Seminario Internacional de Puentes
AMIVTAC - PIARC

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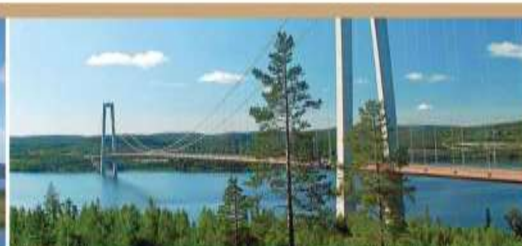
# MONITORING TRAFFIC LOADING FOR OPTIMIZED ASSESSMENT OF BRIDGES


## Dr. Aleš Žnidarič

- **Slovenian National Building and Civil Engineering Institute**
- **Head of Department for Structures**
- ales.znidaric@zag.si





# Outline

- About bridge assessment
- About *bridge weigh-in-motion* or *B-WIM*?
- How to use B-WIM in bridge assessment?
- Examples
- Conclusions and discussion

# Slovenia?




# European B-WIM/assessment history

COST 323

WAVE

COST 345

SAMARIS

ARCHES

HEroad

TRIMM

BRIDGEMON

Re-gen
risk assessment of ageing infrastructure

# Why optimised bridge assessment?



- Because we do not want to spend money for avoidable rehabilitations!
- Fortunately:
  - bridges are stronger than we think
  - load effects are less than in the codes
- Despite being deteriorated bridges are likely safe, but…
- … how to prove their actual safety?

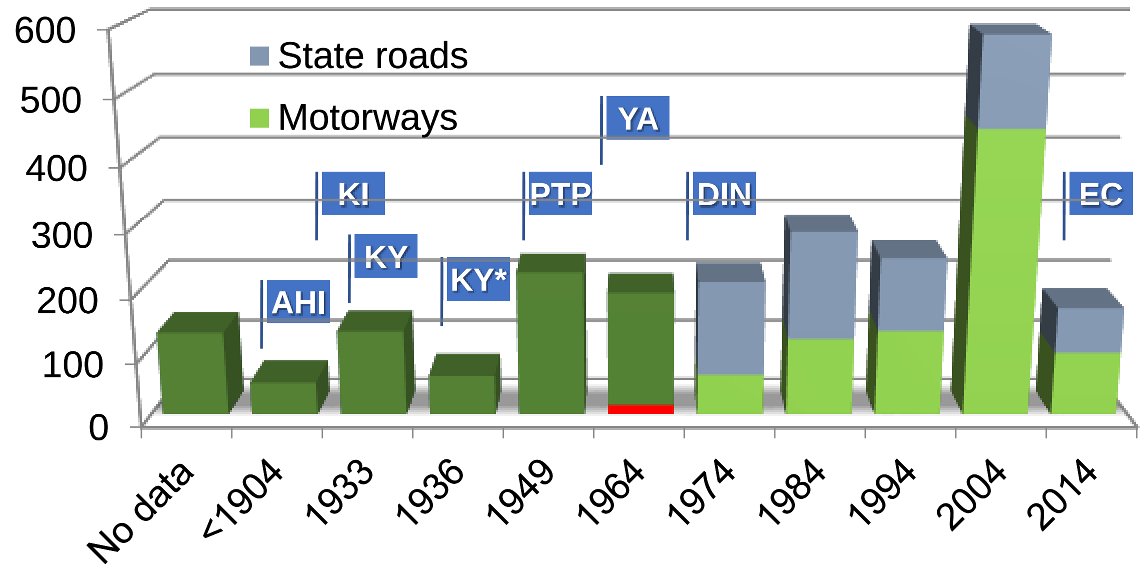
# Optimised bridge assessment



1. What is the condition of the structure?
2. What is its carrying capacity?
3. What is the real traffic loading?
4. What are the load effects due to loading?

# Bridge capacity - Slovenian example

- 2 369 bridges:
  - state roads 1 398
  - motorways 971
  - 1 bridge ≈ every 4 km
- ≈32% (>62% on state roads) over 50 years




- construction rules and design loads:
  - in 114 years 8 codes with different traffic loading schemes
  - structural safety of ≈ 62% of bridges ***on state roads*** and of ≈1% on ***motorways*** questionable due to their age
- in addition, capacity reduced due to deterioration

# Design vs. assessment



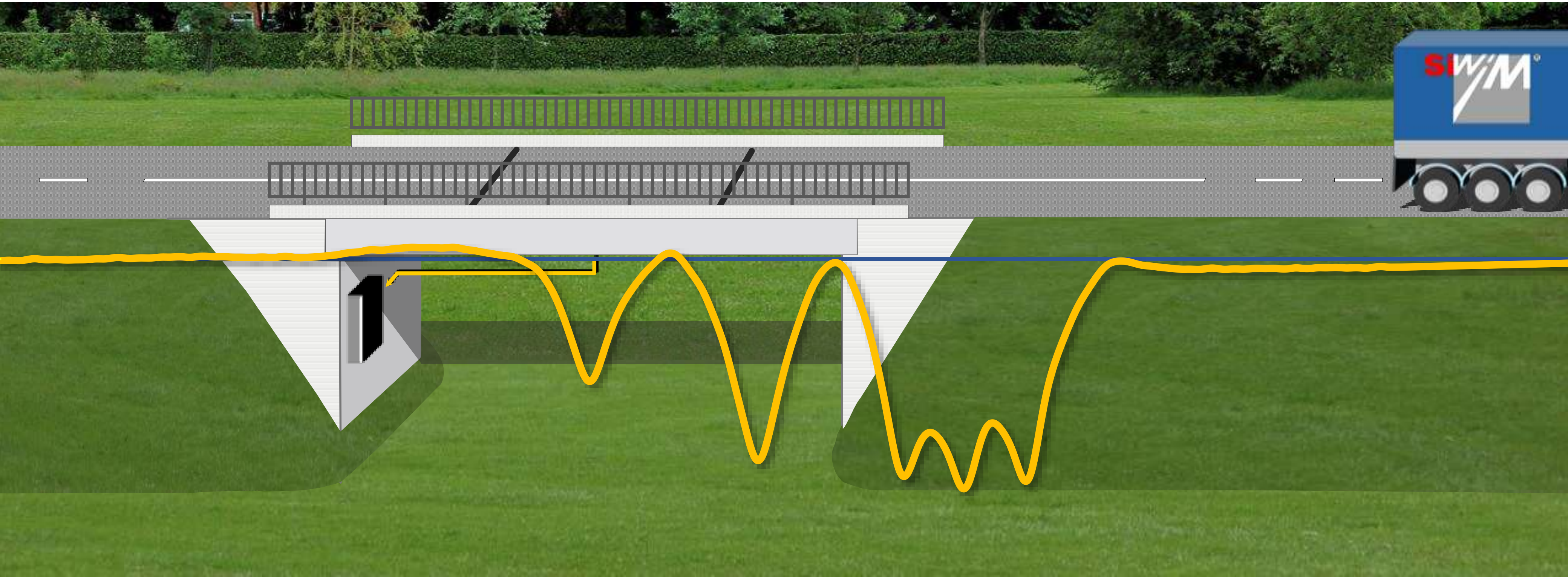
- new bridges shall be designed conservatively, due to uncertainties about increasing loading & decreased capacity


- assessment should be optimal:
  - expensive to post, strengthen or replace a bridge
  - capacity and loading can be measured/monitored

**B-WIM**

# Bridge weigh-in-motion…

… or B-WIM is a measuring system that uses an *existing* instrumented road or rail structure – a bridge or a culvert – to weigh vehicles in motion, at normal highway speed.

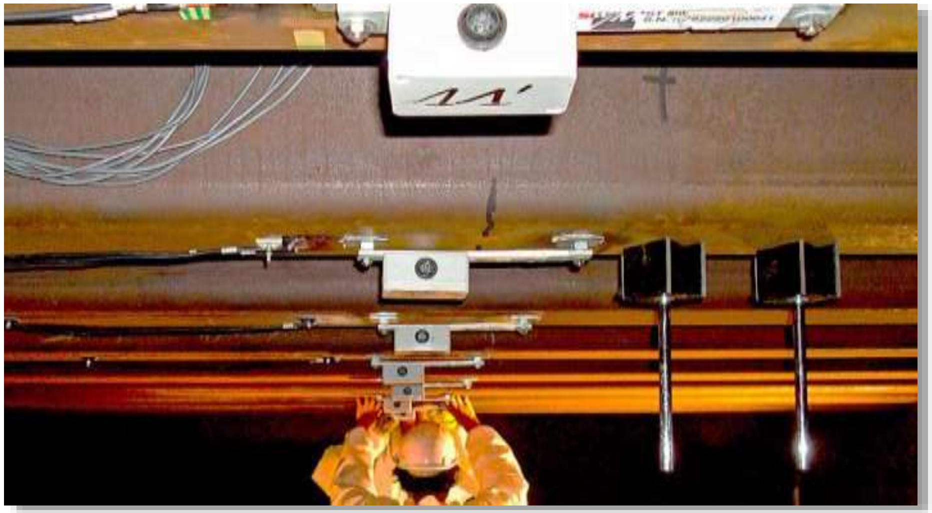


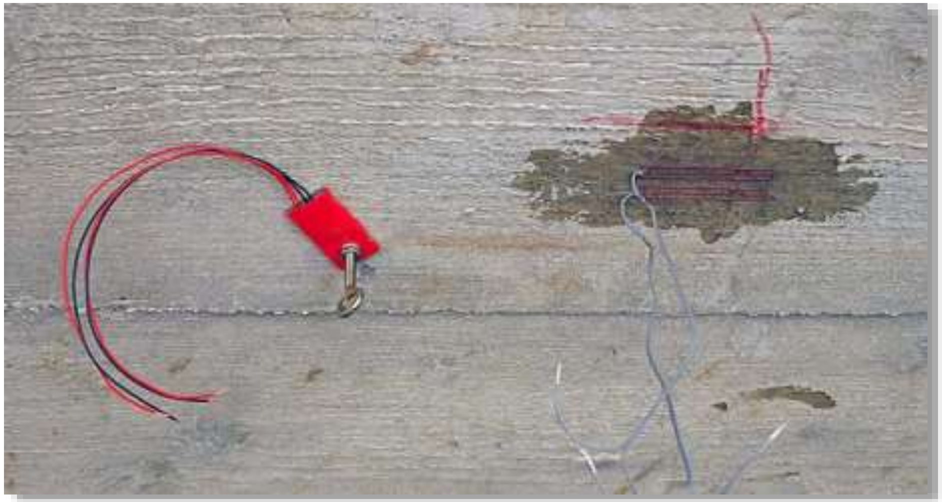

# Bridge weigh-in-motion

- principles published in 1979 in USA
- research in Europe in 1990s
- SiWIM® since 2000
- …nstallations,
- …tages:
    - completely portable
    - high accuracy
    - *no interruption of traffic*
    - provides structural information
- disadvantages:
    - proper bridge is needed
    - requires knowledge about bridges
- B-WIM also in:
    - Australia
    - Canada
    - many universities from USA
    - Japan

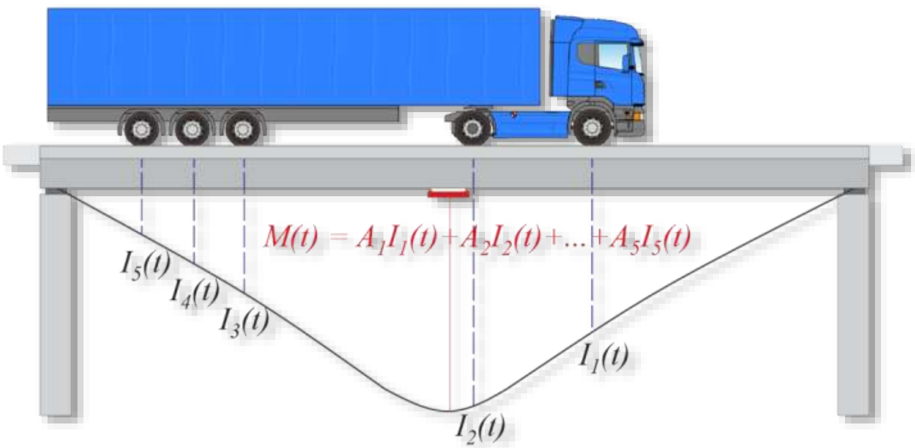

# Strain measurements


- sensors:
  - strain transducers
  - strain gauges
- additional sensors can be synchronised with SiWIM measurements





# Conventional B-WIM algorithm




## Comparison of strains:

Measured:

$$M(t_j) = \sum_{i}^{N_G} M_i(t_j) = E\,W \sum_{i}^{N_G} \varepsilon_i = CF \sum_{i}^{N_G} \varepsilon_i\,(t_j)$$

Calculated:

$$M(t_j) = \sum_{i=1}^{N} AL_i I(x)$$

$$= \sum_{i=1}^{N} AL_i I[v_i(t_i - t_j)];\ j = 1 \ldots N_M$$

- minimisation of the difference between *measured* and *calculated* moments

# 2.5 + 3.0-m integral culvert


# Viaduc de Millau



France

# B-WIM for bridge assessment



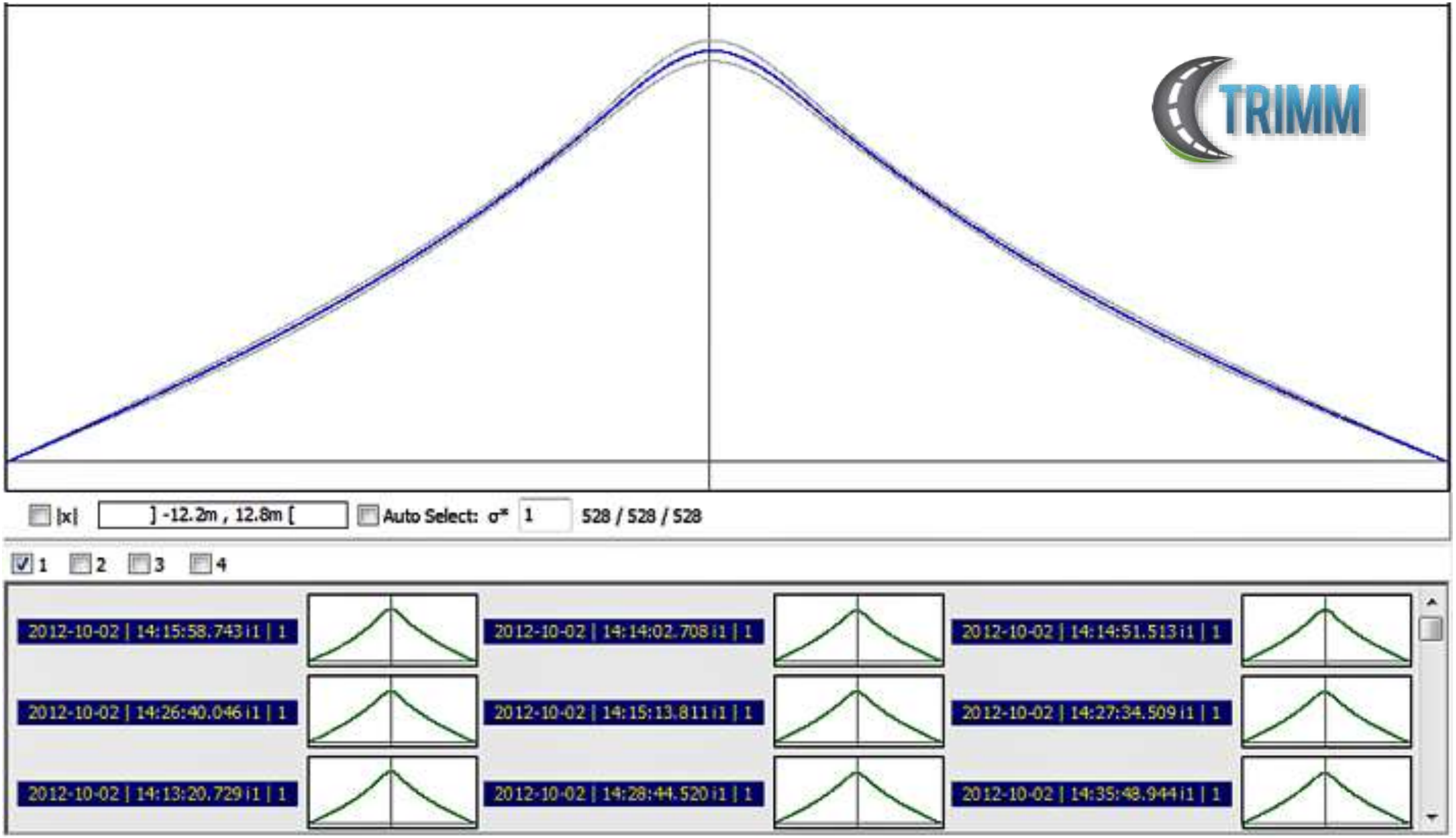
4 parameters that improve structural analysis:

1. Axle loads, spacings, speed, vehicle class..., for assessment of actual traffic loading – from any WIM system

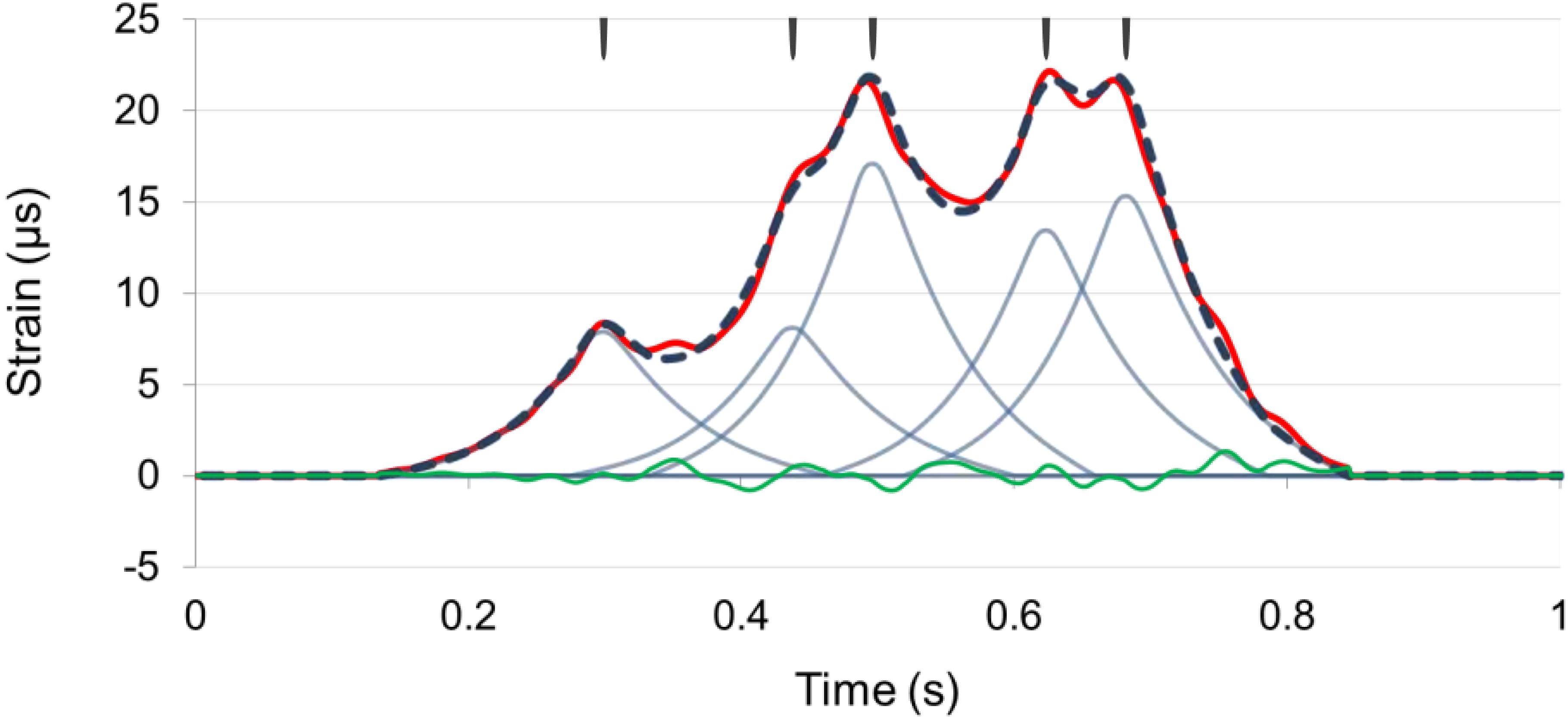
... and 3 measured structural parameters:

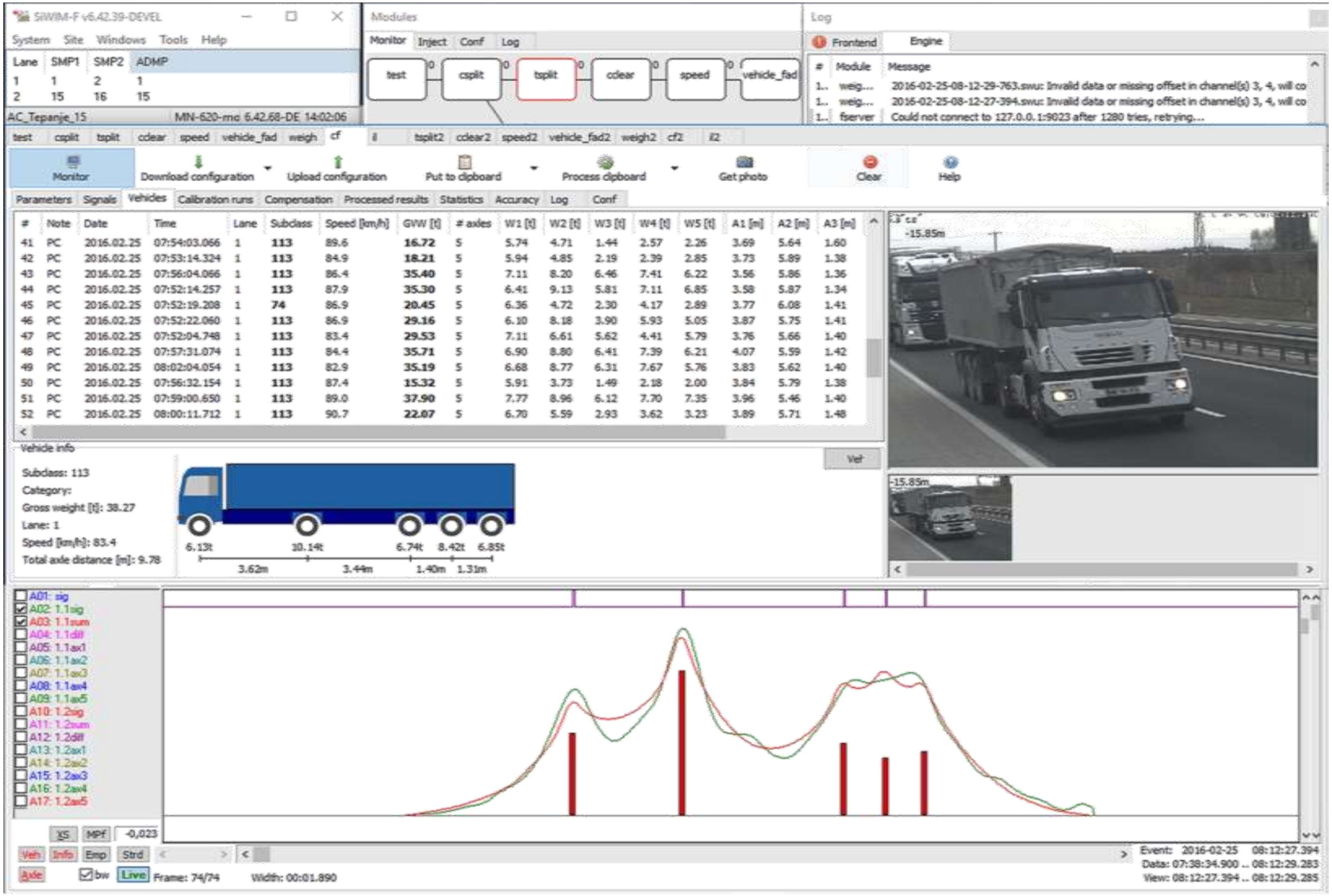
2. Influence lines – IL
3. Distribution of traffic loading over structural members – GDF
4. Dynamic loading – DAF

# Influence Line Calculation



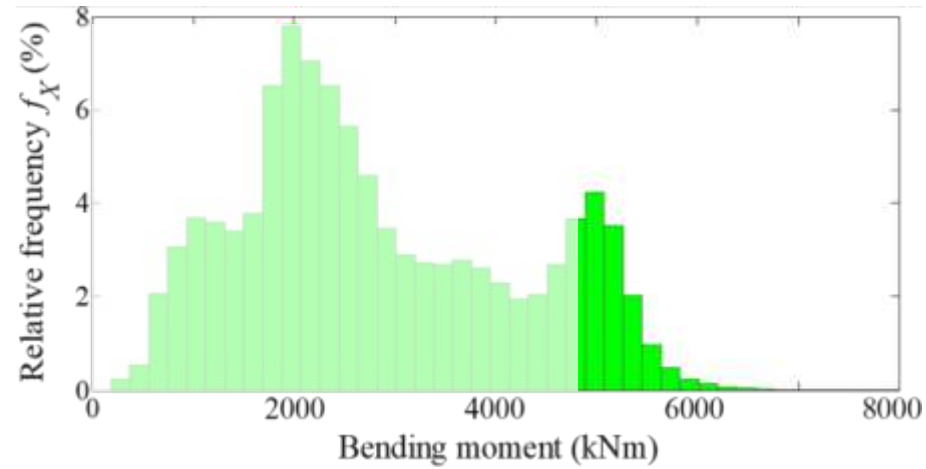
# Influence Line implementation in B-WIM

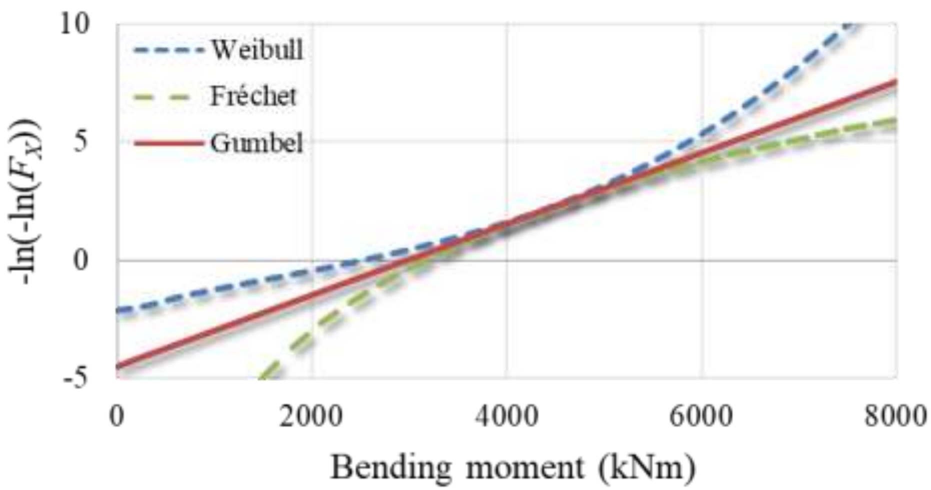


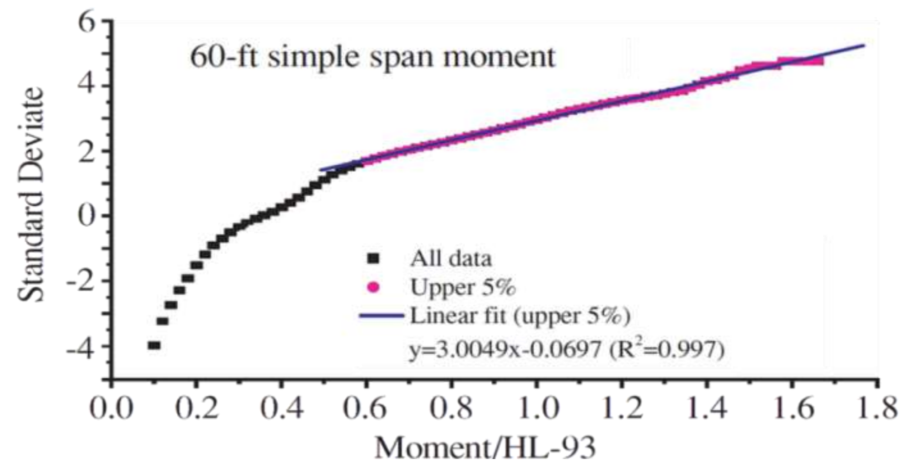


SiWIM-F v6.42.39-DEVEL
System Site Windows Tools Help
Lane SMP1 SMP2 ADMP
1 1 2 1
2 15 16 15
AC_Tepanje_15
MN-620-rnd 6.42.68-DE 14:02:06
Modules
Monitor Inject Conf Log
test csplit tsplit cclear speed vehicle_fad
Log
Frontend Engine
# Module Message
1.. weig... 2016-02-25-08-12-29-763.swu: Invalid data or missing offset in channel(s) 3, 4, will co
1.. weig... 2016-02-25-08-12-27-394.swu: Invalid data or missing offset in channel(s) 3, 4, will co
1.. fserver Could not connect to 127.0.0.1:9023 after 1280 tries, retrying...
test csplit tsplit cclear speed vehicle_fad weigh cf tsplit2 cclear2 speed2 vehicle_fad2 weigh2 cf2
Monitor Download configuration Upload configuration Put to clipboard Process clipboard Get photo Clear Help
Parameters Signals Vehicles Calibration runs Compensation Processed results Statistics Accuracy Log Conf
# Note Date Time Lane Subclass Speed [km/h] GVW [t] # axles W1 [t] W2 [t] W3 [t] W4 [t] W5 [t] A1 [m] A2 [m] A3 [m]
41 PC 2016.02.25 07:54:03.066 1 113 89.6 16.72 5 5.74 4.71 1.44 2.57 2.26 3.69 5.64 1.60
42 PC 2016.02.25 07:53:14.324 1 113 84.9 18.21 5 5.94 4.85 2.19 2.39 2.85 3.73 5.89 1.38
43 PC 2016.02.25 07:56:04.066 1 113 86.4 35.40 5 7.11 8.20 6.46 7.41 6.22 3.56 5.86 1.36
44 PC 2016.02.25 07:52:14.257 1 113 87.9 35.30 5 6.41 9.13 5.81 7.11 6.85 3.58 5.87 1.34
45 PC 2016.02.25 07:52:19.208 1 74 86.9 20.45 5 6.36 4.72 2.30 4.17 2.89 3.77 6.08 1.41
46 PC 2016.02.25 07:52:22.060 1 113 86.9 29.16 5 6.10 8.18 3.90 5.93 5.05 3.87 5.75 1.41
47 PC 2016.02.25 07:52:04.748 1 113 83.4 29.53 5 7.11 6.61 5.62 4.41 5.79 3.76 5.66 1.40
48 PC 2016.02.25 07:57:31.074 1 113 84.4 35.71 5 6.90 8.80 6.41 7.39 6.21 4.07 5.59 1.42
49 PC 2016.02.25 08:02:04.054 1 113 82.9 35.19 5 6.68 8.77 6.31 7.67 5.76 3.83 5.62 1.40
50 PC 2016.02.25 07:56:32.154 1 113 87.4 15.32 5 5.91 3.73 1.49 2.18 2.00 3.84 5.79 1.38
51 PC 2016.02.25 07:59:00.650 1 113 89.0 37.90 5 7.77 8.96 6.12 7.70 7.35 3.96 5.46 1.40
52 PC 2016.02.25 08:00:11.712 1 113 90.7 22.07 5 6.70 5.59 2.93 3.62 3.23 3.89 5.71 1.48
Vehicle info
Subclass: 113
Category:
Gross weight [t]: 38.27
Lane: 1
Speed [km/h]: 83.4
Total axle distance [m]: 9.78
6.13t 10.14t 6.74t 8.42t 6.85t
3.62m 3.44m 1.40m 1.31m
-15.85m
A01: sig
A02: 1.1sig
A03: 1.1sum
A04: 1.1diff
A05: 1.1ax1
A06: 1.1ax2
A07: 1.1ax3
A08: 1.1ax4
A09: 1.1ax5
A10: 1.2sig
A11: 1.2sum
A12: 1.2diff
A13: 1.2ax1
A14: 1.2ax2
A15: 1.2ax3
A16: 1.2ax4
A17: 1.2ax5
Frame: 74/74
Width: 00:01.890
Event: 2016-02-25 08:12:27.394
Data: 07:38:34.900 .. 08:12:29.283
View: 08:12:27.394 .. 08:12:29.285

# Modelling load effects on bridges

1. Measurements of load effects
2. Looking for extreme values:
   a) Extrapolations:
      - GEV distributions (Gumbel, Weibull, Fréchet)
      - normal (log normal)
      - POT (*Peek Over Threshold*)
      - Convolution – in SiWIM®
   
   b) Simulations, in particular long-run




# Convolution method



## Assumptions:

- combine 2 lanes with independent traffic:

$$f_Z(z) = \sum_{k=-\infty}^{\infty} f_X(k)\, f_Y(z-k)$$

to get the distribution of all MP events on the bridge

- valid for spans up to 40 m,
» 95% of all bridges

## Extreme value theory:

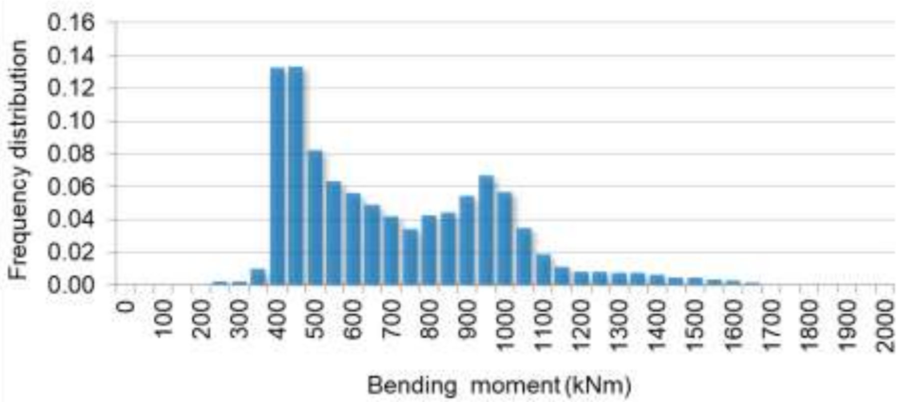
$$F_Z(z) = P\left(Z_{N_T} \leq z\right) = \left(F_Z(z)\right)^{N_T}$$

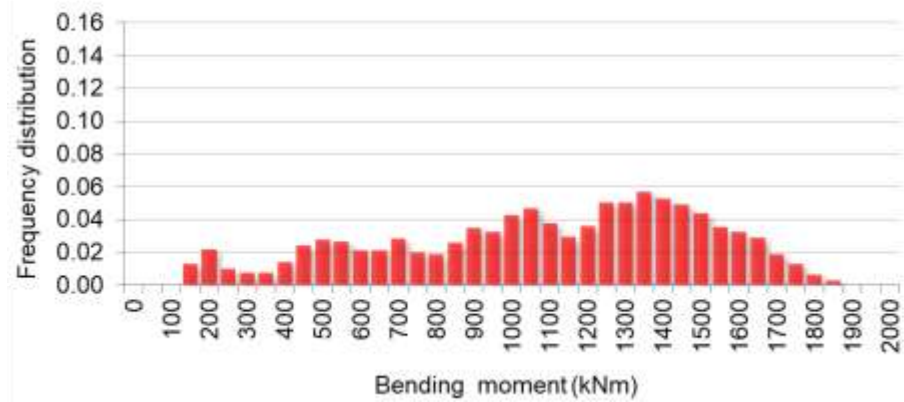
where $N_T$ is number of MP events in forecasted period, e.g. 100 MP per day (from SiWIM®), times 250 working days per year, times 75 years:

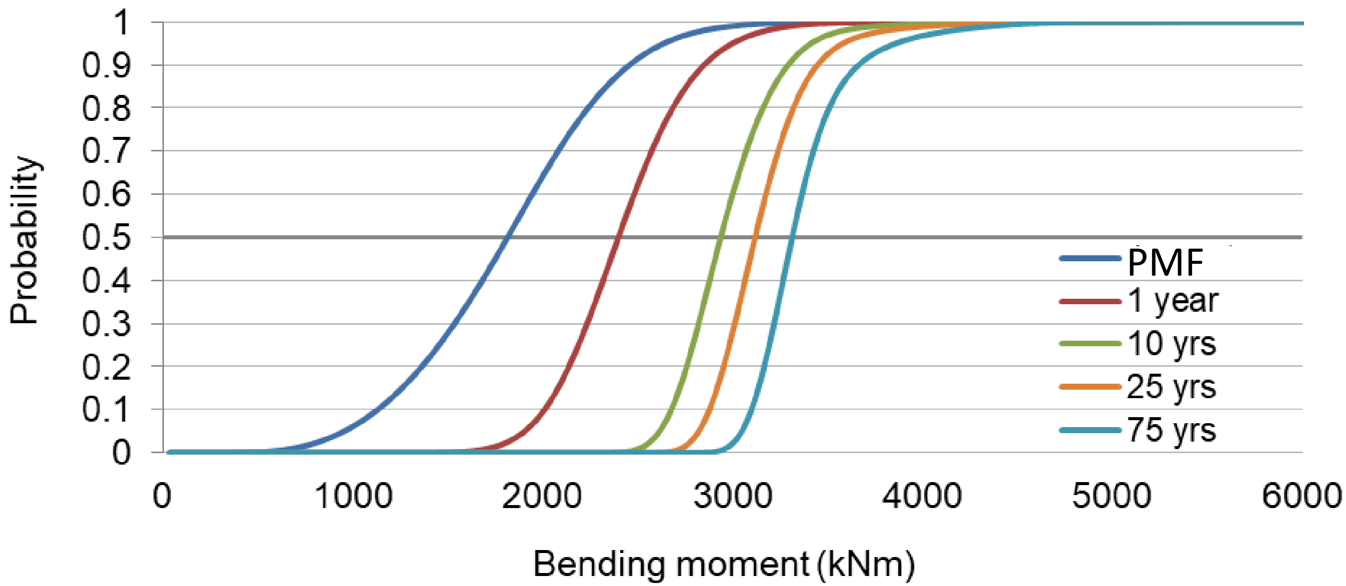
$$N_T = N_{MP}\, N_D\, N_P$$
$$= 100 \times\ 250 \times 75$$
$$= 1\,875\,000$$

# Calculating load effects





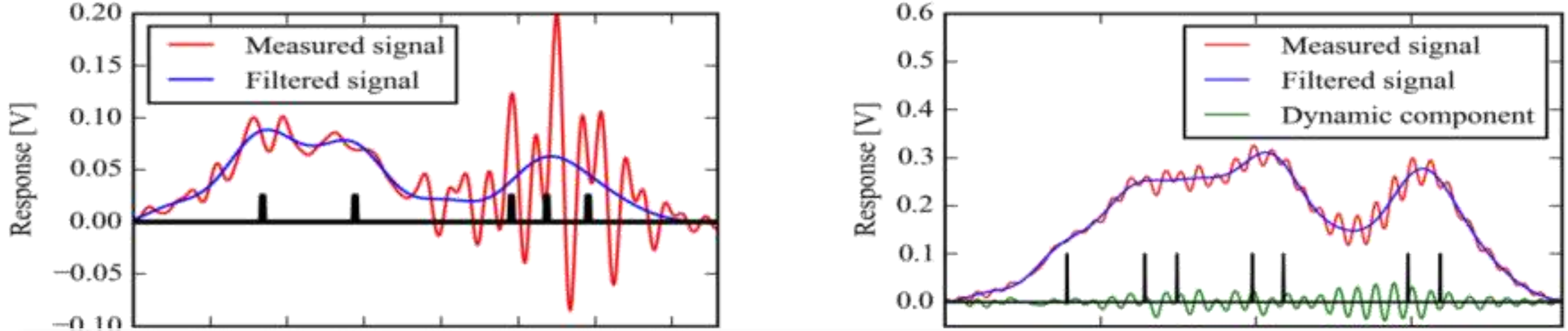



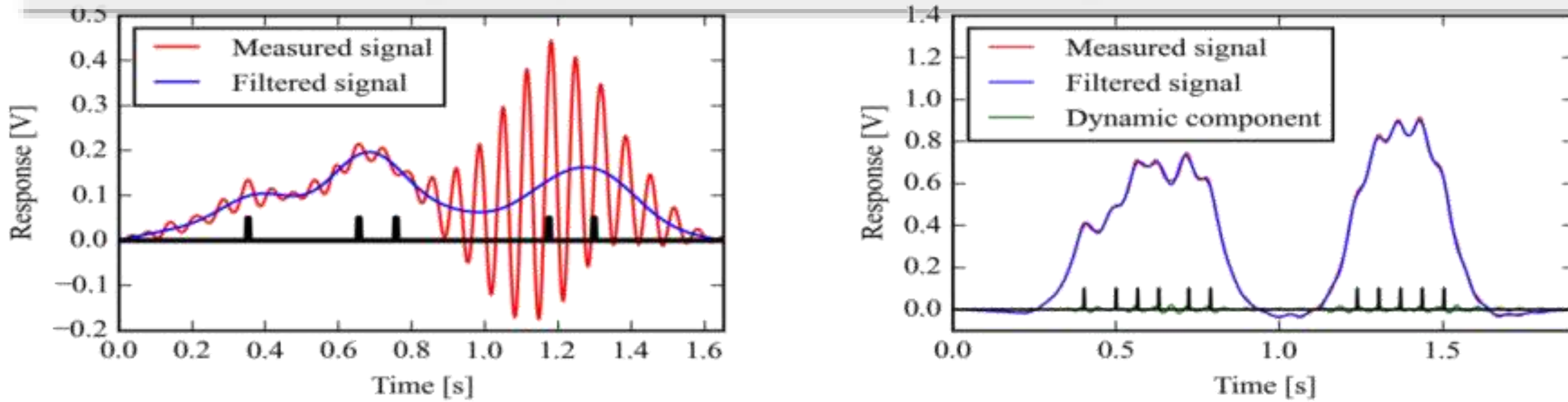

$$M_T \ll M_{CODE}$$

# Dynamic response of bridges





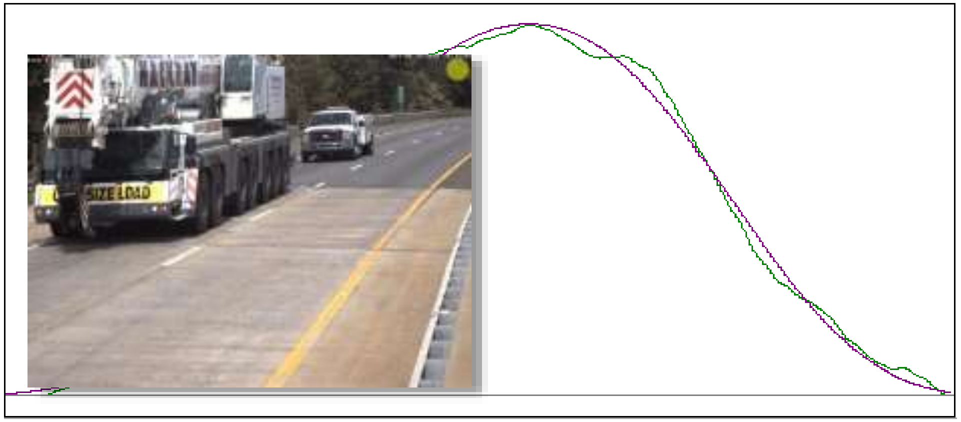

**Bridge-vehicle interaction not only affects B-WIM results, but also has high impact on results of bridge assessment!**

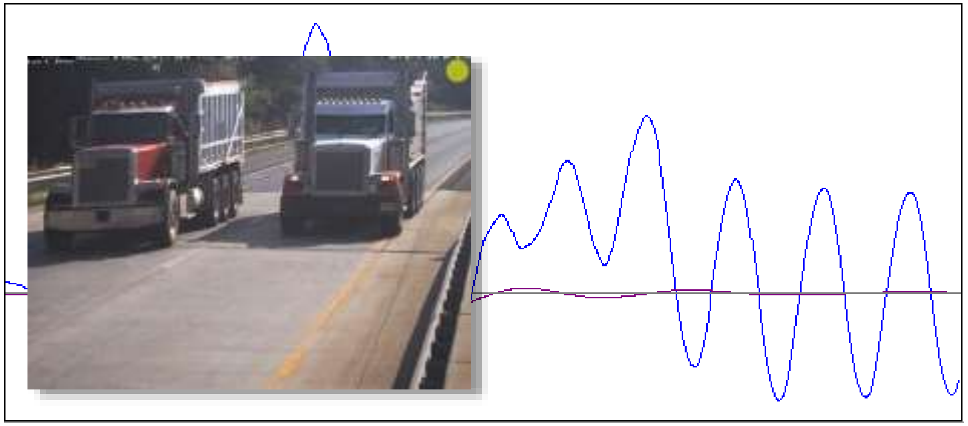


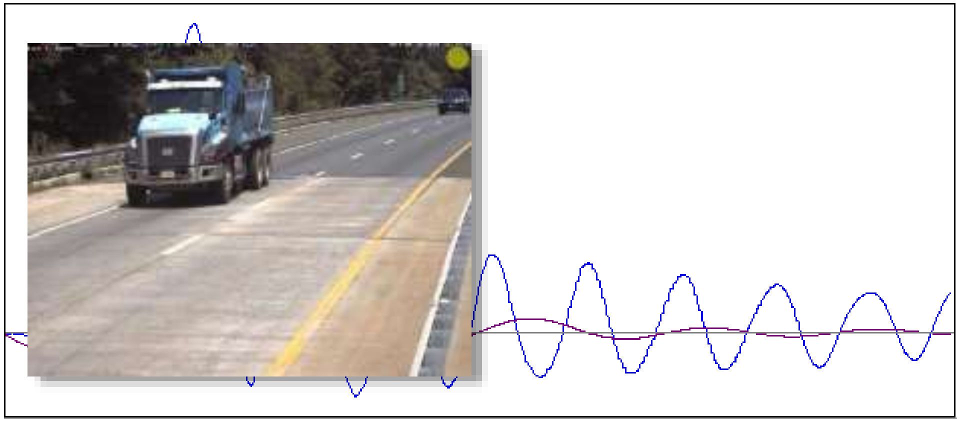

# 27-m long integral bridge

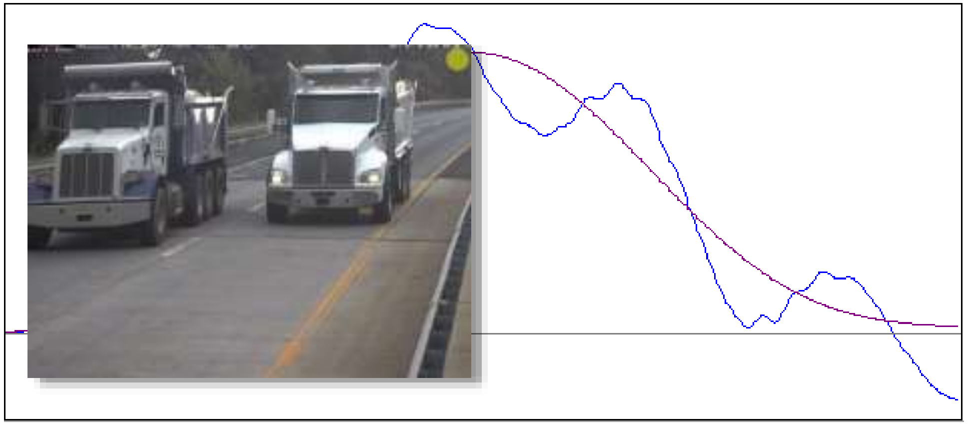
# Dynamic response of 27-m bridge



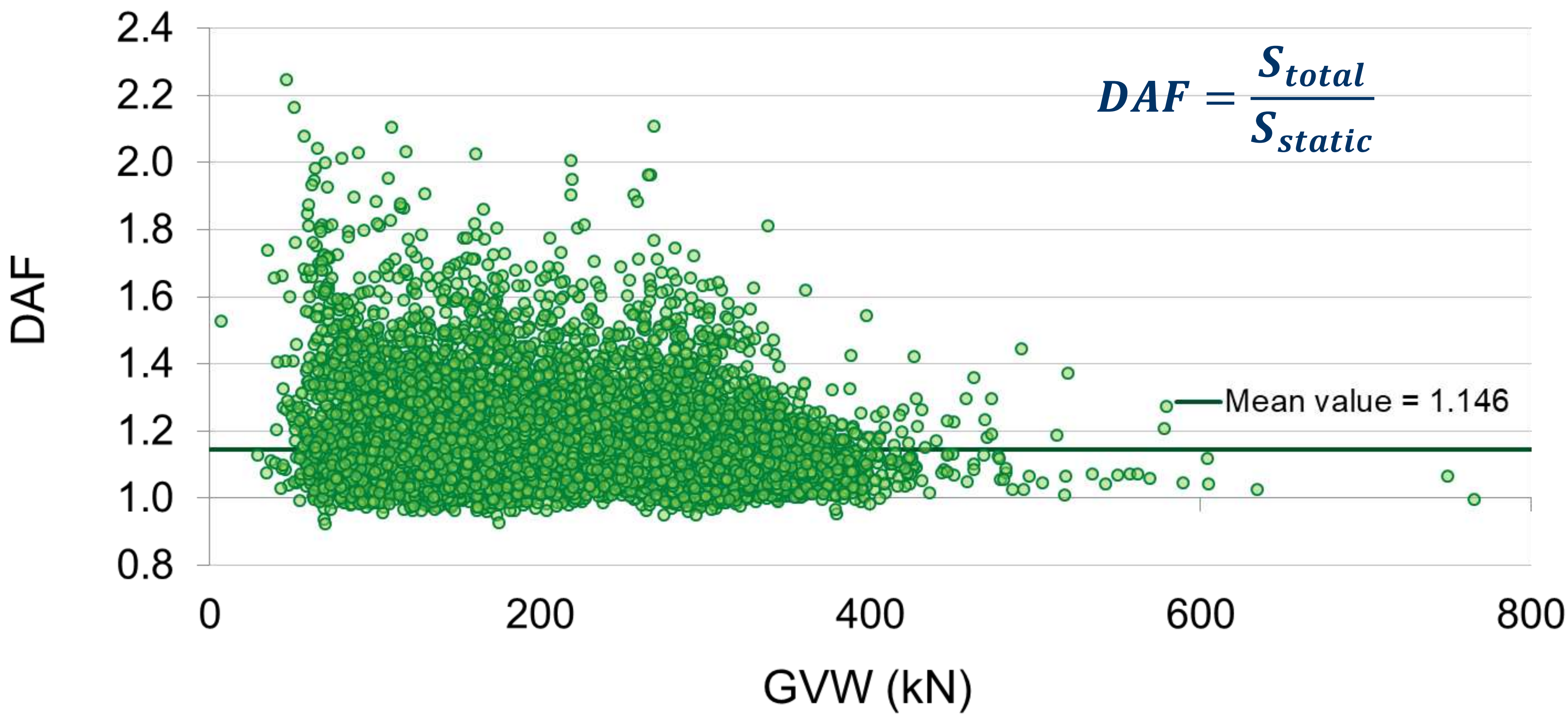


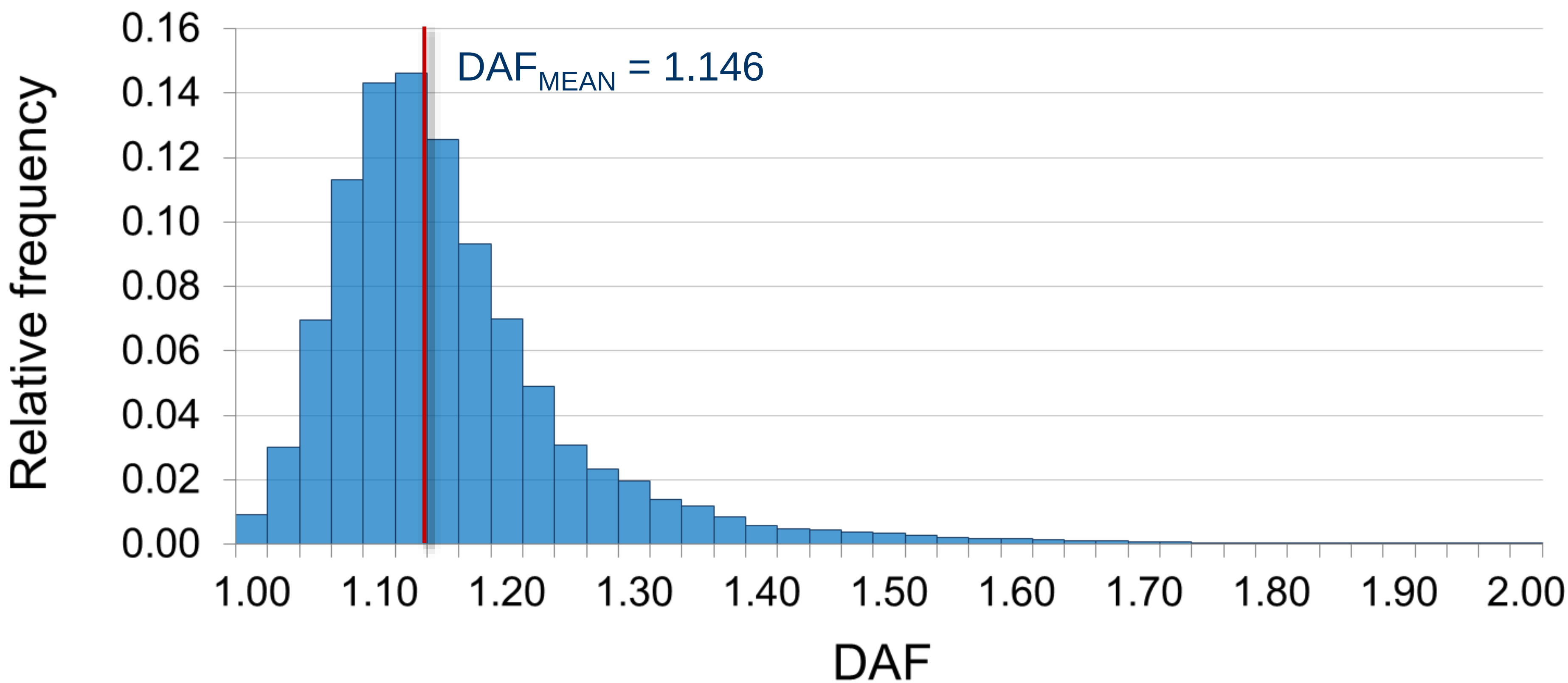




# Dynamic response of 27-m bridge



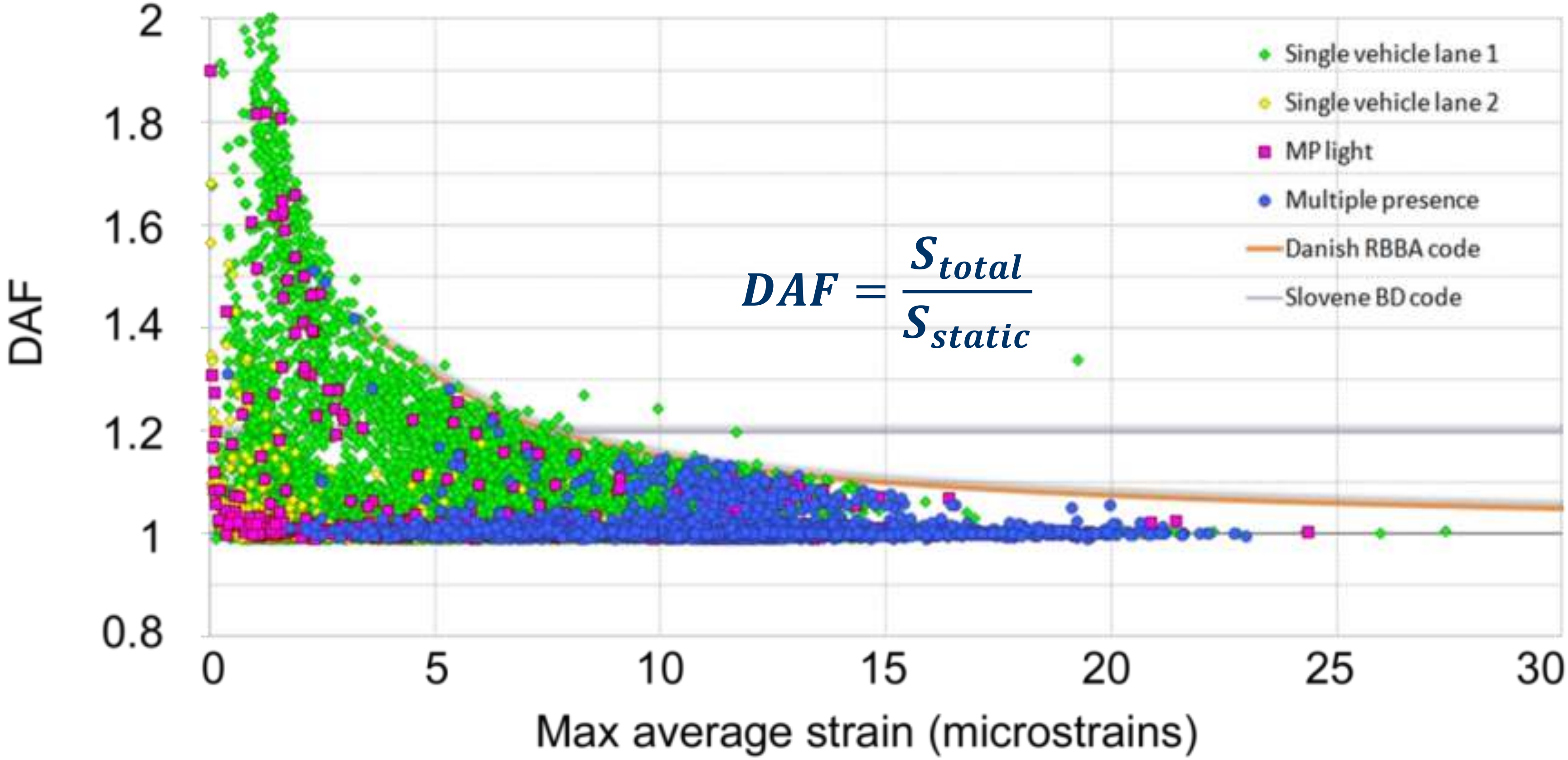

# Dynamic response of bridges


Typical $DAF_{MEAN}$ values around 1.05

# Dynamic response of bridges



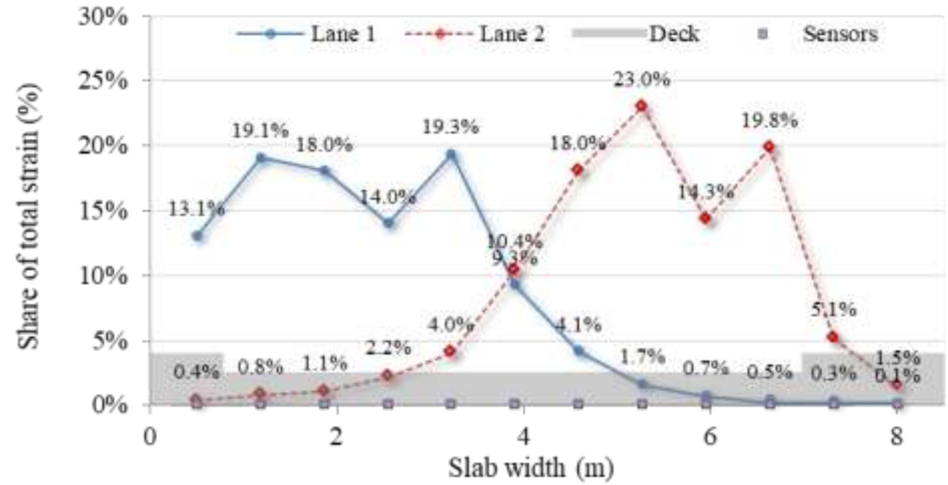


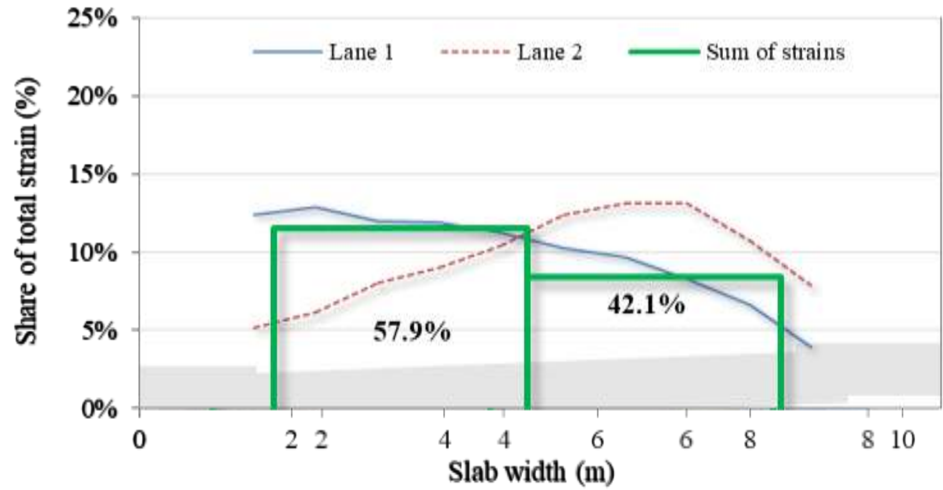

$$DAF = \frac{S_{total}}{S_{static}}$$

# Load Distribution Factors



- measured & statistically evaluated (mean & standard deviation) of:
  - Girder Factors – GDF
  - Lane Factors – LF
- can be very different than in theory




# Safety assessment procedure



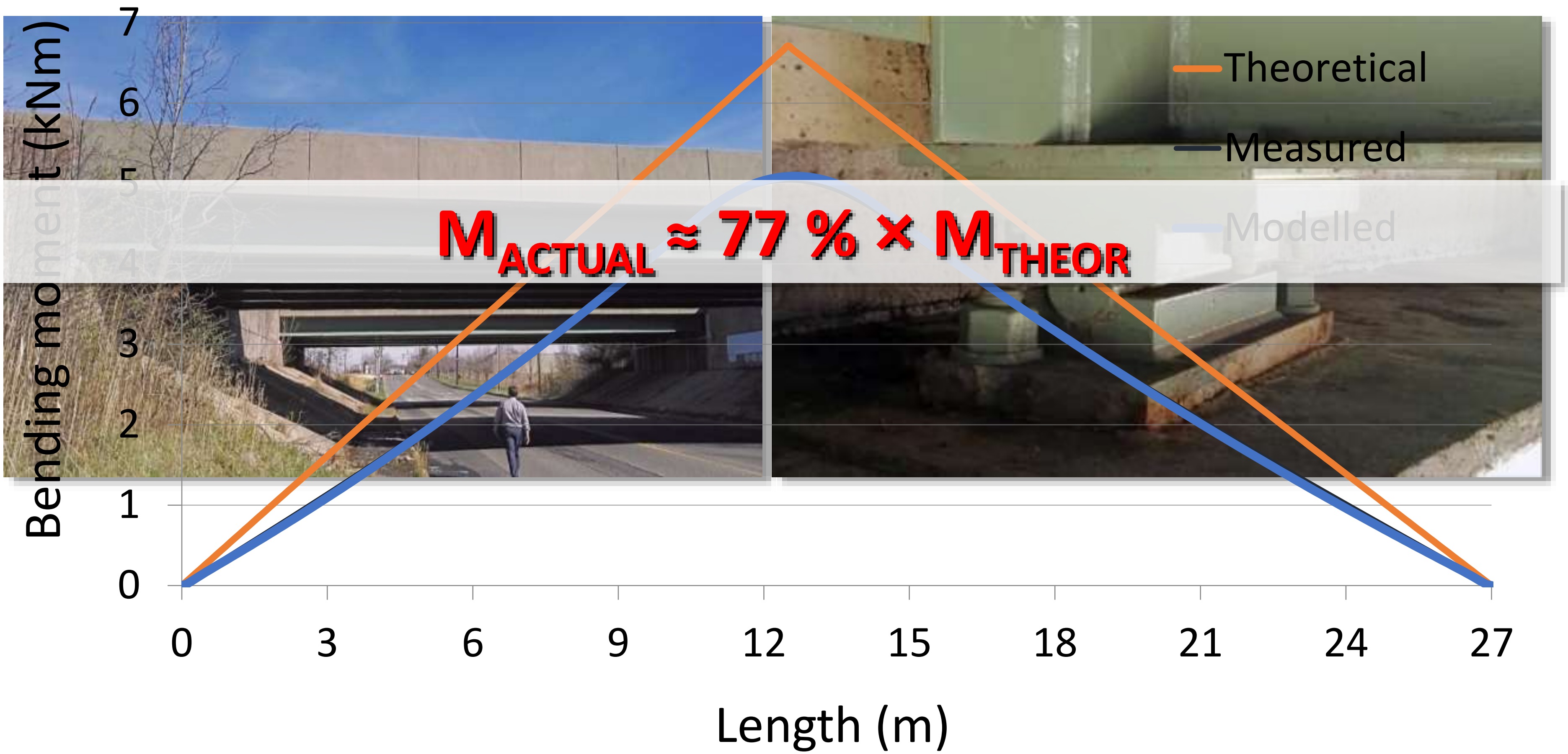
Calculation of structural safety:

$$R > G$$

$$RF = \frac{\Phi . R_d - \gamma_D . G_D}{\gamma_L . G_L . DAF} > \mathbf{1.0}$$

- benefits from B-WIM results:
  - traffic data
  - information about true structural behaviour (load test)
- traditional LTs require closing the bridge
- Soft Load Test (SLT) using SiWIM® data
- for serviceability loads verifications only!

# Soft load testing

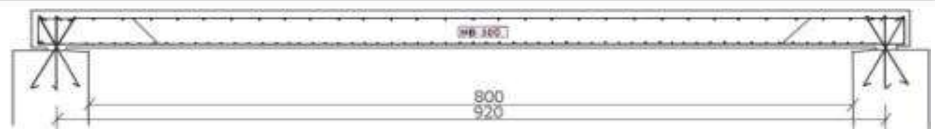


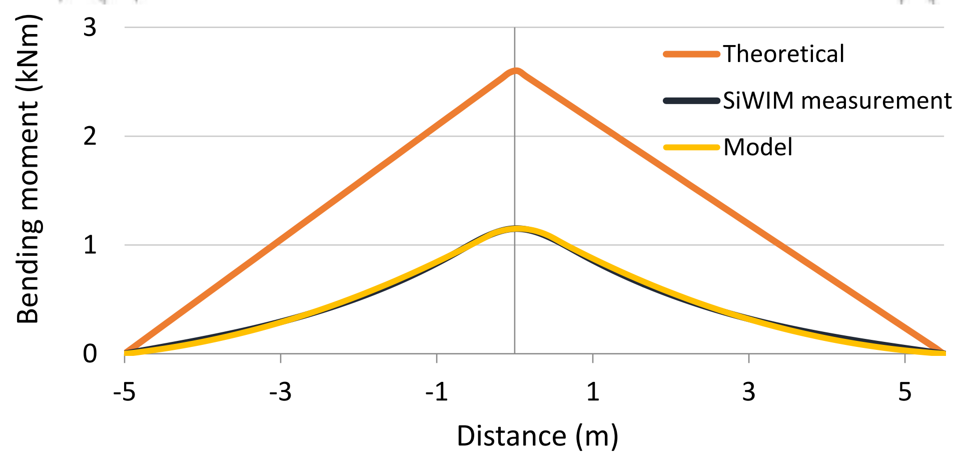

$M_{ACTUAL} \approx 77\ \% \times M_{THEOR}$

# Soft load testing

- 10.5 m slab bridge along the traffic lanes, 9.20 m perpendicular to the abutments
- **not simply supported**

$$M_{ACTUAL} \approx 44\ \% \times M_{THEOR}$$


# Case study

- Slovenia has a bridge at every 4 km of national roads
- condition data exists for the last 28 years, typically around 3% of bridges in inadequate or critical condition
- 40-50 renovations/replacements per year
- estimated replacement cost, with all associated works, around 0.3 to 1.0+ million $ (6 to 18 million MXN) per bridge

# Case study

- in 2004 – 2016 structural safety assessed for 154 deficient bridges
- step-by-step analysis applied:
  1. Initial assessment:
     - thorough inspection
     - assessment loading schemes based on WIM data
     - lower dynamic amplification based on WIM data
     - reduced safety factors
     - simple analytical models
  2. Advanced assessment with SLT and material testing

# Case study

Results:

- initial assessment: 118 of 154 bridges found safe for the existing traffic conditions
- another 23 bridges proven safe after performing the advanced analysis with SLT and material testing
- <u>only 13 bridges</u> of 154 required actions:
  - postings
  - strengthening / replacement

# Case study - Costs

- replacement value of deficient bridges app. **110** M$ (2B MXN)
- initial optimised analysis, with realistic traffic loading and lower safety factors reduced costs to 28 M$ (0.5B MXN)
- use of SLT and material testing left only 13 bridges with required actions, which resulted in actual costs of **10** M$ (180M MXN)
- indirect costs would typically be at least twice the direct ones

# Conclusions

- efficient and optimal bridge safety assessment requires realistic information about traffic loading and calibrated structural models:
  - traffic loading is typically considerably lower than in the codes
  - bridge behaviour is in most cases more affordable
  - higher confidence in data allows using lower safety factors
- B-WIM has been shown as an efficient tool to monitor both
- cost savings shown in tens of millions of $, for Slovenia only

# Thank you for listening!