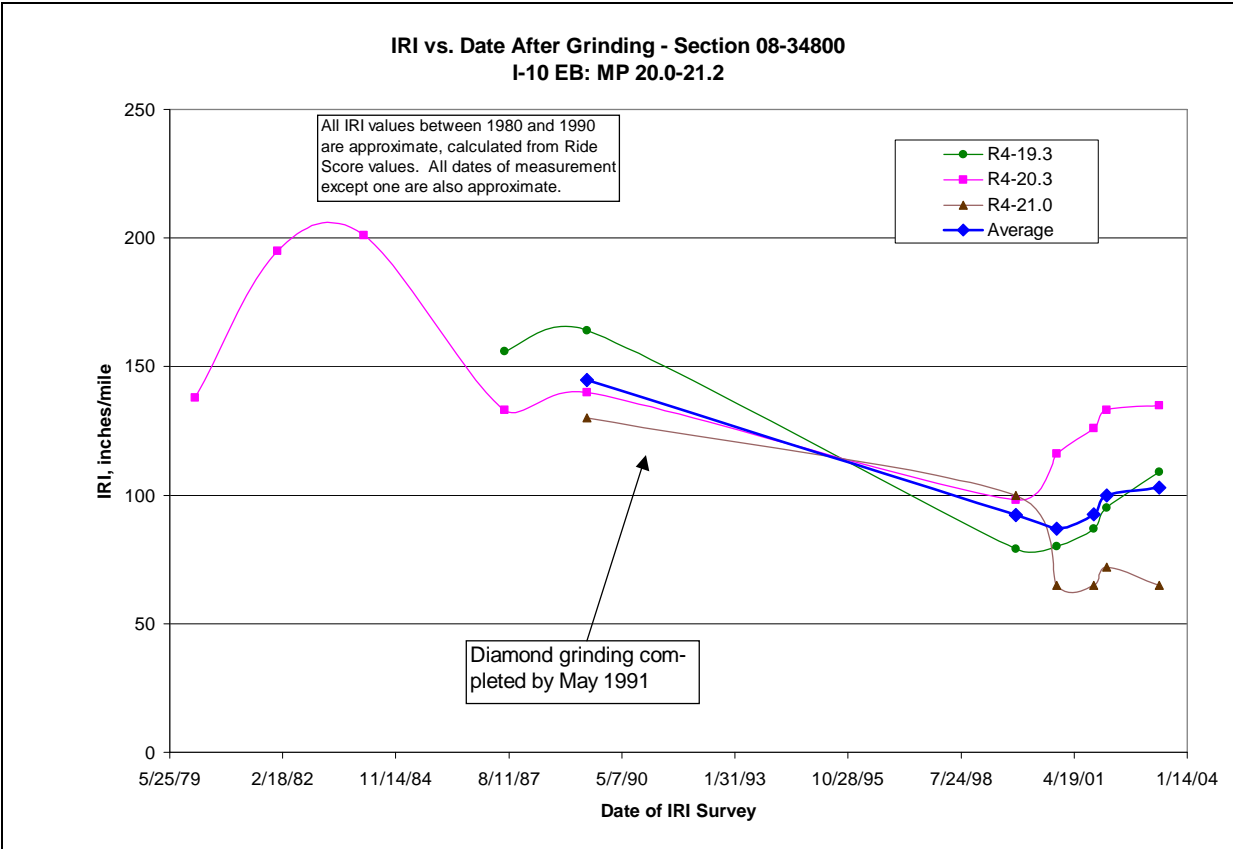
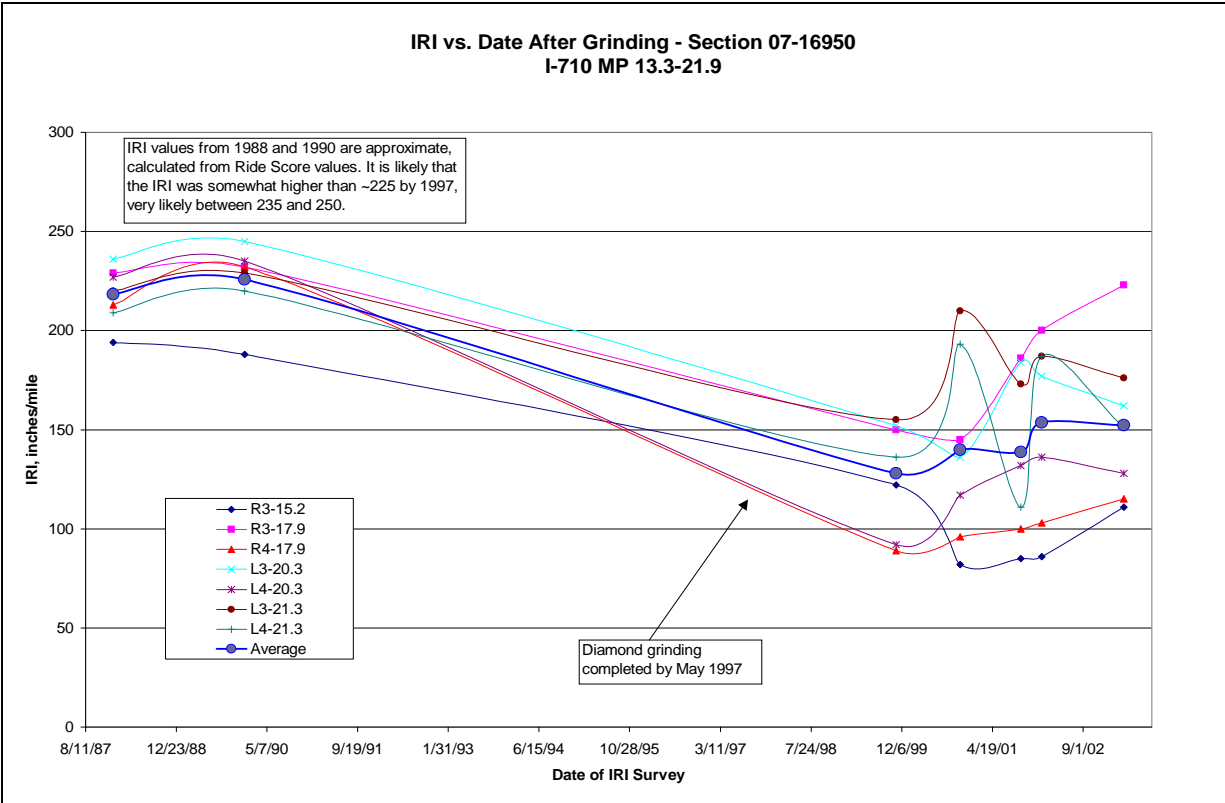


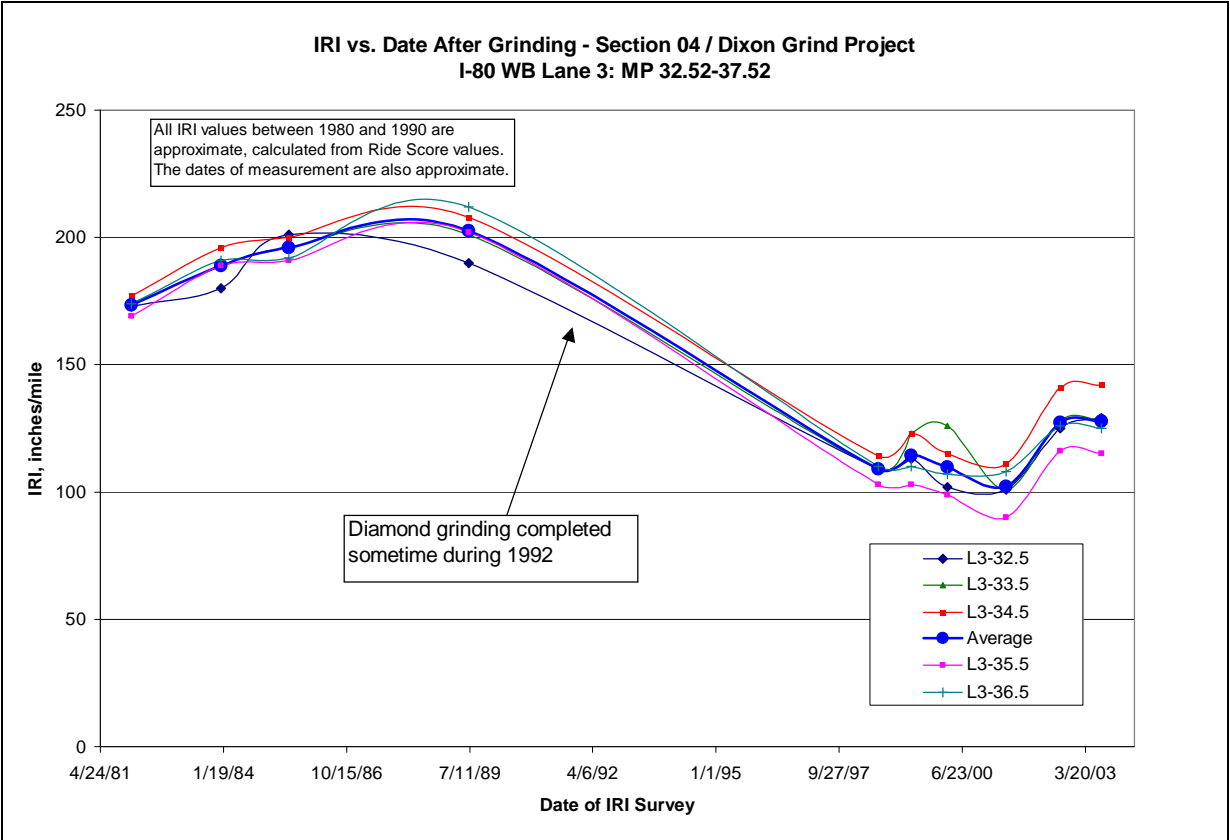
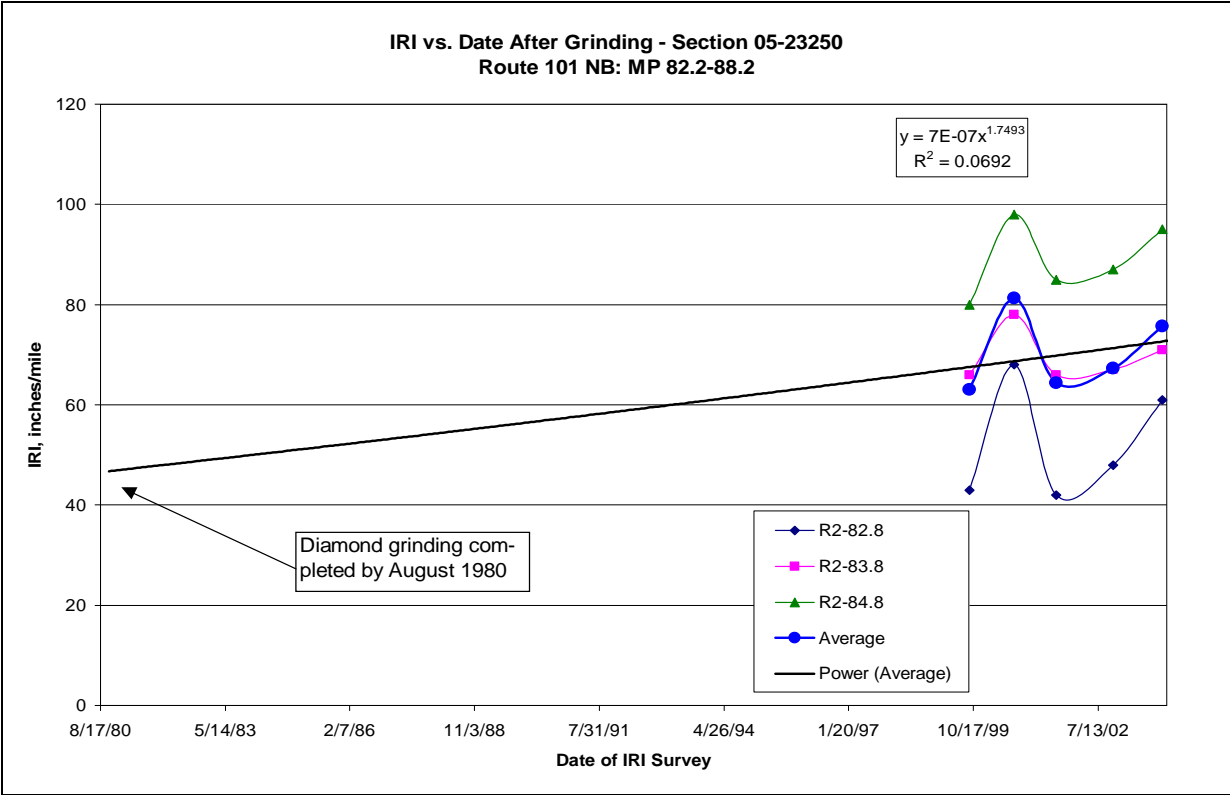












POINTS OF CONTACT

Caltrans METS – Office of Rigid Pavement and Structural Concrete

Tom Pyle	Office Chief	(916) 227-7281
Charles Dayton	Contract Manager	(916) 227-5280
Hector Romero	Senior Engineer	(916) 227-1989
Robert Rogers	Transportation Engineer	(916) 227-7907

Caltrans METS – Office of Rigid Pavement and Structural Concrete

Susan Massey	Office Chief	(916) 654-4792
Rob Marsh	Pavement Management Engineer	(916) 654-5640
Leo Mahserelli	Pavement Management Engineer	(916) 654-2007

Applied Research Associates, Inc. – ERES Consultants Division

Richard Stubstad	Principal Engineer	(805) 649-1111
Michael Darter	Senior Principal Engineer	(217) 356-4500
Chetana Rao	Senior Research Engineer	(217) 356-4500
Walid Tabet	Senior Engineer	(775) 338-9500

Western States Chapter, American Concrete Pavement Association

Tom Salata	Executive Director	(949) 222-9196
------------	--------------------	----------------

Federal Highway Administration, California Division

Steve Healow	Materials Engineer	(916) 448-5849
Jason Dietz	Construction/Maint. Engineer	(916) 498-5886