UNIVERSITY of DELAWARE

Research Update on a Next Generation Rail Wear Model

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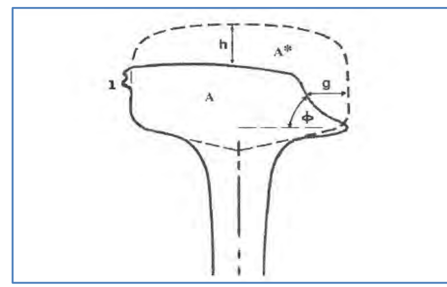
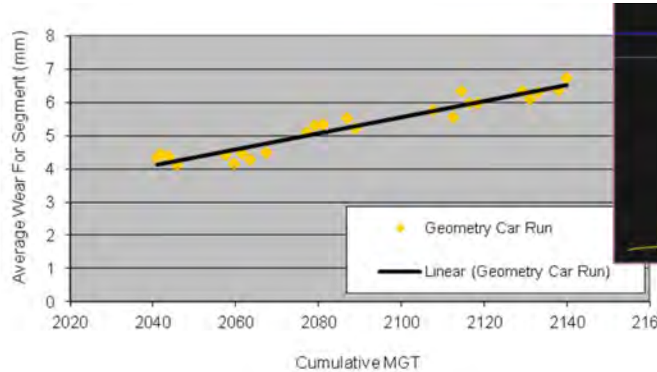
Overview

- Rail is a key component of the track structure
- Rail replacement and maintenance of the order of
  - $2-4 Billion in US alone
  - $8 to 10 Billion worldwide
- Essential for safe operations
- Major failure modes
  - Wear
  - Internal fatigue
  - Surface fatigue
- Long lead time item because of high cost of purchase and installation
  - Necessary for good planning of rail installation
  - Need for good forecasting model for planning of maintenance

Rail Wear Data

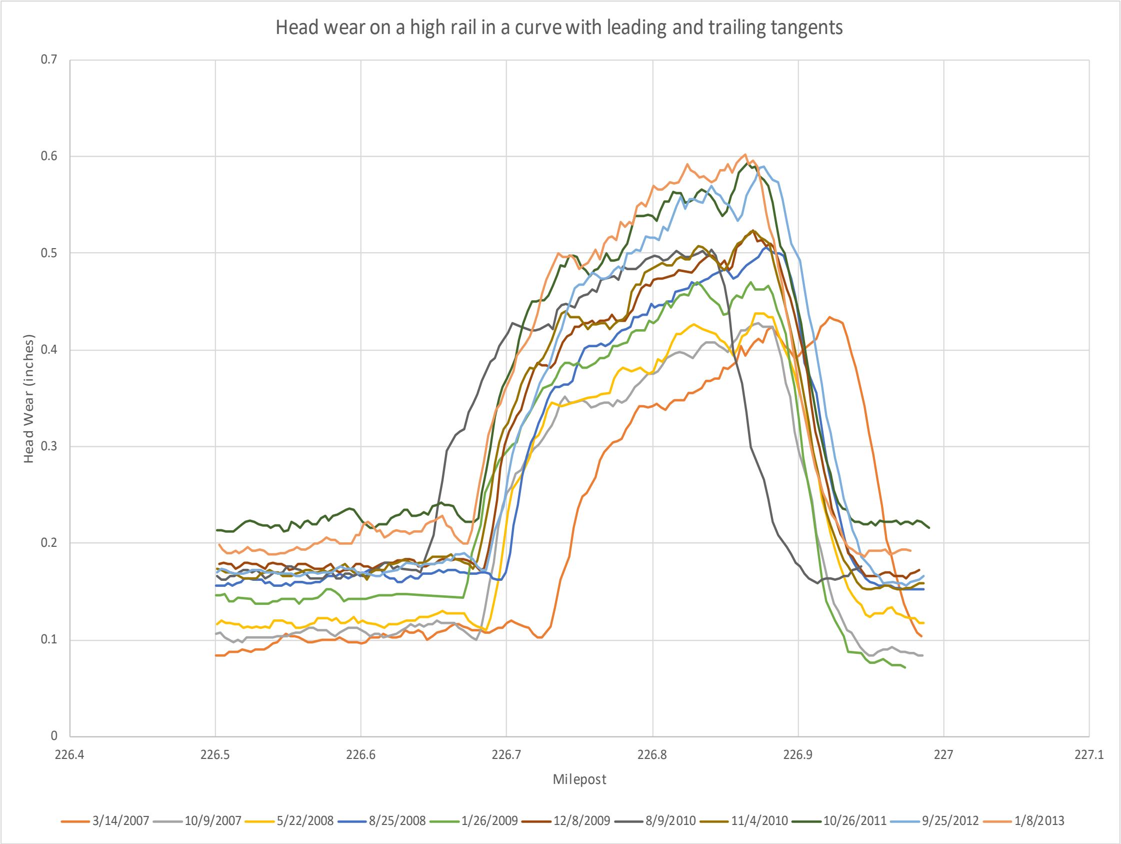
- Currently inspected using machine vision technology
  - Multiple times per year
  - Every 5’-15’
  - Cartesian coordinates of rail profile
- Generates terabytes of data Software to align measured profile to original profile
- Calculate wear parameters
  - A: Area of rail head remaining
  - A*: Area of rail head lost
  - h: Vertical wear (sometimes called head or top) taken at the center of the rail
  - g: Lateral wear (sometimes called gage or side), normally 5/8” below top of rail
  - l: Lip from plastic flow
  - Φ: Gage face angle
- Traditional modeling
  - Simple linear regression
    - Single parameter





Curve Snapshot

- High rail head wear
- 11 measurements in 6 years
- Longitudinal misalignment
- Easily see increase in wear
  - Over time/MGT
  - Uniform in leading tangent
  - Non uniform in curve
- Note misalignment of data



Variations in Data Sampling Intervals

- Common milepost range
- Each wear data point tagged with MP location
- 123 to 174 samples per inspection
- Min shows design sampling interval
  - 15.84’ and 14.78’
    - Likely two separate inspection cars
- Max shows missed samples
  - Due to bad profile data
- Average varies from 15.1 to18.9’

Date	Min	Max	Avg	Count
3/14/07	15.84	32.21	16.93	155
10/9/07	15.84	32.21	16.30	161
5/22/08	15.84	96.10	18.89	139
8/25/08	14.78	44.88	15.72	167
1/26/09	15.84	144.14	21.24	123
12/8/09	14.78	45.94	15.36	169
8/9/10	15.84	48.05	18.47	130
11/4/10	15.84	63.89	16.31	161
10/26/11	3.17	30.10	15.10	174
9/25/12	15.84	49.10	17.16	153
1/8/13	14.78	29.57	15.10	170

New Longitudinal Alignment Process

- Utilize time series stochastic process
  - Requires uniform interval

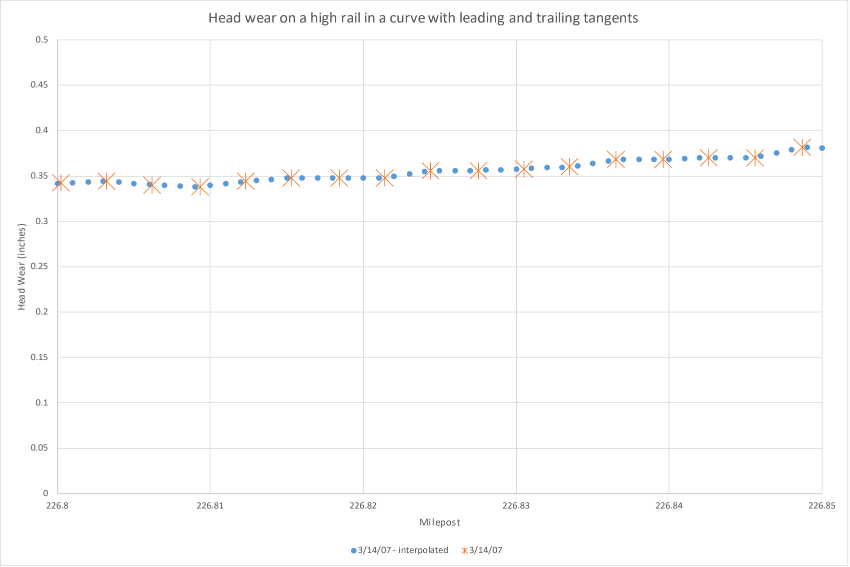
Estimate a function for each inspection series using linear interpolation or spline

Up-sample each inspection series to common interval and milepost

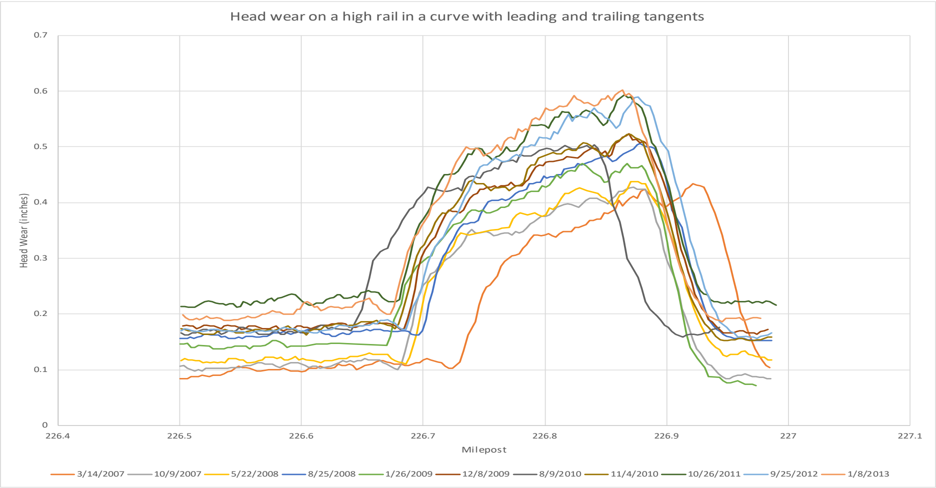
Determine lag to reference series using cross-correlation

$$p(l) = \frac{\sum_{i=1}^{n}[(x(i) - \bar{x}) * (y(i - l) - y_{bar})]}{\mathrm{Root}(\sum_{i=1}^{n}(x(i) - \bar{x})^2)\ \mathrm{Root}(\sum_{i=1}(y(i - l) - y_{bar})^2)}$$

Shift each inspection series to reference according to lag

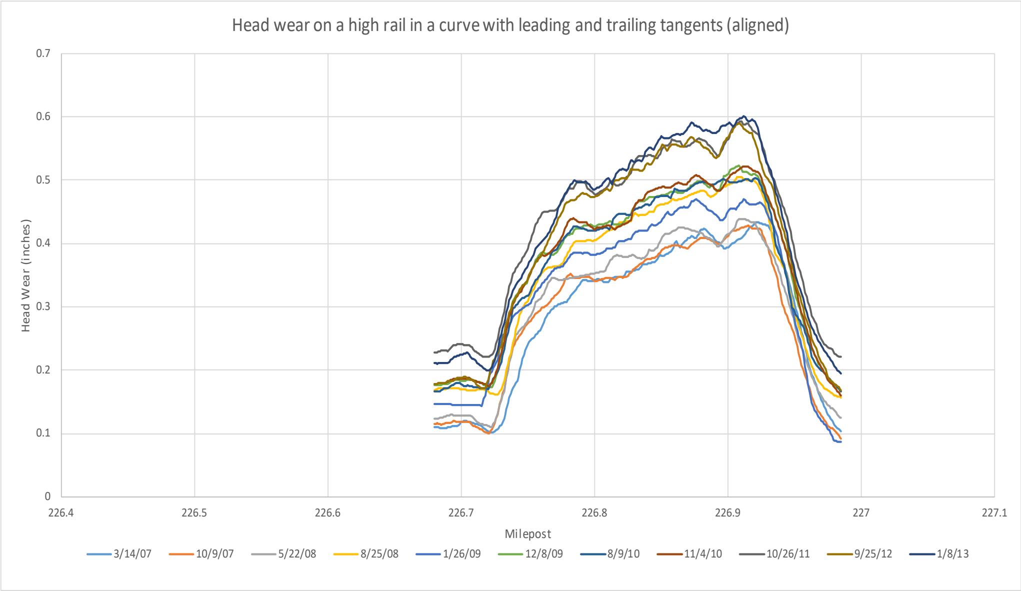


Aligned Data

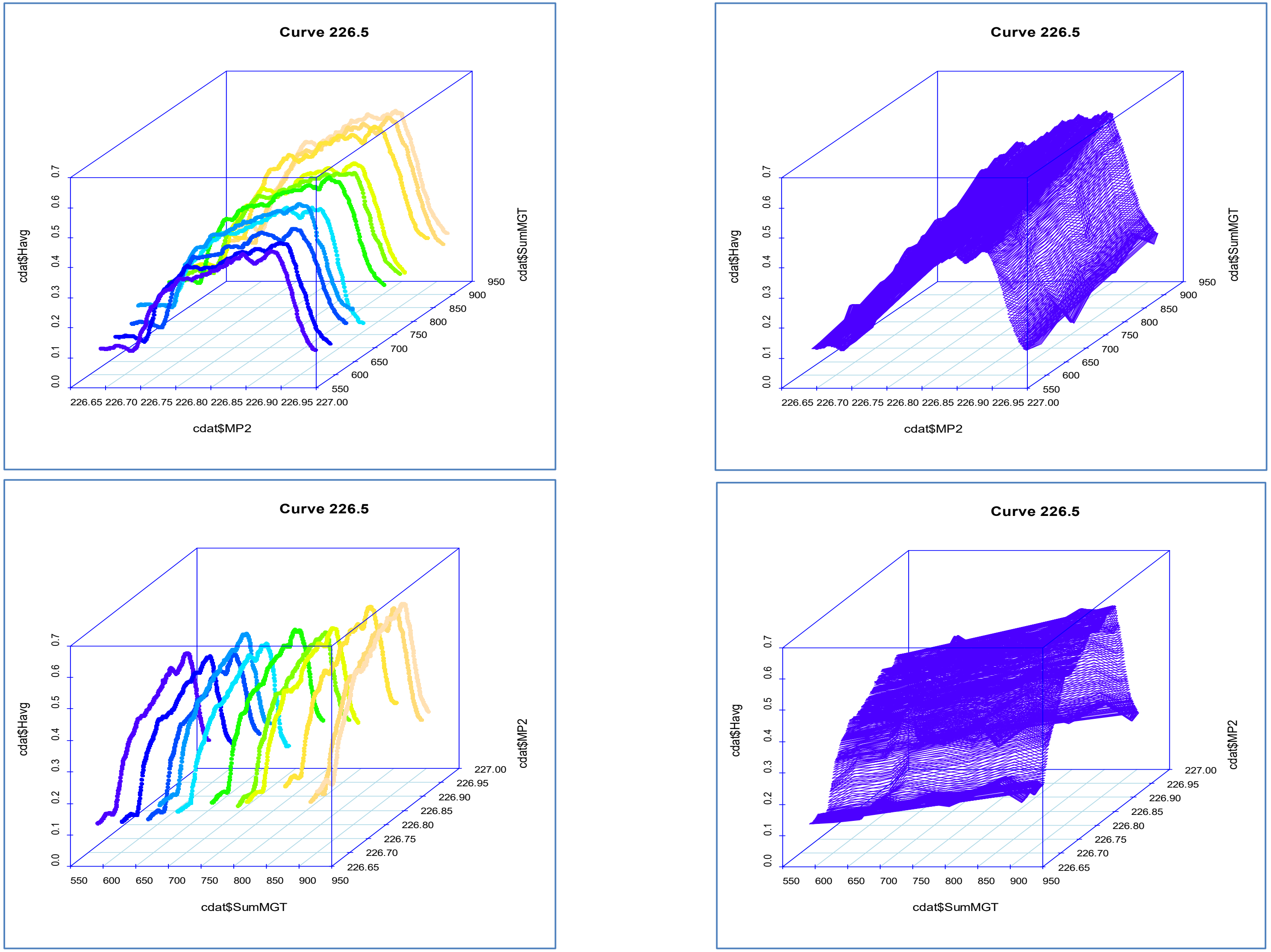


			Shift	
Insp Date	Corr Coef	Lag	Miles	Feet
3/14/07	Reference	0	0	0
10/9/07	0.82	42	0.042	222
5/22/08	0.86	37	0.037	195
8/25/08	0.87	31	0.031	164
1/26/09	0.78	45	0.045	238
12/8/09	0.84	39	0.039	206
8/9/10	0.69	80	0.080	422
11/4/10	0.82	44	0.044	232
10/26/11	0.83	44	0.044	232
9/25/12	0.86	32	0.032	169
1/8/13	0.80	49	0.049	259

Results in 400 samples for each inspection at same milepost locations with consistent distance interval



3-D Plot: Head Wear, MP, Sum MGT



ARIMA – Auto Regressive Integrated Moving Average

Make data stationary – remove linear trend

↓

Fit function – linear interpolation

↓

Up-sample – Common MGT interval

↓

Perform ARIMA modeling

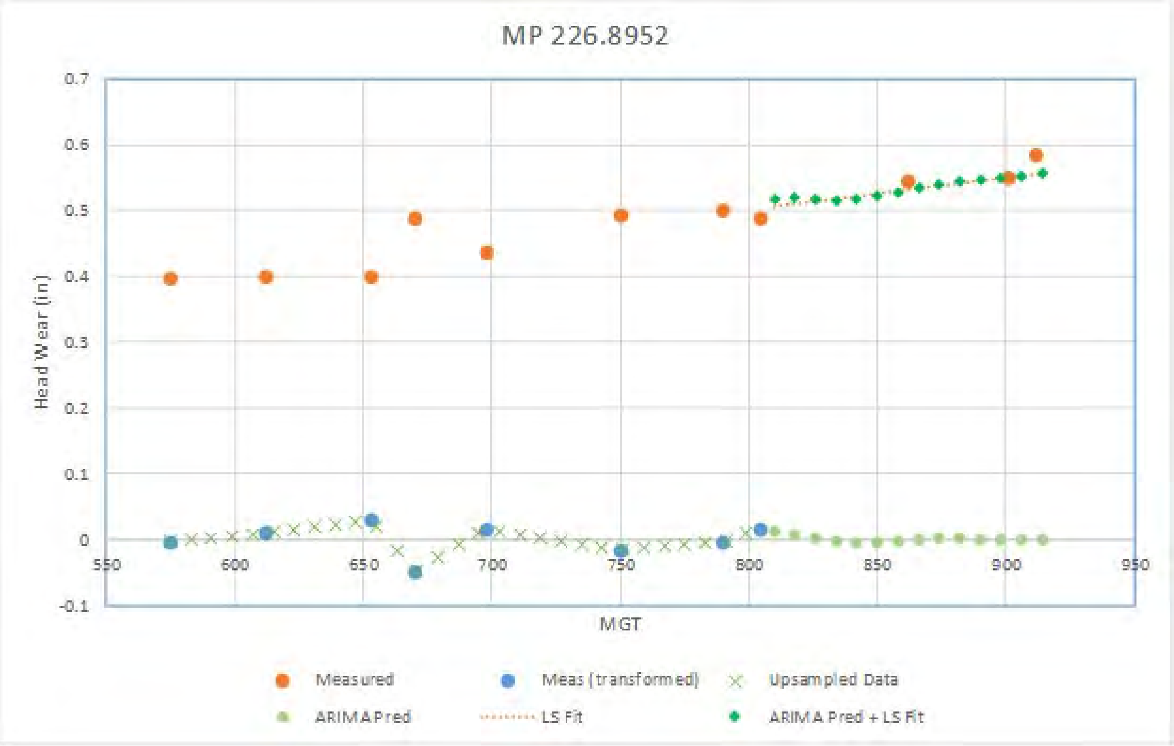
↓

Predict next MGT intervals

↓

Transform to linear trend

ARIMA(p, d, q) = model for describing time series data and for predicting future values



Handles calibration and measurement errors

Converges to linear trend in most cases

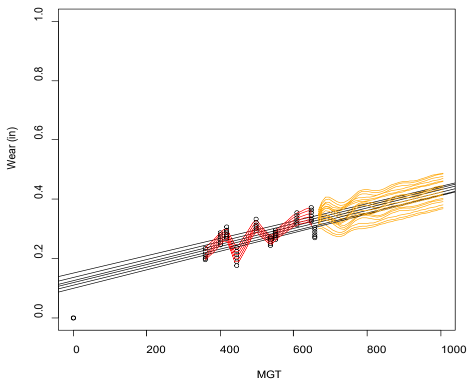
Model developed from 570-804 MGT

Forecast to 910 MGT to compare against next 3 measurements

ARIMA Application Process

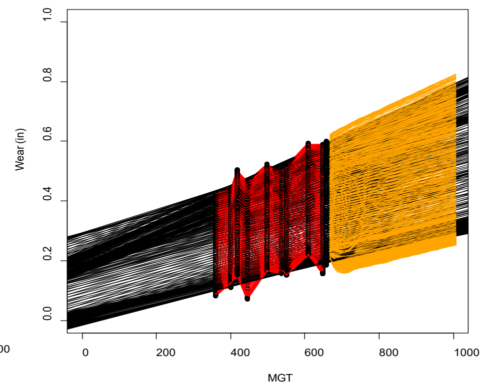
- Perform ARIMA process for each milepost of up-sampled data
- ARIMA factors (*p, d, q*) unique for each milepost
- Linear trend unique for each milepost
- Predict wear to defined MGT value

Subset of MPs in Spiral



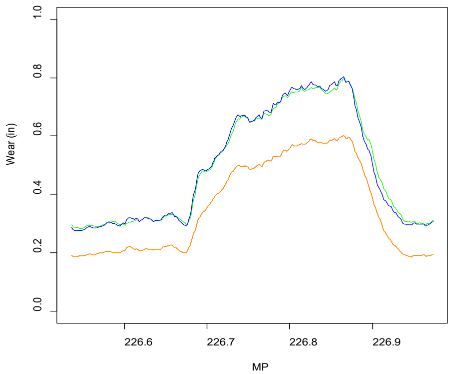
ARIMA forecast not straight line

All MPs



Last measurement varies
Rate varies

Resulting Forecast

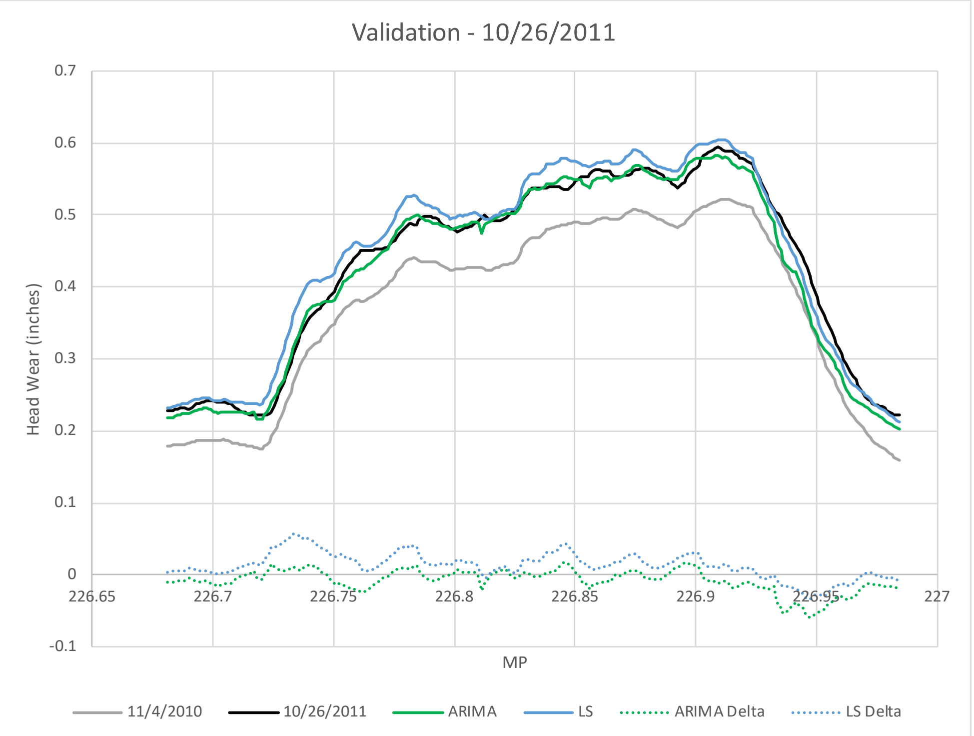


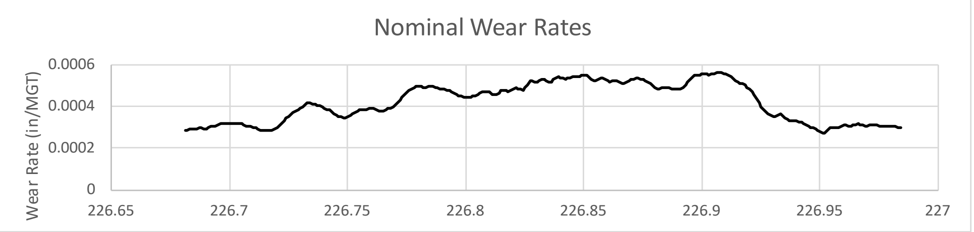
Forecast varies by Milepost

Validation – Entire curve

- Model developed based on 7 inspections from 3/14/07 to 11/4/10
- Predict for next inspection date; 10/26/2011
- ARIMA prediction shows very good agreement to actual
- Linear regression (LS) tends to overstate

	ARIMA	LS
Min (in)	-0.0586	-0.0331
Max (in)	0.0180	0.0564
Avg (In)	-0.0080	0.0131
SD (in)	0.0159	0.0180

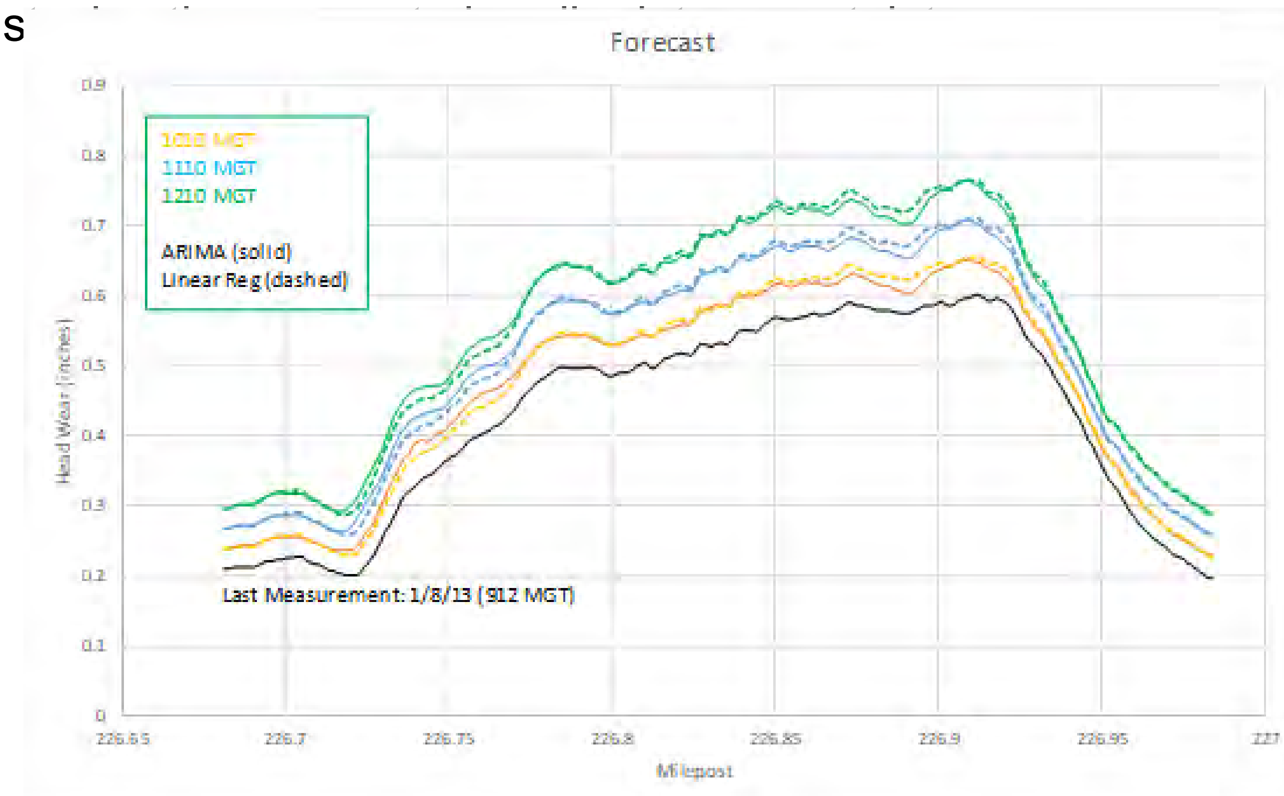




58 MGT (one year) produced 0.035” to 0.075” (average of 0.057”) of head wear in curve

ARIMA Forecast Example

- Traditional forecast uses mean or mean+SD of full body of curve (or segment) to determine rate of wear
- Wear rate non-uniform through curve
- Ability to forecast wear profile in curve
- Take advantage of s



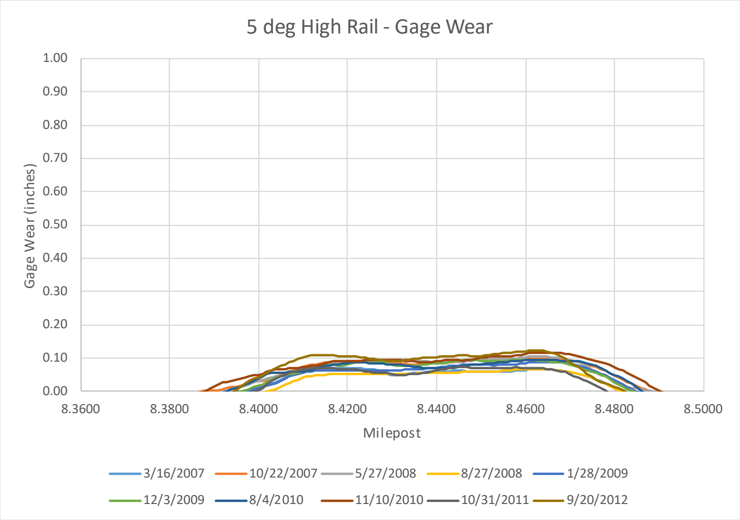
Case Study

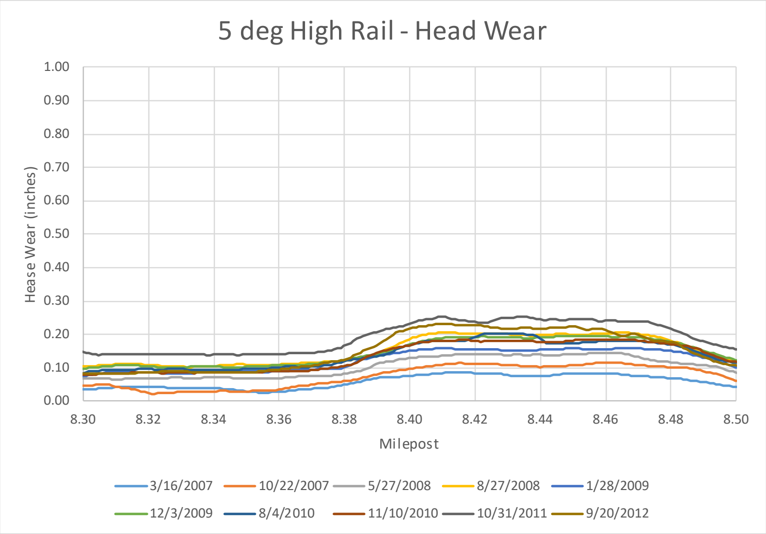
- Two separate curves studied

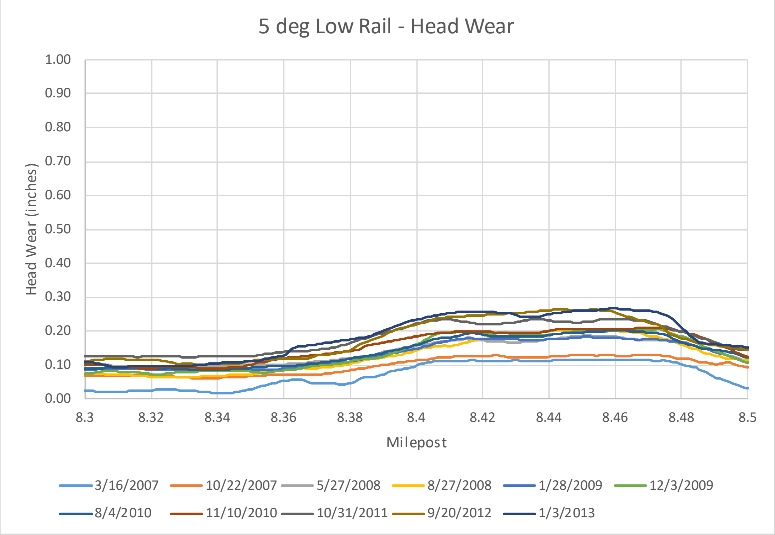
Rail	Length	Deg	SE	Rl Wt	Speed	Installed
1	634	5	1.5	141	25	2002
2	1795	7.25	1.75	141	25	2002

- Forecast to:
  - First instance a point in the full body would reach the limit
  - 50% of full body reaches limit
  - 100% of full body reaches limit
  - Based on 11/16" wear limit (head and gage)

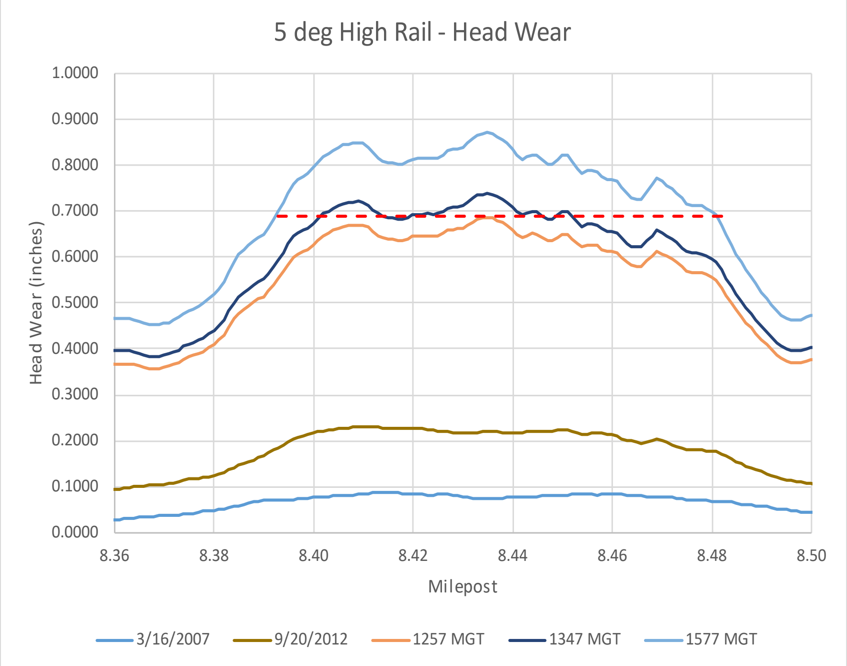
5 Degree Curve

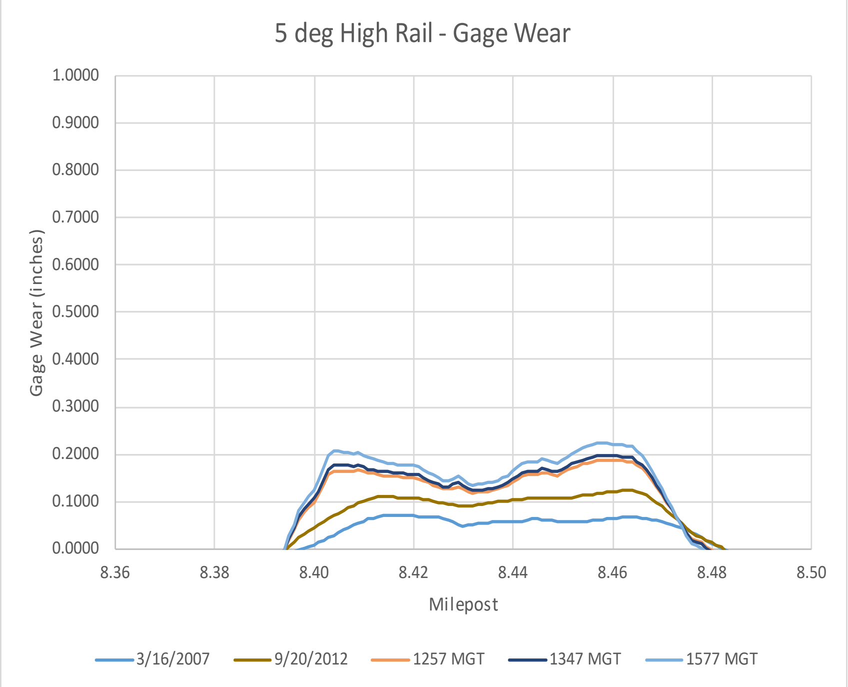


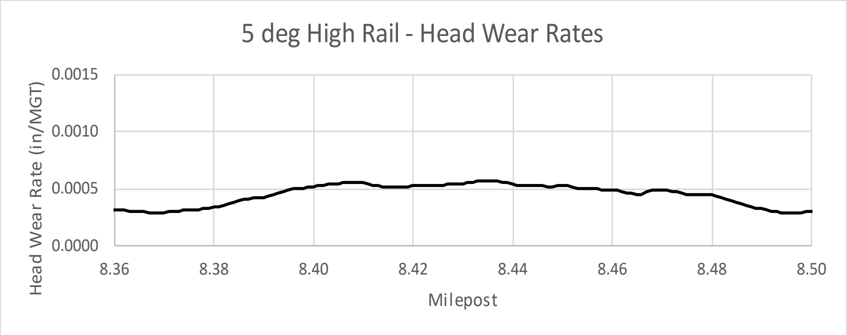


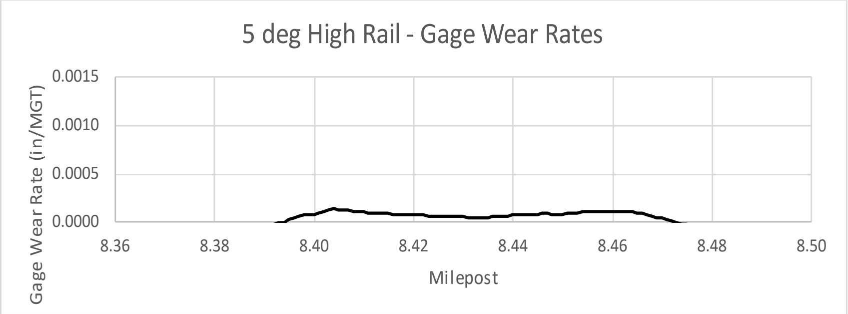


5 Degree Curve – High Rail Forecast

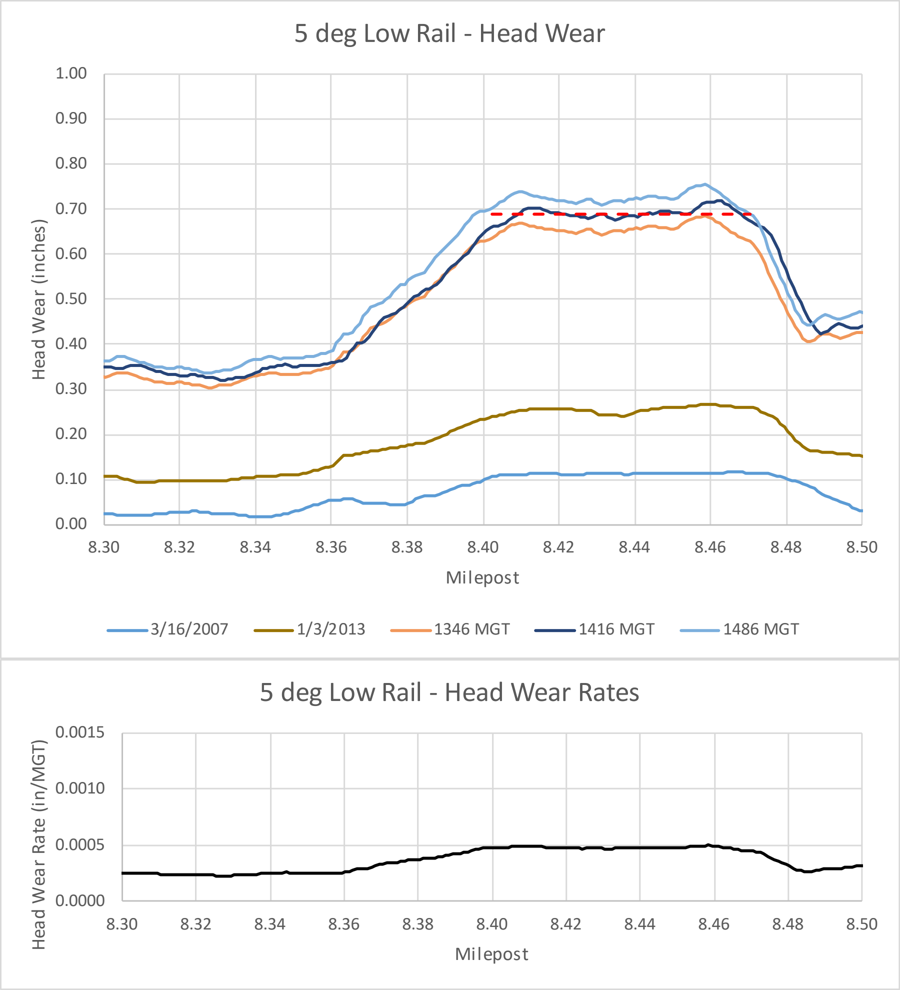








5 Degree Curve – Low Rail Forecast

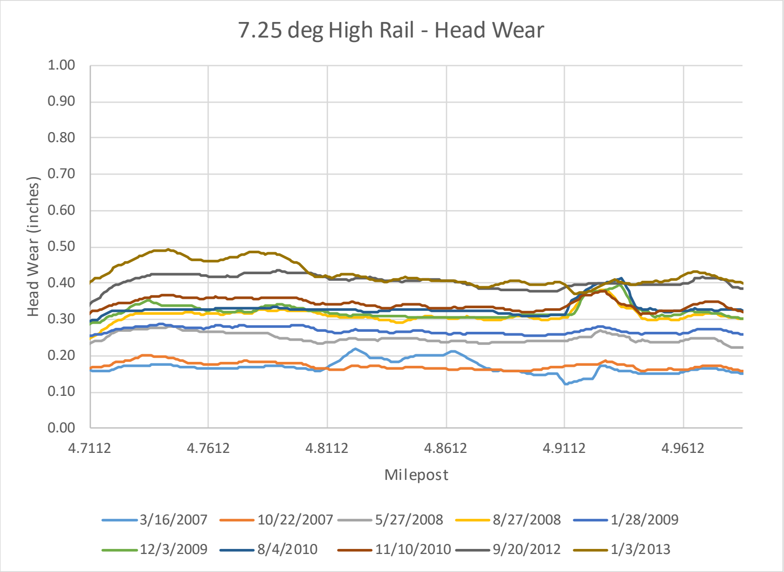


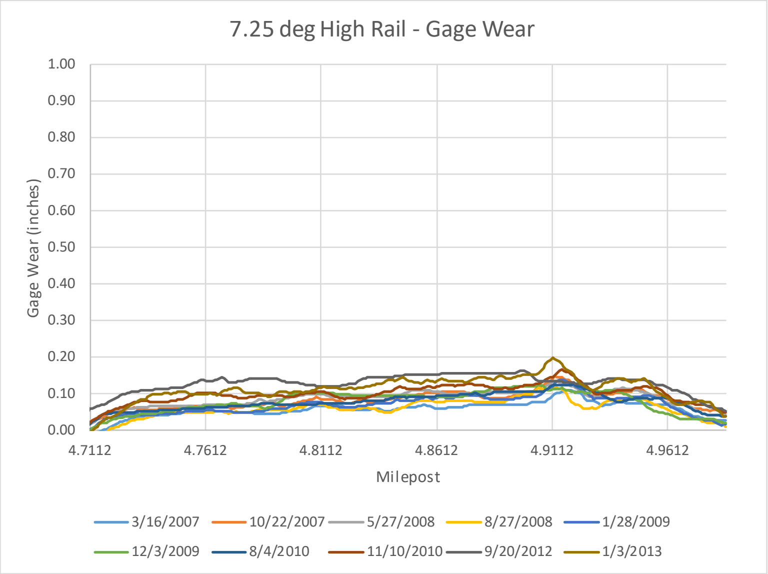
5 Degree Curve Summary

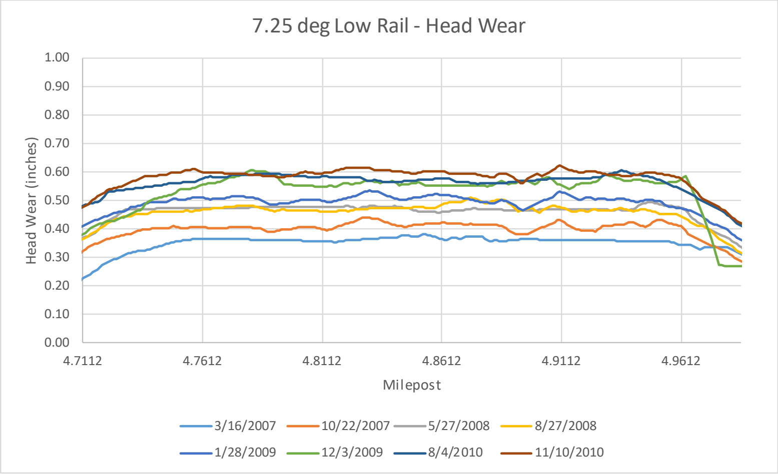
- High rail head wear has most severe rate
- Out paces gage face wear
- Similar to low rail head wear rate
- Head wear controls replacement
- Replace rail in year 2038 – 2045
  - Based on railroads determination of "failure"
- Both rails due between 2041-2045
  - Savings associated with replacing both rails at same time

	Wear Rates (in/100MGT)		
	5 Deg Curve		
	High Rail		Low Rail
	Head	Gage	Head
Minimum	0.0427	0.0003	0.0448
Maximum	0.0574	0.0137	0.0499
Average	0.0515	0.0081	0.0479
Std Dev	0.0036	0.0028	0.0011
	Cumulative MGT to Head Wear Limi		
	High Rail		Low Rail
First Hit	1257		1346
50%	1347		1416
100%	1577		1486
	Replacement Date (30 MGT/Yr)		
	High Rail		Low Rail
First Hit	4/21/2038		4/4/2041
50%	4/20/2041		8/4/2043
100%	12/17/2048		12/2/2045

7.25 Degree Curve

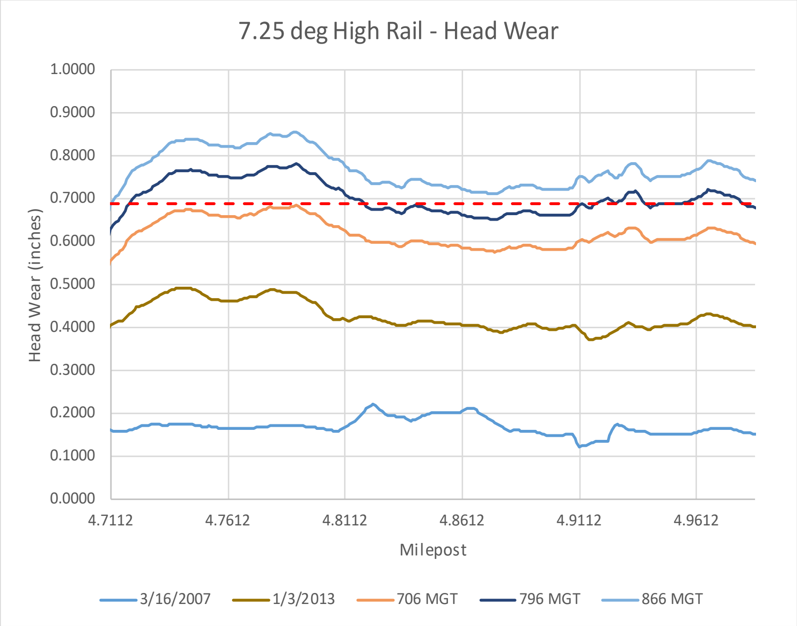


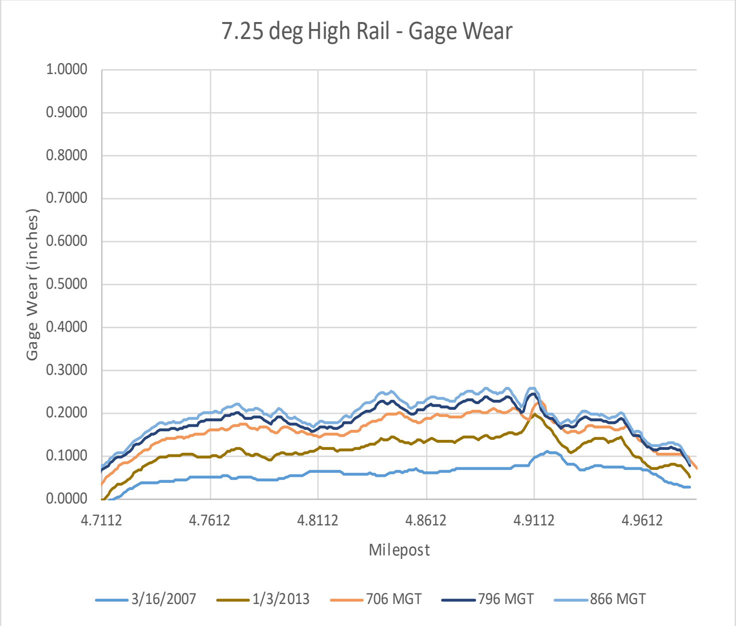


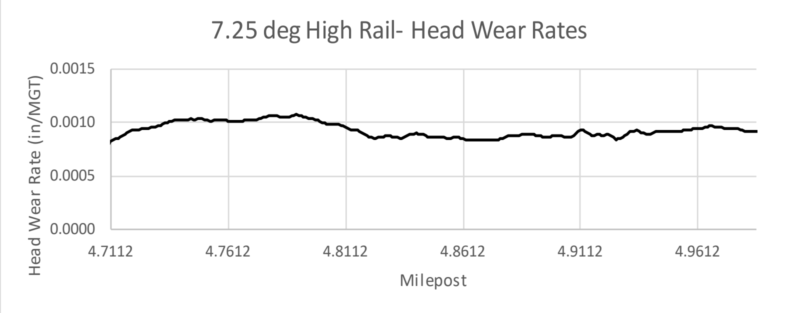


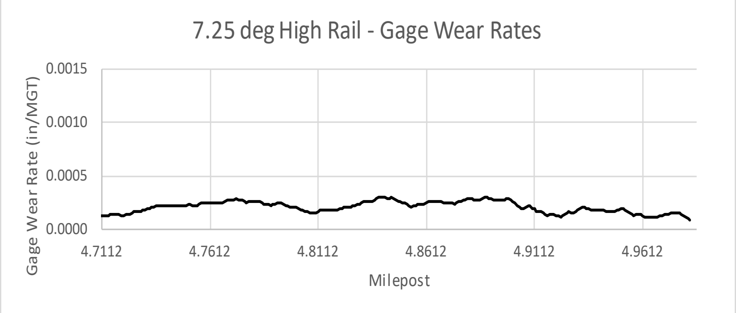
- Note average wear of 0.60” is close to limit of 0.69” as of last measurement (Nov. 2010)

7.25 Degree Curve – High Rail Forecast

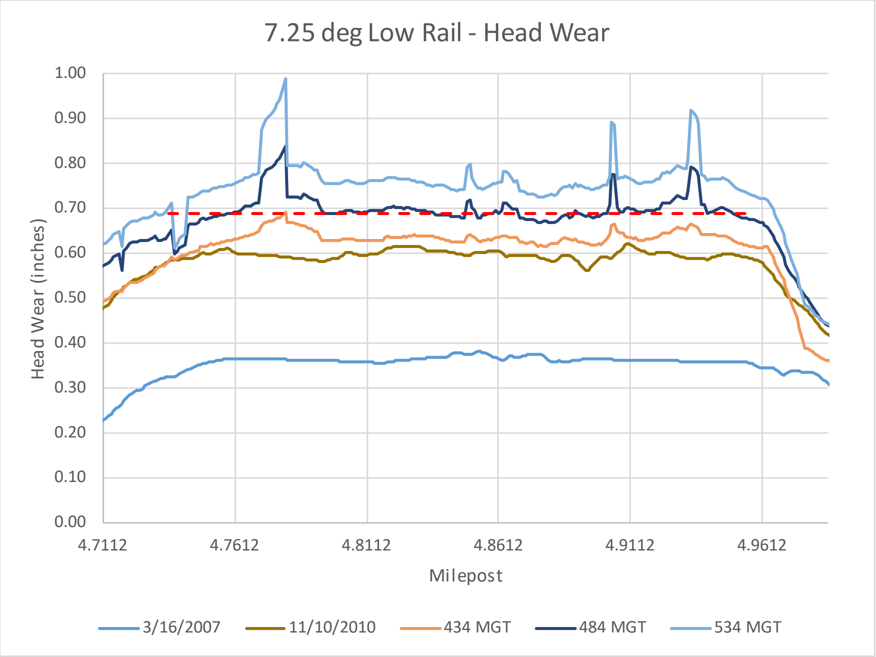


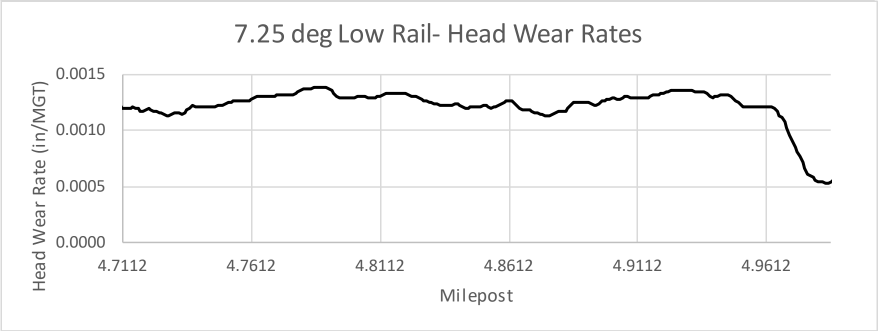






7.25 Degree Curve – Low Rail Forecast





- ARIMA forecast model has some inconsistencies at several locations
- These are currently being investigated

7.25 Degree Curve Summary

- High rail head wear out paces gage face wear
- Low rail head wear has most severe rate
- Head wear controls replacement
- Replace high rail in year 2019 – 2025
  - Based on railroads determination of "failure"
- Replace low rail in year 2011 – 2014
  - Last measurement in 2010
  - Rail actually replaced prior to September 2012 where next two inspections show minimal wear

	Wear Rates (in/100MGT)		
	7.25 Deg Curve		
	High Rail		Low Rail
	Head	Gage	Head
Minimum	0.0823	0.0092	0.1133
Maximum	0.1074	0.0311	0.1390
Average	0.0932	0.0211	0.1273
Std Dev	0.0069	0.0053	0.0060
	Cumulative MGT to Head Wear Limi		
	High Rail		Low Rail
First Hit	706		434
50%	796		484
100%	866		534
	Replacement Date (30 MGT/Yr)		
	High Rail		Low Rail
First Hit	12/9/2019		6/20/2011
50%	12/8/2022		2/17/2013
100%	4/8/2025		10/19/2014

Rail Lives

	5 Deg Curve				7.25 Deg Curve		
	High Rail		Low Rail		High Rail		Low Rail
Cumulative MGT at time of last measurement	489		498		498		416
MGT Remaining (50% Limit)	858		918		298		68
Life (MGT)	1347		1416		796		484

- Sharp curve low rail exhibiting very low life (< 500 MGT)
- Sharp curve high rail exhibiting reasonable life (800 MGT)
  - Due to head wear
  - Gage face wear being controlled
- Moderate Curve high/low rails exhibiting good lives (1350 – 1400 MGT)
  - Due to head wear
- 7.25 degree curve high rail wears faster than 5 degree curve
  - 2x for head
  - 3x for gage
- Head wear outpaces gage wear on high rail
- Low rail head wear dominant on severe curves
- Significant time (MGT) difference to replacement based on first hit, 50% of curve, 100% of curve
  - 3 to 10 year difference in remaining “life”

Conclusions

- Good longitudinal alignment of wear data allows for better understanding of wear rate distribution
- ARIMA stochastic process allows for refinement of wear forecasting
  - More accurate than Least Squares Linear Regression
- Approach allows for defining wear renewal forecast based on wear distribution in curve
  - 1st point, 50%, 100% past wear limit
- Process validated and case study presented

Future Research

- Determine applicability to combined wear parameters
  - Head and Gage
  - Head area loss
- Extend approach to transverse rail profile forecasting
  - Allow for forecasting of rail profile grinding
- Develop comprehensive wear equation
- Develop wear rate distribution analysis
  - Highlight geometry, unbalance issues
  - Identify lubrication effectiveness/implementation

Acknowledgements

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