Use of Falling Weight Deflectometer Data in Predicting Fatigue Cracking

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ABSTRACT

A statistical model was developed for the Alaska Department of Transportation and Public Facilities to predict the occurrence of cracking on paved Alaskan highways. The department has been conducting visual surveys of pavement condition since 1978 on the statewide network of highways. In addition, a falling weight deflectometer has been used since 1982 to provide an indication of the pavement's structural strength. The pavement condition history and deflections were used in a stepwise multiple regression analysis to predict the percentage of pavement area cracked (including the cracked area that was patched) as a function of variables such as pavement age, traffic volume, and deflections. Initially an attempt was made to develop a regression equation to predict the percent cracking for each mile-long road segment. However, this analysis could not produce a regression equation that was statistically significant (the highest correlation coefficient was less than 0.5). An alternative approach was then tried. Rather than predict cracking for each individual mile, it was considered adequate to predict average cracking for each construction project (which might consist of several miles built at the same time). Miles within each construction project that had similar deflections (and hence similar structural strength) were grouped, and average values of cracking and other variables were calculated for each group. Regression analysis of the grouped data produced statistically significant relationships (with correlation coefficients in the range of 0.7 to 0.9). The study demonstrates the development of a performance prediction model with limited inventory and deflection data.

Pavement deflection data have been used in the past by the Alaska Department of Transportation and Public Facilities (DOTPF) to monitor the performance of their highways. These data were used in an earlier study to develop a model for predicting fatigue cracks in the pavements (1). Deflection measurements at the center of the load were used for this purpose.

Two years ago, the Alaska DOTPF acquired a falling weight deflectometer (FWD) to measure pavement deflections. This equipment, in addition to measuring the deflection at the center of the load, records deflections at six other points away from the center of the load. The users of the FWD have reported that the measurements obtained with the help of this equipment can be used to define the shape of the deflection basin (2). Further, it was reported that the deflection basin was a better indicator of the damage potential to highway surfaces than the single measurement of surface deflection under the load center (2).

Based on this experience, it was expected that the fatigue damage prediction model could be improved significantly if FWD data were used in place of deflections at the center of the load. Therefore, the primary objective of this study was to develop a model for fatigue crack prediction using the FWD data. A mechanistic approach has been generally used to model a pavement structure as a multilayer elastic system and FWD data are used to estimate mechanistic layered properties necessary for structural analysis.

However, in this study the authors used an empirical approach because the primary purpose was not to explain theoretical causes for the occurrence of fatigue cracking but to statistically correlate fatigue cracking with field observations. One limitation of this approach is that predictions cannot be made beyond the range of available data with a high degree of reliability. On the other hand, major advantages of the empirical approach are that it is well calibrated with past observations of pavement performance and it can be developed with limited inventory and deflection data. Because the data used in the development of a statistical model covered an adequate range of age, traffic, and pavement conditions in Alaska, the model is expected to provide reliable predictions of fatigue cracking on Alaskan highways.

DATA COLLECTION

The data used in this study were contained in two different files. The pavement inventory data files contained the following items:

- Route number;
- Coordinated data system (CDS) mile;
- Mays roughness;
- Bumps (>1 in., >2 in., >3 in.);
- Percent alligatoring (Type I, Type II);
- Patching (%);
- Average rut depth; and
- Rut depth standard deviation.

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The FWD data files contained the following items:

- Date,
- Temperature (°F),
- Route number,
- CDS mile x 100,
- Load (falling weight), and
- Sensor deflections (sensors 1 to 7, μmm)

All the available inventory data for the years 1981 and 1982 were reviewed for this study. Also, the available FWD data for the years 1982 and 1983 were reviewed for possible use in the analysis.

In addition, data on the surfacing dates on each route were also obtained to determine the age of the pavement on each section of the route.

Finally, data on annual average daily traffic (AADT) and monthly average daily traffic (MADT) for April and May were obtained from the 1981 annual report (3).

DATA ANALYSIS

The data were analyzed in the following manner:

1. Merge pavement inventory files;
2. Estimate age, AADT, and MADT;
3. Select an FWD record for each pavement inventory record;
4. Search for suitable fatigue cracking prediction model;
5. Group data for further analysis; and
6. Search for fatigue cracking model using grouped data.

Merge Pavement Inventory Files

Two pavement inventory files contained 1981 and 1982 data for the state highway system. Because about one-half of the system is surveyed each year, no significant overlap occurred between the two files except for Route 170000. Where overlap did occur, 1982 data were used unless the CDS mile had lower cracking in 1982 and no rehabilitation action was taken in 1981 or 1982. If a -1 appeared as either type of fatigue cracking or patching, the record was omitted. Routes that did not have FWD measurements were also omitted. Finally, portions of routes for which surfacing information was not available were omitted.

The following routes were represented in the merged pavement inventory file:

Route No.	Route Name
130000	Seward/Glennallen Highway
150000	Steese/Elliott/Dalton Highway
170000	Parks Highway
180000	Alaska Highway
190000	Richardson Highway

In the remainder of this paper, these routes will be referenced by the first three digits of the route number. For example, Route 130000 will be referred to as Route 130.

The pavement inventory files recorded the percent alligator (fatigue) cracks by Type I and Type II. Because it may not be practical to predict cracking by Type I and Type II, it was considered appropriate to combine these two types of cracks and treat the total as the observed fatigue cracks.

Although the fatigue cracking data were identified by the year during which they were recorded in the field, a discussion with the Alaska DOTPF staff indicated that some observations might have been recorded during the same period that maintenance work had been done. Thus, it was possible that some of the observations were recorded before maintenance and some of them after maintenance. To reduce this inconsistency, it was decided to combine percentage of patching with the percentage of fatigue cracking to arrive at the total percentage of fatigue cracking in each mile of the route. If this total for any CDS mile exceeded a value of 100.0, it was changed to 100.0.

Estimate Age, AADT, and MADT

The surfacing date was added to each record of the pavement inventory file. An indicator variable, age adjustment (AGE ADJ), was also added to each record to identify which of the two original pavement inventory files it came from. A code of 1 was used for 1981 and a code of 0 was used for 1982. The age of a CDS mile can be calculated by using the formula:

$$AGE = 82 - LAST\ FIX - AGE\ ADJ \qquad (1)$$

where LAST FIX is the last 2 digits of the year of its most recent surfacing. Because some CDS miles on Routes 180 and 190 were last surfaced in 1982 but were only inventoried in 1981, this formula computed a value of -1 for them. Because the previous surfacing dates were not known, these records had to be excluded from the analysis.

Daily traffic is measured at a selected number of points on each route. The values of AADT and MADT for each CDS mile were computed by using the following procedure:

1. Calculate the value of ADT at both end points of the CDS mile by using linear interpolation.
2. If none of the original points at which ADT data were collected falls within this CDS mile, set ADT to the average of the two values calculated in Step 1.
3. If one or more of the original points at which ADT data were collected falls within this CDS mile, set ADT as follows:
    a. Define N-1 intervals where N includes the two endpoints and the other points falling within this CDS mile;
    b. Compute the average ADT for each of the N-1 intervals;
    c. Multiply the average ADT by the length of the interval as a fraction of a mile for each interval; and
    d. Set ADT for this CDS mile to the sum of all N-1 weighted averages.

In some instances, the number of miles between two points on a route on which ADT is measured is significant. The value of ADT for many of these CDS miles would be a general approximation.

This procedure was first done for annual ADT and then repeated for April and May monthly ADT. April and May were selected because most of the pavement damage due to traffic would be expected to occur during the spring thaw period.

Select an FWD Record for Each Pavement Inventory Record

The FWD data were recorded at every 0.2 CDS mile on each route. For numerous sections of the routes, data were recorded on several occasions during the season. This was done because it was not known when a section of road was in its weakest condition. For most records in the pavement inventory file, more

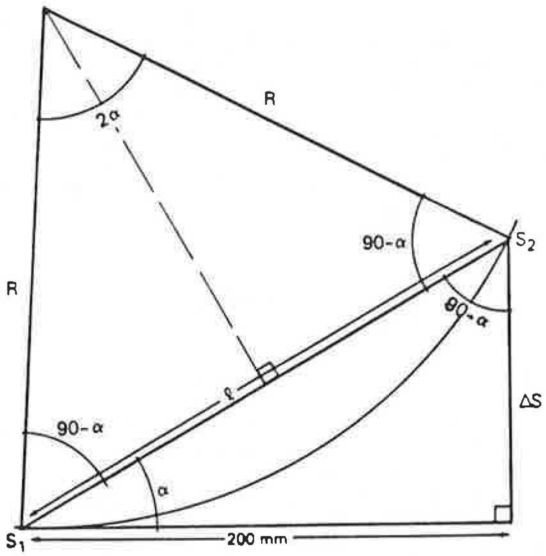

FIGURE 1 Illustration of radius of curvature.

than one FWD record exists. It was decided that a representative record should be selected and that it should represent the CDS mile in its weakest condition. The criterion used to select the FWD record was the radius of curvature. The radius of curvature is the radius of the circle, which is based on the first two sensor readings as described in the following procedure and shown in Figure 1.

1. Let S_1 and S_2 be Sensor No. 1 and Sensor No. 2 readings, respectively.
2. Let $\Delta S = (S_1 - S_2)/1{,}000$.
3. Let ℓ be the length of the chord between S_1 and S_2 on the circle. Because the distance between Sensor No. 1 and Sensor No. 2 on the FWD is 200 mm, a right triangle exists the hypotenuse of which is ℓ and the base of which is 200 mm. The Pythagorean theorem allows us to compute ℓ^2 with the following formula:

$$\ell^2 = (\ S)\Delta + 200^2 \qquad (2)$$

4. Also shown in Figure 1 is a right triangle the hypotenuse of which is the radius of the circle, R, and whose base has a length of $\ell/2$.
5. Noting that the three angles of the triangle in Step 3 are the same as those for the triangle in Step 4 and defining the angle α as is shown in Figure 1, the following formulas are derived:

$$\sin \alpha = \Delta S/\ell \qquad (3)$$

$$\cos 90 - \alpha = \ell/2/R = \ell/2R \qquad (4)$$

$$\cos 90 - \alpha = \sin \alpha \text{ (trigonometric identity)} \qquad (5)$$

$$\Delta S/\ell = \ell/2R \qquad (6)$$

6. Algebraic manipulation gives

$$R = \ell^2/2\Delta S = [(S_1 - S_2)^2 + 200^2]/[2(S_1 - S_2)] \qquad (7)$$

Because smaller values of the radius of curvatures would indicate a pavement with lower structural strength, the FWD record with the smallest radius of curvature was used to represent a CDS mile in its weakest condition. The information on this FWD record was combined with the information on the pavement inventory record to form a single new record.

Search for Suitable Fatigue Cracking Prediction Model

The evaluation of alternative fatigue cracking prediction models was performed by using the multiple linear regression technique and engineering judgment. The first group of regressions was done by using a value of Sensor No. 1 that was adjusted to a standard weight and temperature. The predictor variables that were tried were the seven sensors, radius of curvature, age, AADT, MADT, temperature, and falling weight. A model with an r-squared (R^2) value greater than .20 could not be found. The transformations of these variables that were tried included logarithmic, square root, square, reciprocal, reciprocal square root, and reciprocal square. For temperature and weight, subtracting a constant was tried so that number of degrees above freezing and amount of weight over a specific value could be added to the model. None of these transformations considerably increased R^2 and in most cases actually decreased it. The interaction between age and AADT and MADT was added with no success. Finally, the logarithmic, square root, and reciprocal transformations of fatigue cracking were tried; they also did not yield satisfactory results.

The analysis just described was repeated for Sensor No. 1 with it only adjusted by falling weight; the same results were obtained. The analysis was repeated using the unaltered value of Sensor No. 1. The results were similar to those of the previous two analyses. It should be noted that because the radius of curvature computation depends in part on the value of Sensor No. 1, adjusting its value could, and in many cases did, cause a different FWD record to be selected for a particular pavement inventory record. Because the adjustment for Sensor No. 1 values did not change results significantly, only unadjusted values of Sensor No. 1 were used in subsequent analysis.

Data screening based on fatigue cracking, temperature, falling weight, and route number was tried next. When screening data, records that were in a specified range of one or more variables should be selected. The motivation is that by removing unusual cases, the prediction will be improved. Data screening based on fatigue cracking, falling weight, Sensor No. 1 value, or any combination thereof did not result in a satisfactory model.

At first, selecting records with temperatures in the range of 50 to 80°F appeared to show some promise. But on closer inspection it became apparent that most of the records being excluded were for either Route 170 or Route 180. If only the records corresponding to Routes 130, 150, and 190 are included, then an R^2 of .40 can be achieved. Including only the records of Routes 170 and 180 resulted in an R^2 below .20. A discussion with Billy Connor of the Alaska DOTPF provided valuable insight at this point of the analysis; he said that Routes 170 and 180 were built more recently than the other routes and used different standards. Even the best model that could be found did not explain most of the variation as is reflected in an R^2 below .50. Rather than predicting fatigue cracking for a CDS mile, perhaps predicting the average fatigue cracking for a logical grouping of CDS miles would give better results. This approach is described in the remaining sections of this paper.

Group Data for Further Analysis

A surfacing project on a route covers a consecutive group of CDS miles on that route and is therefore a natural criterion for grouping the data. The data were first ordered by route number and within each route by CDS mile number. The surfacing projects were then numbered consecutively beginning with Route 130 and continuing through Route 190. A total of 35 surfacing projects were found on the 5 routes. For reasons explained earlier in this paper, age could not be established for two of these projects and they had to be excluded from the analysis.

The data in each project were then divided into 3 groups based on the value of Sensor No. 1. These groups were defined as follows:

Group No.	Range of Sensor No. 1
1	0-600
2	60-1,000
3	1,001+

For some projects, the Sensor No. 1 values fell into only one or two of these ranges and therefore only one or two groups were used in the analysis. A new file with one record for each group in each project was created. These records have the same variables as the CDS mile records plus one more. The value for a variable on the new record is the average of the values for that variable across all the records in the group it represents. The variable added to the record is the case weight, which is the number of CDS miles in the group. Table 1 gives data on the first 4 projects on Route 130. Because of the large number of variables, the table has been divided into two sections. Table 2 gives data on the new file whose records are the group averages. The value in the column labeled CDS is the first CDS mile in the project to which that record corresponds. The column headings used in Tables 1 and 2 are explained in Table 3.

Search for Fatigue Cracking Model Using Grouped Data

Weighted multiple linear regression was used to analyze the averaged data. The variable Case Wgt in Table 2 contains the weights used in the analysis. The variety of models that was tried with this data is similar to those models tried with the original data. None of the transformations appreciably improved the fit of the data, and in most cases resulted in a worse fit. With all five routes present in the analysis, the best fit that could be found had an R^2 of about .30.

The atypical values were smoothed out when the

TABLE 1 Subset of Data Before Grouping

Row	Route	Cds	Date	Project	Temp	Wgt	Radius	S1	S2	S3	S4	S5	S6	S7
1	130	239	820524	1	52	584	101010	695	497	374	247	145	83	48
2	130	240	820524	1	52	572	53619	831	458	275	151	80	43	22
3	130	241	820524	1	52	592	51021	1135	743	531	324	181	110	62
4	130	242	820524	1	52	642	57143	1210	860	617	405	262	141	70
5	130	243	820524	1	52	618	72464	976	700	492	287	167	75	46
6	130	244	820524	1	56	562	82988	582	341	195	108	65	42	27
7	130	245	820524	1	56	651	62696	701	382	412	269	163	88	44
8	130	246	820524	1	56	639	75188	628	362	218	111	60	40	27
9	130	247	820524	1	56	592	98522	612	409	280	164	95	53	29
10	130	248	820524	1	56	588	117647	577	407	305	196	117	71	43
11	130	249	820524	1	56	584	75472	616	351	203	113	70	48	33
12	130	250	820524	1	56	658	81633	680	435	261	136	81	53	32
13	130	251	820428	1	54	755	67114	672	374	194	62	8	5	4
14	130	252	820428	1	54	745	74350	617	348	164	42	17	5	4
15	130	253	820428	1	54	707	62500	775	455	238	91	25	3	7
16	130	254	820428	2	54	740	81633	522	277	134	43	12	6	5
17	130	255	820428	2	54	689	80645	706	458	287	175	76	13	7
18	130	256	820511	3	44	651	71943	811	533	352	210	117	53	21
19	130	257	820511	3	68	603	122699	358	195	122	78	50	29	15
20	130	258	820511	4	68	590	55097	1046	683	435	269	153	66	22
21	130	259	820428	4	67	596	71943	723	445	276	158	61	4	4
22	130	260	820428	4	67	593	56818	722	370	218	127	52	12	3
23	130	261	820428	4	67	626	53764	694	322	145	61	27	11	11

Row	Route	Cds	Project	Crk1	Crk2	Patch	Crk	Last Fix	Age Adj	Age	Adt	Apr	May	Apr+ May
1	130	239	1	14	0	0	14	65	0	17	698	3766	4262	8028
2	130	240	1	4	0	0	4	65	1	16	690	3621	4100	7721
3	130	241	1	0	0	0	0	65	0	17	682	3475	3939	7414
4	130	242	1	100	0	8	100	65	1	16	674	3329	3778	7107
5	130	243	1	32	0	11	43	65	1	16	666	3183	3617	6800
6	130	244	1	52	0	16	68	65	1	16	658	3037	3455	6492
7	130	245	1	100	0	29	100	65	1	16	650	2892	3294	6186
8	130	246	1	100	0	3	100	65	1	16	643	2746	3133	5879
9	130	247	1	44	0	0	44	65	1	16	635	2600	2972	5572
10	130	248	1	36	0	30	66	65	1	16	627	2454	2810	5264
11	130	149	1	68	0	22	90	65	1	16	617	2308	2649	4957
12	130	250	1	47	0	0	47	65	1	16	599	2163	2488	4651
13	130	251	1	85	0	0	85	65	1	16	580	2017	2327	4344
14	130	252	1	33	0	0	33	65	1	16	561	1871	2165	4036
15	130	253	1	48	0	4	52	65	1	16	543	1725	2004	3729
16	130	254	2	22	0	3	25	77	1	4	524	1579	1843	3422
17	130	255	2	0	0	39	39	77	1	4	505	1434	1682	3116
18	130	256	3	7	0	7	14	65	1	16	486	1288	1520	2808
19	130	257	3	6	0	6	12	65	1	16	467	1142	1359	2501
20	130	258	4	0	0	2	2	73	1	8	452	996	1198	2194
21	130	259	4	0	0	45	45	73	1	8	450	850	1037	1887
22	130	260	4	0	0	0	0	73	1	8	450	704	875	1579
23	130	261	4	0	0	24	24	73	1	8	450	559	714	1273

TABLE 2 All Data After Grouping

Row	Route	Cds	Project	Wgt	Crk	Age	Apr+May	Radius	S1	S2	S3	S4	S5	S6	S7
1	130	239	1	2	67.0	16.0	5878.0	100317	579.5	374.0	250.0	152.0	91.0	56.5	35.0
2	130	239	1	11	55.6	16.1	5627.6	74961	709.4	433.7	282.8	152.1	82.5	45.1	26.9
3	130	239	1	2	50.0	16.5	7260.5	54082	1172.5	801.5	574.0	364.5	221.5	125.5	66.0
4	130	254	2	1	25.0	4.0	3422.0	81633	522.0	277.0	134.0	43.0	12.0	6.0	5.0
5	130	254	2	1	39.0	4.0	3116.0	80645	706.0	458.0	287.0	175.0	76.0	13.0	7.0
6	130	256	3	1	12.0	16.0	2501.0	122700	358.0	195.0	122.0	78.0	50.0	29.0	15.0
7	130	256	3	1	14.0	16.0	2808.0	71943	811.0	533.0	352.0	210.0	117.0	53.0	21.0
8	130	258	4	3	23.0	8.0	1579.7	60842	713.0	379.0	213.0	115.3	46.7	9.0	6.0
9	130	258	4	1	2.0	8.0	2194.0	55097	1046.0	683.0	435.0	269.0	153.0	66.0	22.0
10	130	262	5	8	7.1	3.0	861.3	104252	487.5	289.3	181.1	119.9	73.8	39.1	20.4
11	130	262	5	3	10.7	3.0	846.0	72602	749.0	466.3	304.0	214.3	151.3	95.7	52.0
12	130	273	6	21	0.2	1.0	846.0	184802	362.0	248.8	175.3	114.9	69.7	39.9	22.5
13	130	294	7	13	8.8	9.0	846.0	121061	474.3	304.6	200.8	126.1	78.6	50.1	31.8
14	130	294	7	3	17.7	9.0	846.0	100248	711.0	507.0	357.3	229.3	136.7	70.7	43.0
15	150	12	8	5	16.6	14.0	1609.4	50495	843.4	440.6	284.4	166.2	94.6	54.8	33.2
16	150	12	8	3	22.3	14.0	1611.3	34406	1389.3	724.7	480.0	258.3	125.3	70.0	44.3
17	150	20	9	13	0.0	2.0	1522.4	64077	862.5	537.9	364.6	217.2	113.4	34.5	13.6
18	150	20	9	4	0.0	2.0	1503.0	49947	1704.8	1253.3	894.5	558.5	313.3	91.3	36.3
19	170	36	10	3	0.0	10.0	2519.3	119020	511.3	336.3	257.7	172.3	113.7	71.3	49.7
20	170	36	10	1	0.0	10.0	2512.0	96619	637.0	430.0	321.0	205.0	136.0	84.0	56.0
21	170	40	11	8	1.9	7.0	2402.4	109652	498.4	312.3	220.9	131.0	79.5	47.4	31.6
22	170	40	11	4	0.0	7.0	2466.3	86967	702.3	465.3	331.8	190.0	93.5	51.0	21.3
23	170	40	11	1	4.0	7.0	2387.0	67797	1098.0	803.0	690.0	452.0	266.0	128.0	93.0
24	170	53	12	4	1.0	17.0	2324.3	135302	403.8	255.5	176.3	103.5	62.0	33.8	18.8
25	170	57	13	12	7.5	5.0	2218.1	111282	484.6	300.8	207.7	122.8	73.3	40.8	29.8
26	170	57	13	2	0.0	5.0	2244.0	95465	674.5	464.0	321.0	183.0	96.5	39.5	19.5
27	170	71	14	20	0.6	12.0	1976.3	114806	467.1	289.6	198.1	113.4	66.6	39.2	25.4
28	170	71	14	9	0.4	12.0	1954.1	94465	674.4	459.0	332.6	197.9	109.4	53.1	34.2
29	170	71	14	2	2.0	12.0	1908.5	62438	1264.0	936.0	727.0	477.0	252.5	102.5	45.0
30	170	102	15	20	33.9	11.0	1638.2	93935	499.3	284.4	182.3	100.3	61.0	38.7	26.8
31	170	102	15	6	37.8	11.0	1612.8	85351	661.8	426.3	273.5	145.2	70.7	31.3	18.3
32	170	102	15	1	0.0	11.0	1715.0	20388	1377.0	396.0	200.0	73.0	28.0	9.0	15.0
33	170	129	16	13	4.5	10.0	1395.3	82484	517.1	266.3	156.2	80.1	49.8	33.0	23.2
34	170	129	16	16	7.6	10.0	1398.3	58538	697.3	348.8	221.4	128.5	76.0	43.7	26.8
35	170	129	16	1	7.0	10.0	1373.0	60606	1174.0	844.0	624.0	372.0	173.0	46.0	21.0
36	170	176	17	1	1.0	7.0	1700.0	50505	596.0	200.0	119.0	67.0	42.0	30.0	23.0
37	170	176	17	23	53.1	7.0	1599.6	45838	733.7	288.9	176.7	105.0	66.7	46.0	32.3
38	170	176	17	4	100.0	7.0	1496.8	36979	1198.8	627.8	426.0	189.3	82.5	41.8	25.8
39	170	204	18	9	15.2	10.0	1775.8	43216	796.2	329.3	214.2	126.0	69.4	40.9	26.4
40	170	204	18	3	20.3	10.0	1741.7	23097	1942.7	547.3	322.7	131.7	65.0	36.7	22.7
41	170	216	19	23	23.4	10.0	1937.8	41945	762.1	280.7	184.0	116.3	76.9	53.3	38.2
42	170	216	19	3	45.0	11.0	1932.7	24871	1277.3	407.3	259.7	155.3	96.3	62.7	41.0
43	170	242	20	3	10.3	5.0	2241.7	79349	482.7	229.0	155.7	96.0	56.7	34.7	24.0
44	170	242	20	24	20.0	5.0	2177.7	60930	749.4	397.9	288.1	193.6	123.8	81.1	54.5
45	170	242	20	3	21.0	5.0	2183.0	17324	3368.7	2011.7	1548.0	1120.0	805.7	539.3	73.0
46	170	272	21	5	19.2	12.0	2188.8	47464	895.0	472.6	340.2	217.6	126.6	74.2	45.4
47	170	272	21	13	40.1	12.0	2185.2	38605	1350.7	807.0	514.8	225.1	71.9	31.3	22.0
48	170	290	22	11	11.4	7.0	1966.6	47332	891.6	463.7	296.5	166.1	82.5	44.6	27.5
49	170	290	22	14	26.0	7.0	2017.1	38162	1358.2	745.0	462.9	234.0	93.3	49.1	29.6
50	170	315	23	1	2.0	2.0	8103.0	59880	383.0	49.0	159.0	83.0	33.0	11.0	8.0
51	170	315	23	3	.0	2.0	4676.7	53761	741.7	369.0	258.0	158.7	90.0	55.3	36.3
52	170	319	24	1	2.0	7.0	9816.0	53476	724.0	350.0	281.0	200.0	127.0	80.0	55.0
53	180	220	25	15	34.3	-1.0	1757.1	127207	431.5	265.1	189.5	132.5	96.6	59.3	40.4
54	180	220	25	9	35.0	-1.0	1513.8	79065	831.5	569.8	409.8	271.7	178.6	91.8	55.2
55	180	220	25	6	47.5	-1.0	1559.7	60985	1079.7	749.2	535.7	348.0	221.5	90.0	48.5
56	180	250	26	6	11.3	7.0	3879.8	105549	479.7	287.7	202.3	135.3	95.5	55.7	38.0
57	180	257	27	6	5.0	11.0	5188.7	120775	422.3	253.5	174.3	113.5	80.2	50.5	34.8
58	180	257	27	2	32.5	11.0	5726.5	55194	655.5	282.5	203.0	163.5	129.5	86.5	59.5
59	180	265	28	16	0.2	7.0	7808.6	168585	298.2	165.4	109.8	73.6	50.6	33.6	23.7
60	180	281	29	6	10.5	10.0	13317.5	152472	348.2	215.5	150.5	105.8	75.3	48.2	33.7
61	190	74	30	6	3.3	3.0	621.8	131447	497.0	344.3	235.8	138.7	70.8	37.7	22.5
62	190	74	30	2	23.5	3.0	593.0	89113	642.0	403.0	258.0	168.5	84.5	38.0	17.0
63	190	82	31	14	2.4	9.0	780.4	140347	476.0	328.2	221.7	136.2	73.0	38.0	21.4
64	190	82	31	1	0.0	9.0	811.0	117647	652.0	482.0	353.0	228.0	131.0	74.0	41.0
65	190	97	32	5	0.6	-3.0	928.2	132891	448.0	296.4	193.2	118.2	71.0	39.0	21.4
66	190	102	33	7	47.1	9.0	1022.2	135314	423.0	270.0	171.7	104.1	62.3	37.3	22.1
67	190	102	33	1	64.0	9.0	1030.0	90090	632.0	410.0	280.0	150.0	50.0	1.0	2.0
68	190	110	34	5	14.4	3.0	1117.8	111581	478.6	285.8	185.2	115.6	73.4	45.2	27.2
69	190	115	35	4	3.5	-1.0	1183.2	165682	364.8	242.8	165.5	103.3	63.8	39.3	23.3

data were averaged. Therefore, no motivation existed to screen out unusual data from the analysis. Dividing the data into two groups of routes, as was done with the original data, could be justified on the basis of inherent differences in the standards to which they were built. As before, one group of routes included Routes 130, 150, and 190, and the other group included Route 170 and 180. Favorable results with respect to both statistical and engineering criteria were achieved for both groups of routes.

Fatigue Cracking Model for Routes 130, 150, and 190

Detailed results of the statistical analysis of this group of routes are given in this section. The fol-

TABLE 3 Definition of Variable Names Used in Tables 1 and 2

Column Heading	Description
Row	Position of record in file
Route	First three digits of route number
CDS	Coordinated data system milepost
Date	Date of FWD data on this record
Project	Number assigned to specific surfacing project
Temp	Temperature (° F)
Wgt	Load (falling weight)
Radius	Radius of curvature
S1-S7	Sensor No. 1 to Sensor No. 7
Crk1	Fatigue cracking, Type I
Crk2	Fatigue cracking, Type II
Patch	Patching
Crk	Sum of Crk1, Crk2, and patch
Last Fix	Surfacing date (1900)
Age Adj	Age adjustment 1:1981 and 0:1982
Age	82 minus Last Fix minus Age Adj
ADT	Annual ADT
Apr	April ADT
May	May ADT
Apr + May	April and May ADT
Case Wgt	Case weight

lowing table gives the regression coefficients, including the constant term with their standard deviations and t-ratios.

Column	Coefficient	S.D. of Coefficient	t-Ratio = Coefficient/ S.D.
Constant	-5.329	6.910	-0.77
Age	0.9563	0.4731	2.02
MADT	0.007618	0.0001546	4.93
Radius	-7.029E-06	0.00004609	-0.15

(Note that for three of the variables the data given are averaged values rather than original data: Age, MADT, and Radius.)

The t-ratio can be used to evaluate the reliability of a coefficient. The absolute value of the t-ratio is taken first. If this value is 2.0 or greater, the coefficient is considered reliable. If this value is between 1.0 and 2.0, the coefficient has moderate reliability. If this value is below 1.0, the coefficient should be used with caution, particularly if extrapolations beyond the range of data used in this analysis are required. It can be observed that AGE and MADT have reliable coefficients, whereas the constant term and the coefficient for Radius are not reliable. In equation form, the model can be expressed as follows:

$$Crk = -5.33 + 0.956\ Age + 0.00762\ MADT - 7.03 \times 10^{-6}\ Radius \qquad (8)$$

where

Crk = fatigue cracking (%),
Age = time since last surfacing (years),
MADT = April and May ADT, and
Radius = radius of curvature (mm).

The value of R^2 is .796; it is the proportion of the total variation explained by the model. The value of .79 obtained for this model is considered good.

The analysis of variance table is as follows:

Due To	DF	SS	MS = SS/DF	F-Ratio
Regression	3	34,157.4	11,385.8	27.2912
Residual	21	8,761.1	417.2	
Total	24	42,918.6		

The sums of squares (SS), degrees of freedom (DF), mean squares (MS), and F-ratio are given. The SS column divides the total variation into Due to Regression (explained) and Residual (unexplained). The ratio of SS due to regression to total SS is R^2. The residual mean square is an unbiased estimate of the remaining variability in the data. The F-ratio is used to test whether the coefficients are all zero.

The following table gives the minimum, weighted mean, and maximum of each variable in the analysis.

	Crk	Age	MADT	Radius
Minimum	0.0000	1.0000	593.00	34,406
Weighted mean	12.7538	6.5846	1,648.36	109,888
Maximum	67.0000	16.5000	7,260.50	184,802

Using values of Age, MADT, or Radius that are outside these ranges (recall these are average values) should be avoided because extrapolation incurs greater uncertainty of the result.

The original value, predicted value, residual = predicted Crk - original Crk, and the standardized residual are given in Table 4. Standardized residual values are used to more easily locate unusual values or outliers. Values above 2.0 in absolute value are possible candidates for outliers and above 2.5 in absolute value are almost always considered outliers. They may be removed after the first pass but not on the second pass. Here a large standardized residual is left in the data because this is the second pass through the data.

TABLE 4 Predicted Values and Residuals for Roads Built to Older Standards

Row	Route	Project	Cds	Crk	Crk Fit	Residual	Std Res
1	130	1	239	67.0000	54.0481	12.9519	0.96663
2	130	1	239	55.6364	52.4053	3.2311	0.84879
3	130	1	239	50.0000	65.3837	-15.3837	-1.19797
4	130	2	254	25.0000	23.9929	1.0071	0.05035
5	130	2	254	39.0000	21.6686	17.3314	0.86352
6	130	3	256	12.0000	28.1636	-16.1636	-0.81057
7	130	3	256	14.0000	30.8592	-16.8592	-0.84080
8	130	4	258	23.0000	13.9288	9.0712	0.79336
9	130	4	258	2.0000	18.6494	-16.6494	-0.82351
10	130	5	262	7.1250	3.3689	3.7561	0.54984
11	130	5	262	10.6667	3.4752	7.1915	0.63351
12	130	6	273	0.2381	0.7738	-0.5357	-0.22209
13	130	7	294	8.8462	8.8725	-0.0263	-0.00537
14	130	7	294	17.6667	9.0188	8.6479	0.75530
15	150	8	12	16.6000	19.9660	-3.3660	-0.42031
16	150	8	12	22.3333	20.0938	2.2395	0.20772
17	150	9	20	0.0000	7.7317	-7.7317	-1.81808
18	190	9	20	0.0000	7.6834	-7.6834	-0.82613
19	190	30	74	3.3333	1.3535	1.9798	0.24641
20	190	30	74	23.5000	1.4317	22.0683	1.55700
21	190	31	82	2.3571	8.2372	-5.8801	-1.32098
22	190	31	82	0.0000	8.6299	-8.6299	-0.42665
23	190	32	97	0.6000	3.6776	-3.0776	-0.34733
24	190	33	102	64.0000	10.4920	53.5080	2.64358
25	190	34	110	14.4000	5.2719	9.1281	1.03076

In Figure 2, the standardized residuals are plotted against the fitted values to see if they are randomly distributed. A nonrandom pattern could indicate inadequacies of the model or the violation of an important assumption of linear models: homogeneity of variance. The individual sensors are not represented in the model because they did not contribute to the predictive ability of the model.

Fatigue Cracking Model for Routes 170 and 180

The results for Routes 170 and 180 are discussed in this section. The following table gives the regres-

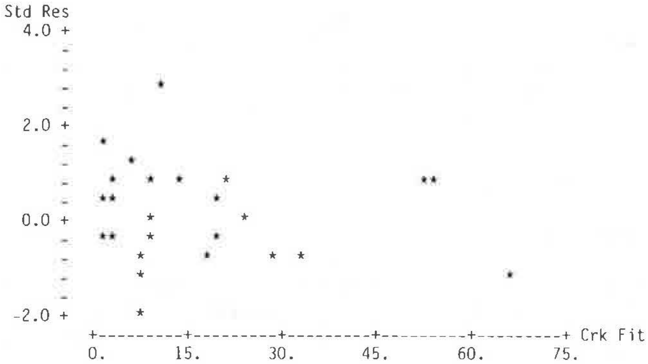

FIGURE 2 Plot of standardized residuals versus fitted values for roads built to older standards.

sion coefficients along with their standard deviations and t-ratios.

Variable	S.D. of Coefficient	Coefficient	t-Ratio = Coefficient/S.D.
Constant	14.094	9.532	1.48
Age	0.1716	0.5613	0.31
Radius	-1.169E-04	0.00006051	-1.93
S1	0.014818	0.007553	1.96
S5	-0.04991	0.02963	-1.68

The t-ratio for Age is low. The remaining coefficients are of moderate quality. In equation form,

$$Crk = 14.1 + 0.172\ Age - 1.17 \times 10^{-4}\ Radius + 0.0148\ S_1 - 0.0499\ S_5 \quad (9)$$

where S_1 is Sensor No. 1 reading in microns and S_5 is Sensor No. 5 reading in microns. Monthly ADT is not in this equation because it is negatively correlated with fatigue cracking. This is most likely due to the amount of interpolation necessary for these routes. The value of R^2 is .50 (rounded from .501), which is a moderately good value.

The hypothesis that all the coefficients are zero is rejected at the .0005 significance level with the value of F-ratio shown in the following analysis of variance table.

Due To	DF	SS	MS = SS/DF	F-Ratio
Regression	4	18,930.4	4,732.59	7.7944
Residual	31	18,822.5	607.18	
Total	35	37,752.8		

The ranges of the predictor variables shown in the following table should be kept in mind when using Equation 9.

	Crk	Age	Radius	S1	S5
Minimum	0.0000	2.0000	17,324	298.19	28.000
Weighted mean	13.0195	8.9297	78,660	755.62	92.371
Maximum	45.0000	17.0000	168,585	3,368.67	805.667

The predicted values and residuals given in Table 5 indicate that two cases are unusual with respect to the rest. However, this is the second pass through the data after having removed outliers from the first pass. The plot of the standardized residuals versus the predicted value of fatigue cracking does not indicate any distinguishable patterns (Figure 3).

TABLE 5 Predicted Values and Residuals for Roads Built to Newer Standards

Row	Route	Project	Cds	Crk	Crk Fit	Residual	Std Res
1	170	10	36	0.0000	3.8032	-3.8032	-0.27169
2	170	10	36	0.0000	7.1689	-7.1689	-0.29235
3	170	11	40	1.8750	5.8966	-4.0216	-0.47755
4	170	11	40	0.0000	10.8703	-10.8703	-0.89296
5	170	11	40	4.0000	10.3652	-6.3652	-0.26172
6	170	12	53	1.0000	4.0862	-3.0862	-0.27659
7	170	13	57	7.5000	5.4662	2.0338	0.31463
8	170	13	57	0.0000	8.9728	-8.9728	-0.52150
9	170	14	71	0.6000	6.3352	-5.7352	-1.19238
10	170	14	71	0.4444	9.6442	-9.1997	-1.17843
11	170	14	71	2.0000	14.9390	-12.9390	-0.76435
12	170	15	102	37.8333	12.2864	25.5470	2.58768
13	170	15	102	0.0000	32.6064	-32.6064	-1.34868
14	170	16	129	4.4615	11.3478	-6.8863	-1.05091
15	170	16	129	7.6250	15.5073	-7.8823	-1.36566
16	170	16	129	7.0000	17.4886	-10.4886	-0.42767
17	170	17	176	1.0000	16.1279	-15.1279	-0.61821
18	170	18	204	15.2222	19.0919	-3.8679	-0.49304
19	170	18	204	20.3333	38.6536	-18.3203	-1.52067
20	170	19	216	23.3913	18.5106	4.8807	1.13050
21	170	19	216	45.0000	27.1948	17.8052	1.28280
22	170	20	242	10.3333	10.0020	0.3313	0.02383
23	170	20	242	20.0417	12.7572	7.2845	1.80210
24	170	20	242	21.0000	22.6325	-1.6325	-0.34562
25	170	21	272	19.2000	17.5496	1.6504	0.15562
26	170	21	272	40.0769	28.0667	12.0102	2.17856
27	170	22	290	11.3636	18.8591	-7.4955	-1.06328
28	170	22	290	26.0000	26.3055	-0.3055	-0.05684
29	170	23	315	2.0000	11.4669	-9.4669	-0.39234
30	170	23	315	0.0000	14.6520	-14.6520	-1.08228
31	170	24	319	2.0000	13.4348	-11.4348	-0.46732
32	180	26	250	11.3333	5.3003	6.0330	0.61585
33	180	27	257	5.0000	4.1229	0.8771	0.09027
34	180	27	257	32.5000	12.7807	19.7193	1.15645
35	180	28	265	0.1875	-2.5166	2.7041	0.61505
36	180	29	281	10.5000	-0.6111	11.1111	1.17380

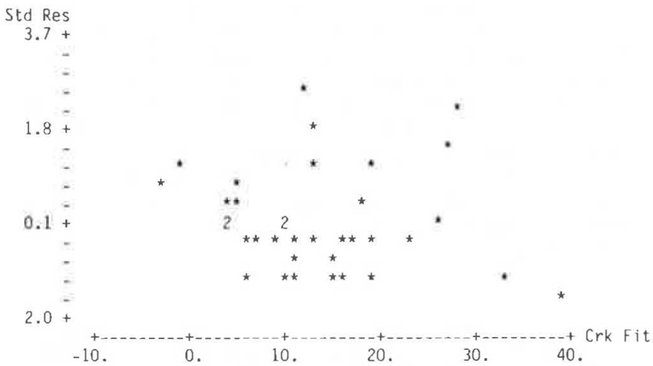

FIGURE 3 Plot of standardized residuals versus predicted value of fatigue cracking for roads built to newer standards.

SUMMARY AND CONCLUSIONS

Deflection measurements at the center of the load (Benkelman beam) were used in the past to develop a fatigue cracking prediction model for highways in Alaska. The Alaska DOTPF has acquired two FWDs to measure deflections for their road deflection inventory. Studies conducted by Alaska DOTPF staff have indicated that the deflection basin measured with the help of FWDs is a better indicator of the damage potential to highway surfaces than the single measurement of deflection under the load. Therefore, the current studies were proposed to develop a fatigue cracking prediction model using FWD data.

The data available on FWD measurements and the fatigue cracking observations were used in developing a suitable fatigue cracking prediction model for Alaskan highways. Preliminary analysis of the data indicated that a careful selection of the data obtained over a period of two to three months (during the thaw season) is needed to relate the deflection basin to fatigue cracking. Therefore, a method of screening and grouping the data has been developed. The data obtained after screening and grouping were used in developing the fatigue cracking prediction models for two groups of routes. The older routes (130, 150, and 190) were in one group and the newer routes (170 and 180) were in the other group. An R^2 of .79 was found for the group of older routes and one of .50 was found for the group of newer routes. Combining all five routes into a single analysis produced an R^2 of .30. If prediction for a route not in this analysis is desired, it will be necessary to classify it as being built to either older standards or newer standards.

To improve the prediction models (increase R^2), it is necessary to modify the existing road inventory procedures so that suitable data for this purpose can be obtained from the survey records. A brief description of some desirable modifications is included in the following section.

RECOMMENDATIONS

Consistency in the fatigue cracking records can be maintained if patching records are subdivided into patching of fatigue cracks and patching of other items. This will allow the appropriate proportion of patching to be included with the observed amount of fatigue cracking.

Any load restrictions imposed during the spring should also be recorded properly so that an estimate of traffic and age can be made for various sections of the route.

The number of points along each route at which traffic data are collected should be increased so that interpolated estimates of ADT are more accurate. To develop reliable prediction models, it would be desirable to establish a reasonable number of control sections along each route. These control sections should be observed more carefully than the regular inventory sections. Any possibility of inconsistency in observations should be avoided (to the extent possible). Chances of error can be minimized if the same personnel and equipment are used for measuring and recording the observations.

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