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WIM-BASED FATIGUE DAMAGE ASSESSMENT

TRANSPORTATION RESEARCH BOARD 2020

Lectern Session 1303 - Effects of Fatigue and Corrosion on Steel Girder Bridges

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ROLE IN THE RESEARCH:
DATA PROCESSING,
ANALYSIS AND
INTERPRETATION OF
RESULTS, DRAFT
MANUSCRIPT PREPARATION



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ANALYSIS AND
INTERPRETATION OF
RESULTS.

PRESENTATION OUTLINE

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ACCORDING TO ASCE INFRASTRUCTURE CARD (2017):



SOURCE: <https://www.bridgemi.com/michigan-government/roads-get-spotlight-447-michigan-bridges-serious-condition-or-worse>

- 4 out of 10 bridges are 50 years or older (avg. age 43 years).
- 25% (151,845) bridges are structurally or functionally deficient.
- 188 million trips through structurally deficient bridges daily.
- About 60,000 bridges (10 percent) are posted for a weight or speed limit.
- A percentage of structurally deficient (SD) bridges reduced from 12.5 to 9% over the last decade due to a number of newly built or replaced bridges.
- Failures due to overload or deterioration are strongly age related.

INTRODUCTION

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TRAFFIC DATA

- As of 2011 over 700 portable and permanent WIM stations are currently in operation around the country (Ghosn et al. 2011).
- As of now traffic data recorded by 1124 WIM stations during recent 10 years from 44 States is available
- The magnitude of traffic loads is controlled by:
 - Legal load limits
 - Permit load and number
 - Control of illegally overloaded vehicles.



SOURCE: <http://www.wimscale.com/en/weigh-in-motion-high-speed.asp>

INTRODUCTION

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AASHTO LRFD Bridge design specifications:

- The stress range calculated for a code-specified fatigue design truck is limited to avoid fatigue cracking caused by the accumulation of damage from repetitive truck loading.
- The AASHTO fatigue design truck is intended to represent truck traffic.
- Steel bridges are more prone to fatigue cracking compared to other types of bridges
- Passage of each heavy truck uses a tiny amount of the fatigue life of a bridge

Stages of Fatigue Process:

1. Initiation of cracks
2. Propagation of cracks
3. Fracture

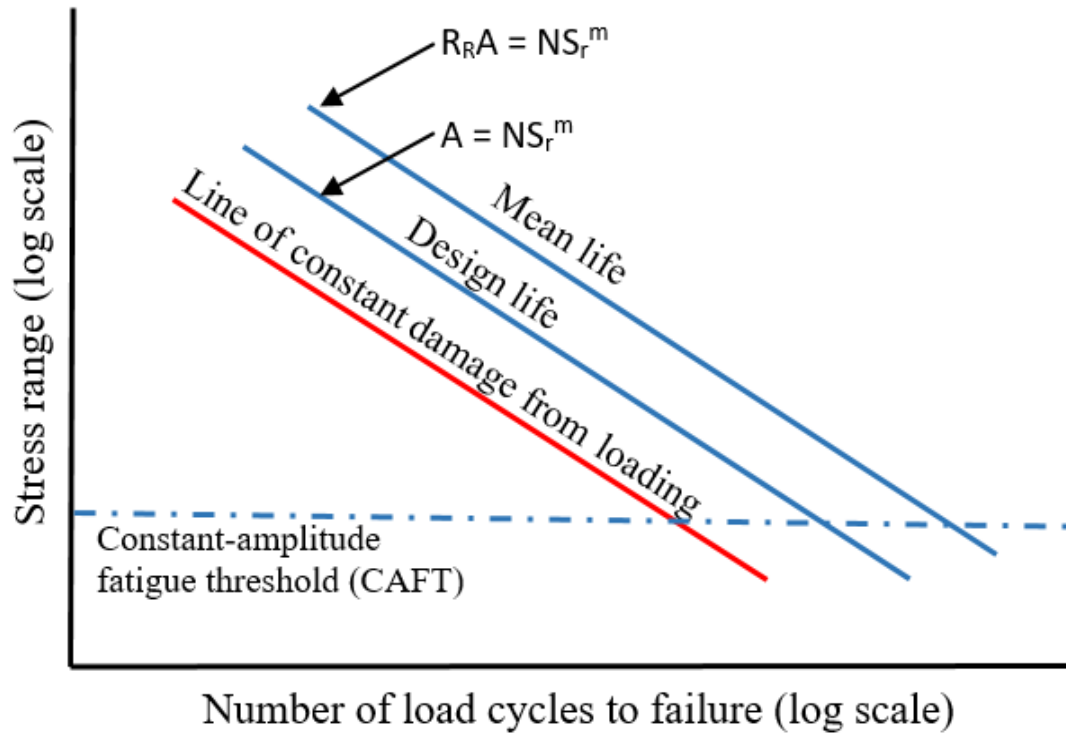
BACKGROUND

SUMMARY OF RELEVANT STUDIES ON ESTIMATED COST OF DAMAGE DUE TO OVERWEIGHT TRAFFIC

The study of the impacts of vehicular traffic on infrastructure has been conducted in many states. Some of the states have sponsored research for an experimental approach and some for analytical studies.

Source	State	Transportation infrastructure	Mechanisms considered	Dataset – Load side
Oversize/Overweight Permit Fee Study Vehicle	Texas	Pavement	Rutting, fatigue cracking, and roughness	OS/OW issued permits
Oversize/Overweight Permit Fee Study Vehicle	Texas	Bridge	Fatigue and different fatigue curves depending upon type of material	1.OS/OW issued permits 2. Non-routed permits
Effects of Overweight Vehicles on NYSDOT Infrastructure	New State York	Bridge	1. Overstress of main members 2. Cyclic fatigue accumulation in main members and decks	Weigh-In-Motion (WIM) data
Effects of Overweight Vehicles on NYSDOT Infrastructure	New State York	Pavements	Incremental cost approach	Weigh-In-Motion (WIM) data
Impact of Freight on Highway Infrastructure in New Jersey	New Jersey	Bridges	Fatigue in steel bridge girders, pre-stressed bridge girder tendons and RC decks	Weigh-In-Motion (WIM) data

FATIGUE LIFE RELATIONSHIP



$$NS_r^m = A$$

Where:

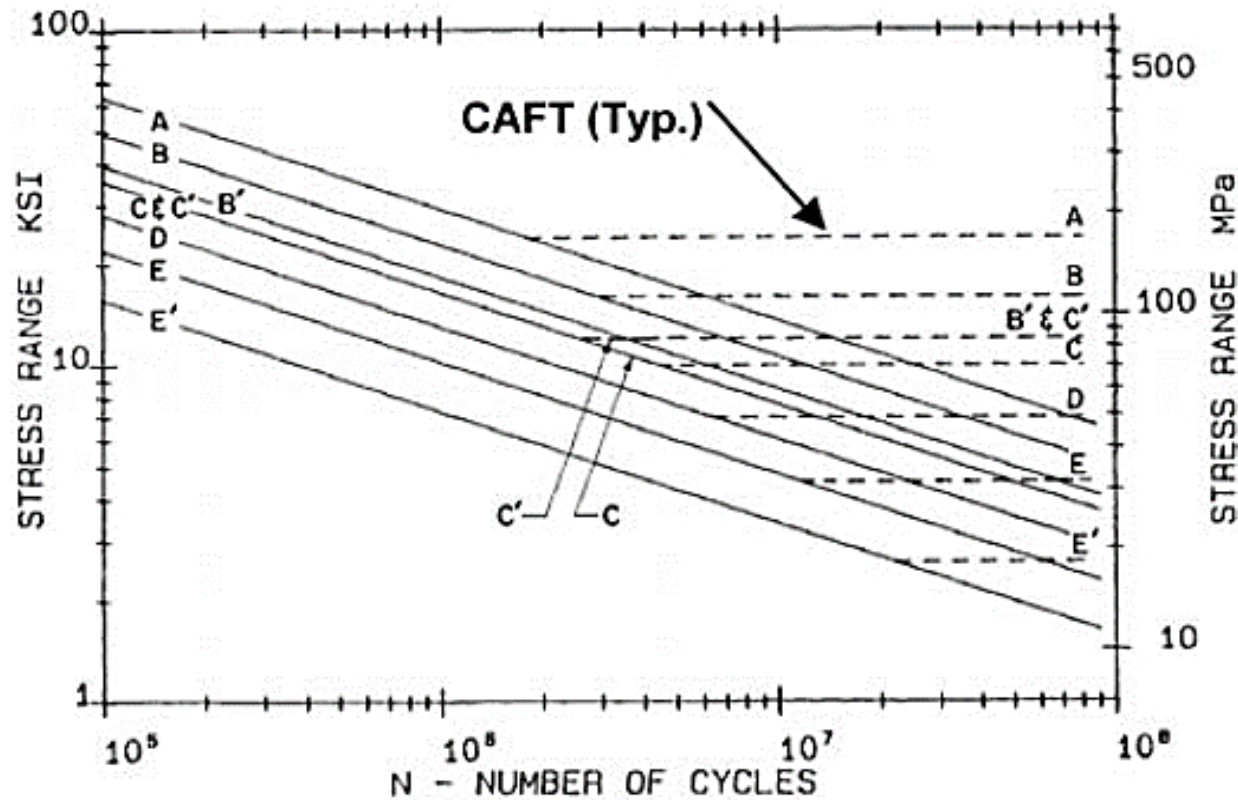
m – slope constant (3 for steel)

S – nominal stress range

N – number of cycles to failure

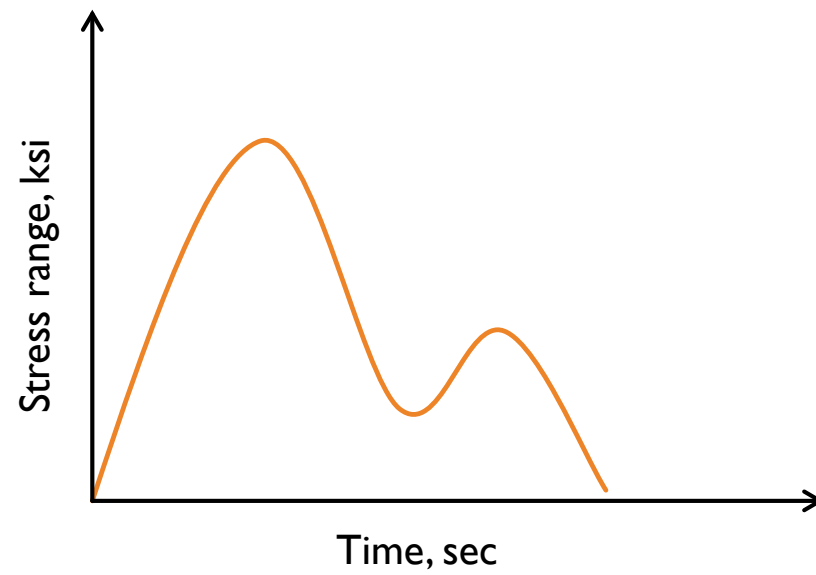
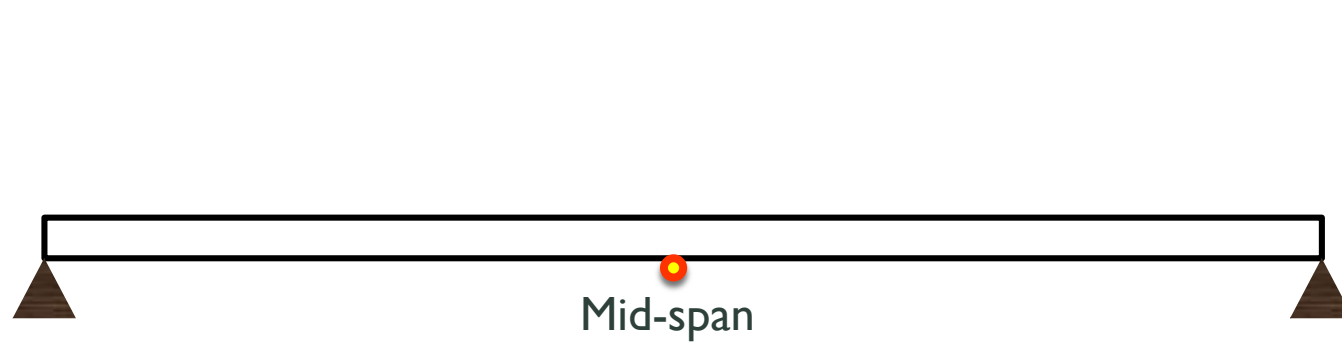
A – constant for a given detail

STRESS RANGE VERSUS NUMBER OF CYCLES (S-N) CURVES (AASHTO 2017)



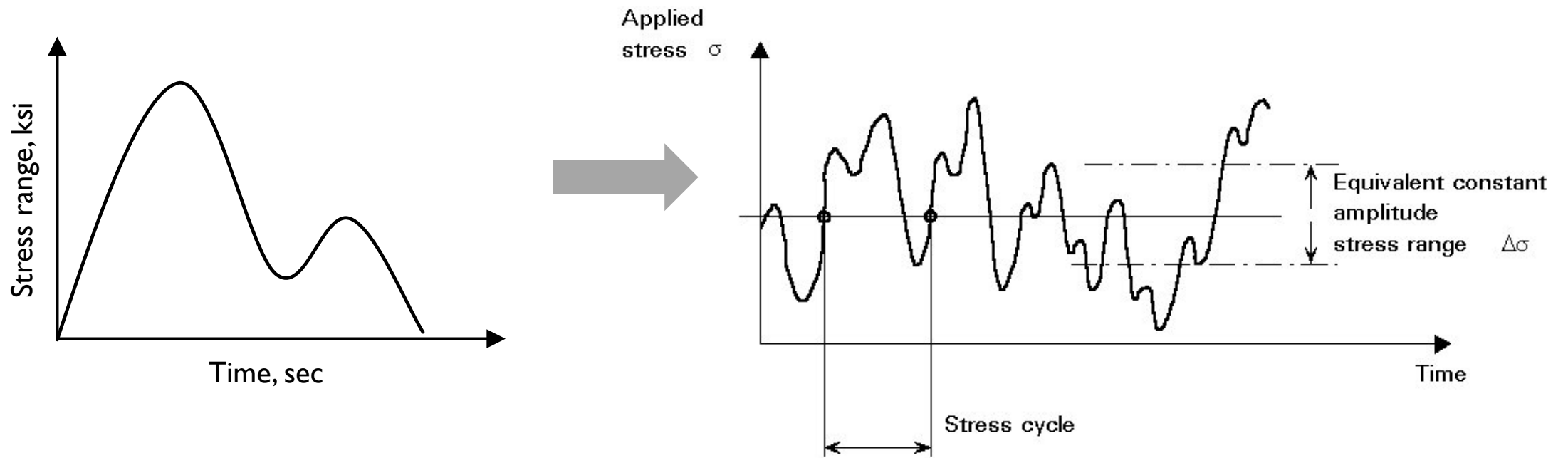
The S-N curves were developed using constant-amplitude stress range test data. However, bridges are subjected to variable amplitude stress cycles

TRAFFIC INDUCED FATIGUE LOADING



TRAFFIC INDUCED FATIGUE LOADING (VARIABLE AMPLITUDE)

Every passage of a truck across a bridge creates one or more stress cycles in the structural components, which results in the accumulation of fatigue damage over time.



LOADING USED IN DEVELOPING S-N CURVES (CONSTANT AMPLITUDE)

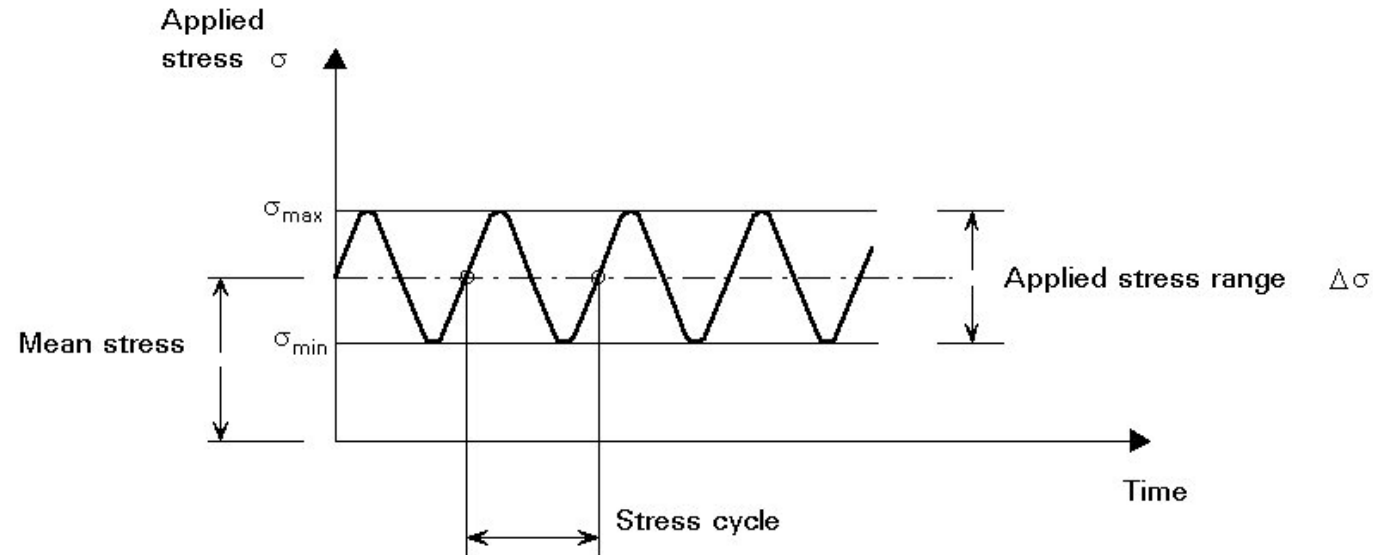
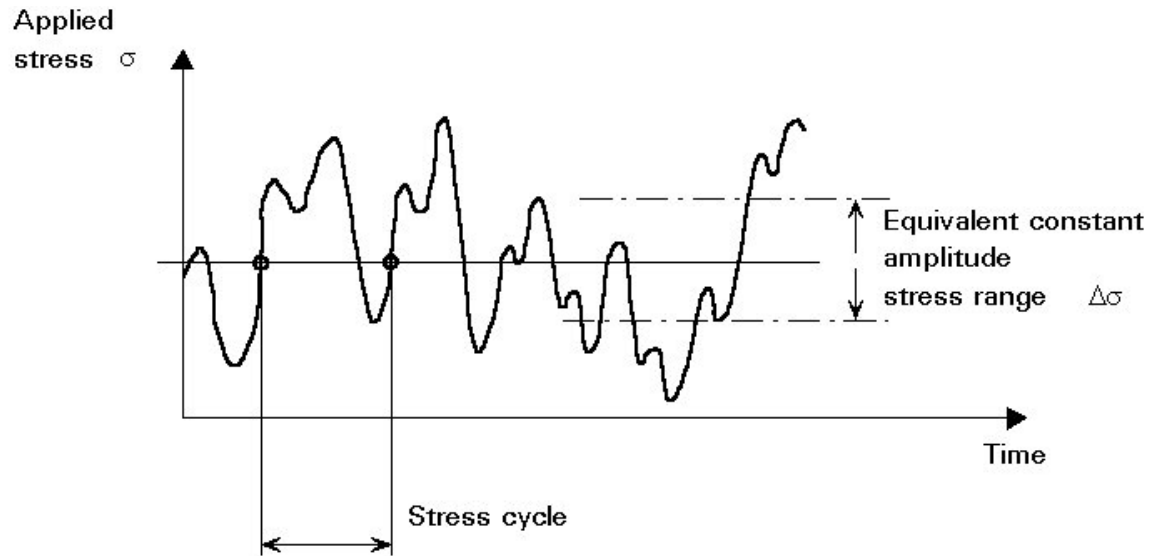
An equivalent constant amplitude stress range, commonly referred to as an effective stress range S_{eff} , can be calculated using Palmgren-Miner rule.

$$S_{\text{eff}} = \left[\sum \frac{n_i}{N} S_i^m \right]^{1/m}$$

where:

n_i – number of cycles at the i^{th} stress range, S_i

N - total number of cycles.

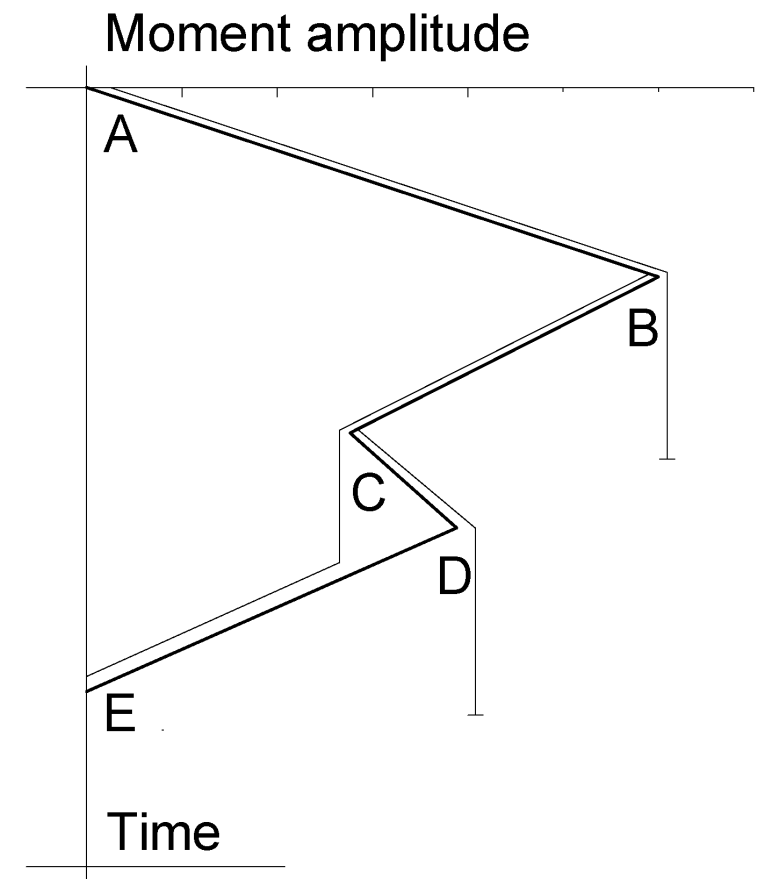


TECHNICAL APPROACH

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CYCLE COUNTING: BENDING MOMENT TIME HISTORY

- Introduced in 1968 by Matsuishi and Endo.
- Convenient to program.
- Counts full and half cycles.
- The magnitude of cycle is calculated as a difference between “peak” and “valley”.
- Once the cycle is identified it is eliminated from the moment time history and the remaining “peaks” and “valleys” are renumbered.



GENERAL APPROACH


The Palmgren-Miner rule provides a rational means to account for the cumulative damage from a spectrum of applied stress ranges of variable amplitude.

$$S_{\text{eff}} = \left[\sum \frac{n_i}{N} S_i^m \right]^{1/m}$$

where:

n_i – number of cycles at the i^{th} stress range, S_i
 N - total number of cycles.

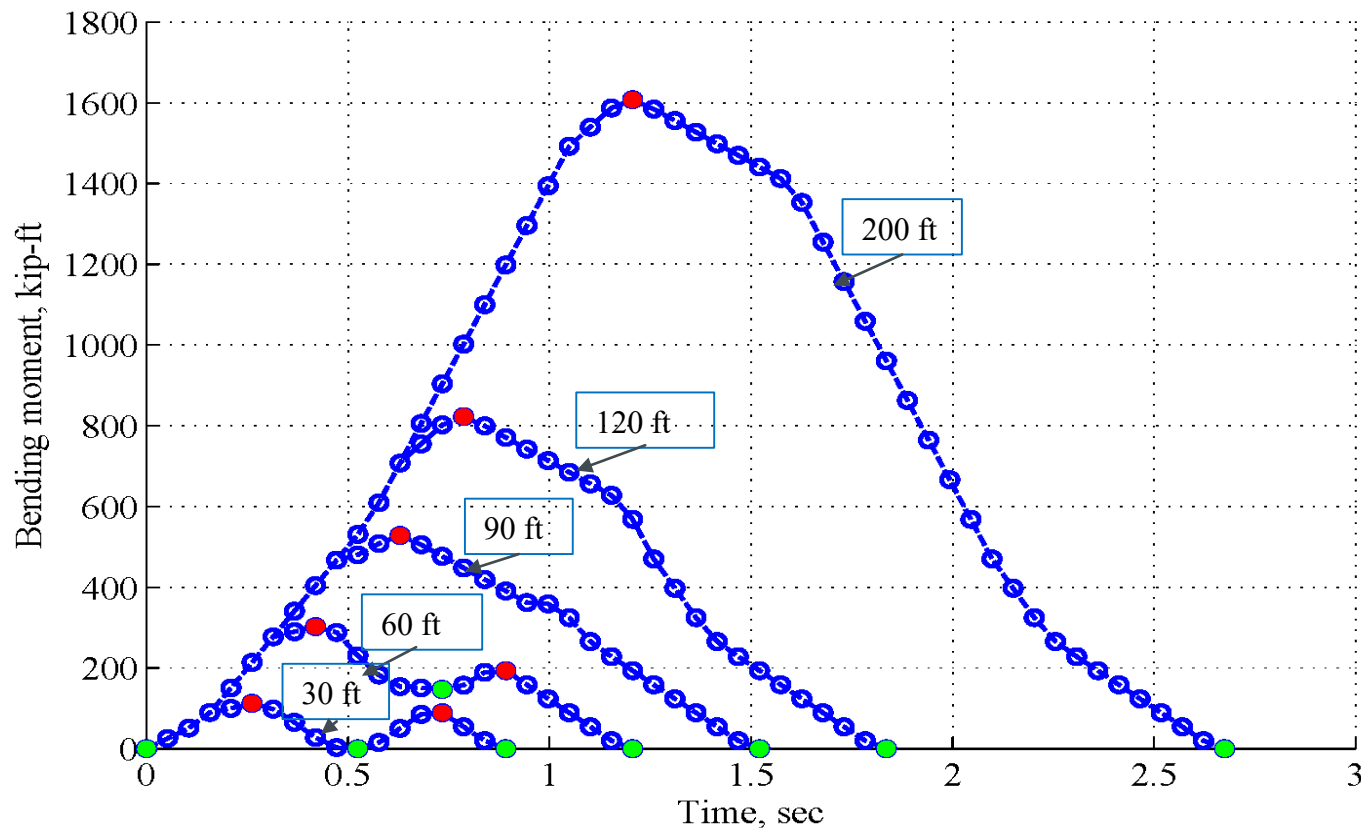
At a specific point along a bridge girder, the applied range of bending moment can be determined by multiplying the applied stress range by the section modulus.


$$M_{\text{eff}} = \left[\sum \frac{n_i}{N} M_i^m \right]^{1/m}$$

where:

n_i – number of cycles at the i^{th} moment range, M_i
 N - total number of cycles.

WIM SITE-SPECIFIC DAMAGE RATIO



- Traffic in both directions of travel are combined.
- Each WIM record is analyzed for 30, 60, 90, 120 and 200 ft span lengths.
- Results presented are for a location 20% of the span length from the upstream support (cover plate end).
- The amount of damage D_m is calculated from the effective bending moment determined from the WIM data.

$$D_m = NM_{\text{eff}}^m$$

TECHNICAL APPROACH

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DAMAGE AT A SPECIFIC FATIGUE PRONE DETAIL - COVER PLATE-ENDS (CATEGORY E')

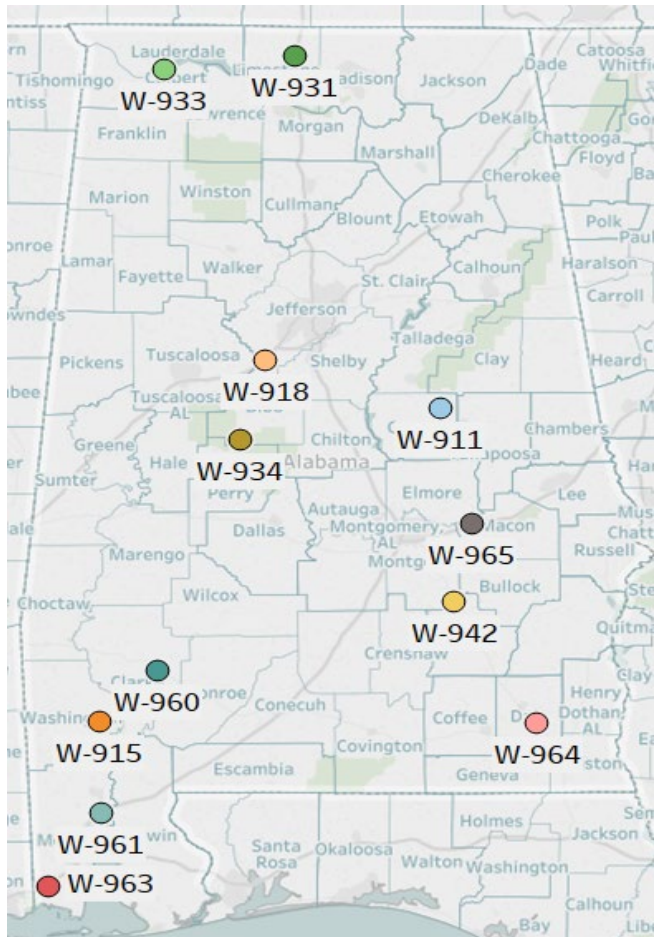
Based on the study performed by Franklin, the base metal at the end of a bottom flange cover plate is considered here as the most fatigue prone detail in Alabama's steel girder bridges.

$$D = \frac{N * S_{eff}^3}{R_R * A}$$

D are calculated from WIM data each month for convenience, the D value for the year will be the sum of the values calculated for each month.



TRAFFIC DATABASES - WIM



- WIM data available from 8 WIM stations
- Duration of WIM recording – year 2014

WIM Site code	County	Number of WIM records before QC	Number of WIM records after QC
911 (US280)	US280 Cosa Co.	1,092,751	357,854
931 (I65)	I65 Limestone Co.	3,655,980	1,584,347
933 (AL I57)	AL I57 US72 Colbert Co.	977,580	427,505
934 (US78)	US78 Walker Co.	688,388	169,407
942 (US231)	US231 Montgomery Co.	1,262,375	787,426
960 (US84)	US84 Clark Co.	521,484	305,566
961 (I65)	I65 Mobile Co.	2,136,008	851,213
964 (US231)	US231 Dothan Co.	1,217,687	642,337
Total		11,552,253	5,125,655

TECHNICAL APPROACH

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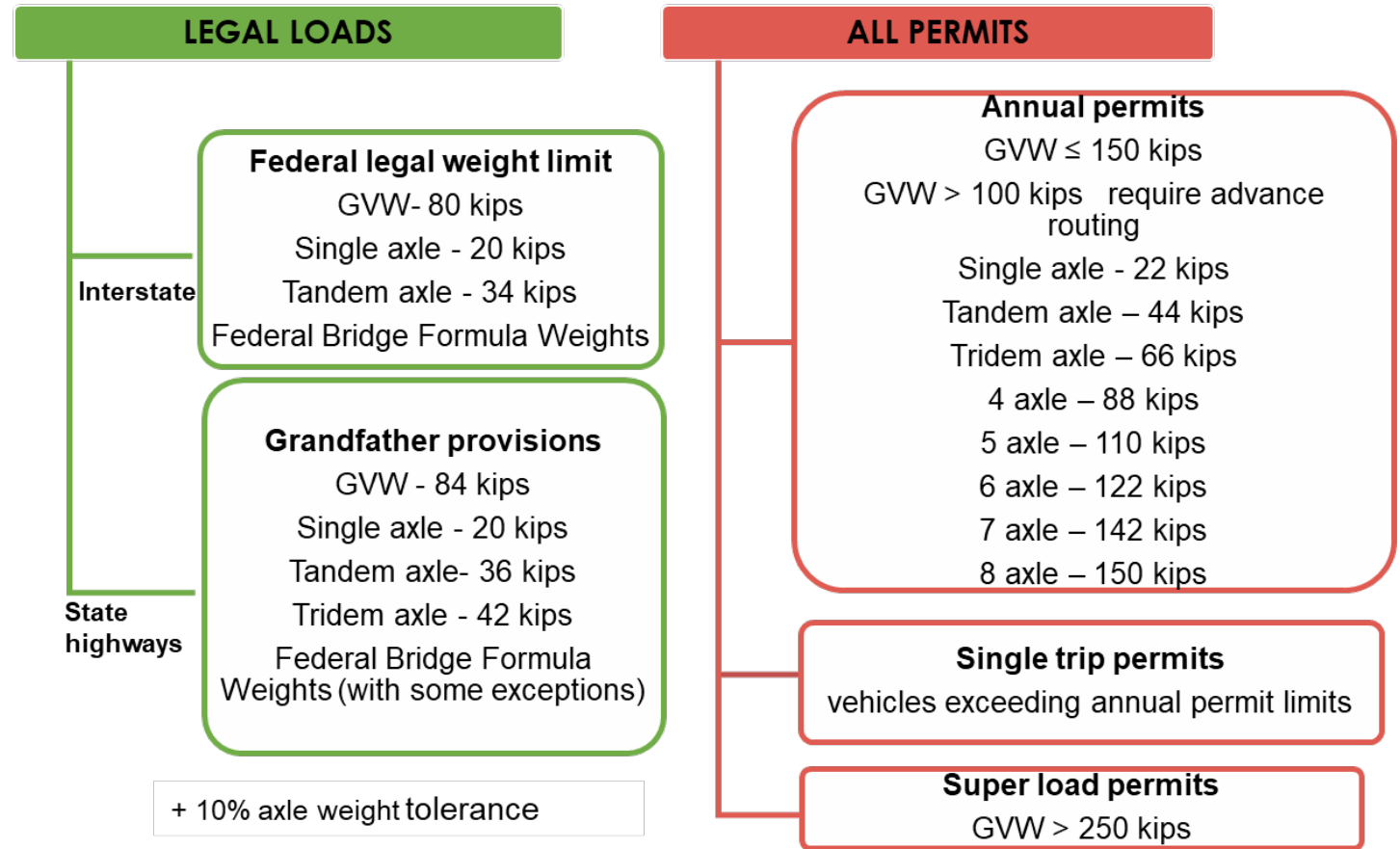
SORTING ALGORITHM – TRAFFIC DATA

- Legal trucks
- Legally overloaded (vehicles operating with permits due to overload)
- Illegally overloaded (overloaded vehicles operating without permits)

Vehicular traffic		
Legal loads	Overloaded	
Federal weight limits	Annual permits	Super load permits
Grandfather provisions	Single trip permits	Illegal trucks

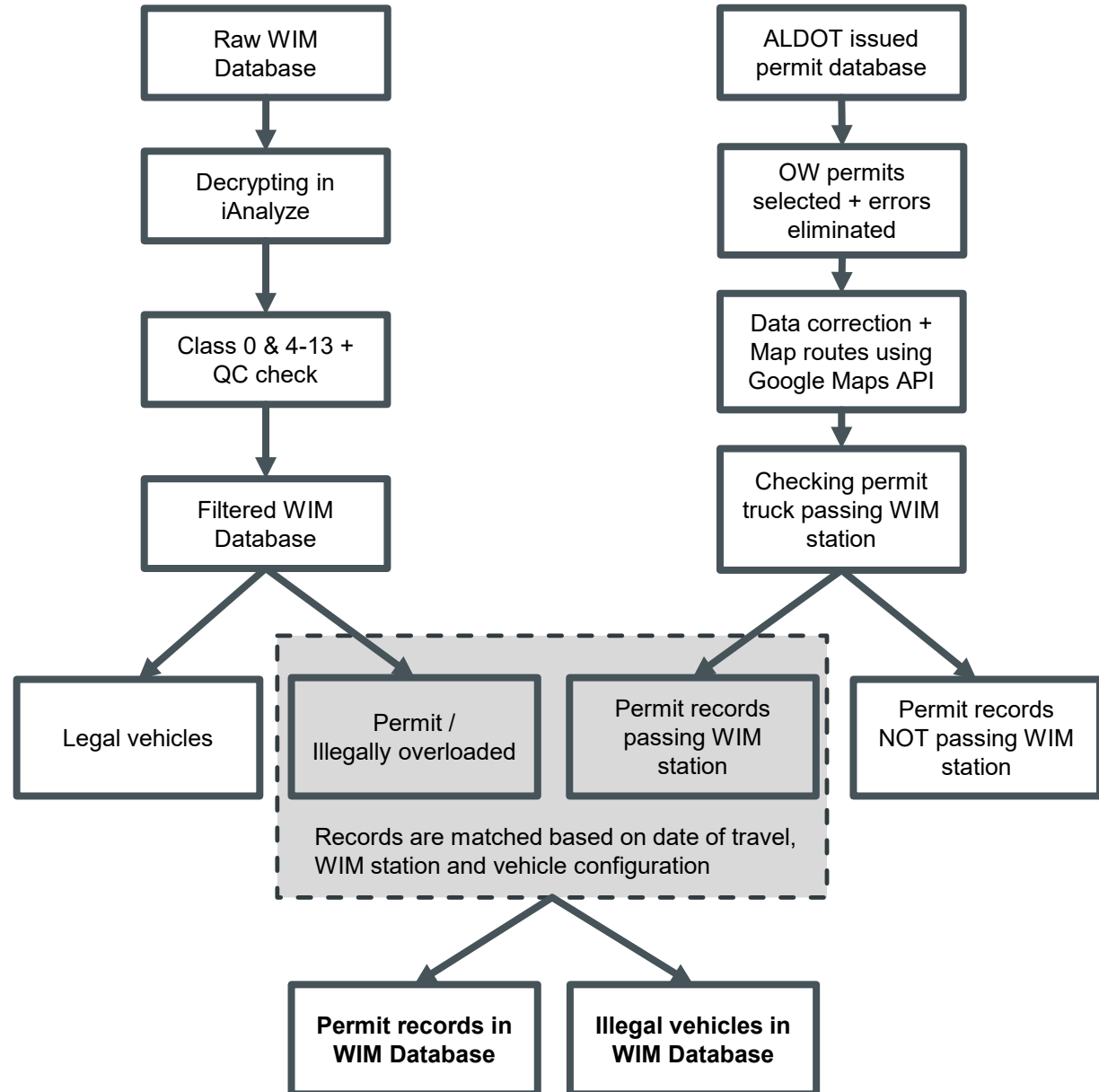
TECHNICAL APPROACH

SORTING ALGORITHM – ALABAMA TRUCK SIZE AND WEIGHT (TS&W) REGULATIONS



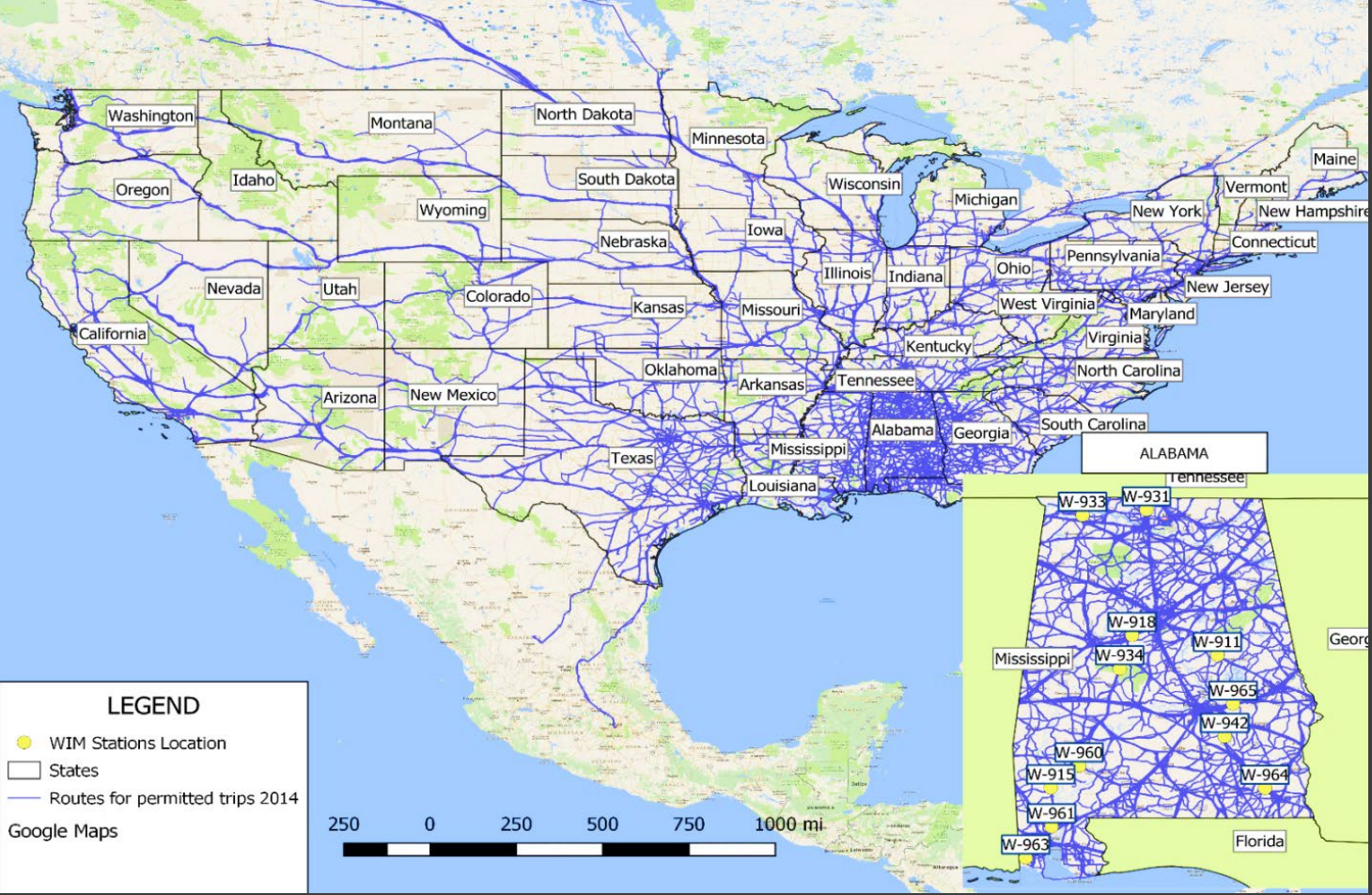
TECHNICAL APPROACH

IDENTIFICATION OF PERMIT & ILLEGALLY OVERLOADED VEHICLES



TECHNICAL APPROACH

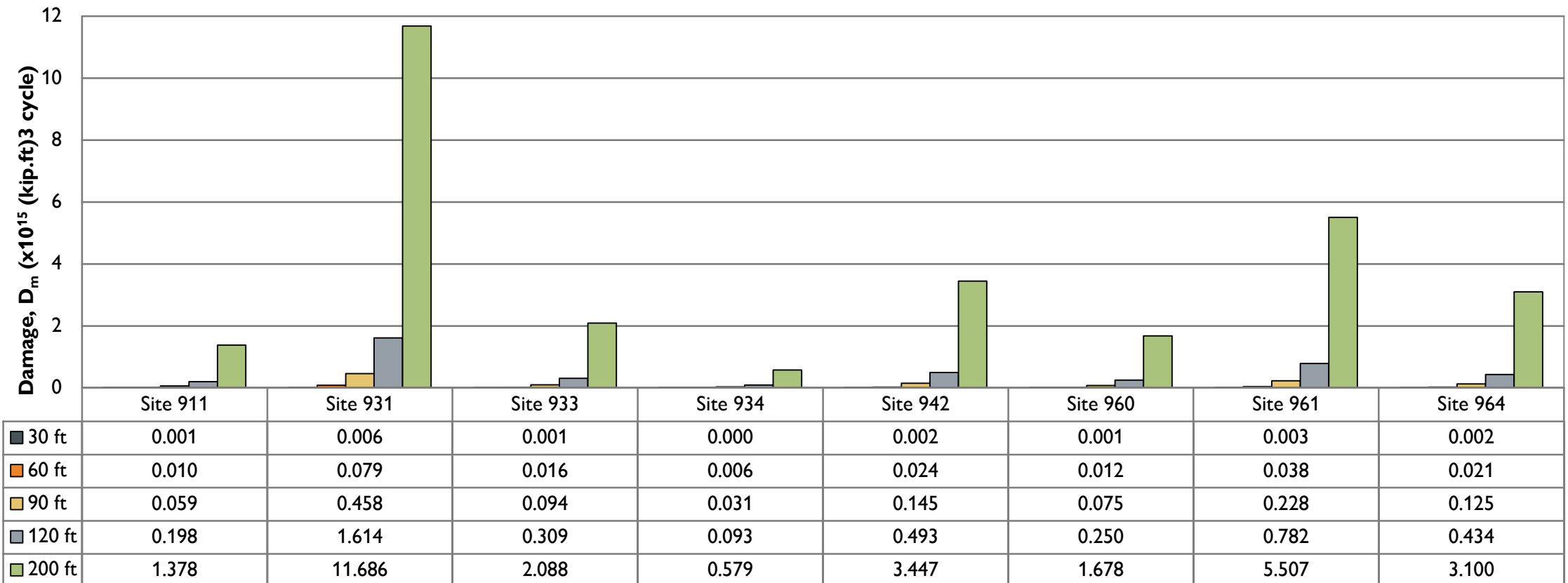
GIS ROUTING PROCEDURE
OW PERMIT TRUCKS - 2014



Credits: Jacek Chmielewski, Ph.D.

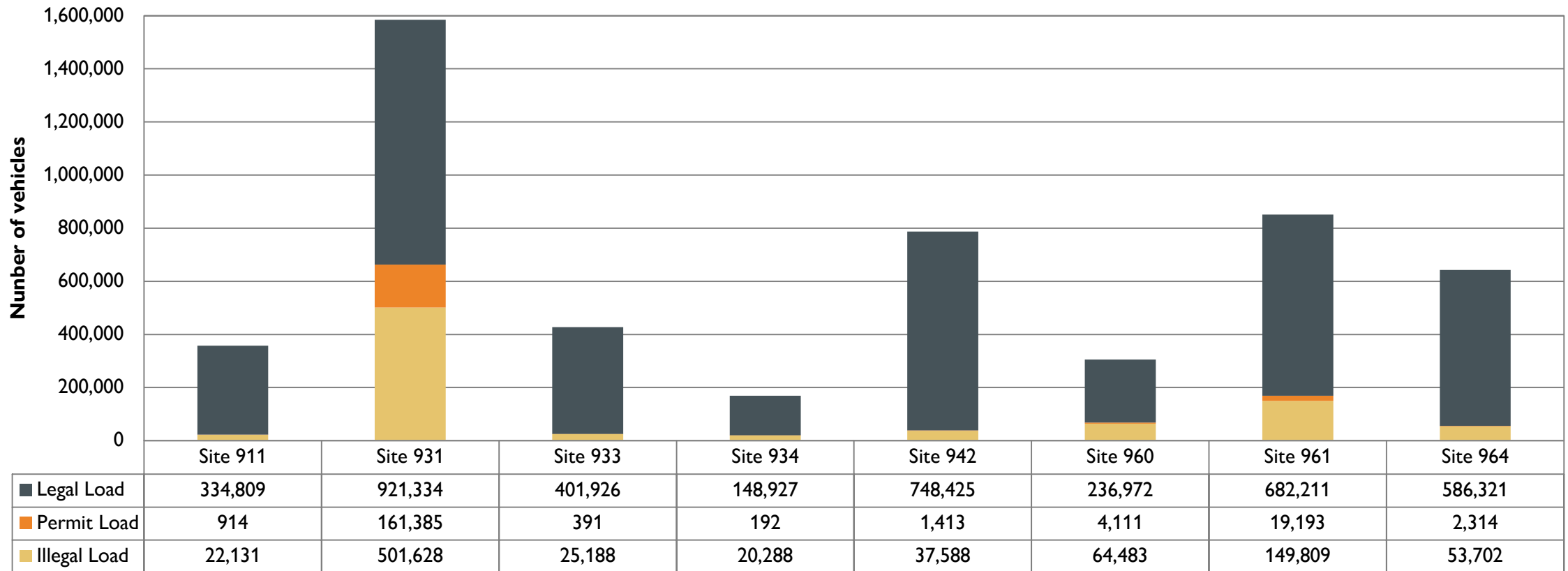
COMPARISON OF WIM SITE-SPECIFIC DAMAGE

ACCUMULATED DAMAGE, D_m AT THE UPSTREAM COVER PLATE END



COMPARISON OF WIM SITE-SPECIFIC DAMAGE

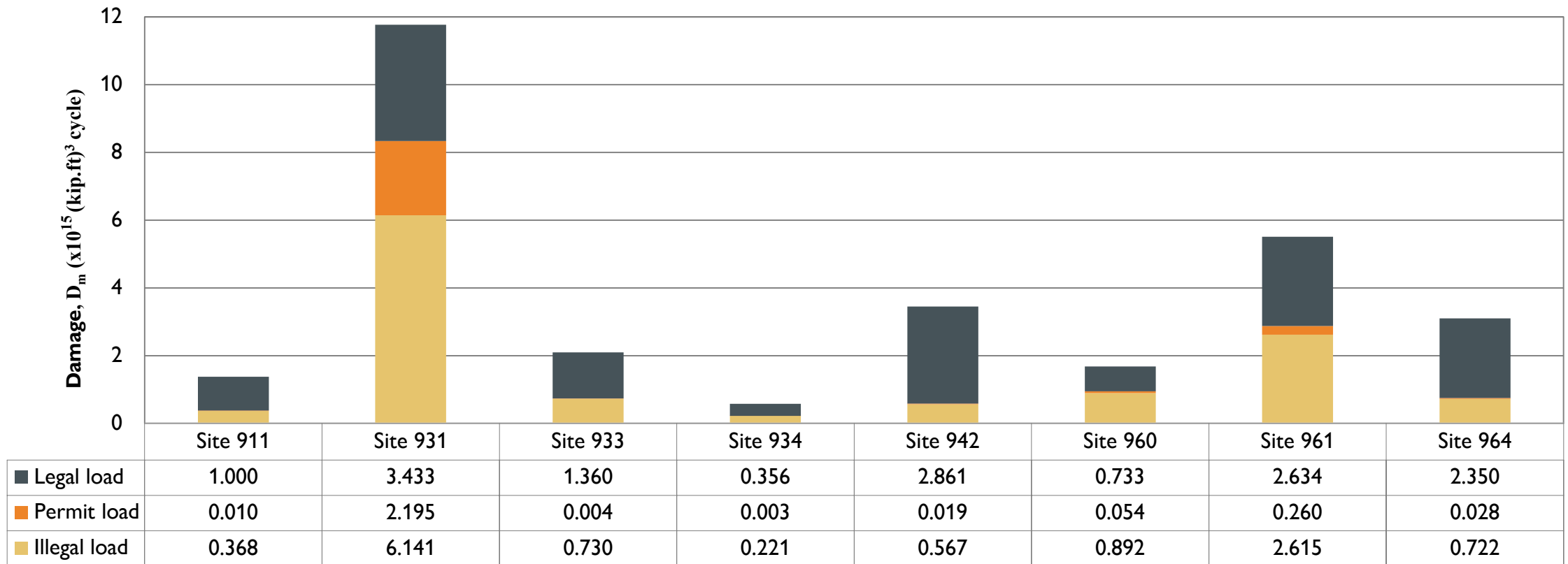
NUMBER OF RECORDS AT THE UPSTREAM COVER PLATE END FOR 200-FT SPAN



COMPARISON OF WIM SITE-SPECIFIC DAMAGE

24

ACCUMULATED DAMAGE, D_m , AT THE UPSTREAM COVER PLATE END FOR 200-FT SPAN

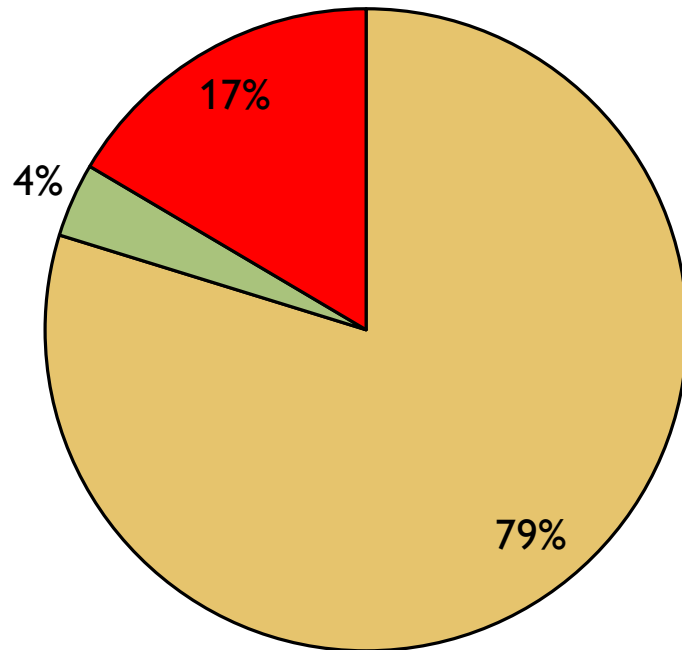


COMPARISON OF WIM SITE-SPECIFIC DAMAGE

25

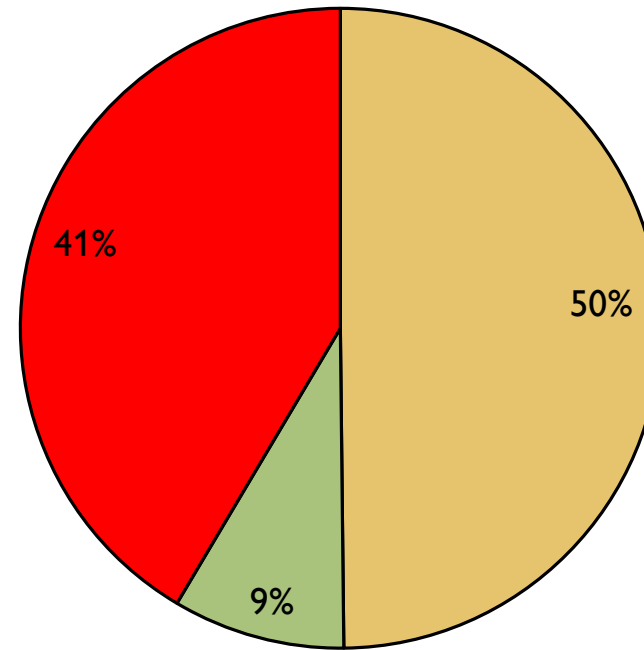
NUMBER OF VEHICLES

Legal load Permit load Illegal load



AMOUNT OF DAMAGE, D_M

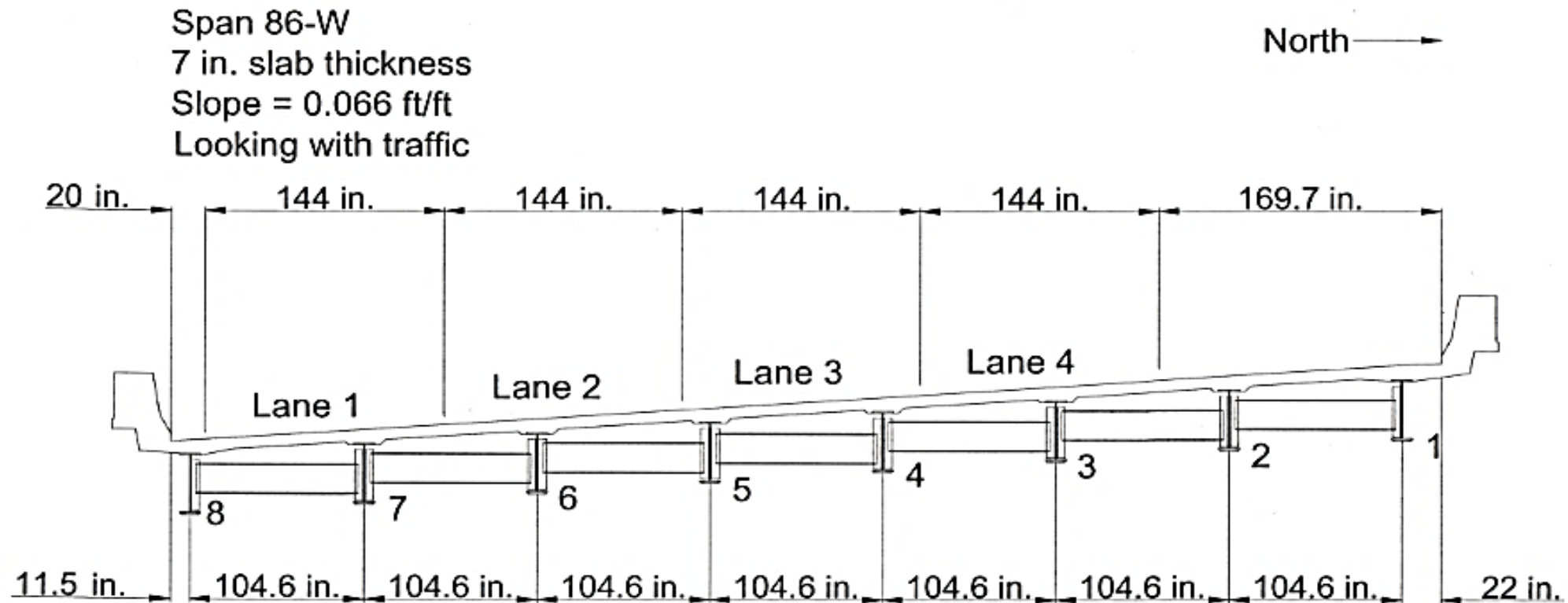
Legal load Permit load Illegal load



DAMAGE AT A SPECIFIC FATIGUE PRONE DETAIL

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SPAN 86-W OF CBD INTERCHANGE IN BIRMINGHAM, AL



DAMAGE AT A SPECIFIC FATIGUE PRONE DETAIL

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BRIDGE DATA INPUTS FOR SPAN 86-W BRIDGE ON INTERSTATE I-59/20 IN BIRMINGHAM, ALABAMA

Section modulus (S)	702 in ³
Span length (L)	60 ft
Girder distribution factor (GDF)	0.51
Dynamic load allowance (IM)	0.15
Location of upstream cover plate end	11.0 ft
x/L of upstream cover plate end	0.2
Location of downstream cover plate end	53.6 ft
x/L of downstream cover plate end	0.8
Number of traffic lanes	4
Direction of traffic	One-direction only
Fraction of truck traffic (p)	0.85
Resistance factor for mean fatigue life for E' detail (R _R)	1.9
Ratio of measured to calculated stress range (P)	0.6
Average daily truck traffic (ADTT)	2809
Number of lanes (n _L)	4

DAMAGE AT A SPECIFIC FATIGUE PRONE DETAIL

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EVALUATION OF A SPECIFIC BRIDGE USING TRAFFIC DATA FROM WIM SITE 93 I

$$D = \frac{p}{R_R * A} * \left(\frac{GDF * (1 + IM) * P * R_p}{S} \right)^3 * NM_{eff}^3$$

Fraction of mean fatigue life expended at the upstream cover plate end, $D_m = 0.0099$

» If a bridge is designed for 75 years, then $\frac{1}{75} = 0.0133 > 0.0099$

Rate of damage accumulation is less than anticipated during the design.

» If there is same annual traffic on the bridge each year of its life, then its mean service life would be $\frac{1}{D} = 101$ years.

DAMAGE AT A SPECIFIC FATIGUE PRONE DETAIL

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FRACTION OF MEAN FATIGUE LIFE EXPENDED AT A SPECIFIC FATIGUE PRONE DETAIL (DM) FOR AISI SHORT SPAN STEEL BRIDGES

AISI Short-Span Steel Bridges (American Iron and Steel Institute 1995) has real-life bridge design examples of composite rolled beams with welded cover plates.

Span (ft)	Beam cross-section	Cover plate		Girder spacing (ft)
		Thickness x Width (in)	Location (in)	
60	W 33x118	3/4 x 9 -1/2	5.5	10
90	W 40x183	1-1/2 x 10	9.5	10
120	W 36x300	2 x 14	14.5	10

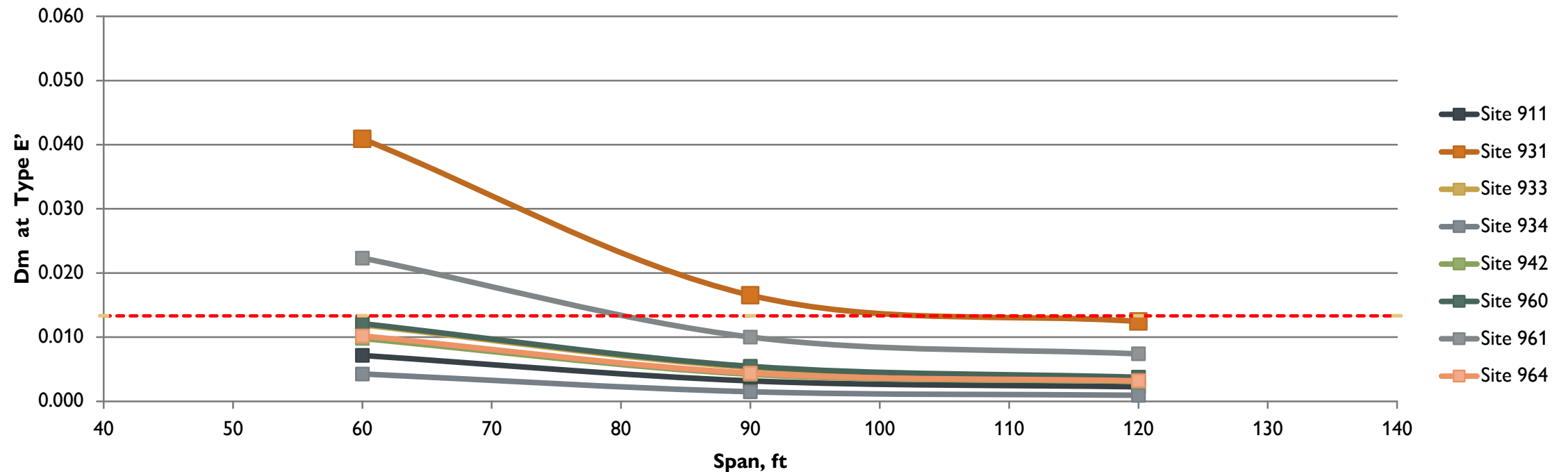
The fraction of mean fatigue life expended at a specific fatigue prone detail (Dm), was calculated for the cover plate ends (detail category Type E') at the upstream and downstream locations for some of these example bridge designs

DAMAGE AT A SPECIFIC FATIGUE PRONE DETAIL

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FRACTION OF MEAN FATIGUE LIFE EXPENDED AT A SPECIFIC FATIGUE PRONE DETAIL (DM) FOR AISI SHORT SPAN STEEL BRIDGES

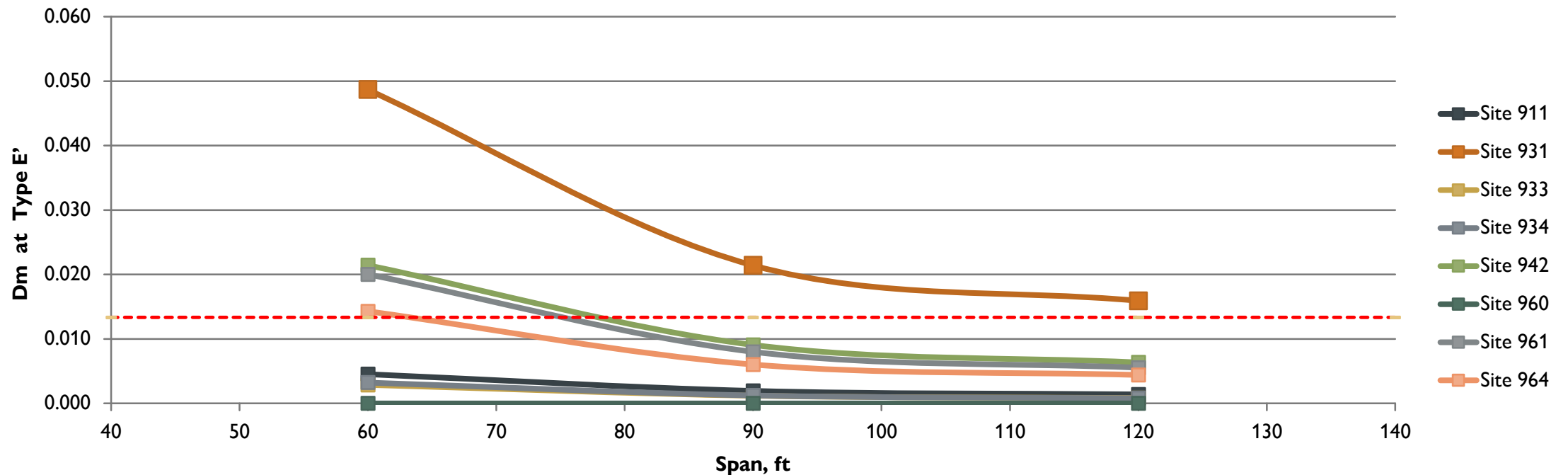
D_m at upstream cover plate end (Lane 1 & 2, year 2014)



DAMAGE AT A SPECIFIC FATIGUE PRONE DETAIL

FRACTION OF MEAN FATIGUE LIFE EXPENDED AT A SPECIFIC FATIGUE PRONE DETAIL (DM) FOR AISI SHORT SPAN STEEL BRIDGES

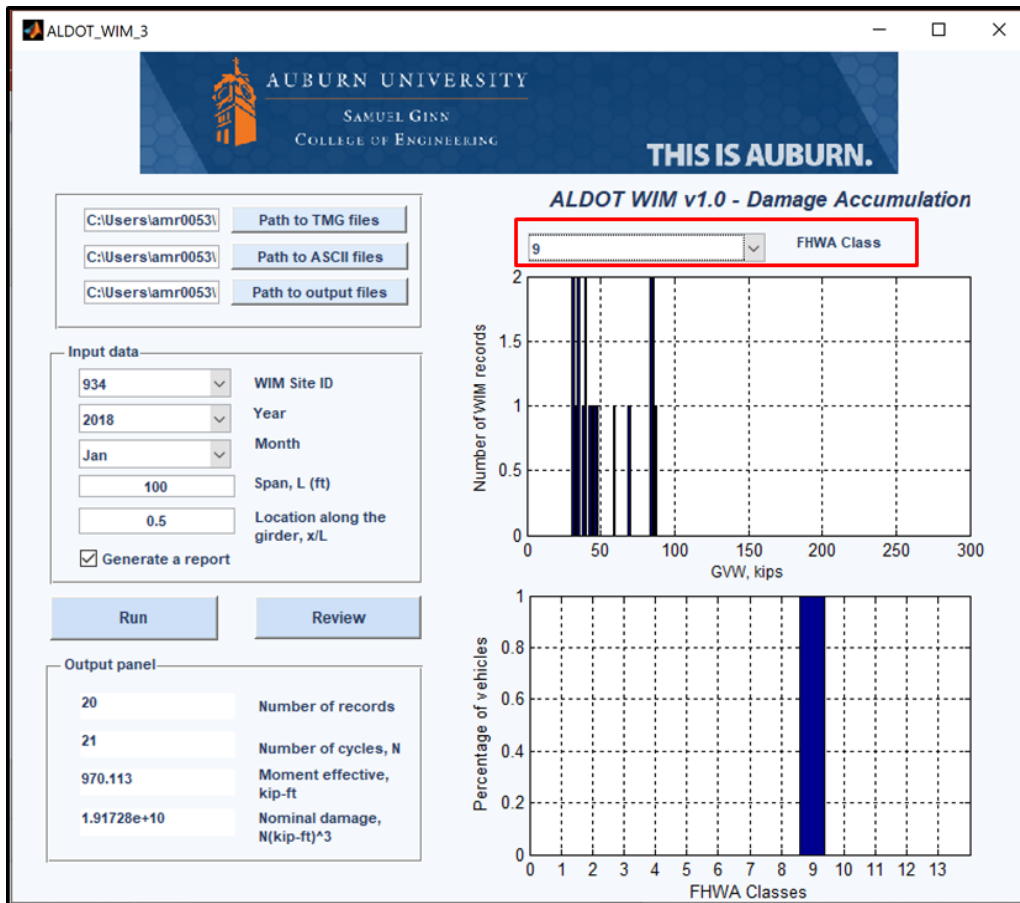
D_m at upstream cover plate end (Lane 3 & 4, year 2014)



DAMAGE AT A SPECIFIC FATIGUE PRONE DETAIL

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EVALUATION OF A SPECIFIC BRIDGE USING TRAFFIC DATA – ALDOT WIM DAI V1.0



- Variable data formats applicable
- WIM Data format conversion
- Comprehensive QC
- Cumulative Nominal Damage (D_m) computation
- To be improved to bridge specific analysis and real-time traffic data processing

EVALUATION OF A SPECIFIC BRIDGE USING TRAFFIC DATA

WIM Station 931 for Year 2014

Year 2014	For L = 60 ft and x/L = 0.2 (upstream coverplate end)			
Month	No. of records	N (cycles)	M _{eff} (kip-ft)	D=NM _{eff} ³ (cycles(kip-ft) ³)
Jan	66423	145916	257.64	2.50E+12

Feb	62731	135516	257.64	2.50E+12
Mar	71102	155916	257.64	2.50E+12
Apr	69661	145916	257.64	2.50E+12
May	73938	155916	257.64	2.50E+12
Jun	72429	155916	257.64	2.50E+12
Jul	71259	155916	257.64	2.50E+12
Aug	73270	155916	257.64	2.50E+12
Sep	67079	145916	257.64	2.50E+12
Oct	79038	155916	257.64	2.50E+12
Nov	66480	145916	257.64	2.50E+12
Dec	67562	145916	257.64	2.50E+12
T = 842972				4.03E+13

AL WIM DAI v1.0

UI Figure

C:\Users\lamr0053\ Path to TMG files

C:\Users\lamr0053\ Path to ASCII files

C:\Users\lamr0053\ Path to output files

Input data

934 WIM Site ID

2018 Year

Jan Month

100 Span, L (ft)

0.5 Location along the girder, x/L

Generate a report

Run Review

Output panel

23 Number of records

24 Number of cycles, N

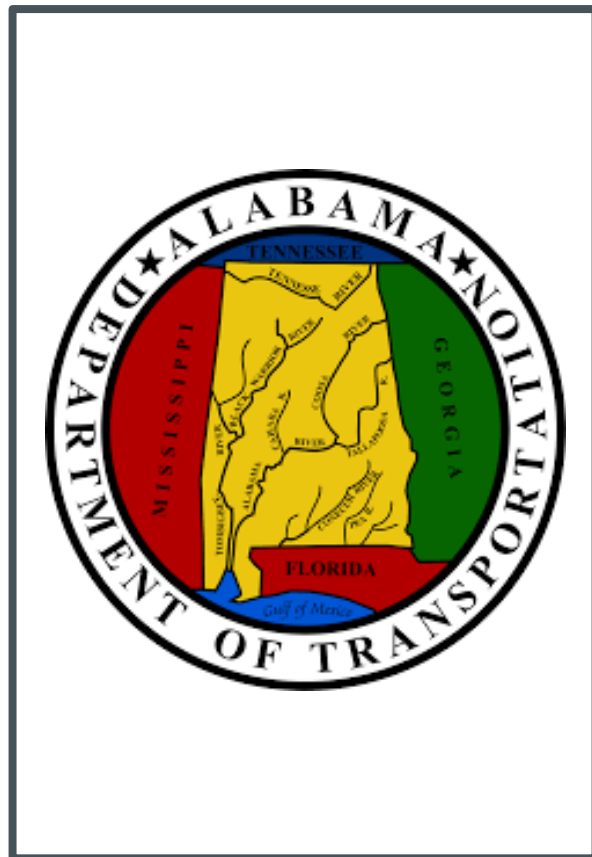
933.107 Moment effective, kip-ft

1.94987e+10 Nominal damage, N(kip-ft)³

CONCLUSIONS

- Based on the combined WIM data, 20% of the vehicles are overloaded (both permit loads and illegal loads), and this create more than 50% of the total fatigue damage.
- The 16-18% of trucks that are illegally overloaded create more than 40% of the total damage.
- 5-axle Class 9 trucks cause more than 70% of fatigue damage.
- For traffic recorded at WIM site 931 (Athens), the fatigue life of steel girder bridges is consumed four times faster than expected for a design life of 75 years.
- **AL WIM QC** helps in timely identification of malfunctioning of WIM systems. **AL WIM DAI** provides significant information of damage accumulation on bridges.

ACKNOWLEDGEMENTS



The presented research is co-sponsored by the Alabama Department of Transportation, which is gratefully acknowledged. The authors thank the ALDOT technical staff for their advice, discussion, and constructive comments. Special thanks are due to Randy Braden and Kevin Perdue for providing access to the WIM and permit databases.



THANK YOU FOR YOUR ATTENTION!



QUESTIONS?

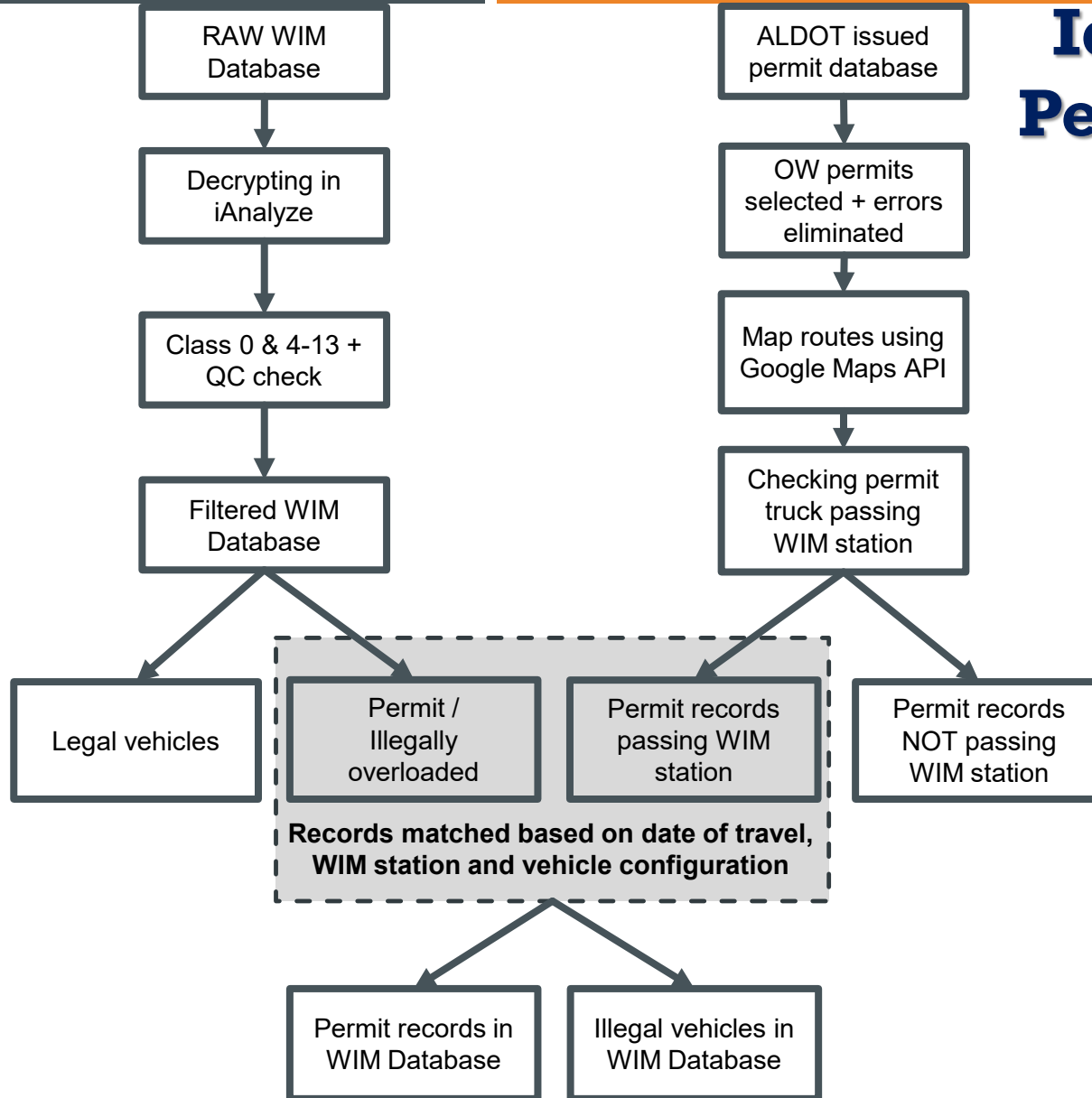
WIM Data

Permit Data

Part 2 :

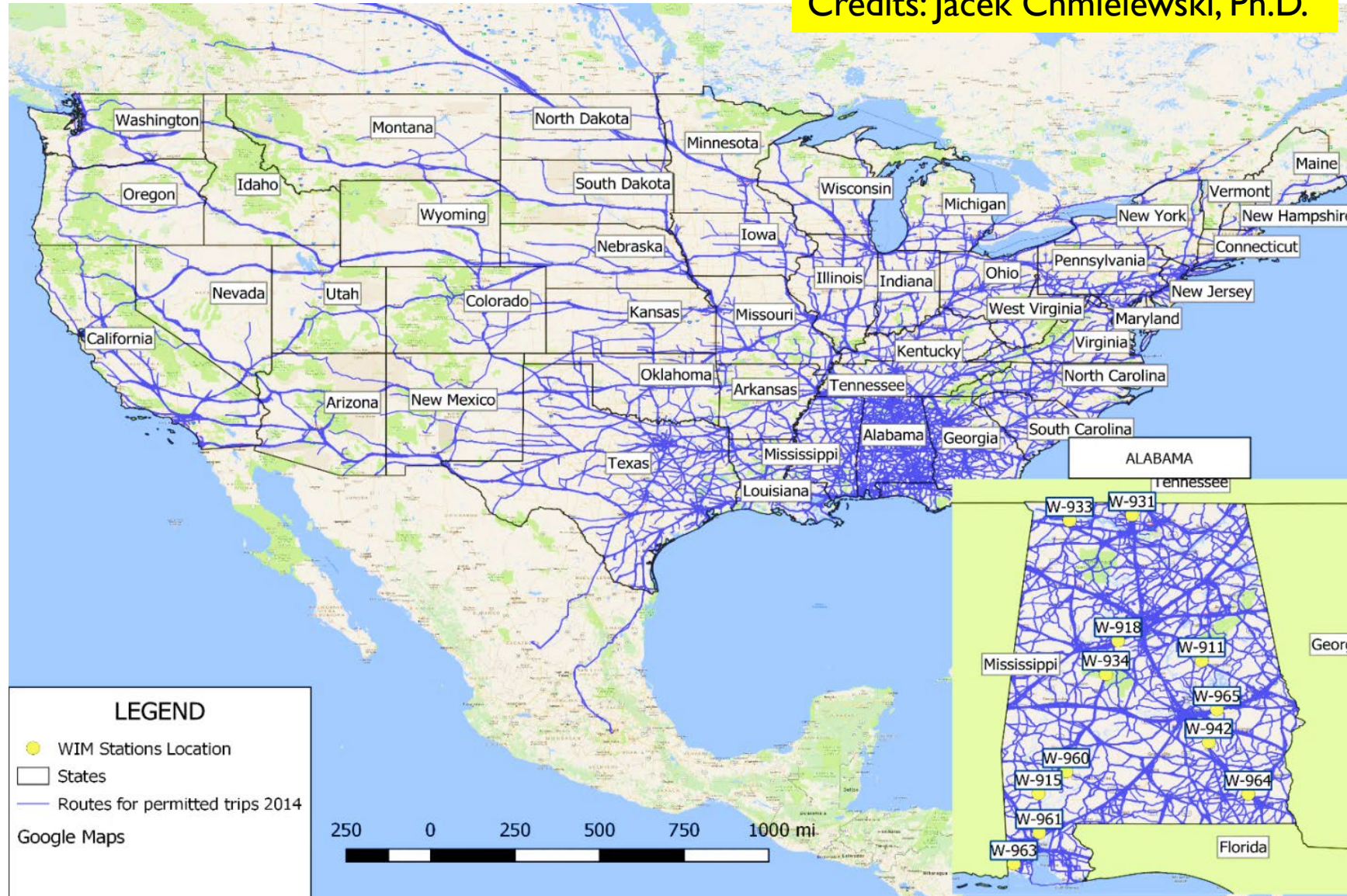
Identification of Permit & Illegally Overloaded Vehicles

GIS routing procedure



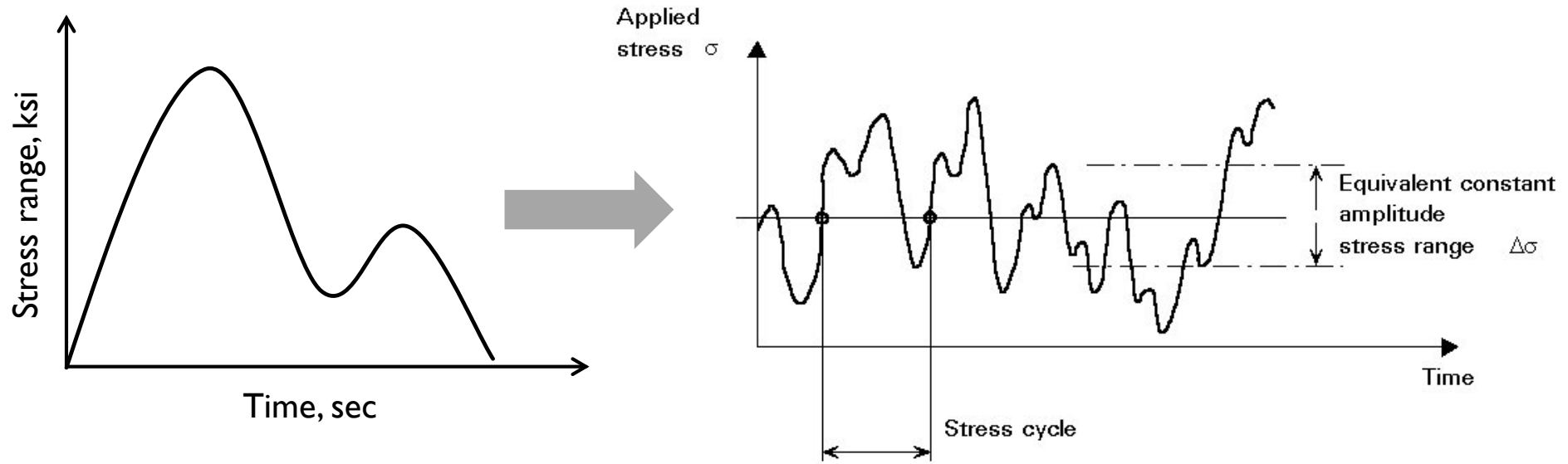
Permit Truck Routes – Year 2014

Credits: Jacek Chmielewski, Ph.D.

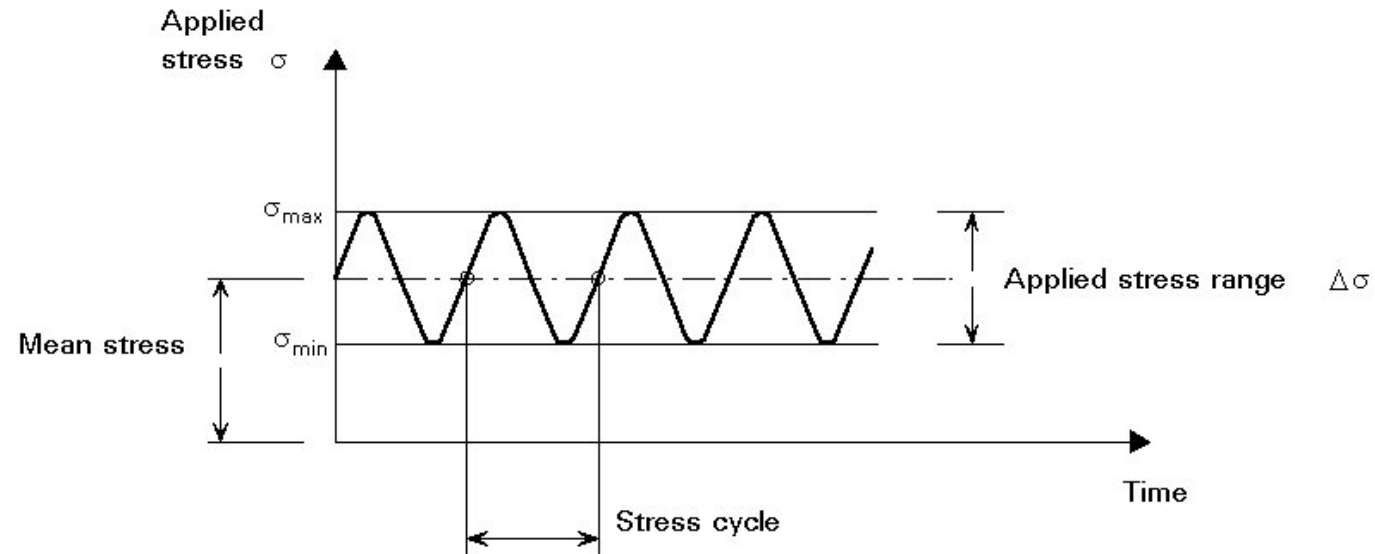


Part 3 : Assessment of Fatigue Damage Accumulation

Traffic induced fatigue loading (variable amplitude)



Loading used in developing S-N curves (constant amplitude)



DAMAGE AT A SPECIFIC FATIGUE PRONE DETAIL

The effective stress range, S_{eff} , is calculated

$$S_{\text{eff}} = \frac{M_{\text{eff}} * \text{GDF} * (1 + \text{IM}) * P}{S}$$

where:

M_{eff} – effective moment range from WIM data

GDF – girder distribution factor for a single loaded lane

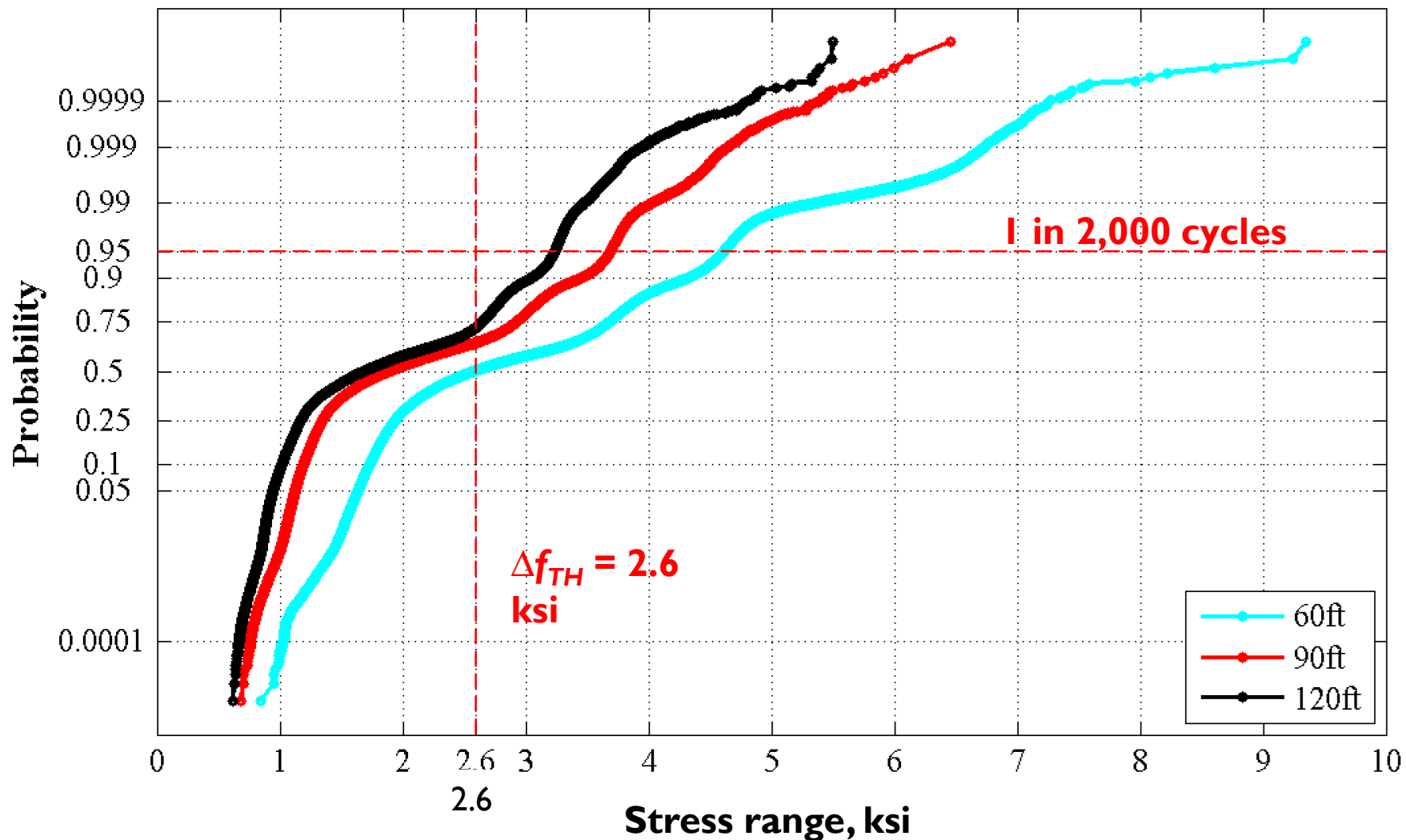
IM – dynamic load allowance

P – ratio of measured to calculated stress range

S – section modulus for the specific fatigue detail

Finite Life Check

Maximum stress range at the upstream cover plate end – E' type detail



Generic – Q4: How do the amounts of fatigue damage caused by various classes of trucks

Location 911 compare? Cover plate end

