Structural health monitoring data analysis on two cable stayed bridges in the UK & China

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Contents

- Background
- Temperature field analysis
- Traffic induced deflections
- Conclusions

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Background

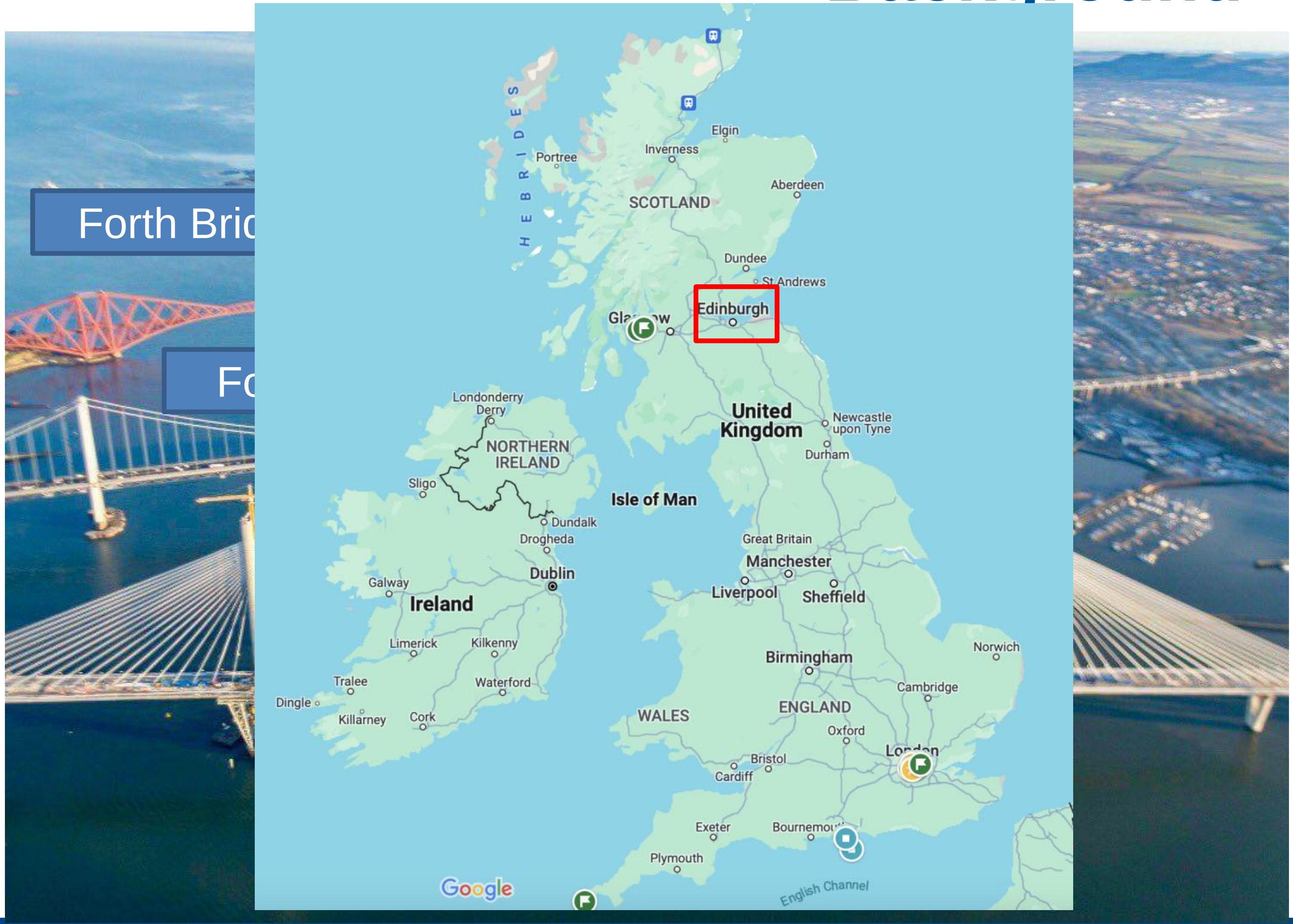
Long-span bridges significance

- At critical locations, providing vital links
- High cost to construct and maintain
- Extensive social impact – closure due to structural issues

Long-span bridges issues

- Ageing bridges – 42% of bridges are 50+ years old in the US
- 7.5% of bridges are structurally deficient in the US
- Truss end link failure discovered on the Forth Road Bridge, Edinburgh, UK in 2015

Background



Project Ambition:

Big Data & Data Centric Engineering:
The Forth Bridges

Aim:

Develop this new holistic structural health monitoring SHM strategy on the Forth Bridges and then extend the research via the Yangtze River Bridge - towards the *“International Living Bridge Laboratory”*

(a) The Queensferry Crossing in the UK

(b) The Nanjing Dashengguan Yangtze River Bridge in China

- The NDB, formerly known as the Third Nanjing Yangtze River Bridge, opened in 2005
- Vital transportation link crossing the middle and lower Yangtze River & connecting Nanjing City and its Liuhe District.
- It is a double-steel-tower cable-stayed bridge with a main span of 648m.
- A unique feature of this bridge is its 215m-high arc-shaped steel tower - first-of-kind among such long-span bridges .
- Superstructure deck: 3.2-m deep x 37.5-m wide orthotropic steel box girder - 3 traffic lanes in each direction.

Background

Inspections

- **Visual Inspection**
- **Structural Health Monitoring (SHM)**
- **Non-destructive Testing (NDT)**

- Using periodically sampled response measurements to monitor changes to the material and geometric properties of engineering structures.

The difference between NDT and SHM is the sensors in the SHM systems are permanently installed on the structures to monitor environmental factors, external loadings and structural responses.

Sensors on bridges

Structural health monitoring (SHM) Sensor Type	Queensferry Crossing	Forth Road Bridge
Accelerometers	102	-
Air Temperature Sensors	13	2
Anemometer	11	2
Asphalt Temperature Sensors	40	6
Barometers	2	1
Bearing Gauges	16	8
Bearing Pressure Sensors	-	8
Concrete Deck Temperature Sensors	70	-
Concrete Tower Temperature Sensors	46	-
Corrosion Sensors	360	-
Displacement Transducers	32	48
Dynamic Weigh-in-Motion Sensors	96	64
GPS Location	21	10
Rainfall Gauges	2	1
Relative Humidity Sensors	12	34
Strain Gauges	887	128
Stay cable temperature sensors	56	-
Steel Surface Temperature Sensors	158	32
Main Suspension Cable Acoustic Monitoring	-	116
Tiltmeters	48	16

- Various original sampling rates (e.g. 1Hz, 10Hz)
- Recorded sampling rate: 1Hz
- Data size
  - FRB: 24GB/month
  - QC: 200GB+/month

Number of sensors	Bridge
~2,000	Queensferry
~192	Forth Road Bridge
~1,000	Yangtze Bridge

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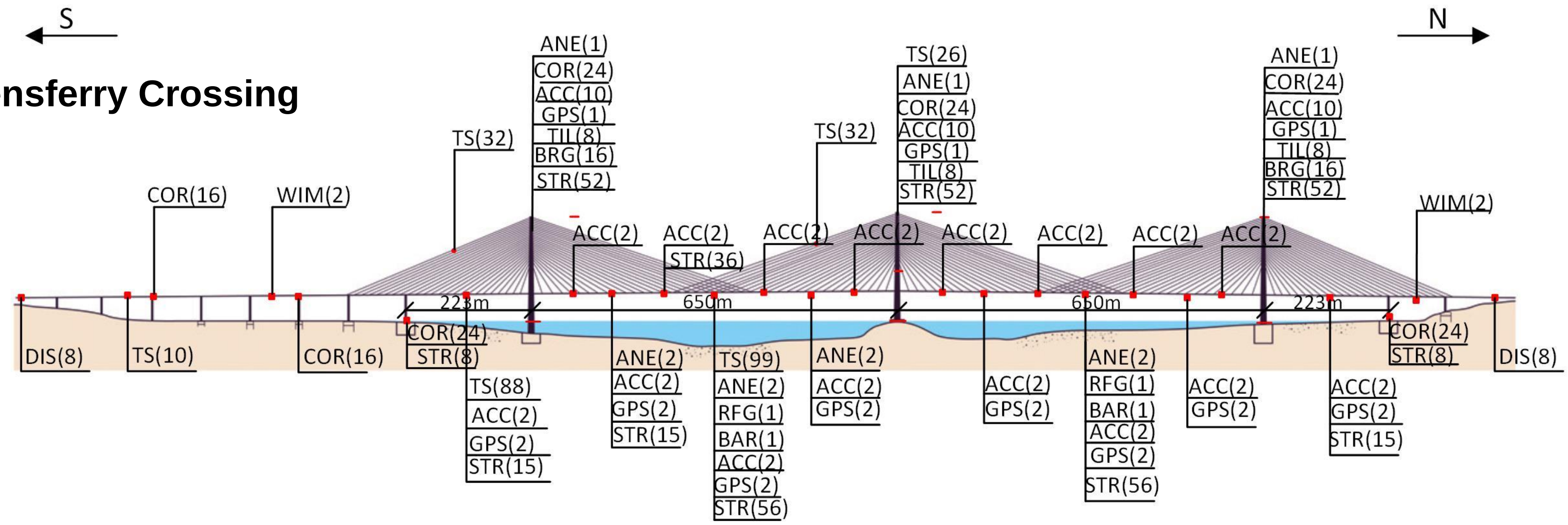
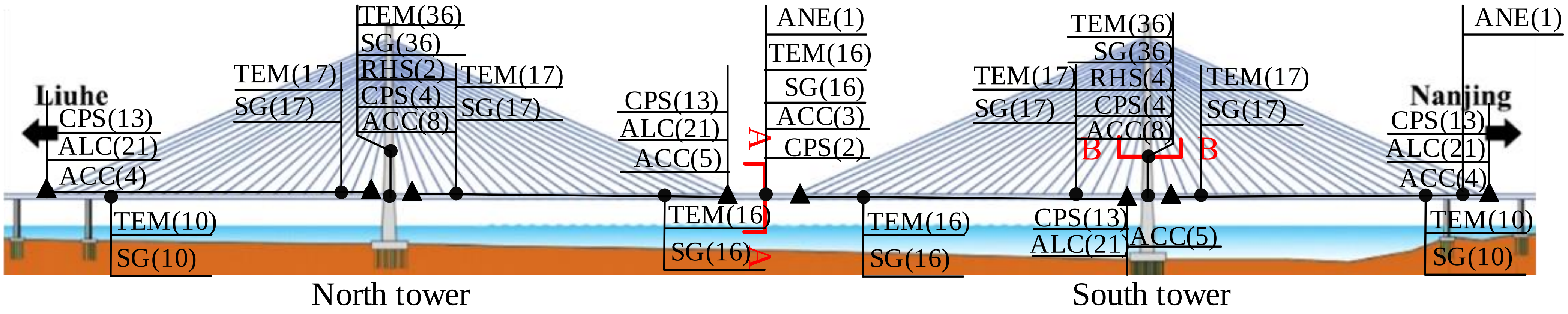
Sensors layout

Queensferry Crossing



TS – Temperature sensor; ANE – Anemometer; RFG – Rainfall gauge; BAR – Barometer;
COR – Corrosion; WIM – Weigh-in-motion; ACC – Accelerometer; DIS – Displacement transducer;
GPS – Global position system; TIL – Tiltmeter; BRG – Bearing gauge; STR – Strain gauge

Sensors layout

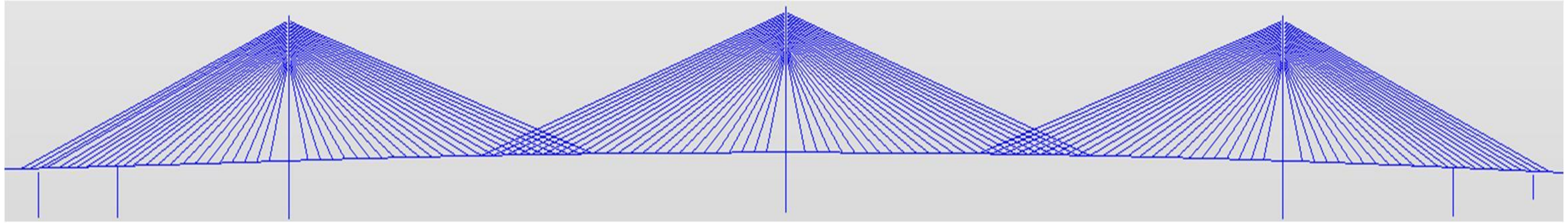


ANE: anemometer CPS: connected pipe system ACC: accelerometer SG: strain gauge

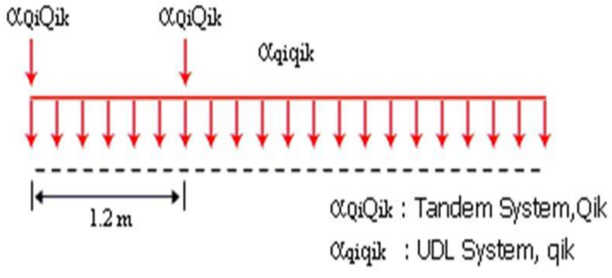
TEM: temperature sensor ALC: anchor load cell RHS: air temperature and relative humidity sensor

Yangtze River Bridge

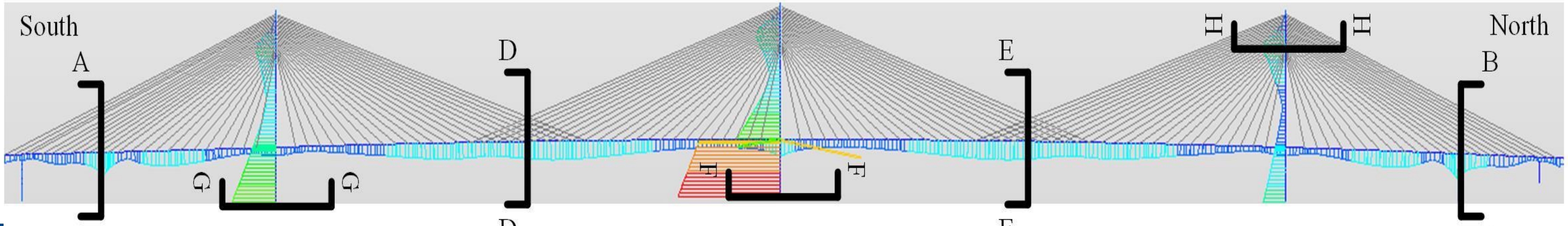
Queensferry Crossing – finite element model



(a) Finite element model of the QC

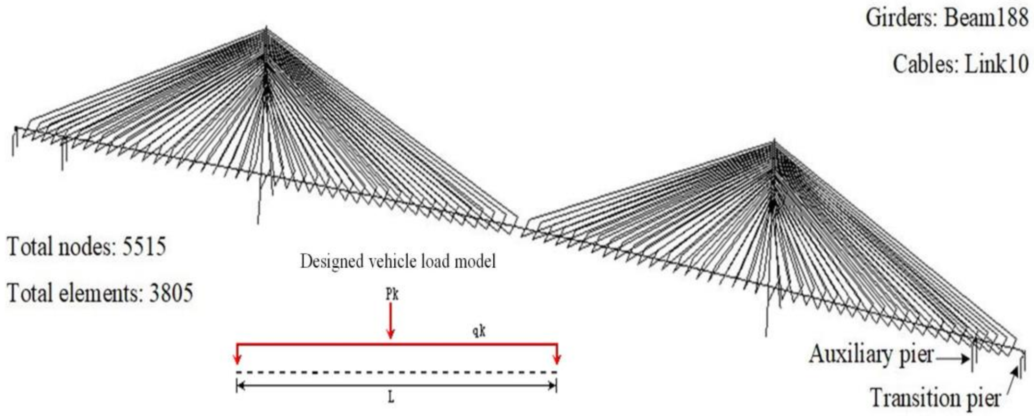


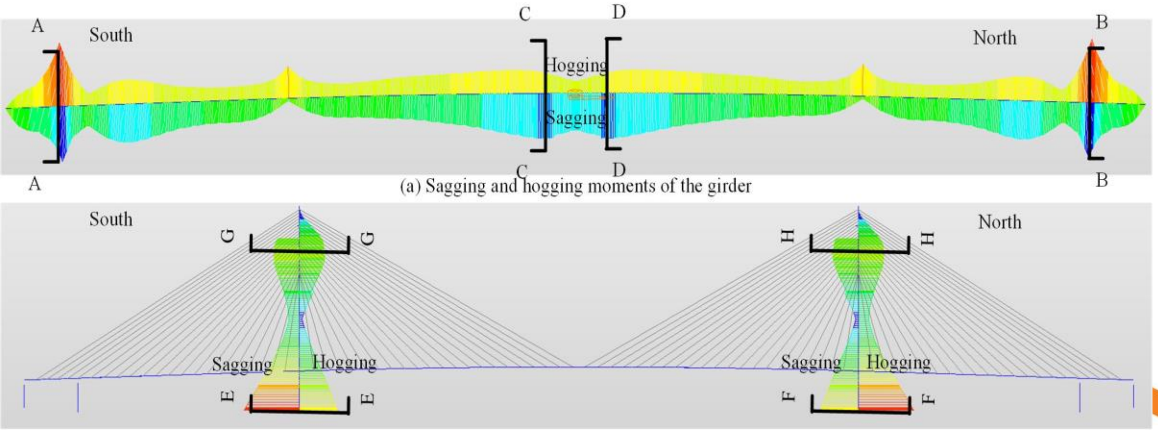
(b) Vehicle load model I in the Eurocode



(c) Sagging moments of the towers and girders

Yangtze River Bridge – finite element model

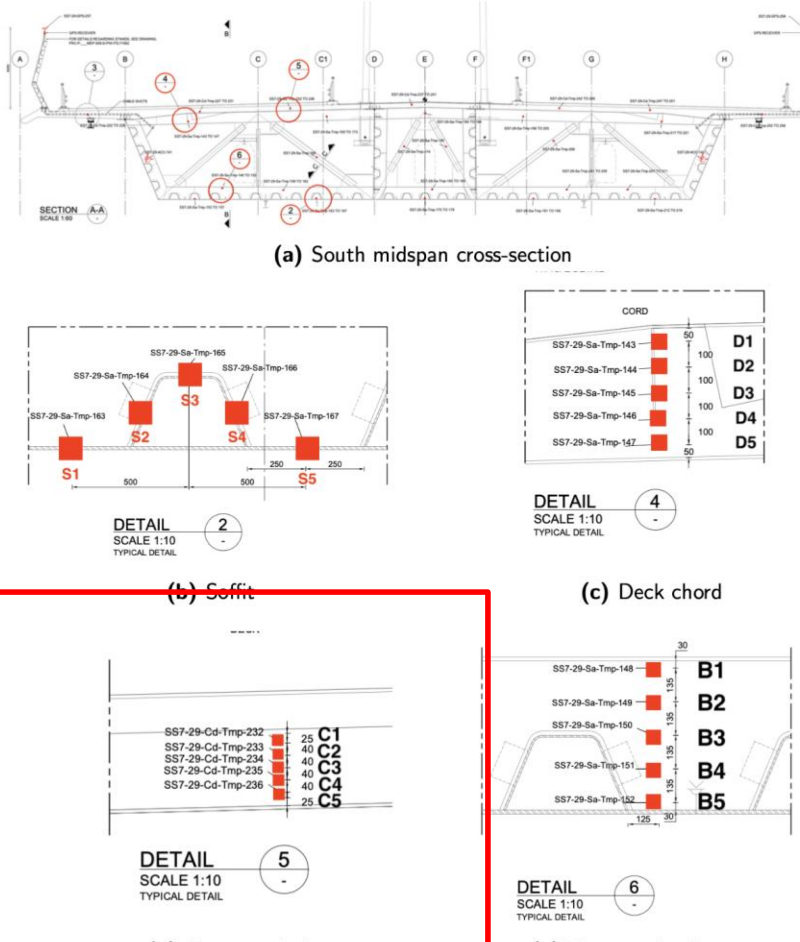




(a) Sagging and hogging moments of the girder

(b) Sagging and hogging moments of the tower

Temperature field – concrete deck



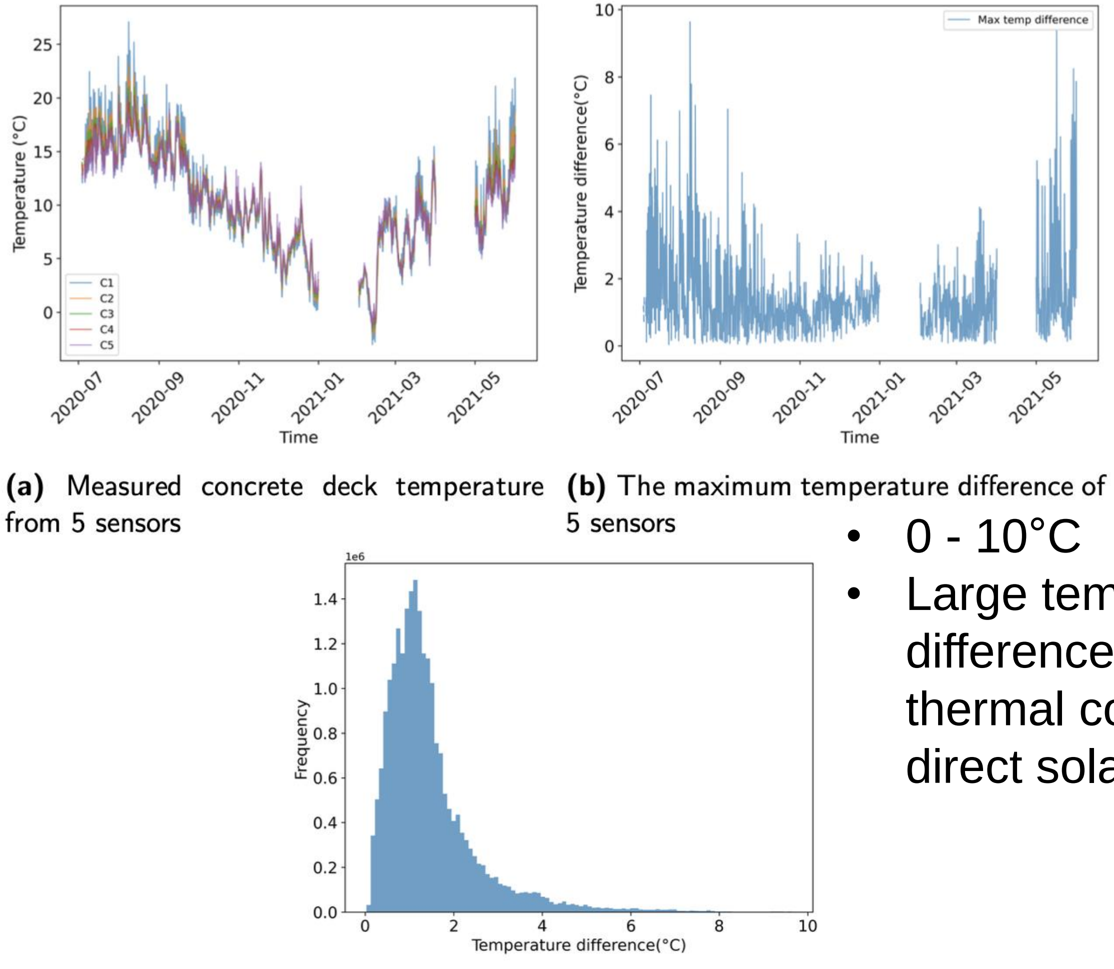
(a) South midspan cross-section

(b) Soffit

(c) Deck chord

(d) Concrete deck

(e) Bottom chord



(a) Measured concrete deck temperature from 5 sensors

(b) The maximum temperature difference of 5 sensors

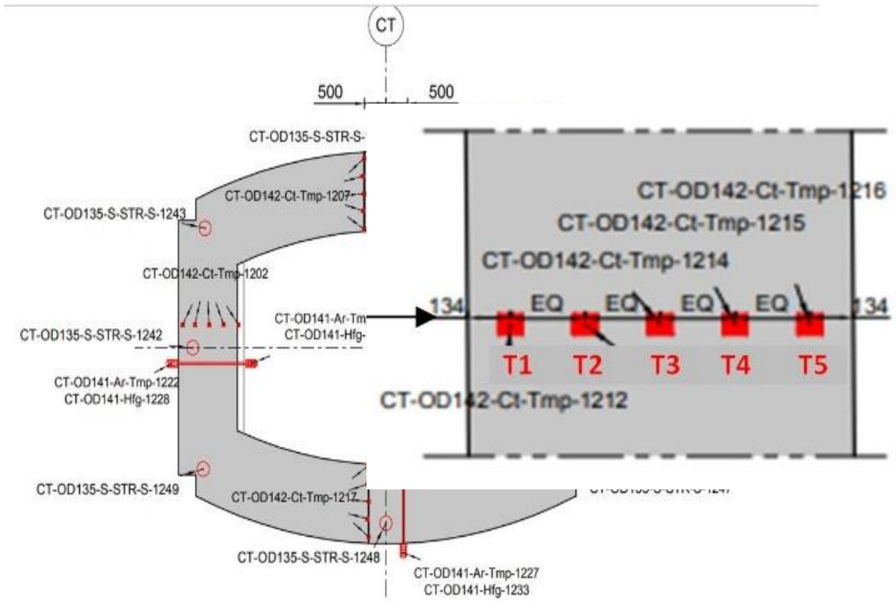
(c) Distribution of the maximum temperature difference

Figure 6.12: Temperature features of the concrete deck

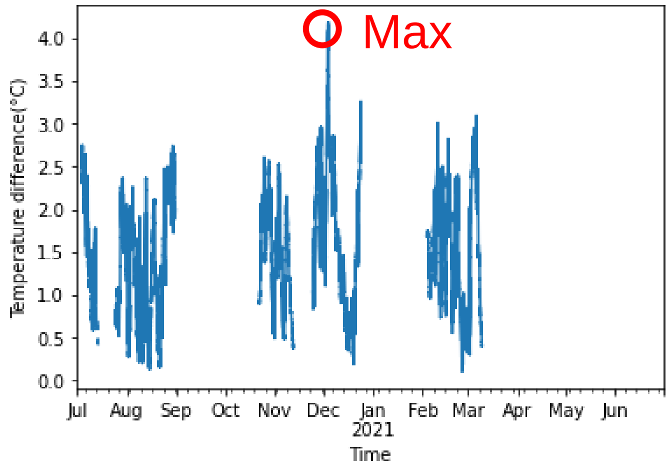
- 0 - 10°C
- Large temperature difference due to low thermal conductivity and direct solar radiation

Temperature field – Tower temperature difference

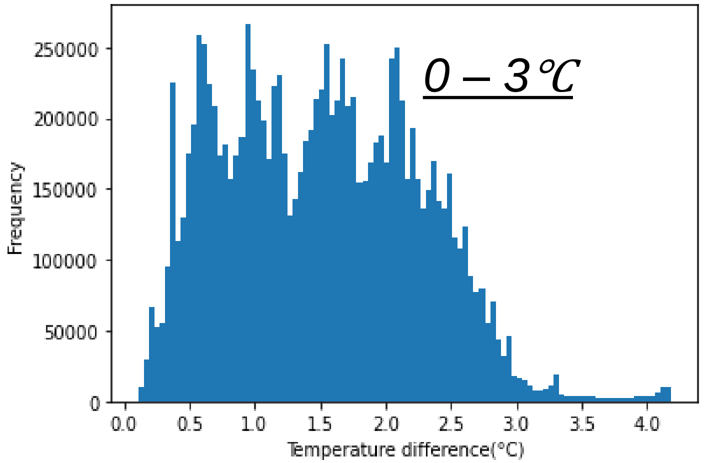
- QC: thermal centre tower



Temperature difference (Max)

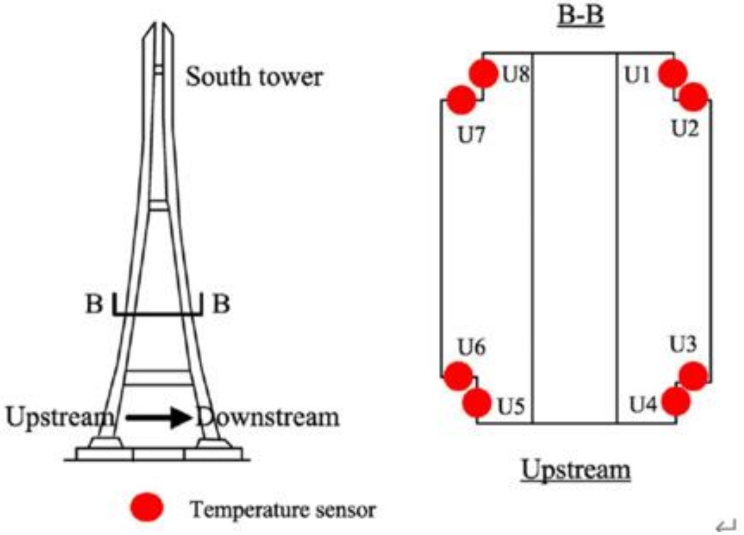


Distribution of temperature difference

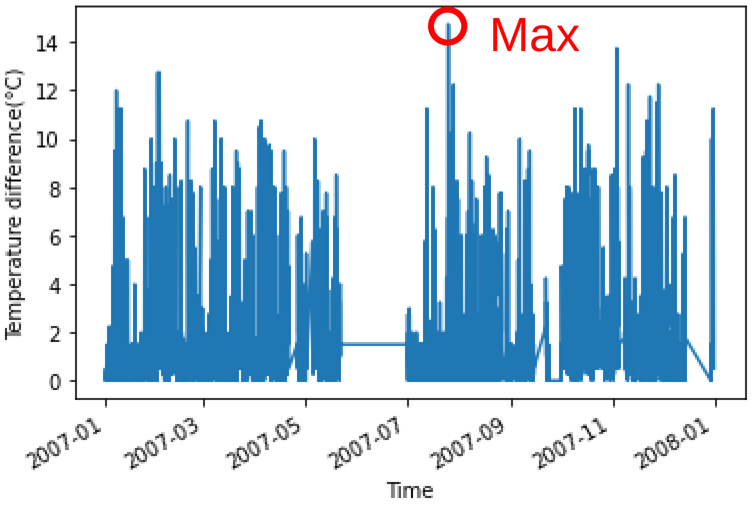


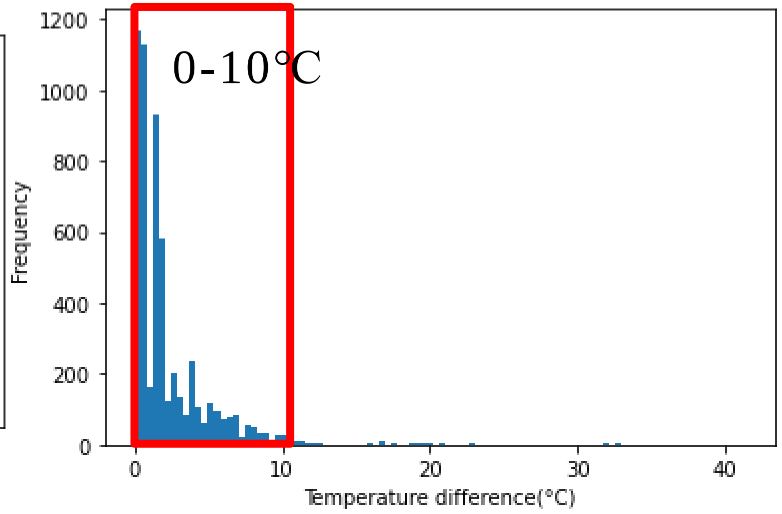
Temperature field – Tower temperature difference

- NDB: thermal centre tower



Temperature difference (Max)





Extreme temperature estimation – GPD

The standard cumulative distribution function (CDF) of the GPD is defined by:

$$G(x;\sigma,\xi) = \begin{cases} 1-(1+\xi\frac{x}{\sigma})^{-1/\xi} & \text{for } \xi \neq 0 \\ 1-exp(-\frac{x}{\sigma}) & \text{for } \xi = 0 \end{cases}$$

Calculate the mean excess

$$e(u) = \frac{1}{N_u}\sum_{i=1}^{N_u}(x_i-u) = \frac{\xi}{1-\xi}u + \frac{\sigma}{1-\xi}$$

Plot the MEF Plot the mean excess $e(u)$ against the threshold u.

Identify the threshold In the GPD, the mean excess function is linear in the threshold for a suitable choice of threshold. The point where the plot starts to appear linear can be considered as a good threshold.

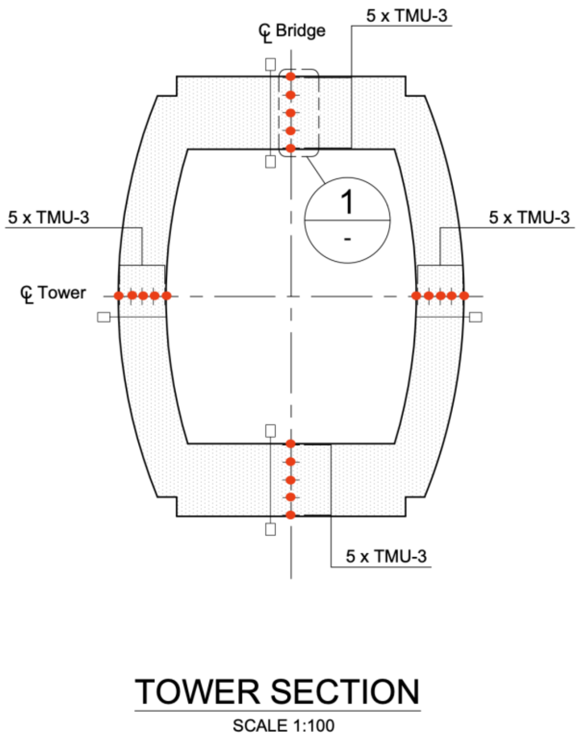
Calculate cumulative probability:

$$p = (1-P_r)^{1/N}$$

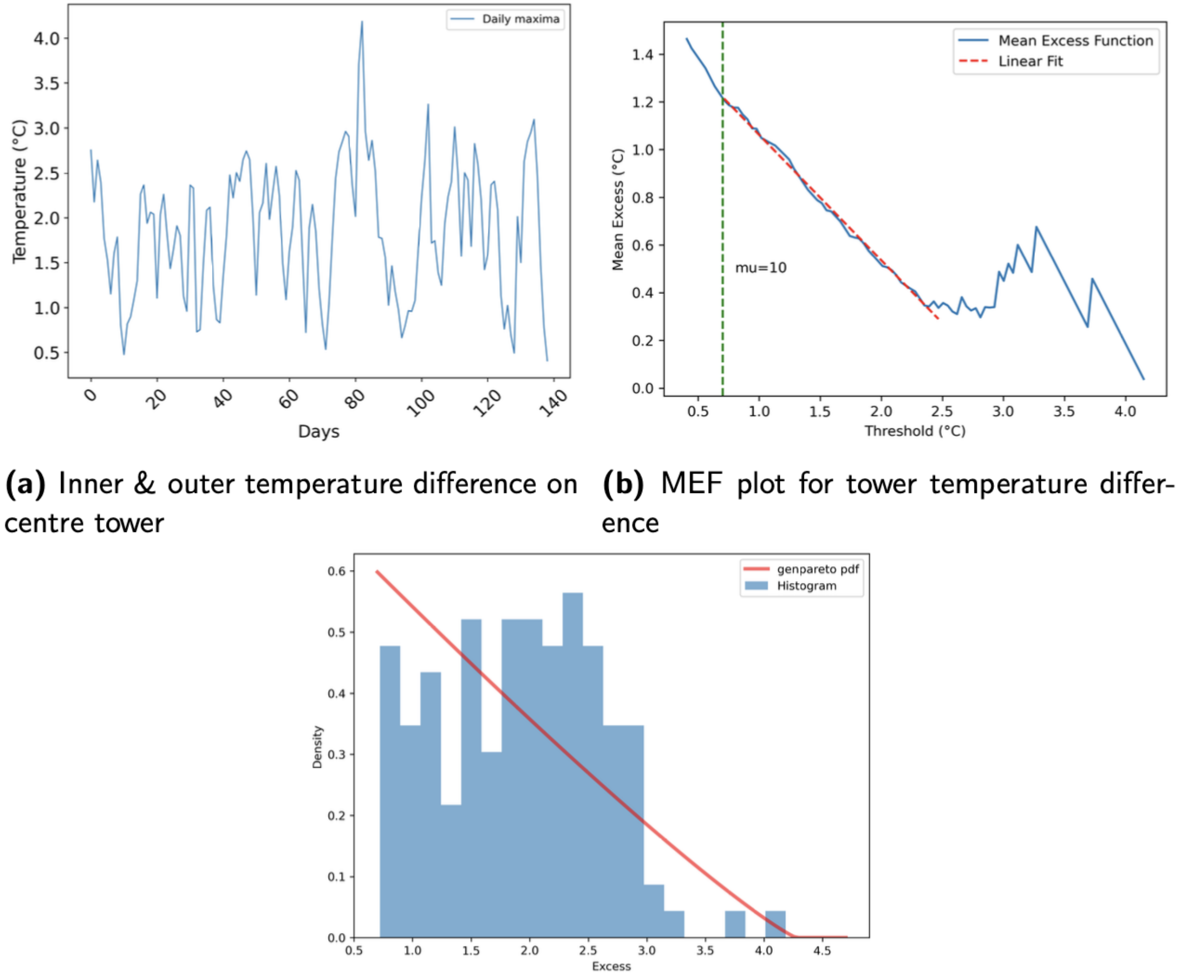
Calculate the extreme value x_p

$$x_p = u_0 + \frac{\sigma}{\xi}\left[\left(\frac{n}{N_u}(1-p)\right)^{-\xi} - 1\right]$$

Extreme temperature estimation – Tower



- Estimated maximum temperature difference in 120 years is 4.66°C
- Not specified in Eurocode
- Chinese Design Code, 5°C

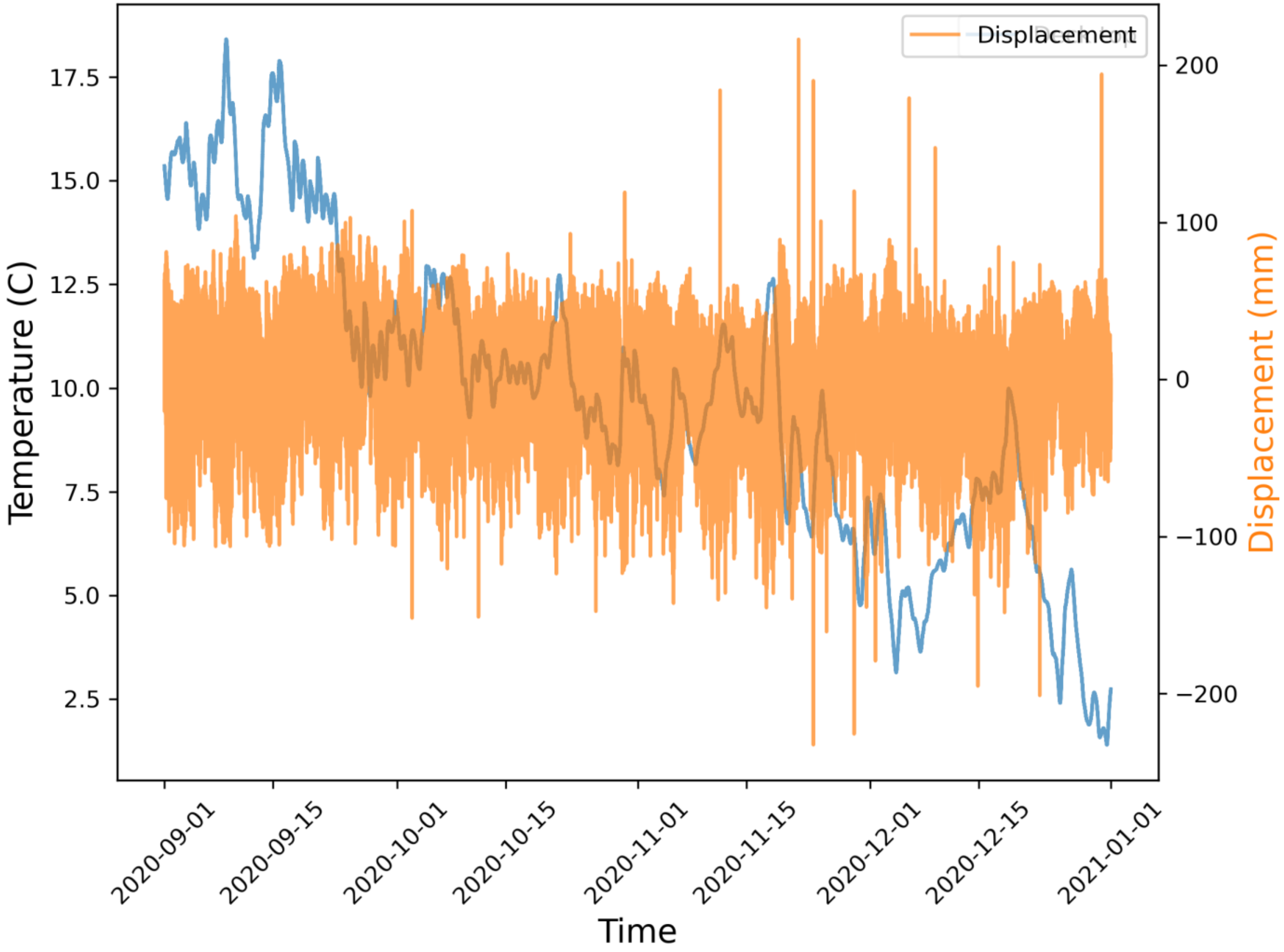


(a) Inner & outer temperature difference on centre tower **(b)** MEF plot for tower temperature difference

(c) GPD plot for tower temperature difference

Figure 6.23: Tower inner & outer temperature difference analysis

Thermal-deflection relationship



- Displacements oscillate in a higher frequency compared to temperature
- High frequencies due to dynamic loads need to be separated from the signal

p

WT is develop… o high frequencies
in a series of s…

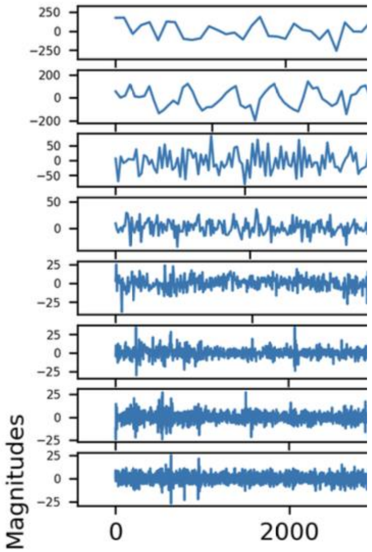
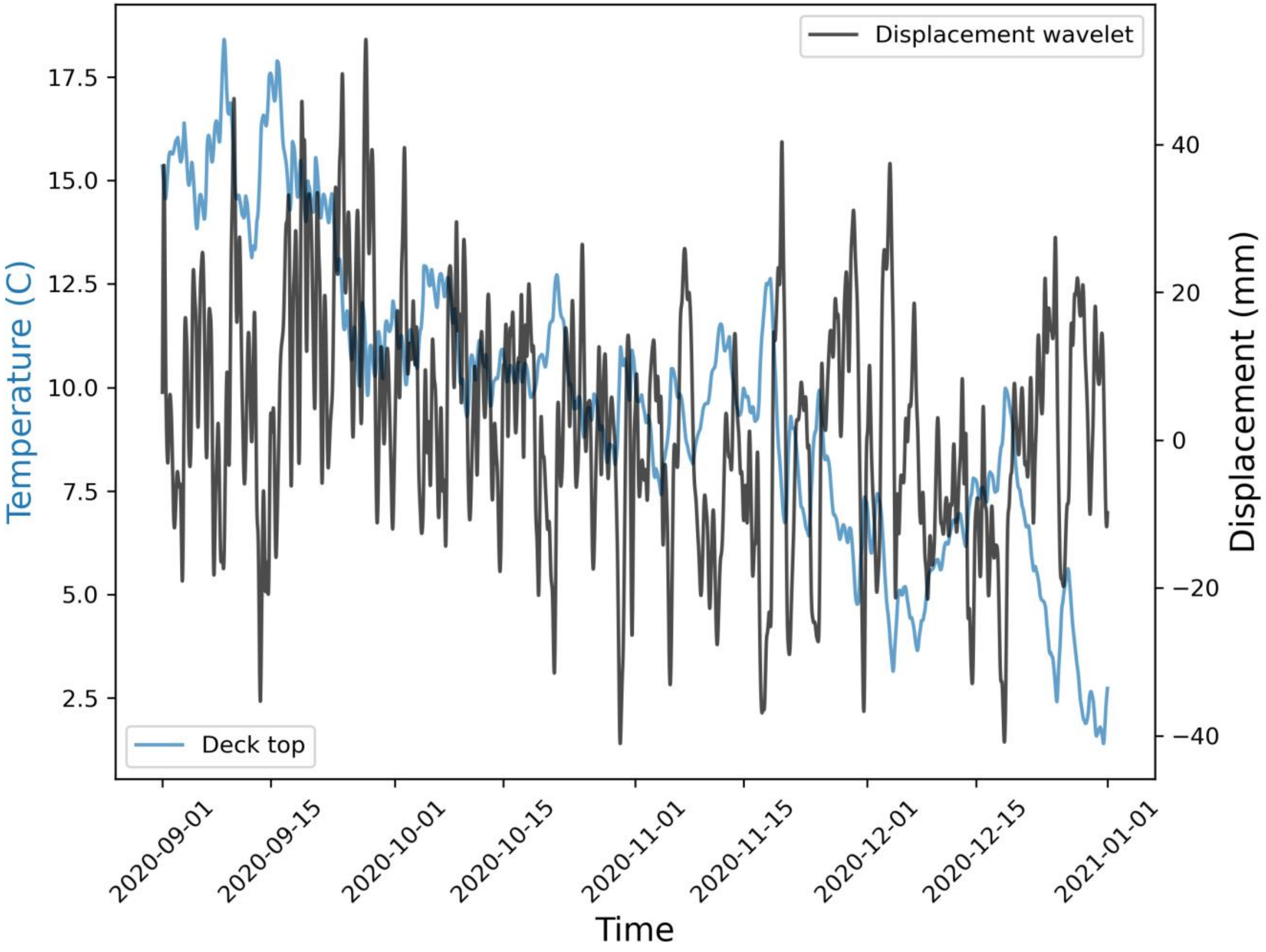
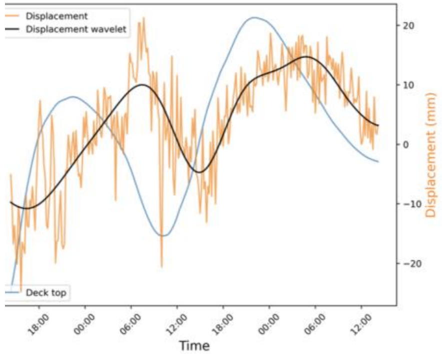
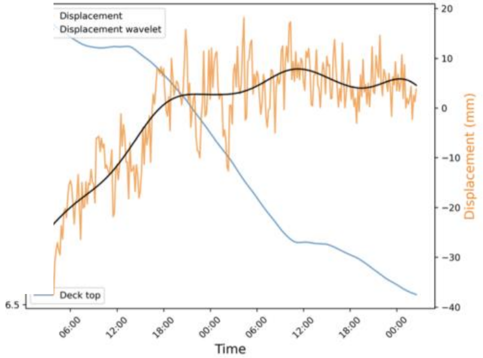
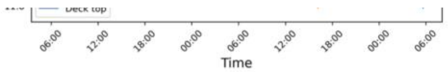


Figure 7.11: Detail coefficients for 8 levels decomposition









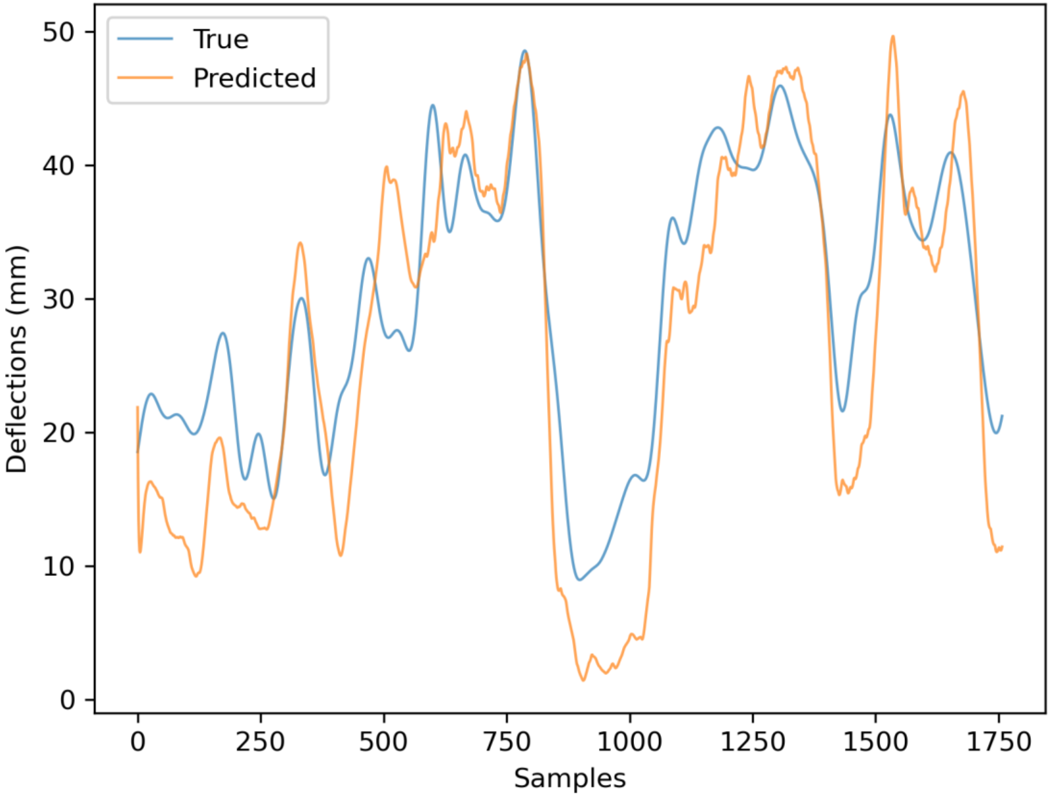
Thermal-deflection relationship

Table 7.2: Thermal-induced deflection predictions data samples (part 1)

Time	Sdeck_bottom ($^{\circ}C$)	Sdeck_top ($^{\circ}C$)	cabletem lowerend ($^{\circ}C$)	cabletem upperend ($^{\circ}C$)	Sdeck soffit ($^{\circ}C$)
15:10	14.505	14.971	13.778	15.845	14.304
15:20	14.505	14.978	14.003	15.875	14.327
15:30	14.510	14.988	14.250	15.894	14.367
15:40	14.520	15.001	14.347	15.901	14.408
15:50	14.535	15.016	14.565	15.958	14.464
16:00	14.555	15.032	14.429	15.990	14.488
16:10	14.571	15.049	13.931	15.982	14.453
16:20	14.574	15.063	13.601	15.935	14.391
16:30	14.565	15.075	13.538	15.854	14.328
16:40	14.547	15.084	13.338	15.772	14.254

Table 7.3: Thermal-induced deflection predictions data samples (Part 2)

Time	cdeck_1 ($^{\circ}C$)	cdeck_2 ($^{\circ}C$)	cdeck_3 ($^{\circ}C$)	cdeck_4 ($^{\circ}C$)	cdeck_5 ($^{\circ}C$)	GPS (mm)	gps wavelet (mm)
15:10	16.575	15.564	14.728	14.460	14.266	-0.065	-1.734
15:20	16.595	15.583	14.754	14.469	14.263	0.343	-1.603
15:30	16.606	15.602	14.779	14.480	14.297	4.730	-1.542
15:40	16.611	15.620	14.803	14.492	14.346	-2.684	-1.526
15:50	16.614	15.637	14.825	14.506	14.397	3.921	-1.526
16:00	16.617	15.657	14.846	14.522	14.429	-3.585	-1.521
16:10	16.618	15.674	14.867	14.540	14.390	-1.843	-1.491
16:20	16.610	15.691	14.887	14.558	14.307	1.209	-1.419
16:30	16.583	15.707	14.907	14.575	14.247	-10.630	-1.285
16:40	16.532	15.722	14.926	14.590	14.180	-9.717	-1.071



- High predicting accuracy: R=0.927

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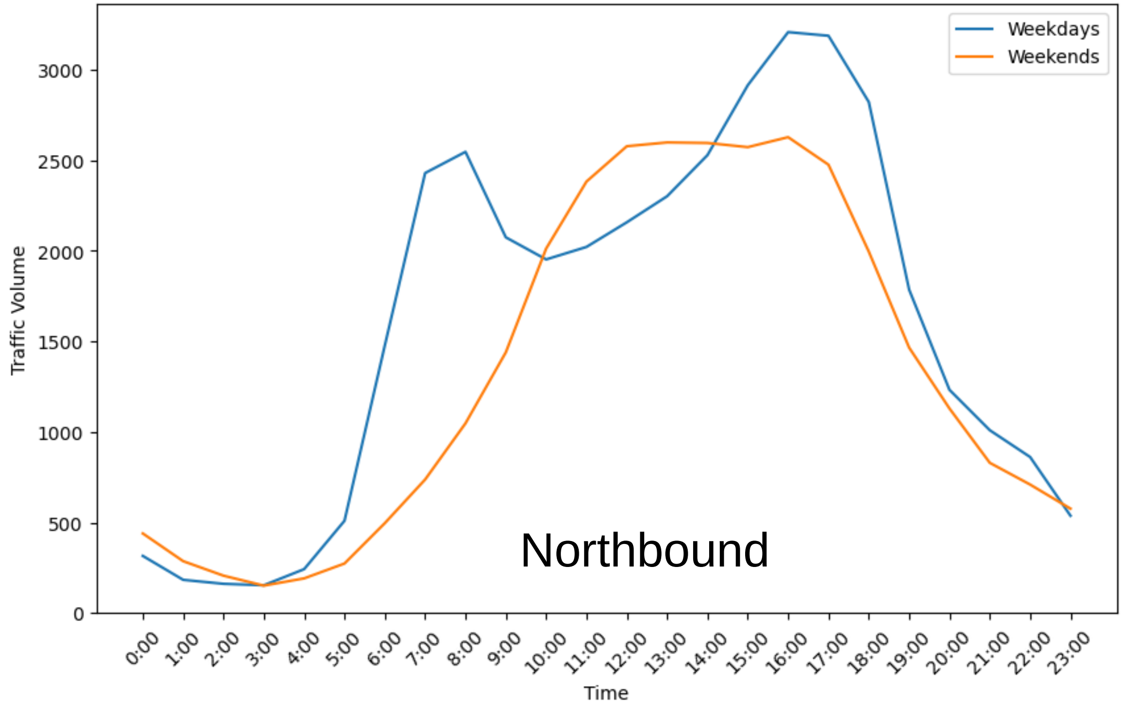
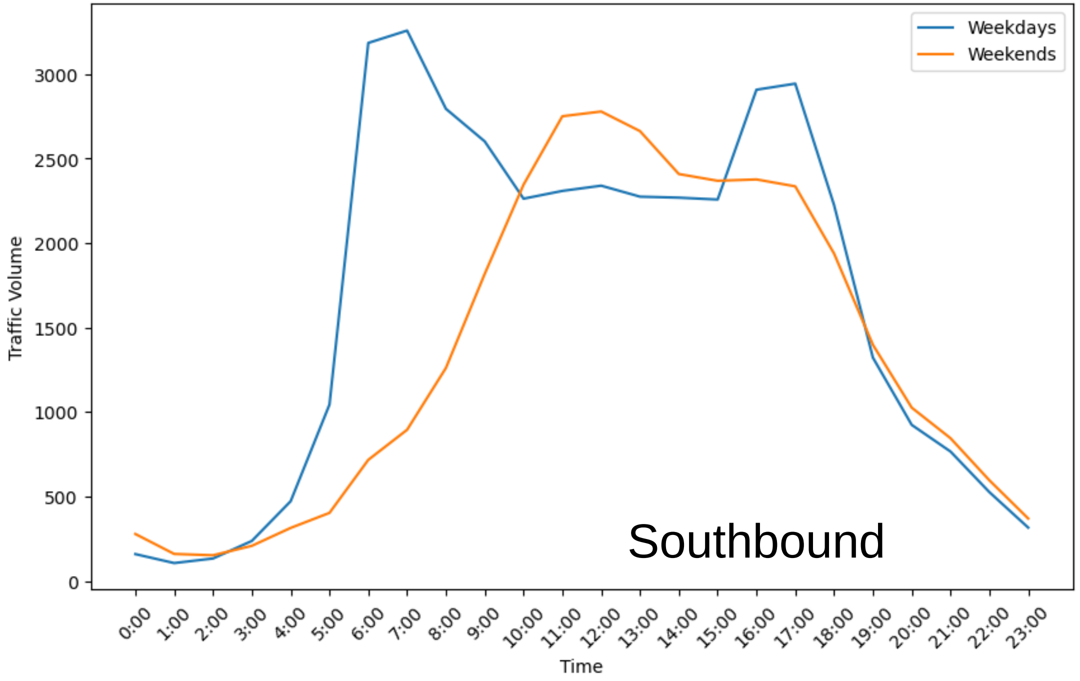
Traffic induced deflections – traffic simulations

Queensferry Crossing traffic flow



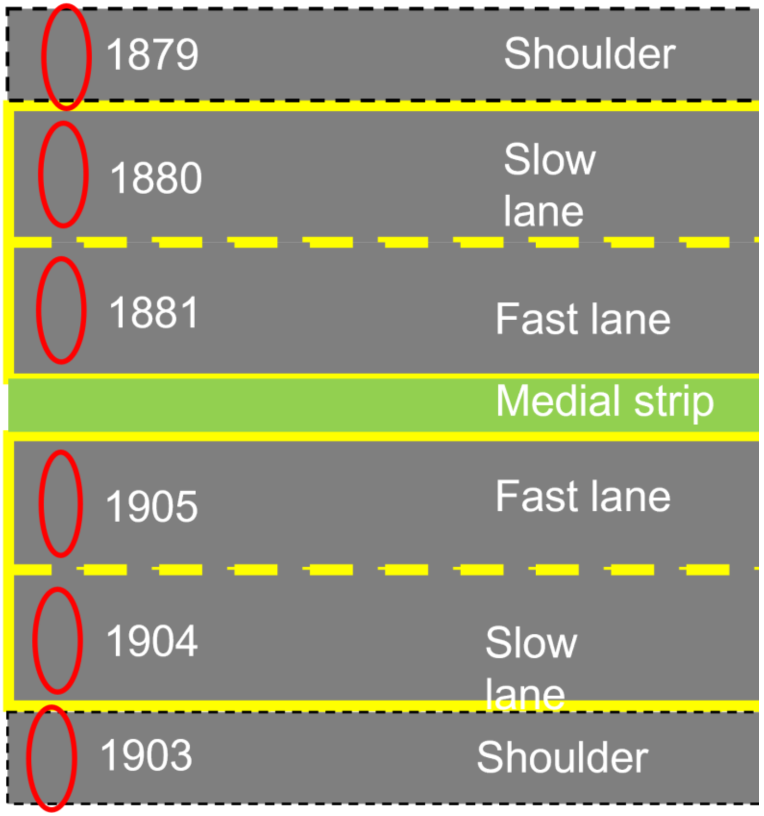


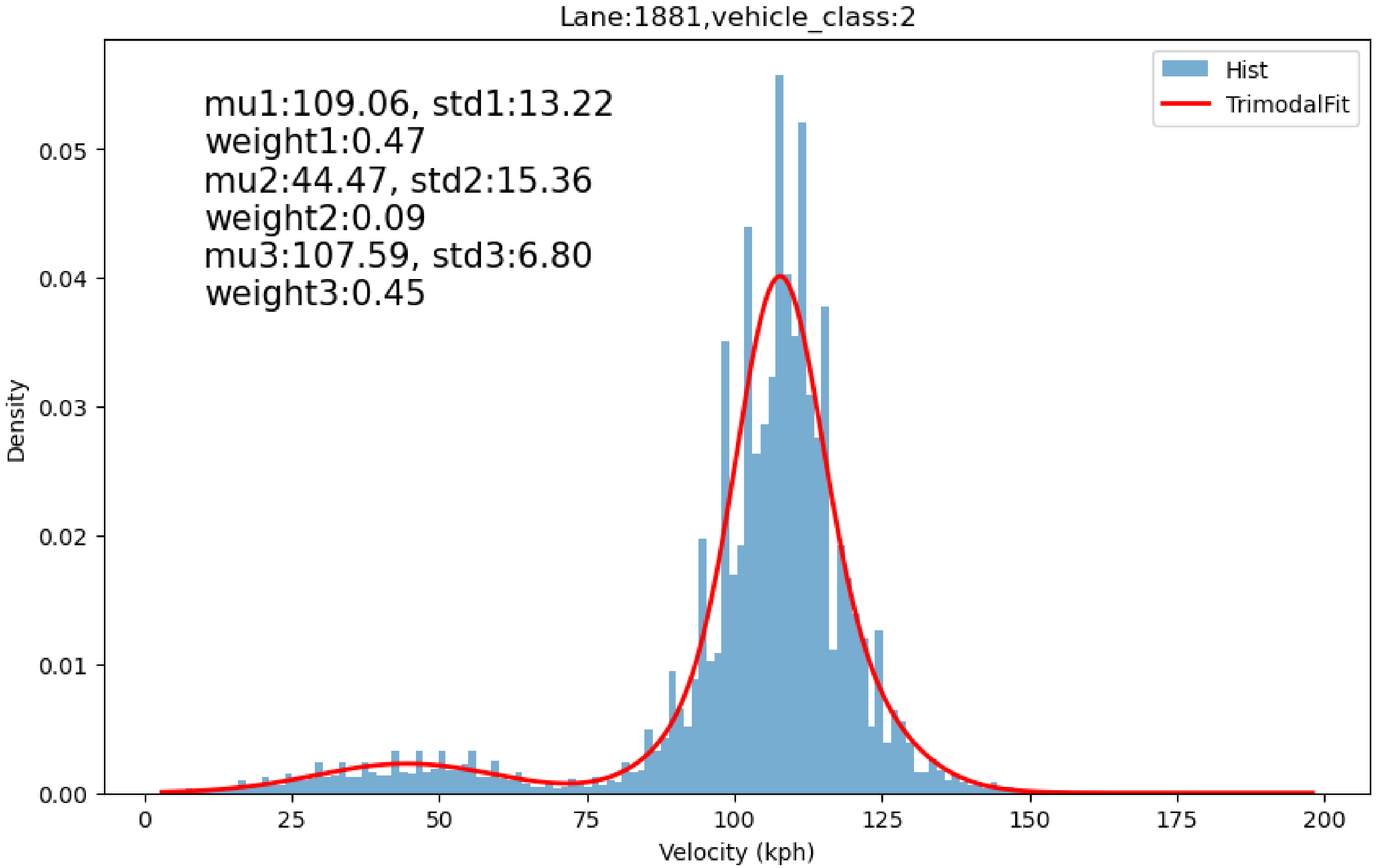
Average: 80,000 vehicles per day on the Queensferry Crossing

Traffic induced deflections – traffic simulations

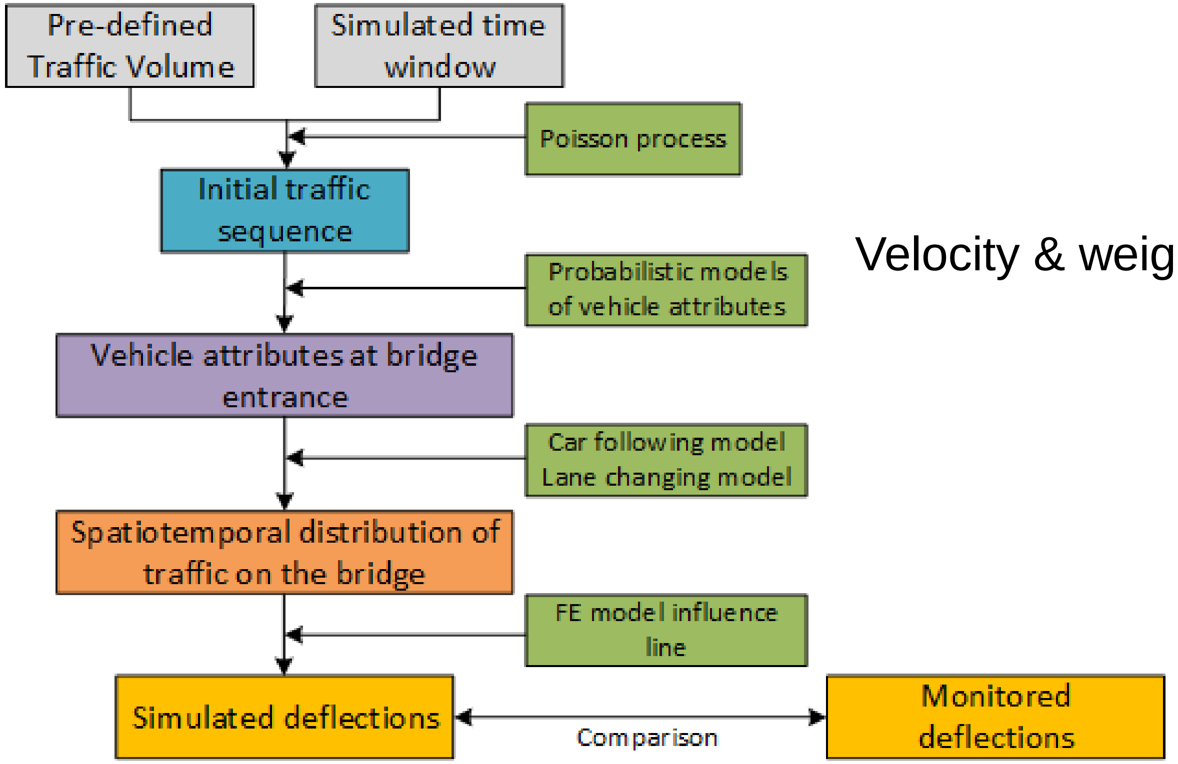
S Dynamic Weigh-in-motion (DWIM) N

timestamp	sensor_id	axles	length	speed_kph	class	gross	headway

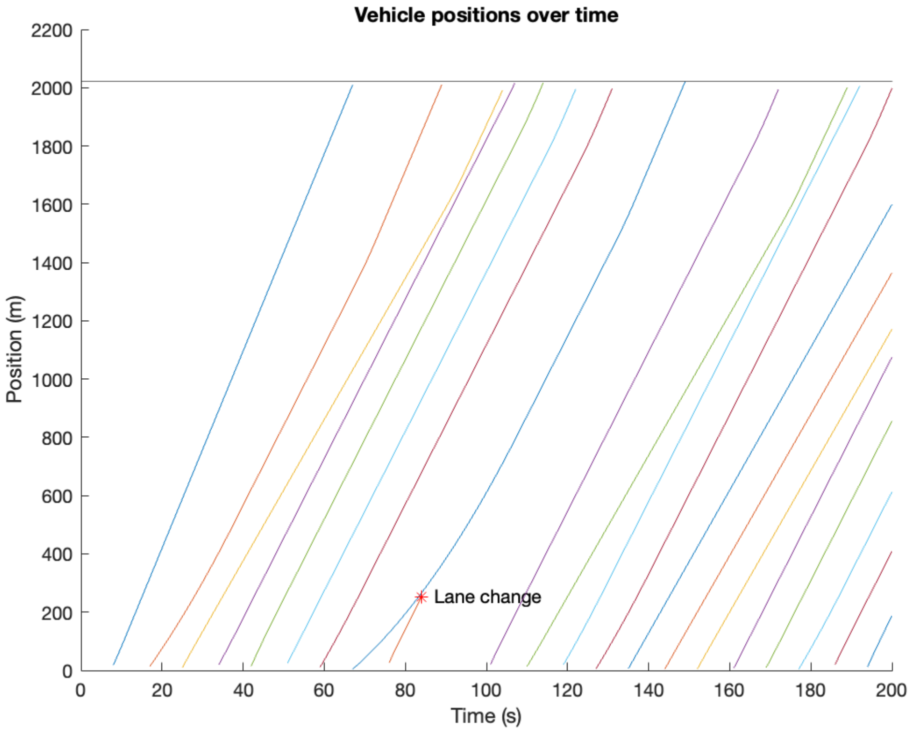


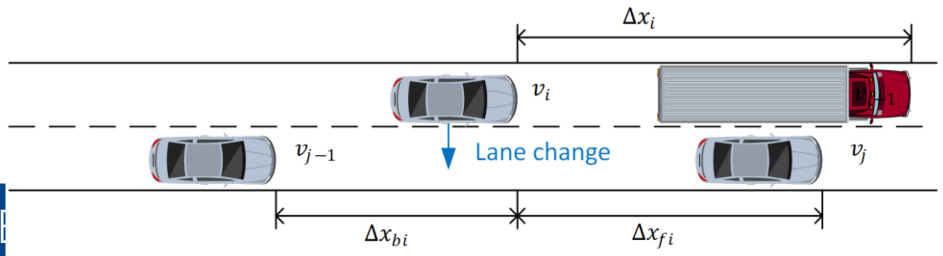


Traffic induced deflections – traffic simulations



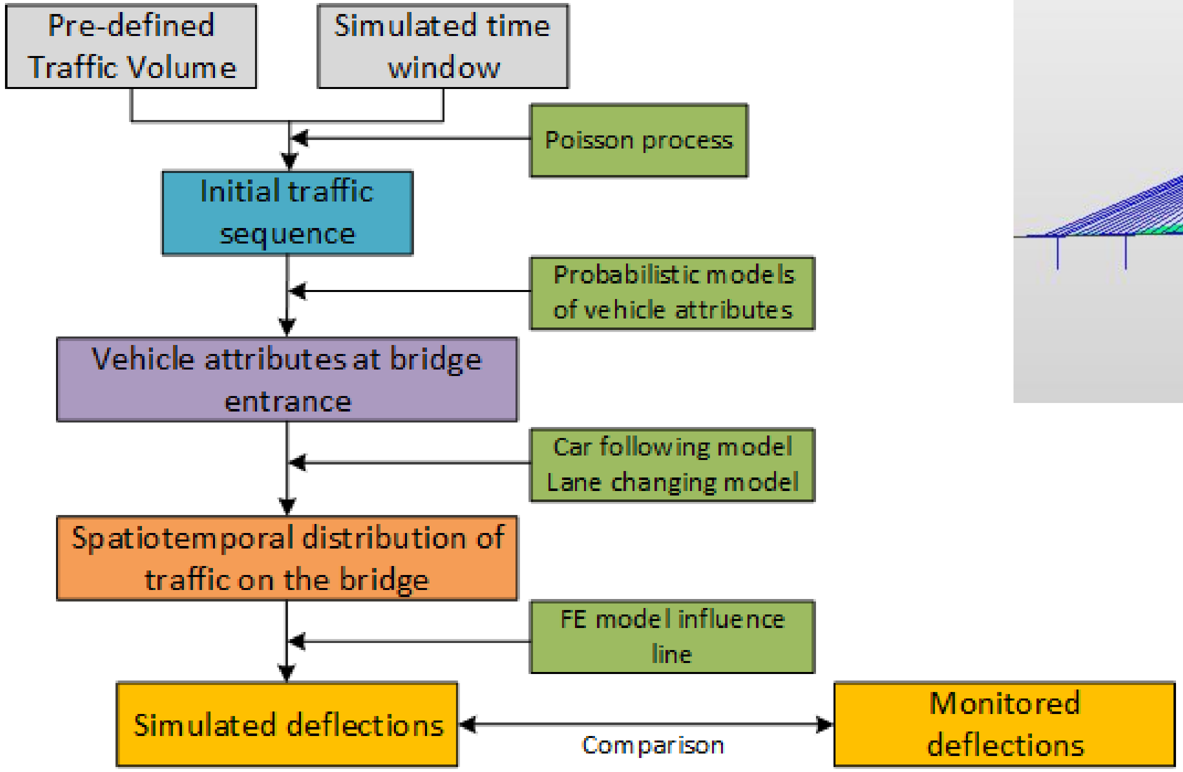
Velocity & weights



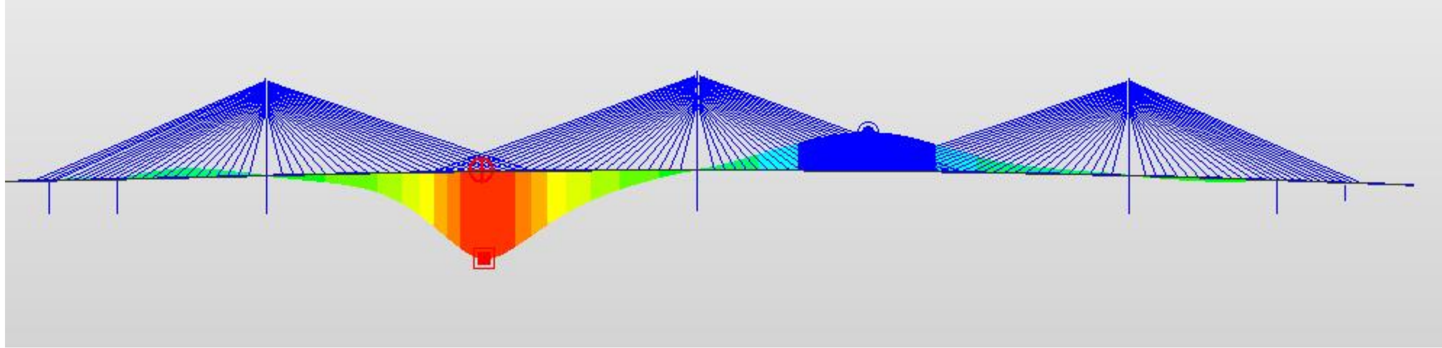


Simulated vehicle flow trajectory

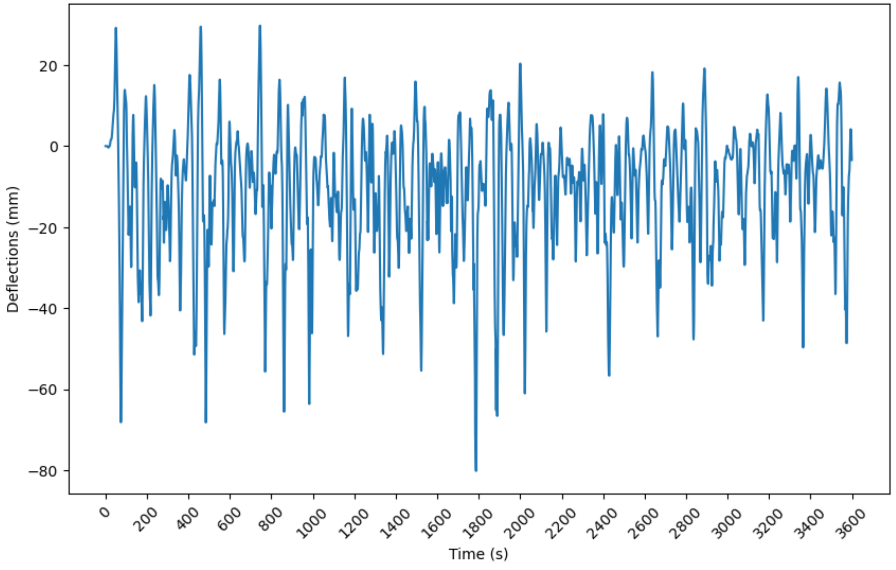
Traffic induced deflections – traffic simulations



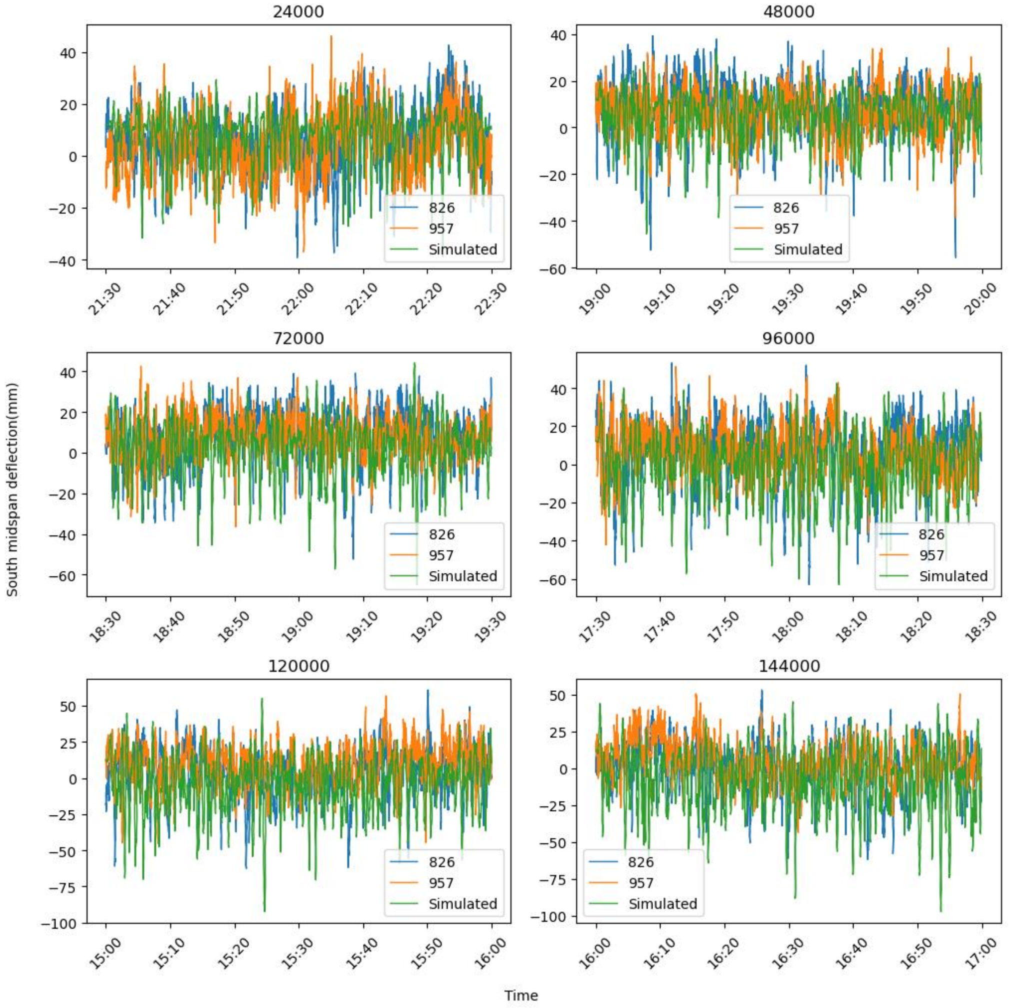
Deflection influence line at the south midspan



Simulated deflections at the south midspan



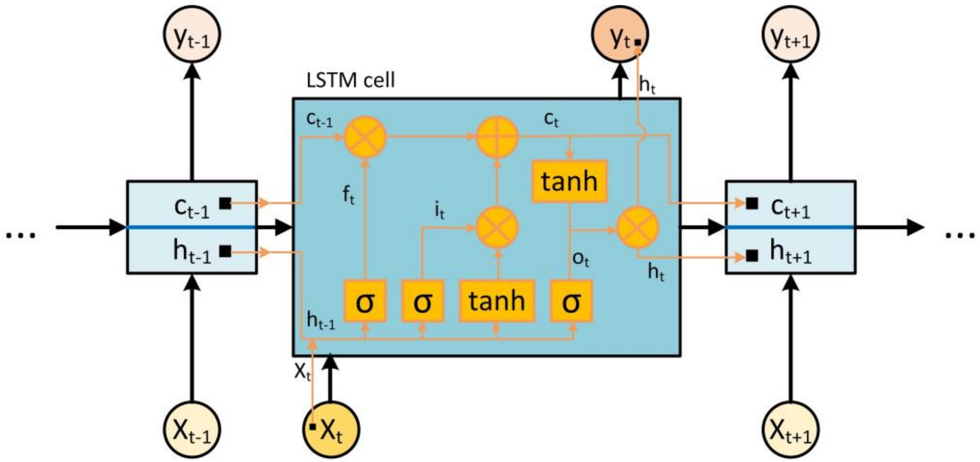
Traffic induced deflections – traffic simulations



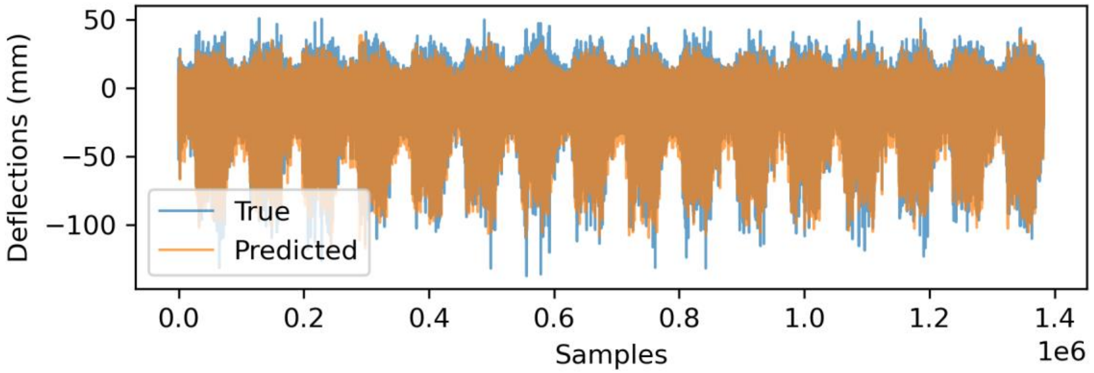
- 2 GPS stations installed at the south midspan
- The simulated deflections show similar pattern as the monitored data

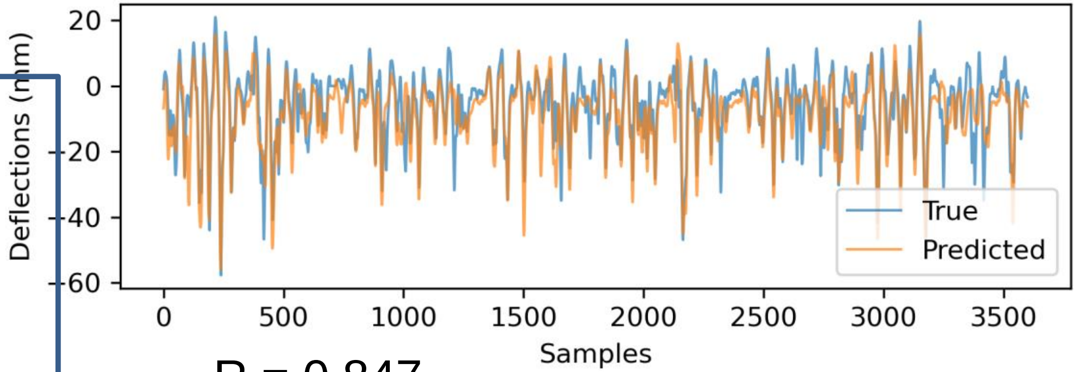
Traffic induced deflections – predictions

Neural networks predictions

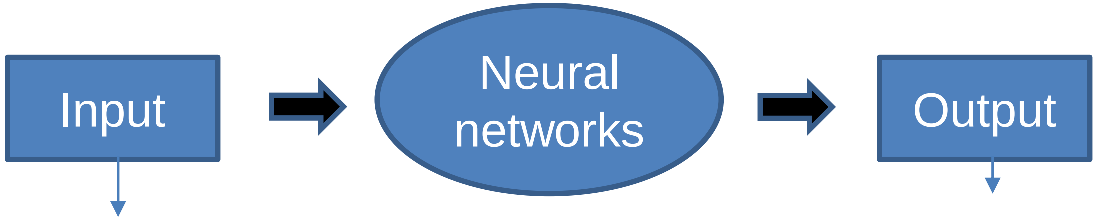


Long-short term memory (LSTM)





Forecasting



Vehicle attributes at entrance LSTM Mid-span deflection

R = 0.847

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Conclusions

- Temperature difference should be considered in the analysis for concrete sections
- Extreme temperature difference analysis reveals that the extreme estimation for bridge tower thermal load is close to the Chinese Design code - A revision of Eurocode in this part should be considered.
- LSTM is efficient in mapping the relationship between traffic attributes and deck deflections - In practical use, the model can be first trained on simulated data and then calculate the actual deflections at any locations of interest by being provided with real WIM data.
- LSTM demonstrates robust predictive capability on temperature-deflection relations even with time lag between them.

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SCREENING EAGLE

TRANSPORT SCOTLAND
CÒMHDHAIL ALBA

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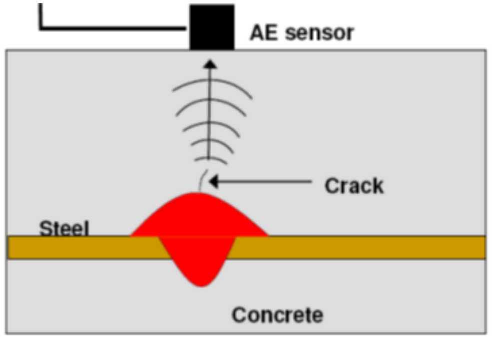

Abstract deadline: 30th April 2024

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