Characteristic Service Life of Minnesota's Unbonded Concrete Overlay

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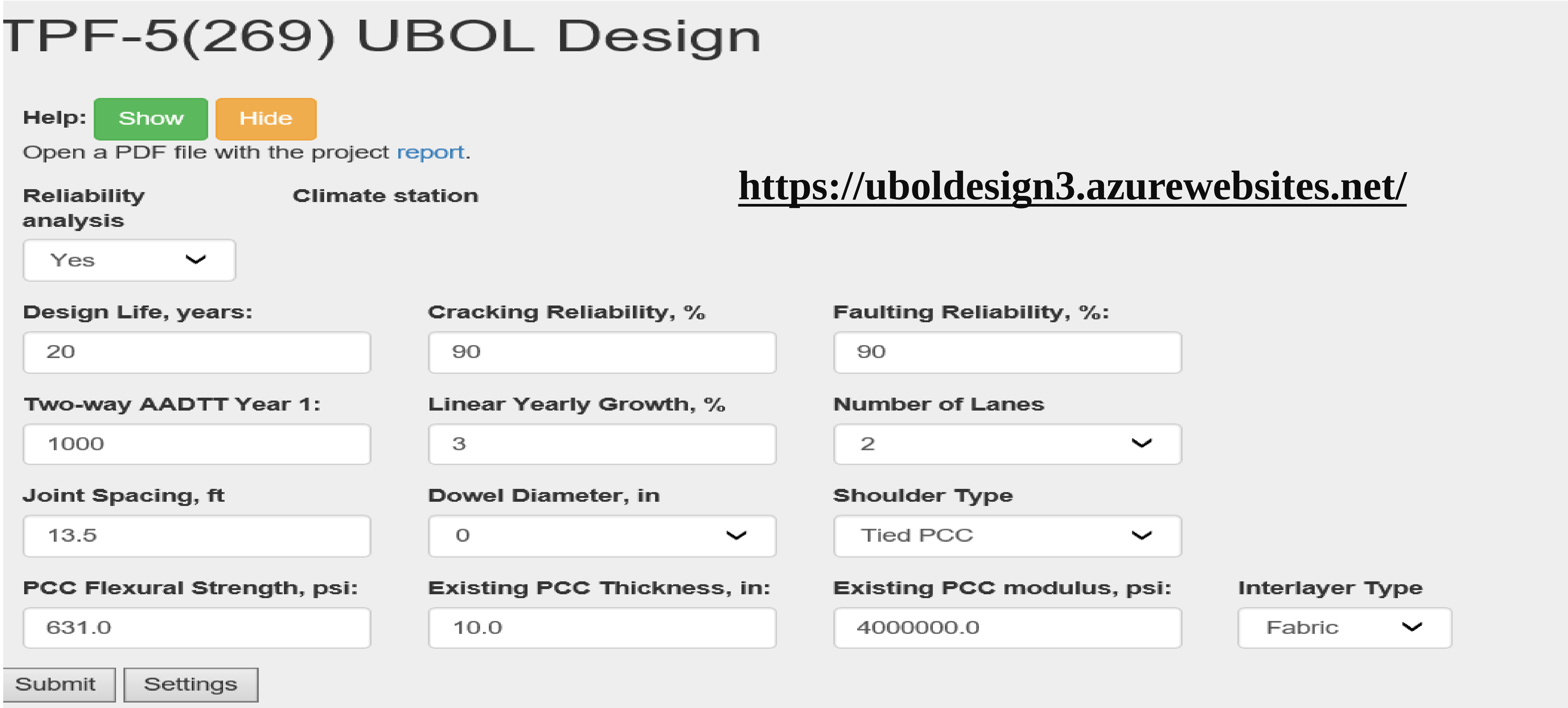
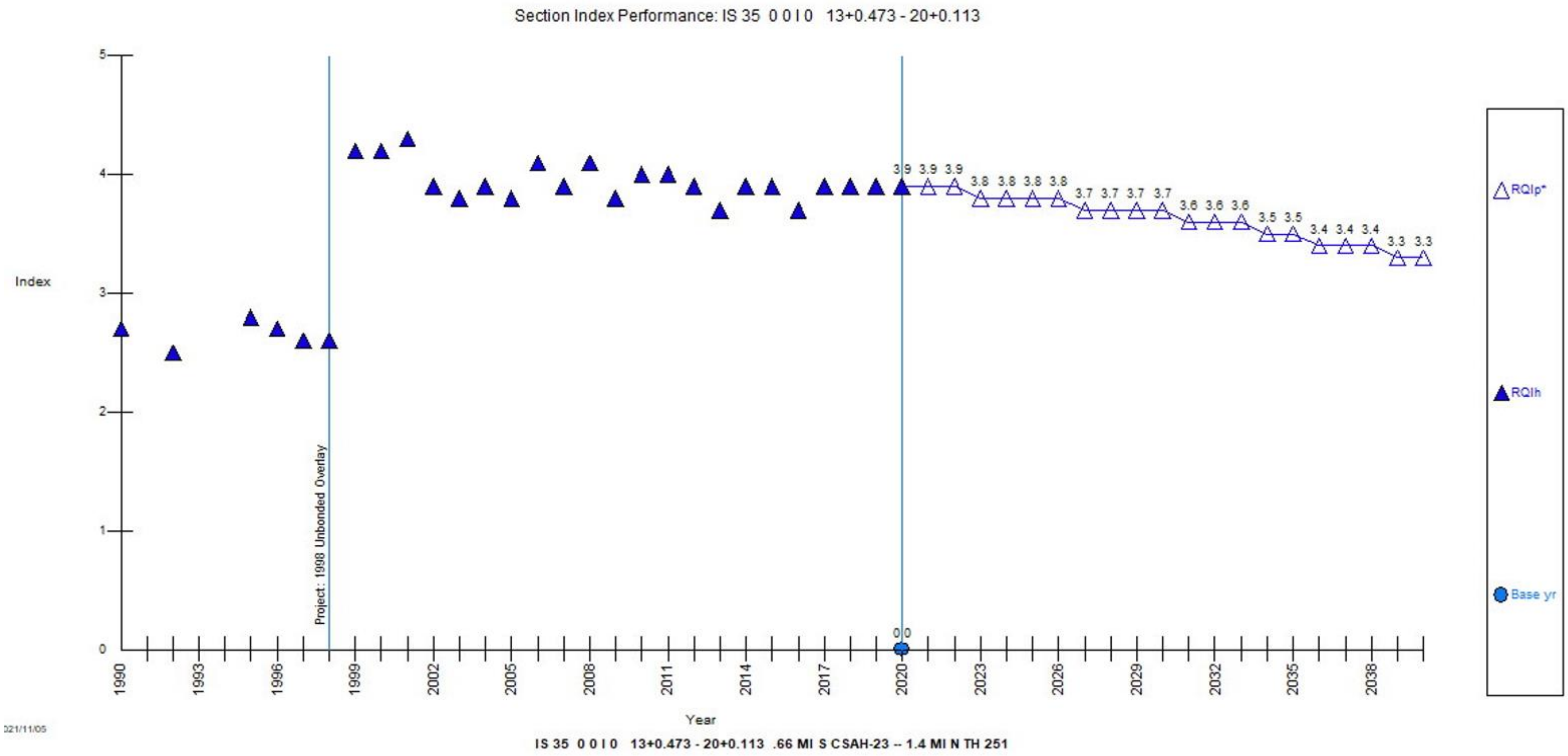
UBOL DESIGN



https://uboldesign3.azurewebsites.net/

My Favorite Pavement Section… Jerry Geib MnDOT



Published Paper

Published Paper

Izevbekhai, B.I., Farah, N. and Engstrom, G.M., 2020. Reliability Analysis of Minnesota's Unbonded Concrete Overlay Performance. Transportation Research Record, 2674(9), pp.617-626.

- **Norma Josephine Farah** Student Worker Paraprofessional (MnDOT) → **Greener Pastures Software Engineering**

- **Glenn M Engstrom** Director, Office of Materials and Road Research (MnDOT)

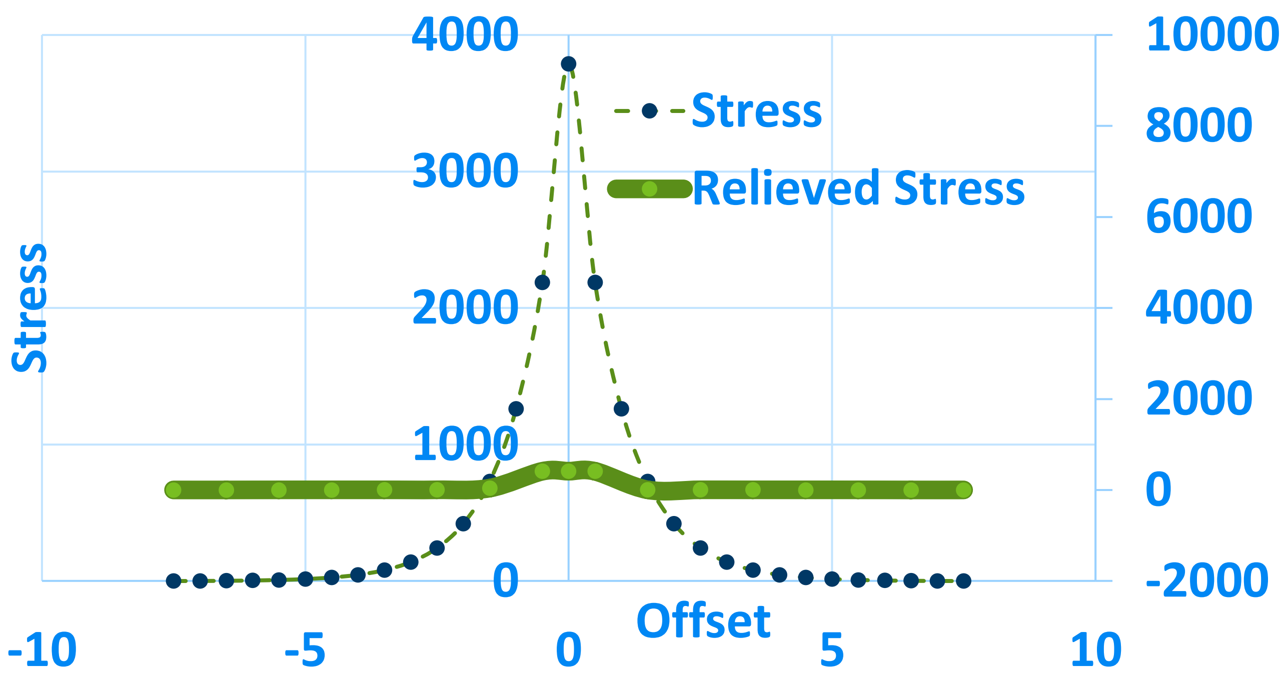
ORDER OF BUSINESS

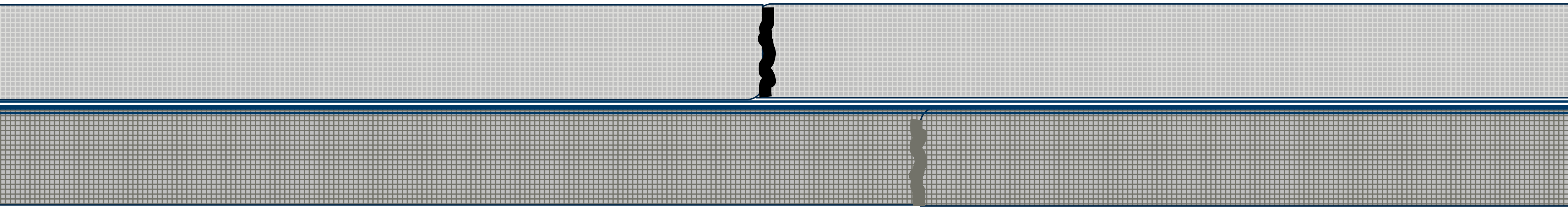
- Network Asset Implications
- Definitions and Characteristics
- Data Sourcing and Arrangement
- Performance Curve Characteristics
- Predictive Variables
- Weibull Analysis
- Closing

DEPARTMENT OF TRANSPORTATION

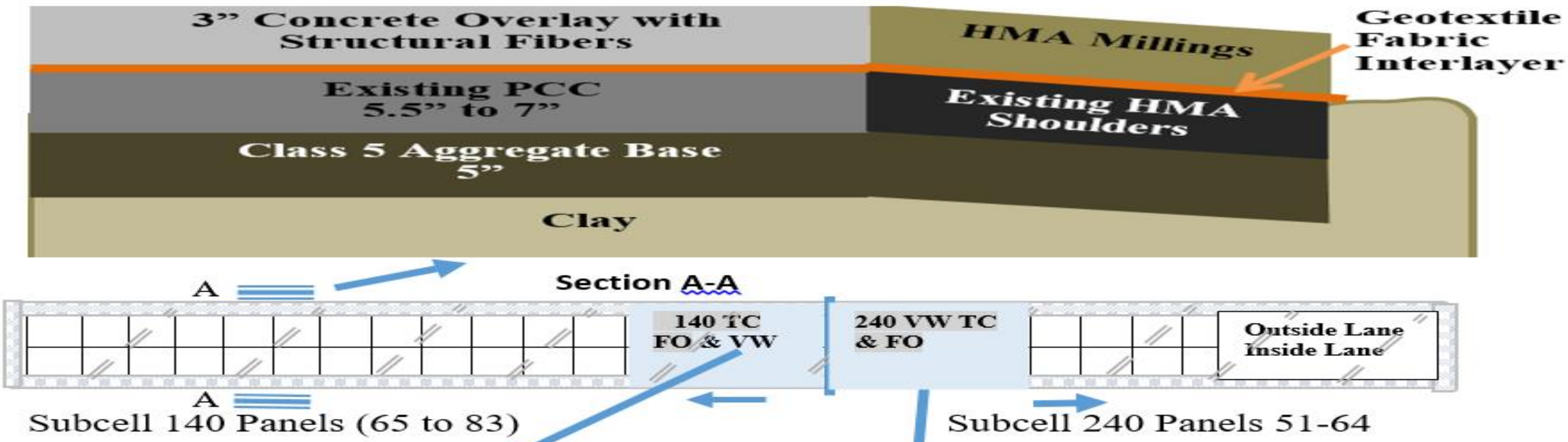
DEFINITIONS AND CHARACTERISTICS

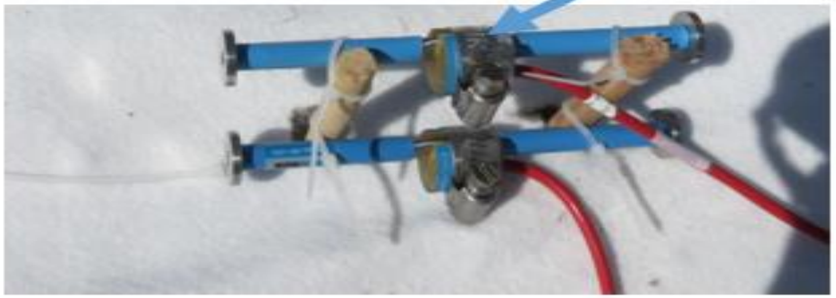
STRESS RELIEF ACTION





UBOL Stress Relief Observation

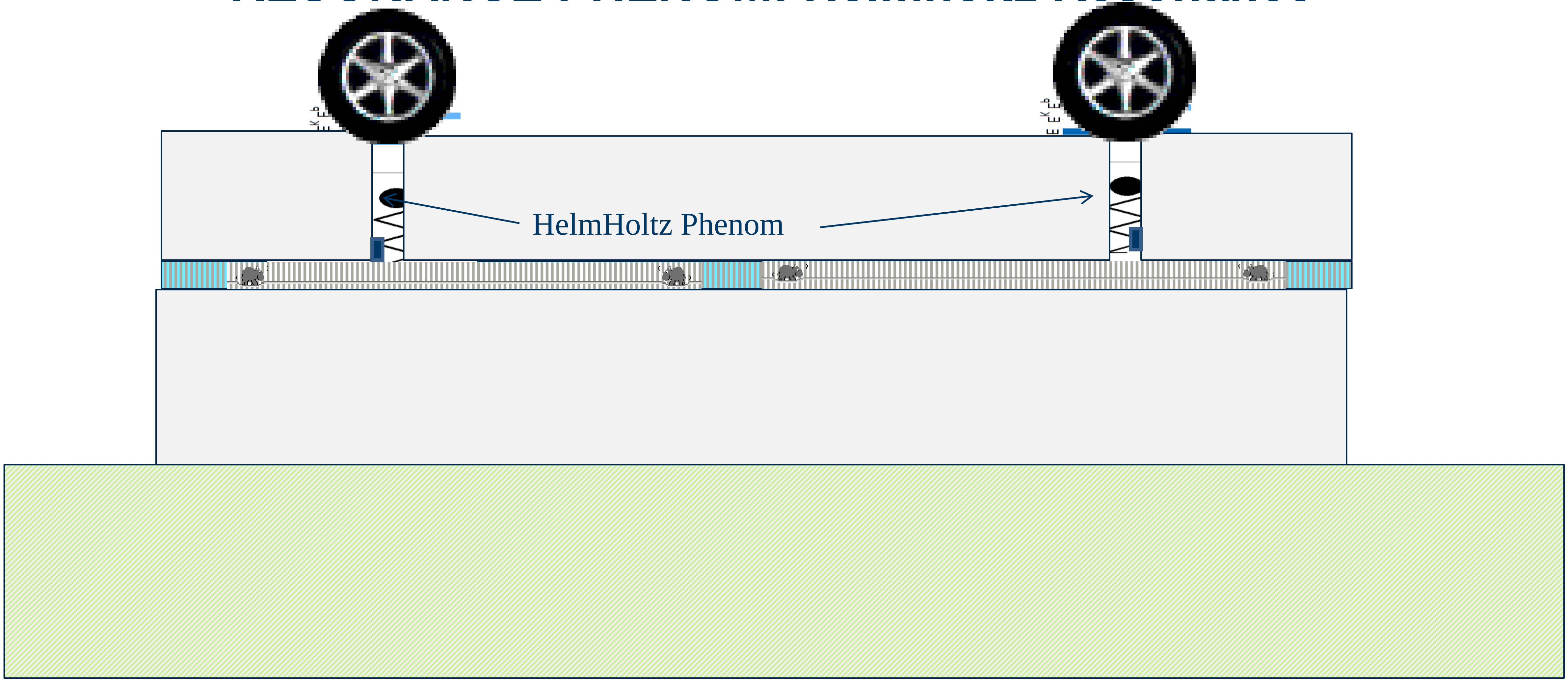




Vibrating wire (VW) strain gauges
(odd # Top and Even # Bottom)

Fiber Optic (FO) Sensor layout
(White Interlayer below Sensor)

RESONANCE PHENOM: Helmholtz Resonance



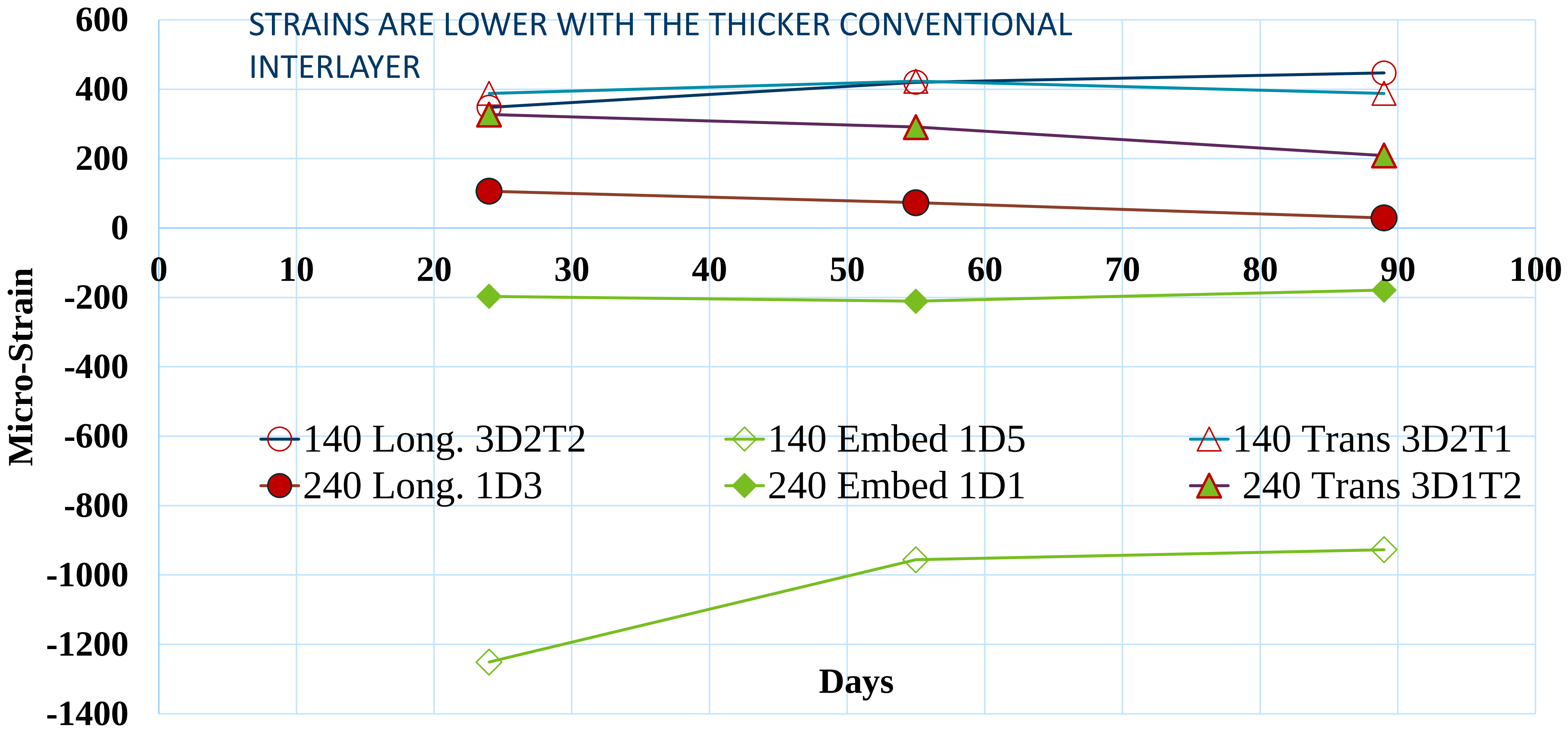
Helmholtz Resonance & Pipe Resonance

MnROAD OBSERVATION OF STRESS RELIEF Fiber Optic Response

	Cell 140 Thin Interlayer µ-strain			Cell 240 Thick Interlayer µ-strain		
Days	140 Long. 3D2T2	140 Embed 1D5	140 Trans 3D2T1	240 Long. 1D3	240 Embed 1D1	240 Trans 3D1T2
24	348.00	-1251.0	388.00	106.00	-197.00	327.00
55	420.00	-956.00	423.00	73.00	-211.00	291.00
89	447.00	-927.00	388.00	29.00	-179.00	209.00

Stresses are Lower with Thicker Interlayers

STRAINS ARE LOWER WITH THE THICKER CONVENTIONAL INTERLAYER



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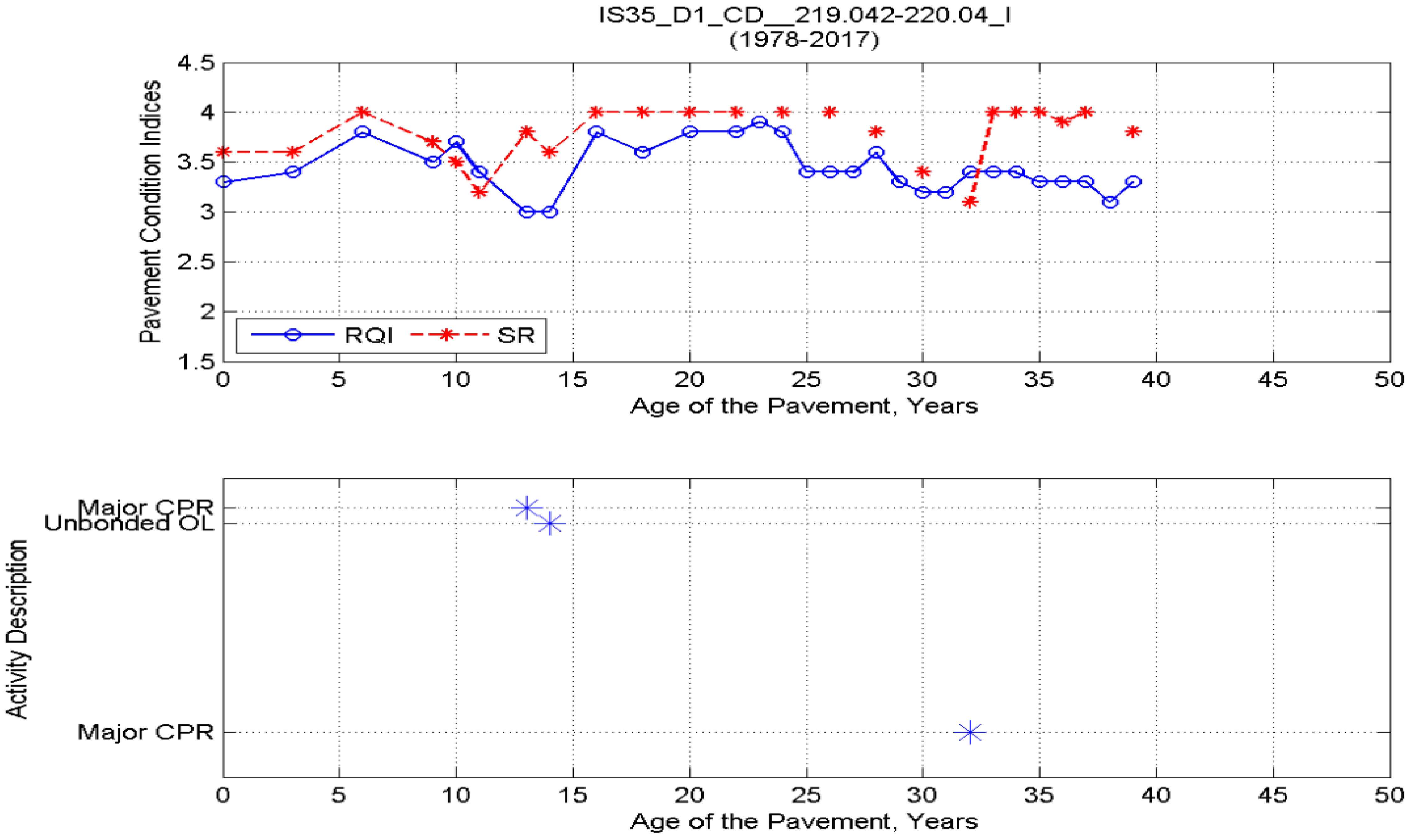
DATA SOURCING & INITIAL ANALYSIS

Data Sourcing and Initial Organization

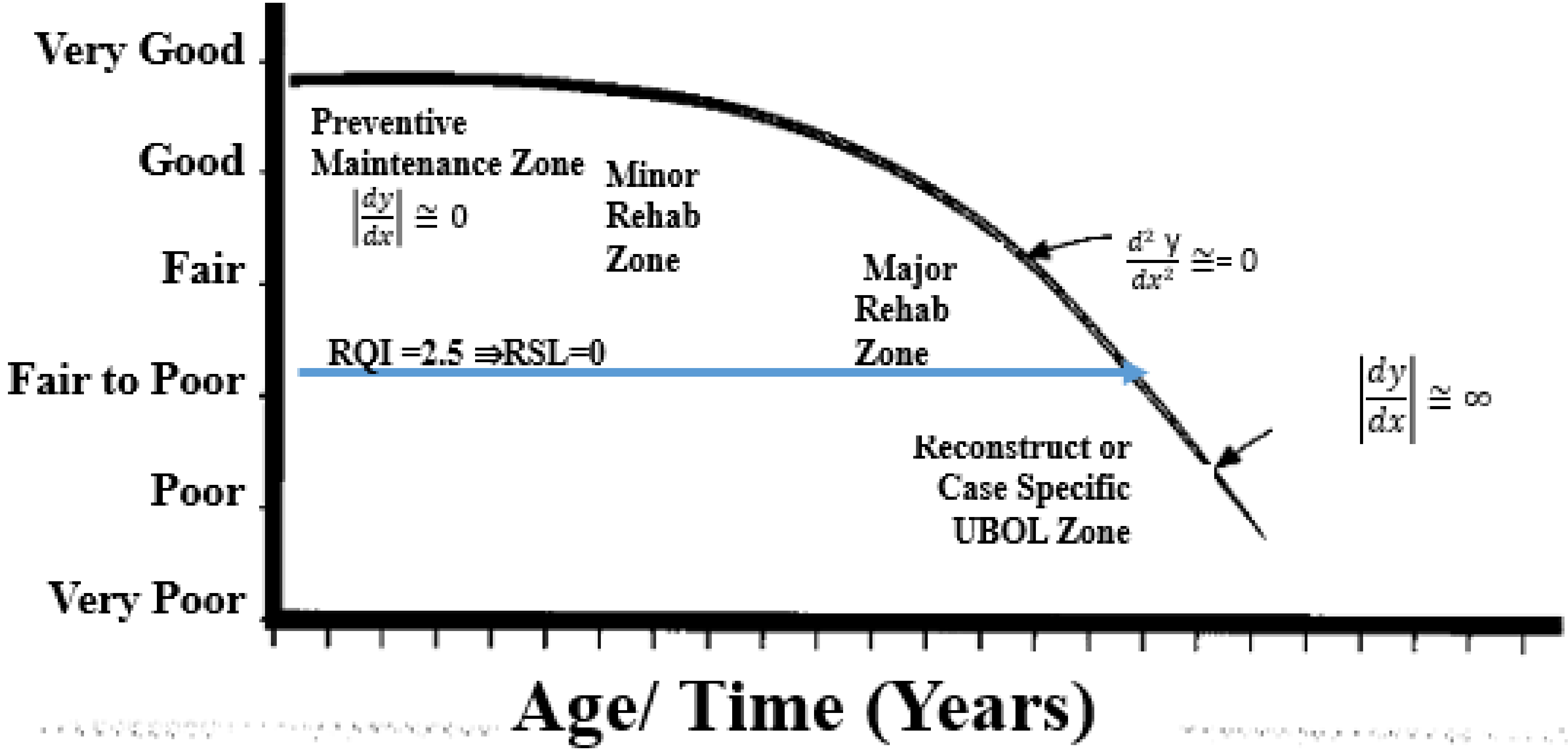
- Analyzed 535,000 rows of M-Records Data
- Produced 15,800 network performance curves for 25 identified interventions including UBOL with) Database.
- Created Program that plotted 15800 (HPMA-parameter RSL Vs time performance Curves)
- Examined 850 performance curves to create a simplified (2-parameter) default curve in lieu of the HPMA 4-parameter curve initially deemed somewhat unwieldy.
- Stepwise Linear Regression to ascertain variables associated with RSL
- They also performed reliability (Weibull) analysis, to solve for Characteristic Life (Scale Parameter, μ), Threshold time to failure (Location Parameter, t_0) and Failure Mode (Shape Parameter, β).



IS35_D1_CD__219.042-220.04_I
(1978-2017)
Pavement Condition Indices
RQI
SR
Age of the Pavement, Years
Activity Description
Major CPR
Unbonded OL
Major CPR
Age of the Pavement, Years

UBOL PERFORMANCE CURVE

Concrete Pavement Condition Schematics



The UBOL Performance Curve Variables

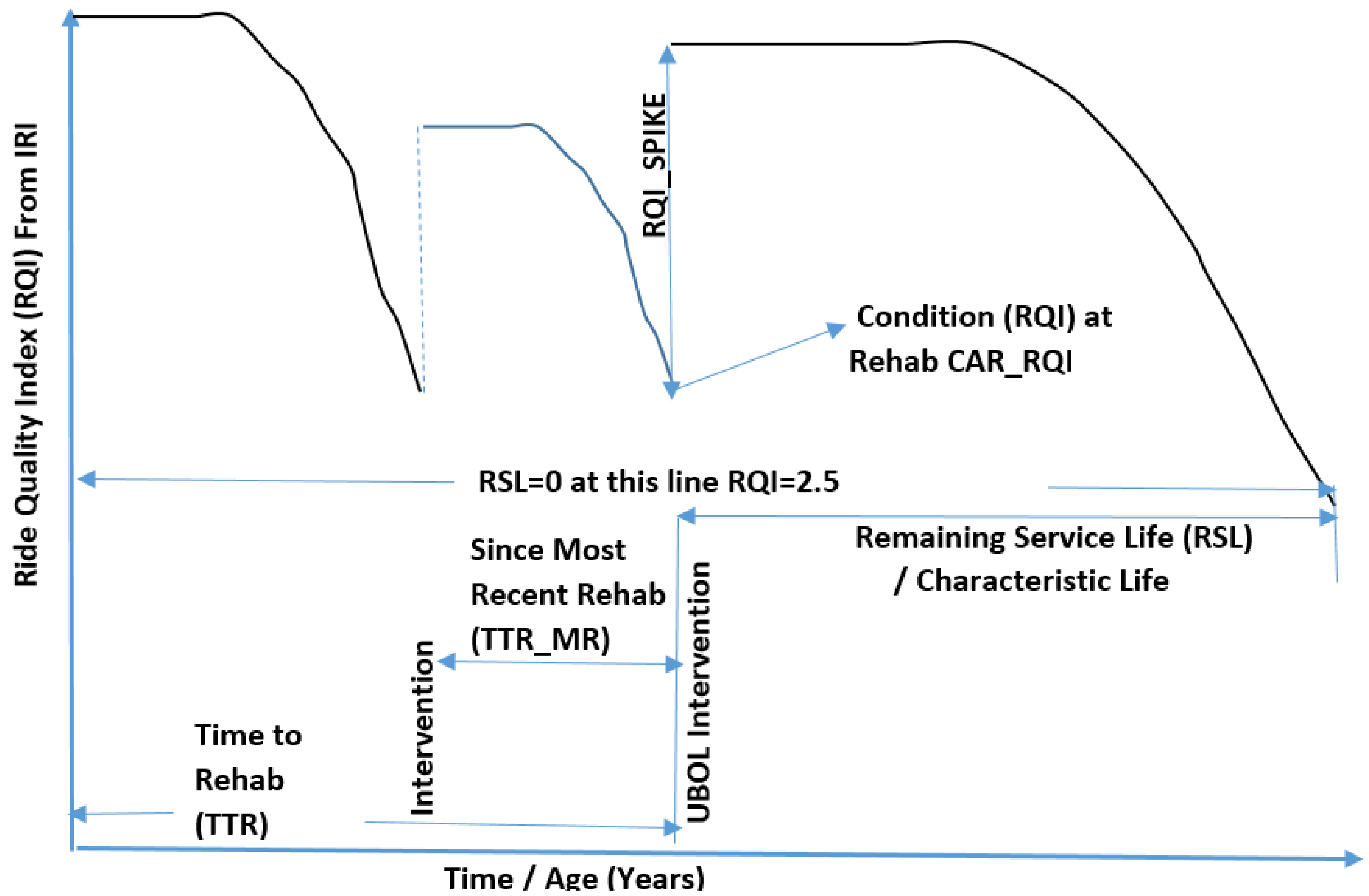


Figure 1 Example of a typical performance curve

UBOL Performance Curve Models

- **HPMA Sigmoidal Predictor** $SIG\_RQI = Q - e^{(a - b * c^{t})}$
  Where SIG_RQI represents the sigmoidal RQI value; a, b, c and Q are model constants while $t = \log_e\left(\frac{1}{age}\right)$ and age is in years.
- **Improved 2-Parameter Model Predictor**
- $RQI = Z + 1 - e^{(Bt)}$
- Where Z is a proxy for initial post-intervention RQI and B is a decay constant.
- Finally, they performed the 3-parameter Weibull analysis to determine Characteristic Life (μ), Failure Mode (β) and Threshold Time to Failure (t_0) for UBOL.
-

HPMA Sigmoidal Predictor

- SIG_RQI=Q−$e^{(a-b*c^{t})}$ Where

SIG_RQI represents the sigmoidal RQI value; a, b, c and Q are model constants while t= $\log_e\left(\frac{1}{age}\right)$ and age is in years.

	coef_a	coef_b	coef_c	Q
Current	14.119	24.052	1.195	3.780
Proposed	14.119	20.100	1.110	3.800

Curve Comparison

HPMA Sigmoidal Predictor $SIG\_RQI = Q - e^{(a - b * c^{t})}$

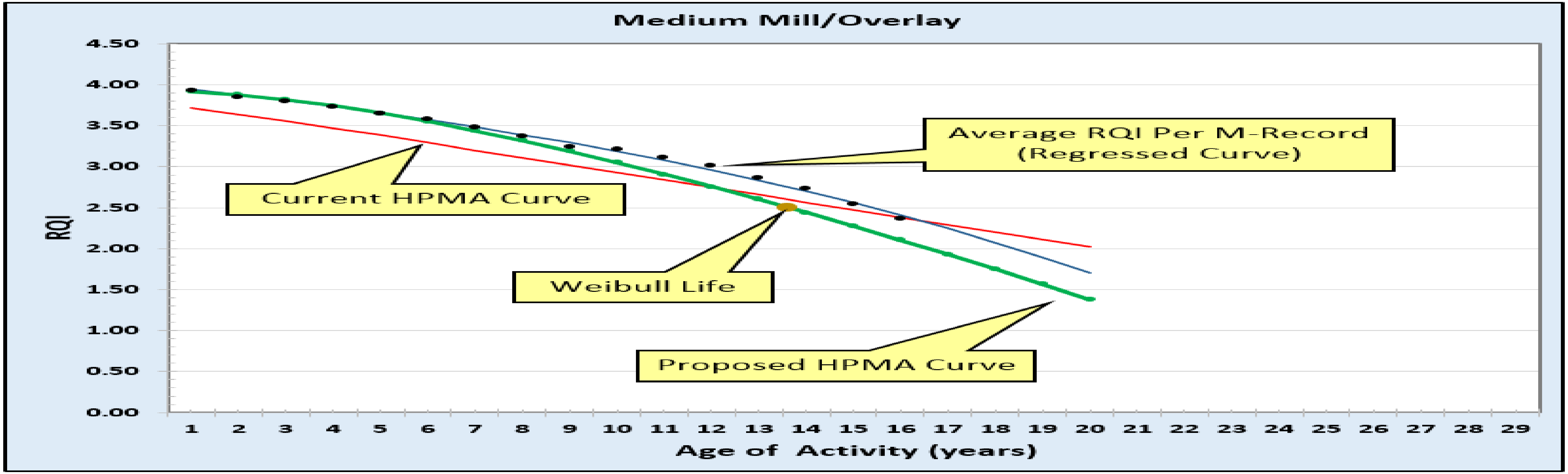
Where SIG_RQI represents the sigmoidal RQI value; a, b, c and Q are model constants while $t = \log_e\left(\frac{1}{age}\right)$ and age is in years.

Improved 2-Parameter Model Predictor

$RQI = Z + 1 - e^{(Bt)}$

(3)

Where Z is a proxy for initial post-intervention RQI and B is a decay constant.

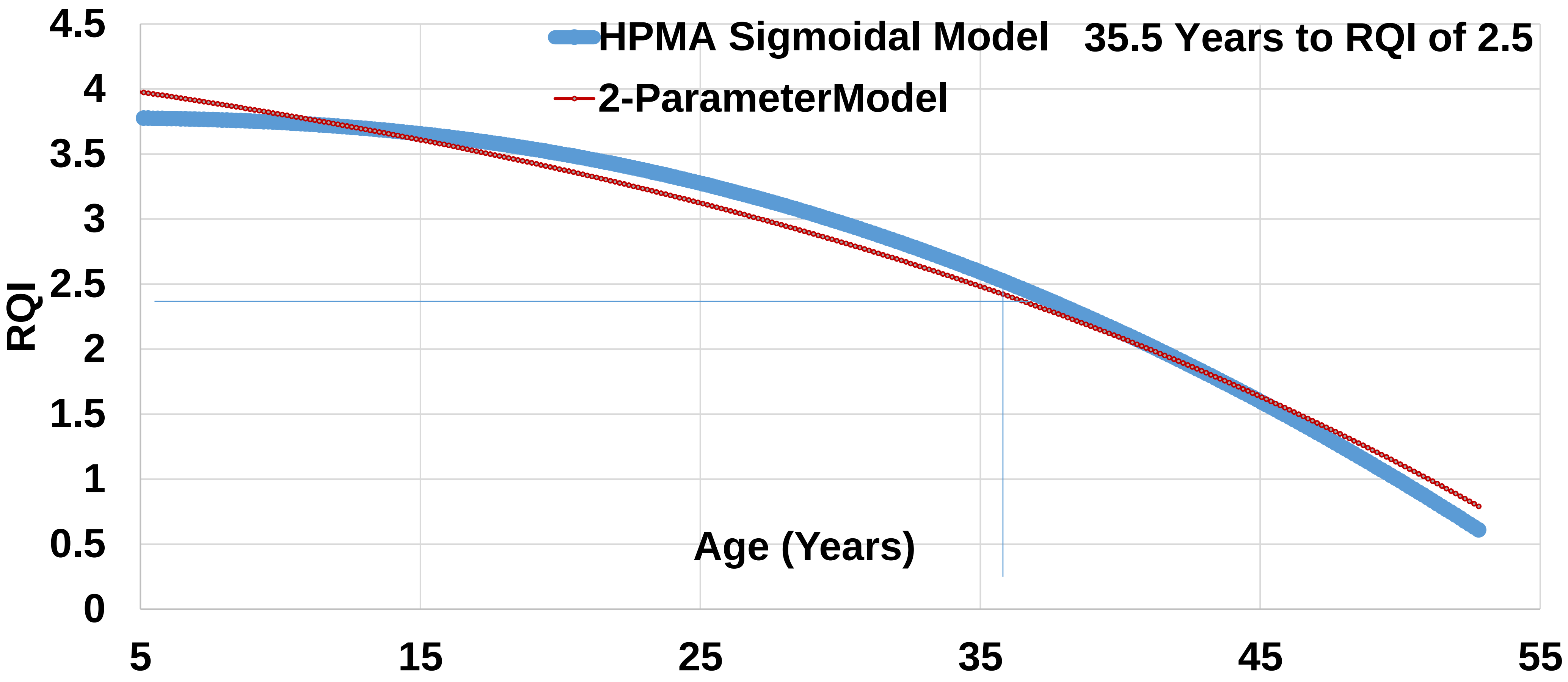


Performance Curve Improvement

HPMA Sigmoidal Model				Simplified Model	
Coefficients				Coefficients	
a	b	c	Q	Z	B
14.12	20.10	1.11	3.80	4.12	0.02

Sigmoidal and improved model showed characteristic life of 35.5 and 35.8 years respectively KL =0.6

Two Parameter Model Vs Sigmoidal (Four Parameter Model)



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PREDICTIVE VARIABLES

Stepwise Regression

- Time from original construction to rehabilitation (TTR), TTR_MR, CAR_SR, CAR_RQI, SR_Spike, and RQI Spike were all set as non-forced independent variables.
- The program automatically identified and rejected any variables it found to be insignificant. (Based On adjusted R^2 (R^2_{Adj})
- $R^2_{Adj} = 1 - \left[\frac{(1-R^2)(n-1)}{n-k-1}\right]$ where R^2 is coefficient of Determination, n is number of data points in a multiple regression and K is the number of independent variables.
- The datasets were opened in StatistiX 10. Unforced regression analysis based on a 95% confidence level (p-values 0.05).
- $\sum_{i=1}^{K}[KP_i]$ regressions are run simultaneously. Only the Regressions with the significant variables survive and the regression with the max number of significant variables is chosen

UBOL Stepwise Regression Results

Variable	Coefficient	Standard Error	T Stat	P-value
Intercept	29.21	1.00	29.15	3.12E-114
TTR_MR	0.14	0.05	2.86	0.0045
TTR	Dropped by stepwise regression process (not significant)			
CAR_SR	Dropped by stepwise regression process (not significant)			
SR_Spike	Dropped by stepwise regression process (not significant)			
CAR_RQI	Dropped by stepwise regression process (not significant)			
RQI_Spike	Dropped by stepwise regression process (not significant)			

Time since most recent intervention TTR_MR was found to be an RSL predictive variable. Other explanatory / starting variables including RQI_Spike, time from original construction to intervention (TTR) and condition at Rehabilitation (CAR_RQI) were found to be non-significant ($\alpha >> 0.05$) in the prediction of remaining service life.

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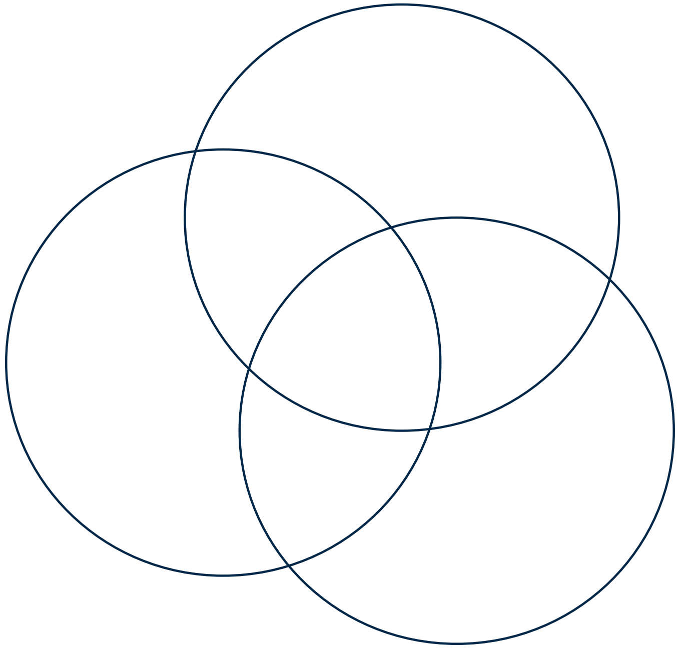
Weibull Analysis of UBOL Data

Planning Predictions and Prognostications

- Purposes and Objectives are Deterministic

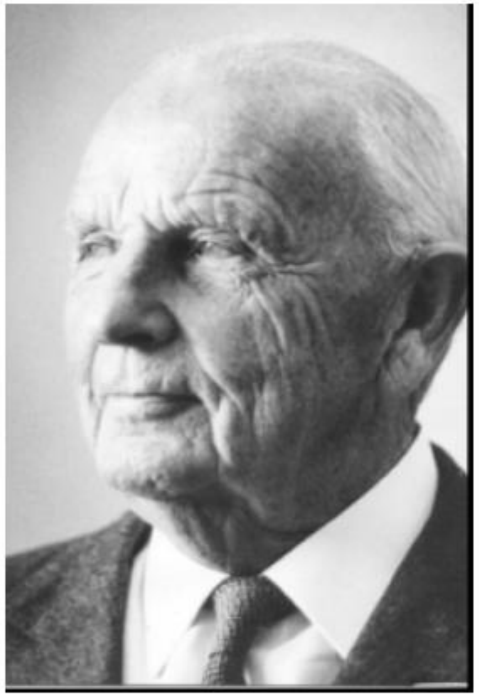
- Solution Matrix is Stochastic



- Expected Results are Probabilistic

Reliability Analysis ≈ Reliable Approach !!

Weibull Method



Dr. E. H. Waloddi Weibull (1887-1979)
Swedish Scientist & Mathematician

- Assumes no Distribution Type but Discovers What it is
- Provides the Three Parameters and More
- Applicable to all Fields of Human Endeavor
- Needs more Usage in Infrastructure

IMPORTANT WEIBULL CHARACTERISTICS

t_0 Location Parameter (Threshold time-to-failure), or guaranteed life. In many cases of wear-out the first failure does not appear until some significant running time t_0 has elapsed.

μ= Scale Parameter (Characteristic life). When $t - t_o = \mu$, P(t) = exp (-1) = 0.37, μ is the interval between t_o and the time at which to expect the 63.2 percentile life.

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β= Shape Parameter (Failure Mode): A measure of burn-in, random failure or wear-out.

Weibull Process

- Scan all the Performance Curves/ Performance Data RSL Vs Time
- Arrange RSL in increasing order
- Find the Fx = CDL and Plot CDL Vs RSL
- 63.2nd percentile is approximate Value of Characteristic Life
- Plot LnLn(I /(1-Fx) against various LN(t- t_0) (reasonably assumed t_0 values)
- Most Linear Form is generated by the correct t_0
- Slope is Shape Parameter β
- Scale Parameter Characteristic life $\mu = \text{EXP}\left\{-\frac{Intercept}{\beta}\right\})$

Determining Shape Parameter)

In the Weibull distribution various failure probability density functions are represented in a single expression. These are dependent on the shape factor β that characterizes the failure mode.

The Cumulative probability function

$$F(t) = 1 - e^{\left\{-\left[\frac{t-t_0}{\mu}\right]^{\beta}\right\}} - (1)$$

Shape Parameter β

Taking Log twice, $\mathrm{LN}\ \mathrm{LN}\ (1 - F(t))^{-1} = \beta \mathrm{LN}\ (t - t_0)\ +$

$\beta\ \mathrm{LN}\ \mu$

Evidently β= slope of$\mathrm{LN}\ \mathrm{LN}\ (1 - F(t))$ Vs $\mathrm{LN}\ (t - t_0)$ *curve*

and $\beta\ \mathrm{LN}\ \mu$ is the Y − intercept

Location Parameter

- **Location Parameter (Threshold Time t_0)**

If $Log\ Log\ (1 - F(t))^{-1}$ is plotted against $log\ (t - t_0)$ a family of curves is generated with many hypothetical t_o values. Using the "t_0" value derived from the previous step the slope of the line is the shape parameter. Threshold time to failure t_0 or location parameter can also be detected by assuming certain realistic values for t_0 and examining which "t-t_o" best represents a linear fit with $Log\ Log\ (1 - F(t))^{-1}$.

- Irrespective of the method, the true t_o value will yield the right intercept β LN μ and also provide a tenable value of characteristic life.

Expected service Life = Weibull Scale Parameter

Scale Parameter μ or Expected Service Life

- The Scale parameter t_0 was obtained by using the intercept and slope accordingly

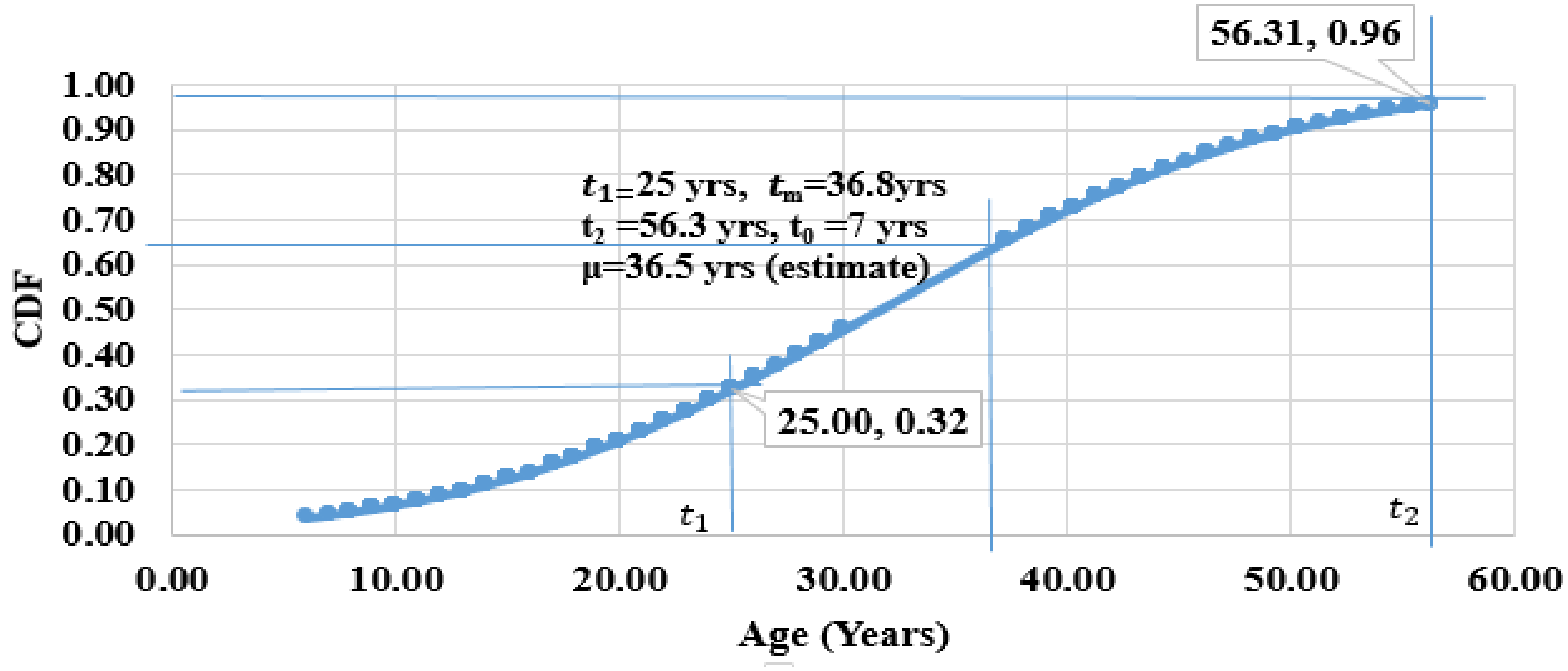
Scale Parameter Characteristic life

$$\mu = \text{EXP}\left\{-\frac{Intercept}{\beta}\right\})$$

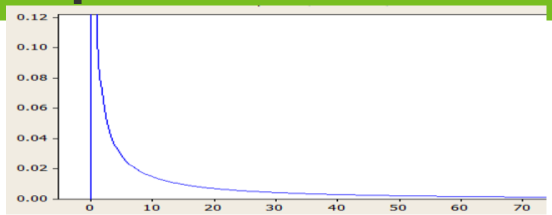
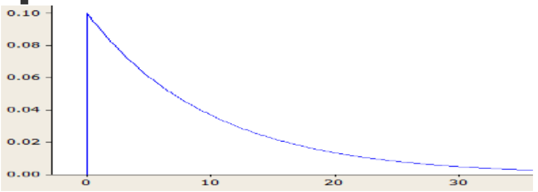
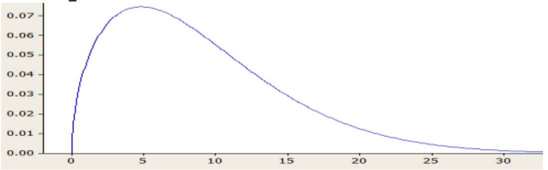
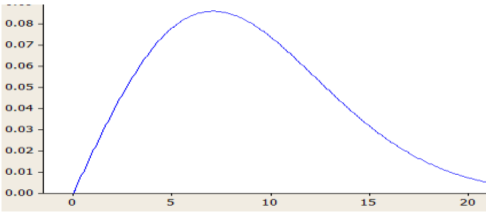
Validation of Threshold Time to Failure

- An alternative algorithm for determining the threshold time to failure t_0 is somewhat sensitive to small changes in boundaries especially as t_1, t_2 and t_m are defined as the lower bound, upper bound and mid-point values of the convex part of the CDF versus age curve an estimate for threshold time to failure is expressed as follows:
- **Estimate** $t_0 = t_m - \frac{(t_2 - t_m) * (t_m - t_1)}{(t_2 - t_m) - (t_m - t_1)}$
- Parabolic portions of the curve are noted as t_1 and t_2 while the bisector of the projections of t_1 and t_2 on the Y-axes is projected to the x-axis and noted as t_m.

Initial Value of Characteristic Life



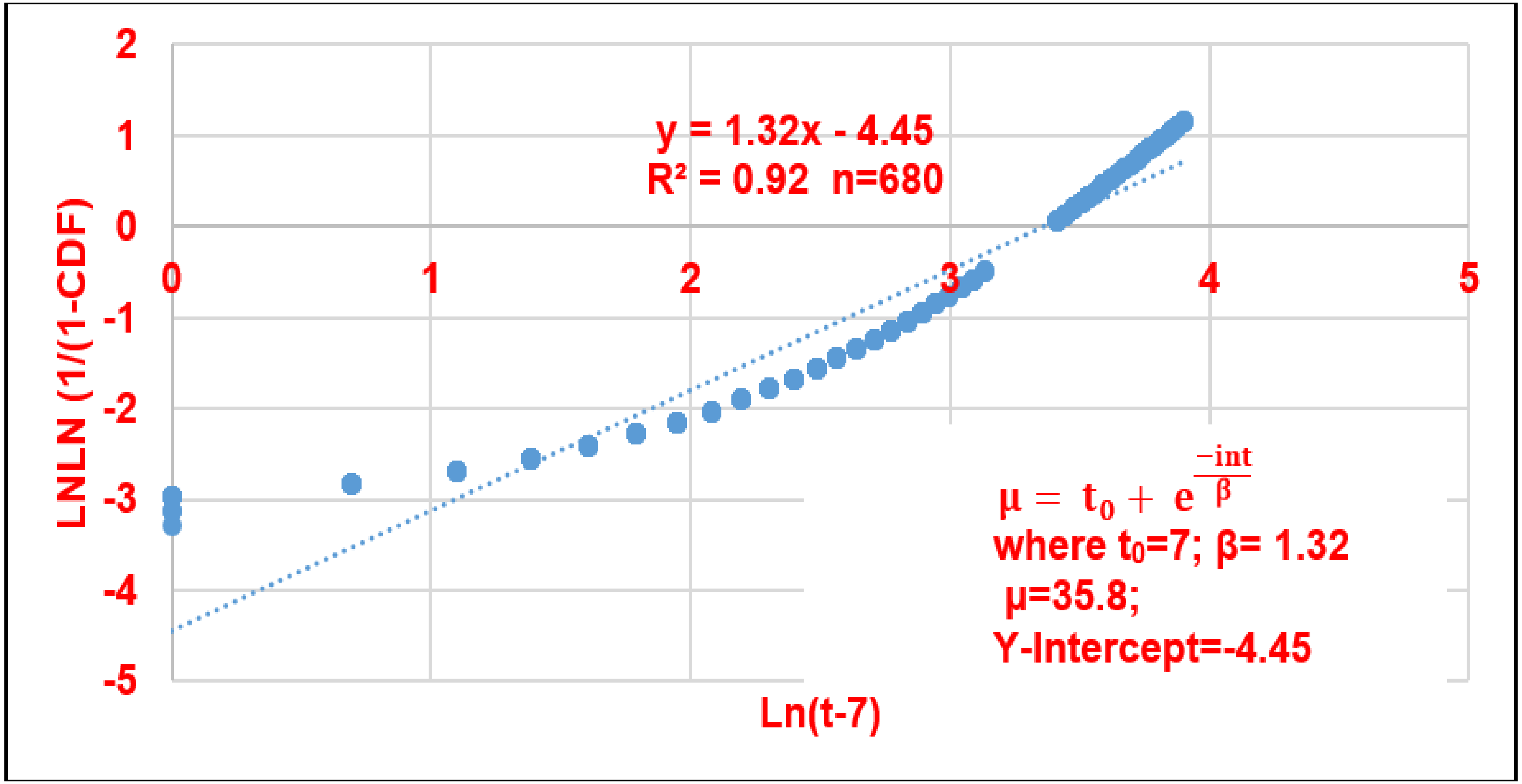
IMPLICATIONS OF SHAPE PARAMETER

Shape Function and Plot	Distribution Type
0<β<1 	Infantile failure mode. Initial high failure rate that decreases with time. Typical loss of support type failure
β =1 	Weibull distribution decreases exponentially from $1/t_o$, where $/t_o$ = the threshold time to failure. Essentially, this means that over time the failure rate remains consistent. This can be used to model the useful life of products. This is an Exponential distribution
1<β<2 	Weibull Distribution rises to a peak quickly, then decreases over time. The failure rate increases overall, with the most rapid increase occurring initially. This shape is indicative of early wear-out failures.
β =2 	A linearly increasing failure rate, where the risk of wear-out failure increases steadily over the infrastructure's lifetime. This form is also known as the Rayleigh distribution. Crack related distresses may fall here.

Implication of UBOL Solution

- A family of curves was generated by plotting LNLN $(1-F(t))^{-1}$ against LN $(t-t_0)$ with many assumed t_0 values. Threshold-time-to-failure was detected and independently validated when the line was most linear. The slope of the most linear fit line is β. Finally μ (expected life or RSL) was obtained from β and intercept
- Shape Parameter = 1.32. This is an end-of-life type failure mode but is not far removed from the random mode.
- Weibull prediction for μ = 35.8 Yrs validated the improved 2 parameter model.
- Threshold time to failure (7 years) implies a substantial preventive maintenance window.

Weibull Analytic Solution



Shape Parameter = 1.32. This is an end-of-life type failure mode but is not far removed from the random mode. Weibull prediction for μ = 35.8 Yrs validated the improved 2 parameter model.

FIX	REMAINING SERVICE LIFE BASIS				OTHER RELIABILITY DESCRIPTORS		
	USED RSL yrs	HPMA CURVE	TRIAL CURVE	Weibull Life	Beta	t_0	Comment
Min. CPR/Grd D	17	22	13.6	13.7	2.93	0	Definition of Minor
Min. CPR/Grd UD	17	22	10.3	13.7	2.93	0	
Chip Seal=	12	12	12	10.18	2.64	0	Partly dependent on substrate
Thin Mill/OL BOB	11	11	15	11	1.67	0	Quasi Random to Wear Out Failure
Thin Mill/OL-BOC	11	10	11	11	1.67	0	
Micro-Surface=	6	10.62	6.46	*7.02*	8.47	0	Partly Dependent on Substrate
Major CPR=	22	22	15	14.8	2.64	0	Dowelled Undowelled
UTBWC	12	12	24	10.08	5.41	0	
CIR	17	16.7	19.0	9.3	4.23	0	PMW=0 Wear Out;
FDR	24	24	19	17.9	4.4	2	2-Year Maintenance Window
Thin OL	12	12	12	13.3	3.08	0	Wear Out
Medium OL BOB	17	18.7	18.5	14.91	14.35	0	Extreme Wear Out
Medium OL BOC	17	16.3	18.6	14.91	14.35	0	Extreme Wear out
MMO BOB	15	13	16.5	13.62	3.61	0	Wear Out
MMO BOC	15	14.5	17	14.11	3.15	0	Wear Out
Thick M/O BOB	17	16.5	15.8	15.94	10.16	0	Extreme Wear Out
Thick M/O BOC	17	14.9	17.3	15.94	10.16	0	Extreme Wear out
Maj. CPR/Gd. D	22	22	15.5	14.8	3.68	0	Wear out
Maj. CPR/Gd. UD	22	22	15.3	14.8	3.68	0	Wear out
Thick OL BOB	18	19.1	15.8	14.92	14.35	0	Extreme Wear Out
Thick OL BOC	18	15.4	17	14.92	14.35	0	Extreme Wear out
Whitetopping D	22	NSD	NSD	NSD	NSD	NSD	NSD=No Sufficient Data
Whitetopping UD	22	22	15	12.9	14.64	0	Undowelled/ Dowelled NSD=No Sufficient Data
Unbonded OL	34	34	34	35.22	1.24	7	Random to Wear-Out T_0 peaks at 7 Years
Rural Regrade (CONC)	28	28	24	21.5	1.73	6	Quasi- Random-WEAR-OUT
Urban Regrade (CONC)	28	28	24				Quasi-Random-WEAR-OUT
Rural Regrade (BIT)	15	15	17	15.3	4.1	0	WEAR-OUT
Full Depth BIT	15	15.7	13.0	15.9	4.75	0	Wear-Out
Urban Regrade BIT	NSD	NSD	NSD	NSD	NSD	NSD	HNSD

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CLOSING

Conclusions

Number of years from most recent intervention proved to be a significant predictor of UBOL RSL.

A simplified typical UBOL performance curve developed in this study has an initial post-intervention RQI and an exponential decay constant. It predicted an **RSL of 36 years** consistent with results from reliability analysis.

Results also accentuated **random (uniform rate of failure) to end-of-life (wear-out) failure mode (β =1.32)** and a **7-year Threshold-Time-to-Failure** (Location Parameter).

Conclusion

This study thus identifies UBOL as a long term intervention with a potential for even higher service life if preventive maintenance is done within the first 7 years. Continuing research will periodically review and update performance model with new data.

Predictive Parameters Validate Markovian Assumption. Time since last Intervention is a Predictive variable.

Limitation: This study does not investigate the comparative performance of interlayer types. **Nevertheless, it has produced solid information that can be used in a Network Pavement Investment**.

Relevant References on UBOL & Inter-Layer

- Engstrom G. M. Unbonded concrete overlays: Minnesota experience. Minnesota Department of Transportation, Engineering Services Division, Office of Materials and Research, Physical Research Section; 1993.
- Khazanovich L, Ioannides AM. Structural analysis of unbonded concrete overlays under wheel and environmental loads. Transportation Research Record. 1994(1449).
- Zhang Z, Huang Y, Palek L, Strommen R. Glass fiber–reinforced polymer–packaged fiber Bragg grating sensors for ultra-thin unbonded concrete overlay monitoring. Structural Health Monitoring. 2015 Jan;14(1):110-23.
- Izevbekhai, B.I. Optimized Thickness of Non-Woven Geofabric Stress Relief Layer for Unbonded Overlay Paper # 20-00452 Presented in Session # 1590 January 14 2020

Acknowledgements

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Those Constant Check ins from Matt Zeller CPAM Executive Director were very helpful.

Build it Right!!!

Pavements are Herded (Headed) in the Right Direction if

We Build em right.!!!

QUESTIONS