UNIVERSITÀ DEGLI STUDI DI BRESCIA

Department Civil, Environmental, Architectural Engineering and Mathematics (DICATAM)

REAL-TIME EVALUATION AND MANAGEMENT OF EXTREME TRAFFIC LOAD RISK ON MAIN ROAD'S BRIDGES

Roberto VENTURA

Benedetto BARABINO

Giulio MATERNINI

Montréal 2023
World Conference on Transport Research

17-21 JULY, 2023 | MONTRÉAL, QUÉBEC, CANADA

CENTRO NAZIONALE PER LA MOBILITÀ SOSTENIBILE

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

Ministero dell'Università e della Ricerca

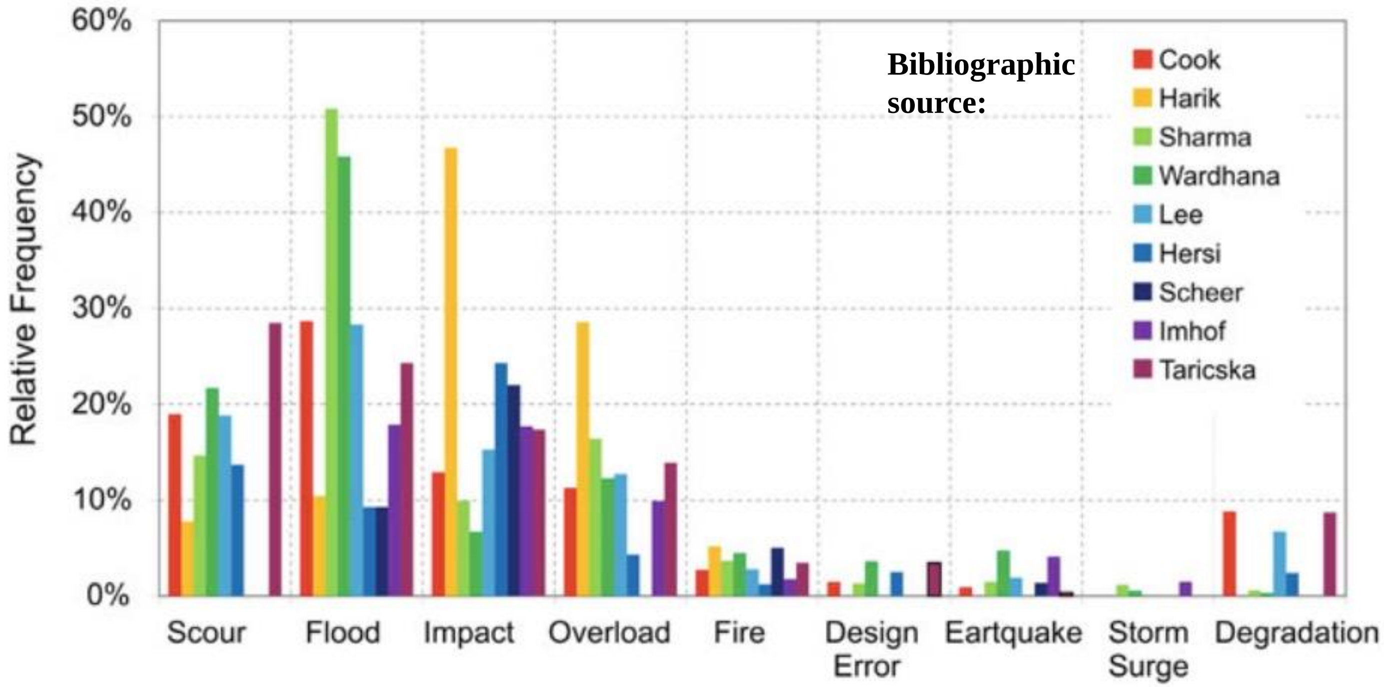
Finanziato dall'Unione europea NextGenerationEU

Summary

1. Introduction

- **Bridges** are among the most vulnerable elements of road networks (Zanini et al, 2017).
- **Vehicular traffic hazard** (impact and overload) is one of the main causes of bridge ***failures*** (Proske et al, 2018).
- **Extremely heavy vehicles** above the mass limits of Traffic Codes menace bridge safety (Ventura et al, 2020).
- Systems **to real time monitor and manage the risk** of extreme traffic load are essential for bridge safety.

Source: Proske et al. (2018)



1. Introduction

The goals of this research are:

- Providing a **comprehensive list of safety factors** related to bridge failure events.
- **Real-time evaluating** and **managing** the **risk** induced by **extreme traffic load** on **bridges**.
- Integrating **WIM (Weight-in-Motion)** systems to collect **site specific traffic load data.**
- Developing **probabilistic models** (GLRs e ANNs) to predict the risk components (frequency and severity) by **computationally efficient** elaborations.
- Defining an **ITS (Intelligent Transportation System) architecture** based on a CD (Cloud Platform), VMS (Variable Message Signals) and TL (Traffic Lights) for a **real-time risk management strategy**.

2. Literature review

Methodologies for bridge risk assessment

Three main research directions emerged:

I. Assumes **traffic load hazard** as a **component** of a broader **multi-hazard risk assessment framework** (e.g., Fiorillo & Nassif, 2020; Zhu & Frangopol, 2016).

II. Focuses on the risk posed by **traffic load hazard** (e.g., Fiorillo and Ghosn, 2022).

III. Focuses on the **consequences** induced by bridge *failure* events (e.g., Abarca et al, 2022).

Two different risk definitions emerged:

I. States the risk as the sum of the **probability of occurrence of each *failure* scenario** times the associated **(direct and indirect) consequences** (e.g., Fiorillo and Ghosn, 2022; Cosenza and Losanno, 2021).

II. States the risk merely as the **probability of occurrence of an undesired event** (Wijesuriya & Tennant, 2021; Davis-McDaniel et al., 2013).

2. Literature review

Although previous studies provided valuable results, **several gaps persists**:

I. The absence of a comprehensive **list of safety factors** related to bridge ***failure*** events.

II. The **source of analysed data** (WIM data were rarely integrated into risk analyses).

III. The **type of predictive models** adopted to forecast the risk components (ML was never applied)

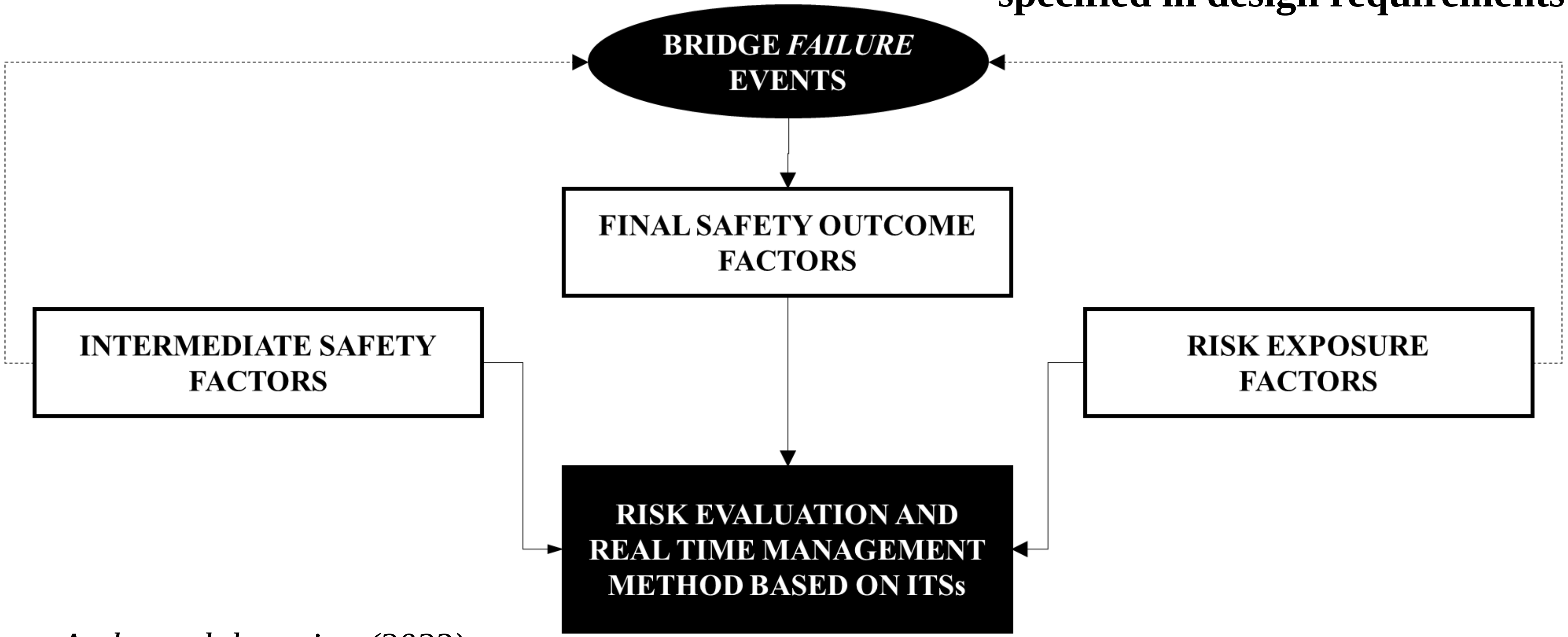
IV. The **computational effort** required by risk management procedures (expensive techniques were proposed).

V. The **type** of proposed **risk management actions** (only "static" measures were proposed).

3. Methodological framework

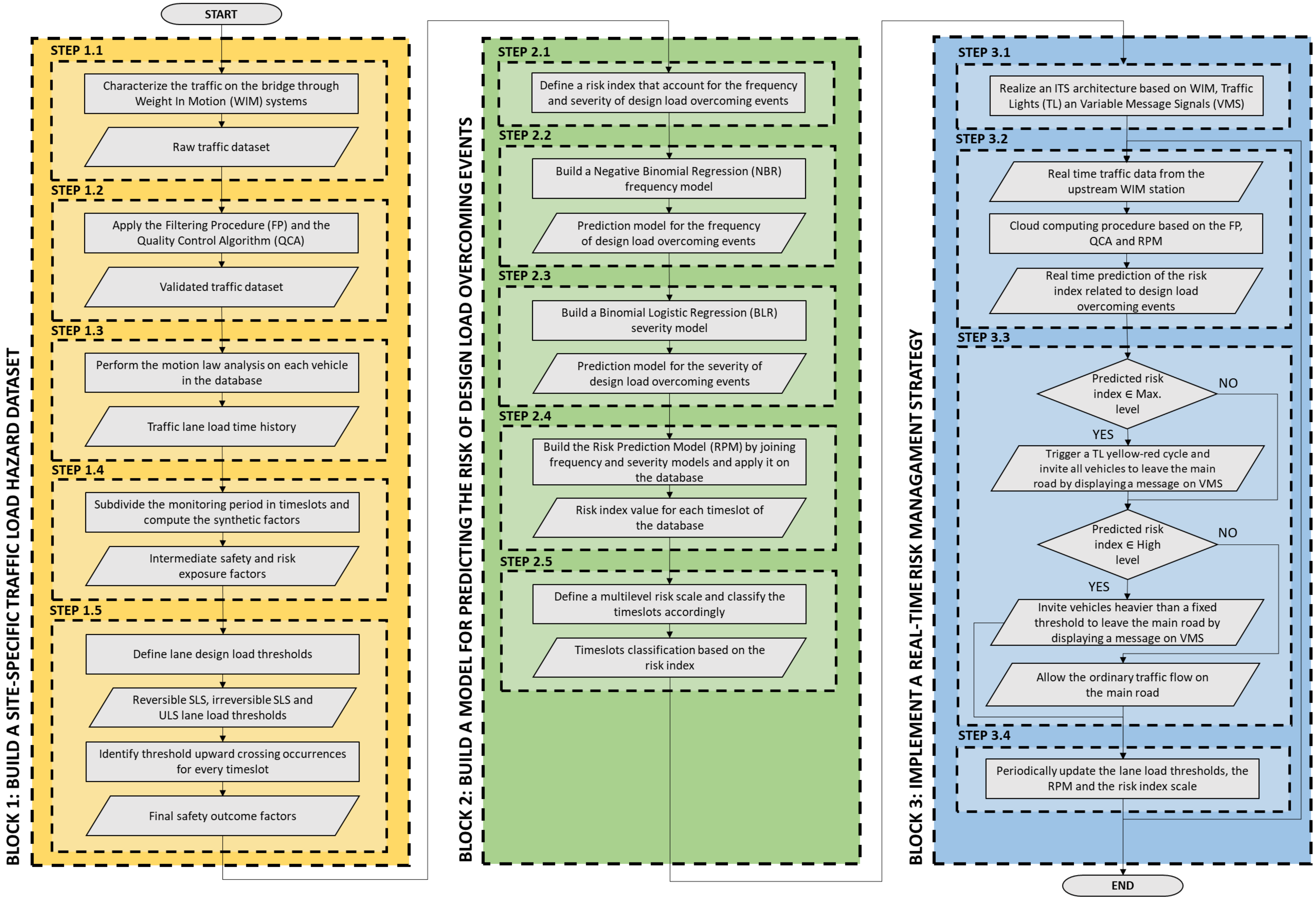
- It draws from the well-accepted framework of **ISO-EN 39001** (2012) for road safety analysis.
- It estimates the **frequency** and the **severity** of bridge *failure* events by adopting a simplified procedure inspired by the Limit State Method of **Eurocodes** (2003).

***failure* event $\stackrel{\text{def}}{=}$ incapacity of performing as specified in design requirements**



Source: Authors elaboration (2023)

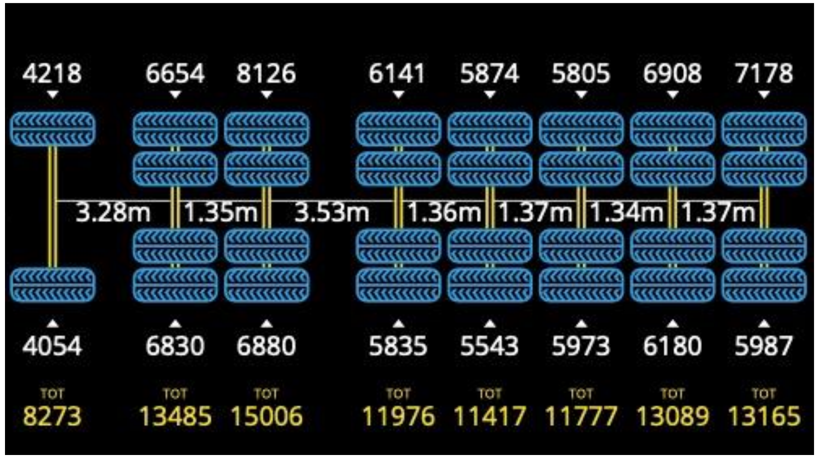
3. Methodological framework



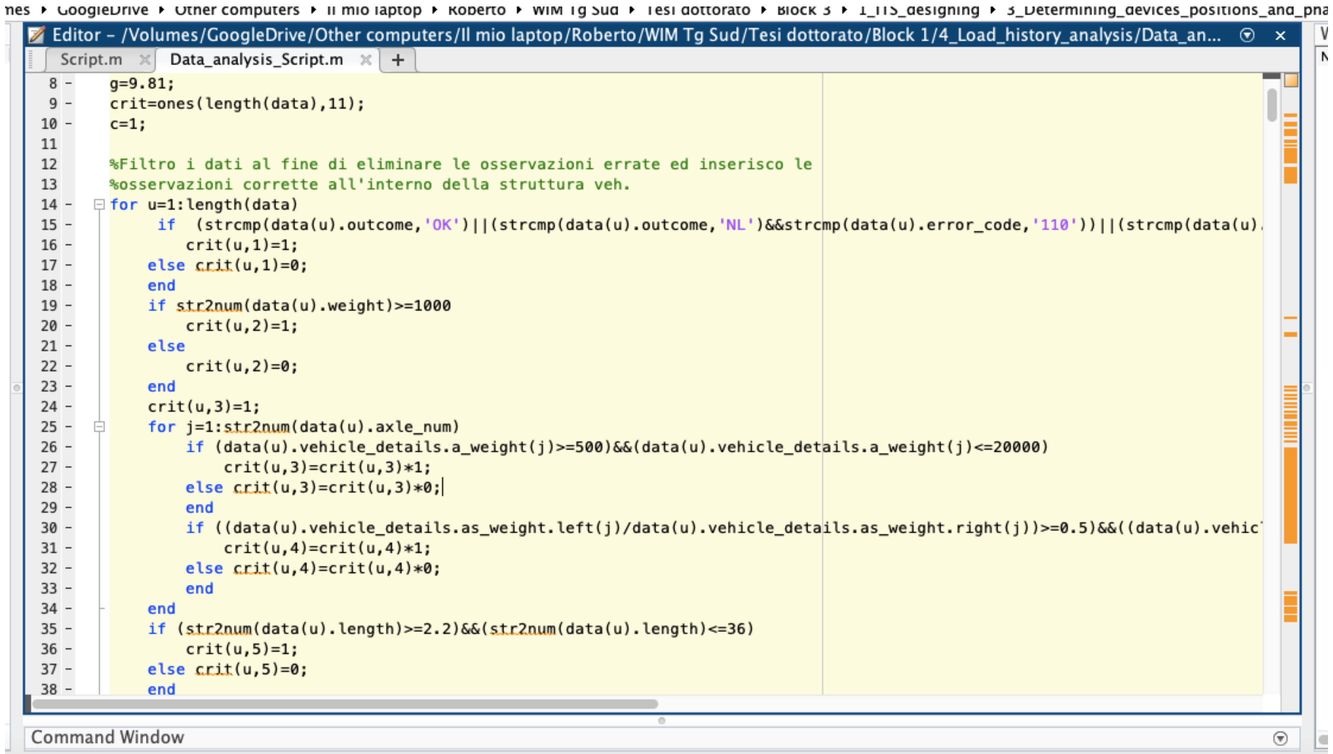
3. Methodological framework: Block 1

- **Acquires RAW data** through the **WIM** system during a monitoring period (*T*)

Source: IWIM Srl (2022)



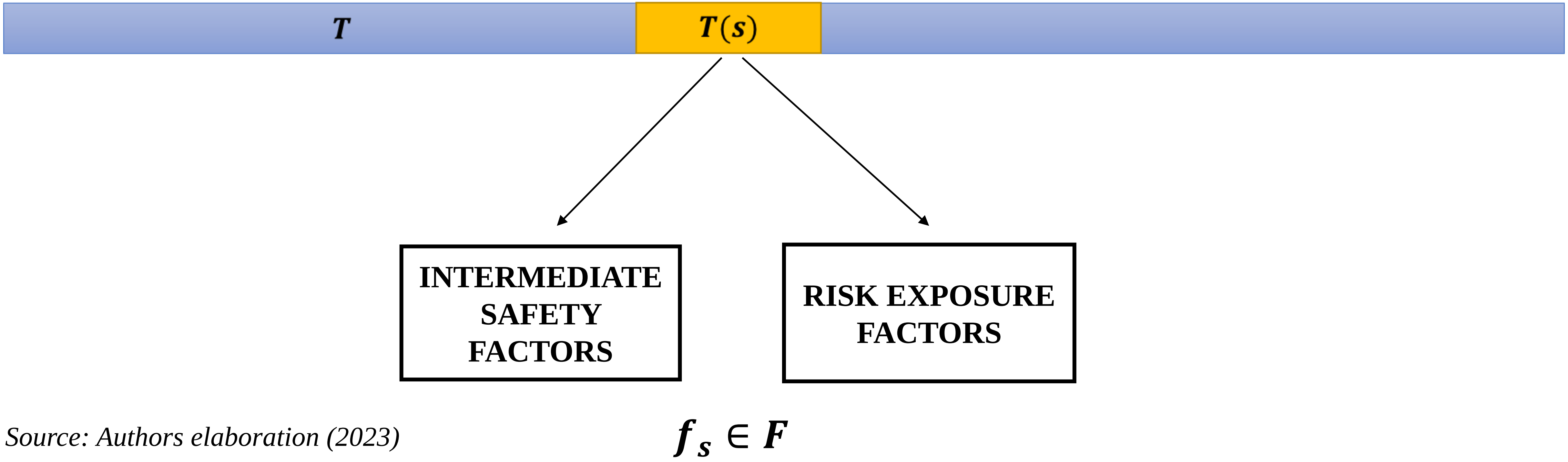
- **Pre-process data** to remove anomalies and outliers through a **Quality Control Algorithm**:



Source: Authors elaboration (2023)

3. Methodological framework: Block 1

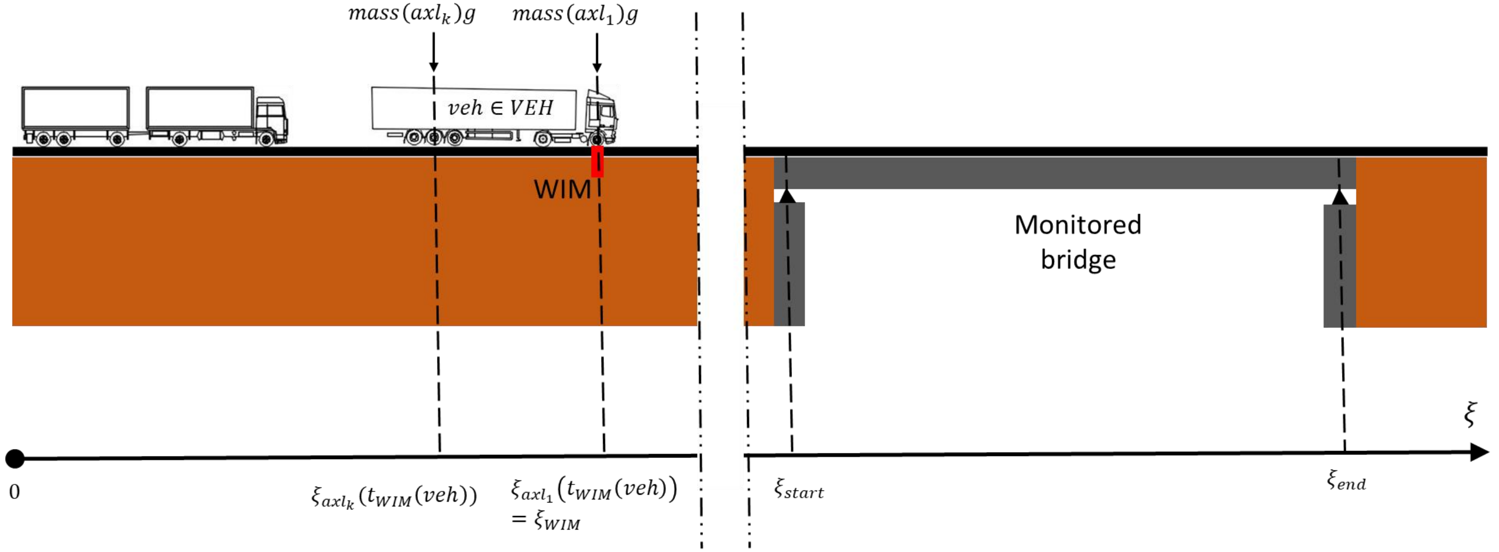
- Defines equal sized **temporal slots** ($s \in S$) and computes the **intermediate safety** and **risk exposure factors** ($f_s \in F$) related to traffic load hazard acting on the bridge during each $T(s)$



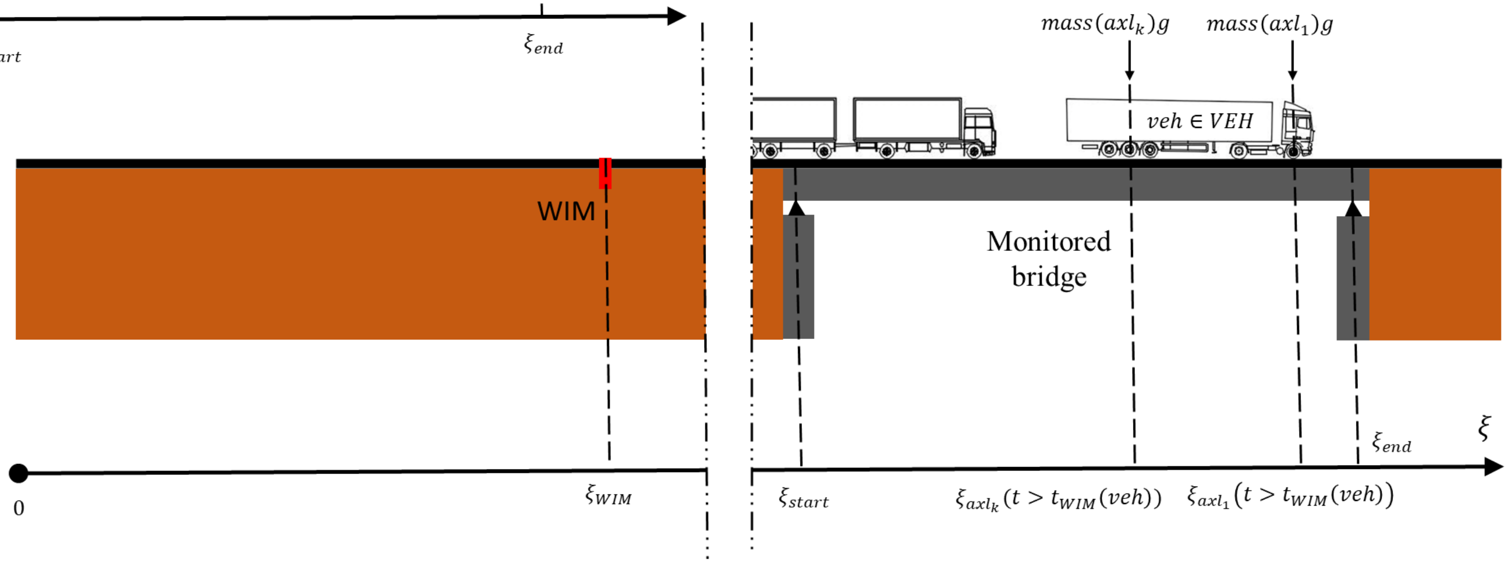
Source: Authors elaboration (2023)

3. Methodological framework: Block 1

- Determines the **time history of the traffic load** ($G(t)$) acting on each monitored lane by analysing the **motion law** of the axles of each passing vehicle ($\xi_{axl_k}(t)$):



Timestamp: $t_{WIM}(veh) \in T$



Timestamp: $t > t_{WIM}(veh) \in T$

Source: Authors elaboration (2023)

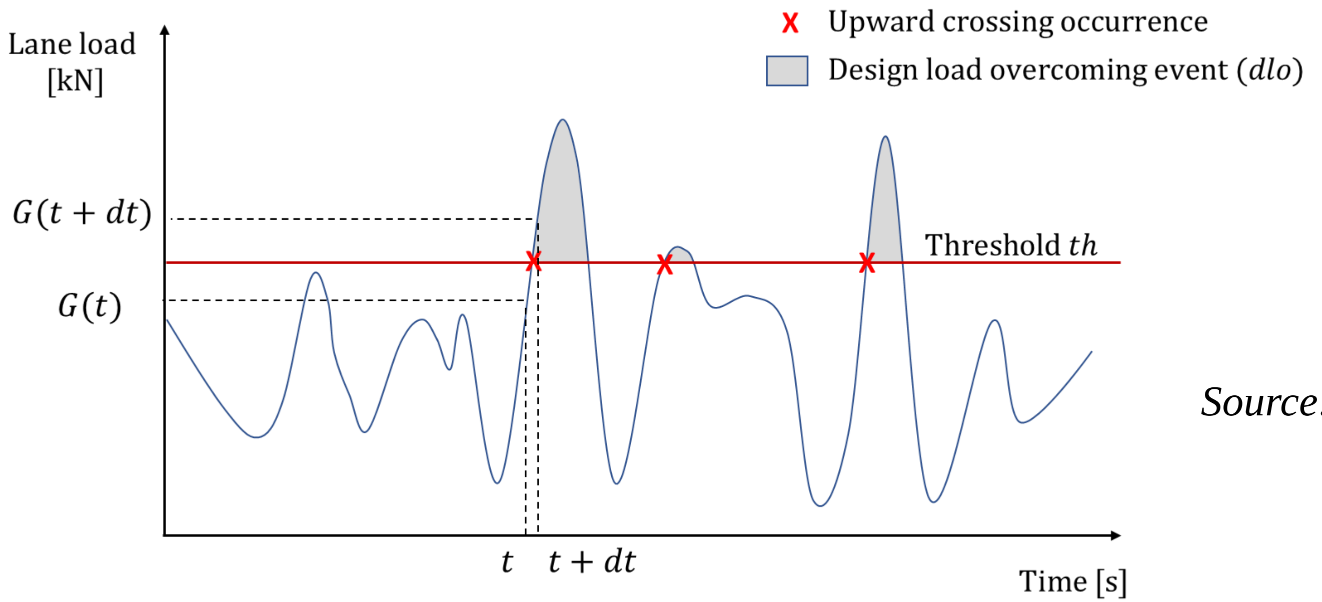
3. Methodological framework: Block 1

- Computes the **final safety outcome factors** by identifying the **design load overcoming events**, according to the lane load thresholds prescribed by **Eurocode 1** for three different Limit States.

$$th_{FuC_i} \stackrel{\text{def}}{=} max\{\gamma_Q 2Q_{ik} + \gamma_Q \psi_0 q_{ik} Lw_i;\ \gamma_Q q_{ik} Lw_i + \gamma_Q \psi_0 2Q_{ik}\}\ RF;\ \forall i \in I \qquad \text{(ULS)}$$

$$th_{ChC_i} \stackrel{\text{def}}{=} max\{2Q_{ik} + \psi_0 q_{ik} Lw_i;\ q_{ik} Lw_i + \psi_0 2Q_{ik}\}\ RF;\ \forall i \in I \qquad \text{(ISLS)}$$

$$th_{FrC_i} \stackrel{\text{def}}{=} max\{\psi_1 2Q_{ik} + \psi_2 q_{ik} Lw_i;\ \psi_1 q_{ik} Lw_i + \psi_2 2Q_{ik}\}\ RF;\ \forall i \in I \qquad \text{(RSLS)}$$



Source: Authors elaboration (2023)

3. Methodological framework: Block 2

- Defines a **risk index** related to traffic load hazard:

$$R_s \stackrel{\text{def}}{=} P_s E_s C_s = H_s(E_s, X_s) V_s(Y_s);\ \forall\ s \in S;$$

- Builds two alternative **models for predicting the frequency** of design load overcoming events:

$$\widetilde{H_s} \stackrel{\text{def}}{=} \sum_{th \in TH} |DLO(th,s)| = \alpha E_s^{\beta} e^{\sum_{x_j \in X} \gamma_j x_{j,s}};\ \forall\ s \in S;\ \text{(Mixed model: Power \& Negative Binomial Regression)}$$

$$\widetilde{H_s} \stackrel{\text{def}}{=} \sum_{th \in TH} |DLO(th,s)| = \widetilde{\omega}\left(\{f_s \in F\}, \bar{\bar{\theta}}_{freq,0}\right);\ \forall\ s \in S;\ \text{(Artificial Neural Network)}$$

- Builds two alternative **models for predicting the severity** of design load overcoming events:

$$\widetilde{V_s} \stackrel{\text{def}}{=} P\left(z_s = 1 \underset{y_j \in Y}{|} \{y_{j,s}\}\right) = \frac{e^{\delta + \sum_{y_j \in Y} \eta_j y_{j,s}}}{1 + e^{\delta + \sum_{y_j \in Y} \eta_j y_{j,s}}};\ \forall\ s \in S;\ \text{(Binomial Logistic Regression)}$$

$$\widetilde{V_s} \stackrel{\text{def}}{=} P\left(z_s = 1 \underset{y_j \in Y}{|} \{y_{j,s}\}\right) = \widetilde{\omega}\left(\{f_s \in F\}, \bar{\bar{\theta}}_{sev,0}\right);\ \forall\ s \in S;\ \text{(Artificial Neural Network)}$$

3. Methodological framework: Block 2

- **Multiplies frequency and severity predictions** to compute the risk index:

$$\widetilde{R_s} = \left(\alpha {E_l}^{\beta} e^{\sum_{j=1}^{|X|}\gamma_j x_{j,s}}\right)\left(\frac{e^{\delta+\sum_{j=1}^{|Y|}\eta_j y_{j,s}}}{1+e^{\delta+\sum_{j=1}^{|Y|}\eta_j y_{j,s}}}\right);\ \forall\ s \in S; \text{(Generalized Linear Regressions)}$$

$$\widetilde{R_s} = \underset{f\,\in\,F}{\widetilde{\omega}}\left(f_s, \bar{\bar{\theta}}_{0,freq}\right)\ \underset{f\,\in\,F}{\widetilde{\omega}}\left(f_s, \bar{\bar{\theta}}_{0,sev}\right);\ \forall\ s \in S; \text{(Artificial Neural Networks)}$$

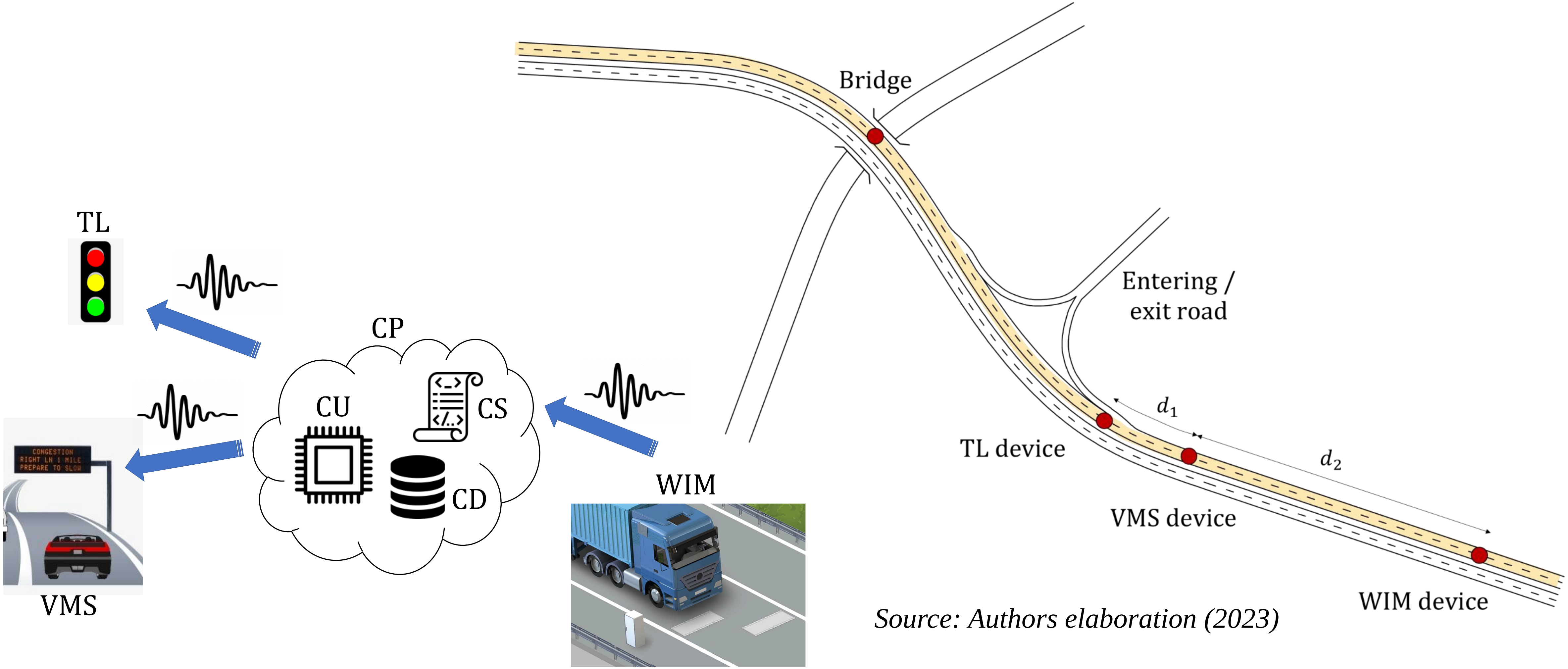
- **Defines a five-level risk scale** to rank the timeslots and identify the most critical ones:

Risk level	Lower limit	Upper limit	Colour
RL_1 - Maximum	χ_{99}	$\max R_s$	
RL_2 - High	χ_{75}	χ_{99}	
RL_3 – Above average	χ_{50}	χ_{75}	
RL_4 – Below average	χ_{25}	χ_{50}	
RL_5 - Low	$\min R_s$	χ_{25}	

Source: Authors elaboration (2023)

3. Methodological framework: Block 3

- Defines an **ITS-based risk management architecture**, composed by WIM, VMS, and TL devices.



Source: Authors elaboration (2023)

3. Methodological framework: Block 3

- Implements a **Risk Management Algorithm** based on traffic control actions:

Algorithm Risk Management

For each $mw \in MW$
    If $(R_{mw} \in LR_1)$ **Then**
        Display "*Bridge closed for all vehicles. Please take the next exit*" on the VMS
        And Trigger a yellow − red cycle on the TL
    Else If $(R_{mw} \in LR_2)$ **Then**
        Display "*Bridge closed for vehicles with a mass over 180 t. Please take the next exit.*" on the VMS
    Else Do nothing
    End If
End For

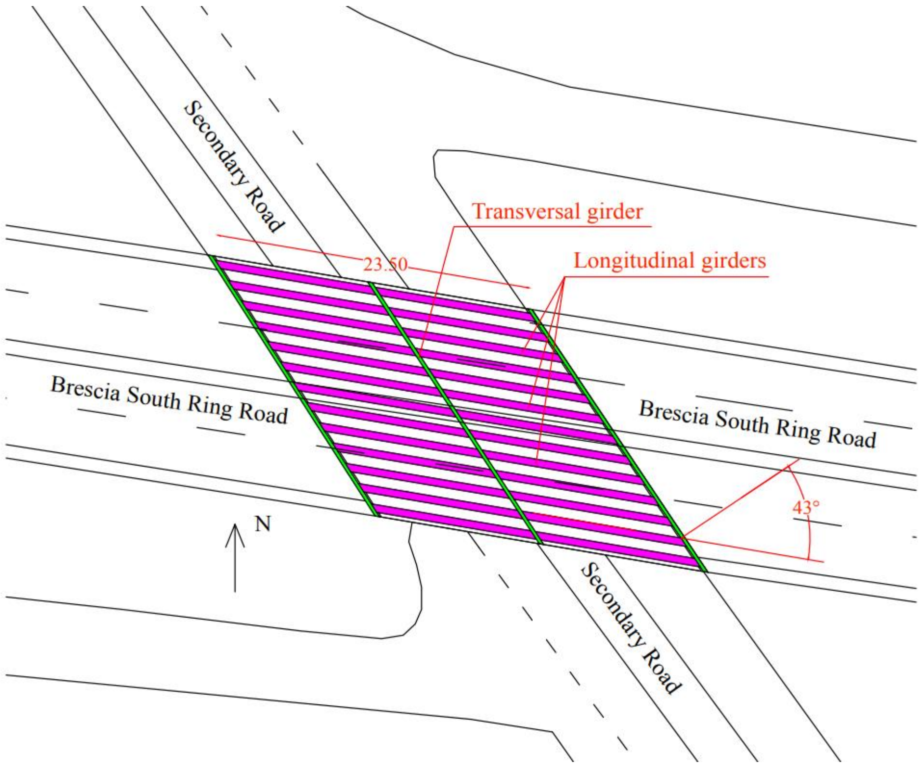
Source: Authors elaboration (2023)

- **Periodically updates** the risk prediction model and the risk scale.

4. Real world experiment: Site

- A **bridge** along the **Brescia's South Ring Road** was considered as **Case Study**.

- It is a **simple supported** structure, composed by **13 longitudinal precast concrete girders**.

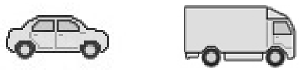
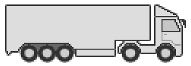
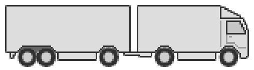
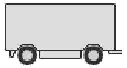


Source: Authors elaboration (2023)

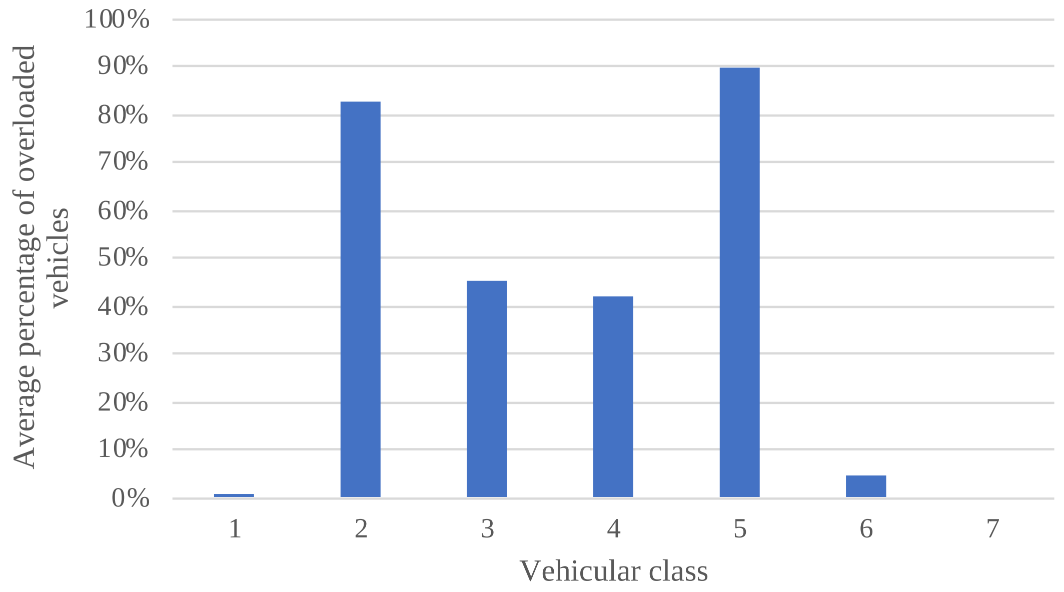
4. Real world experiment: Block 1

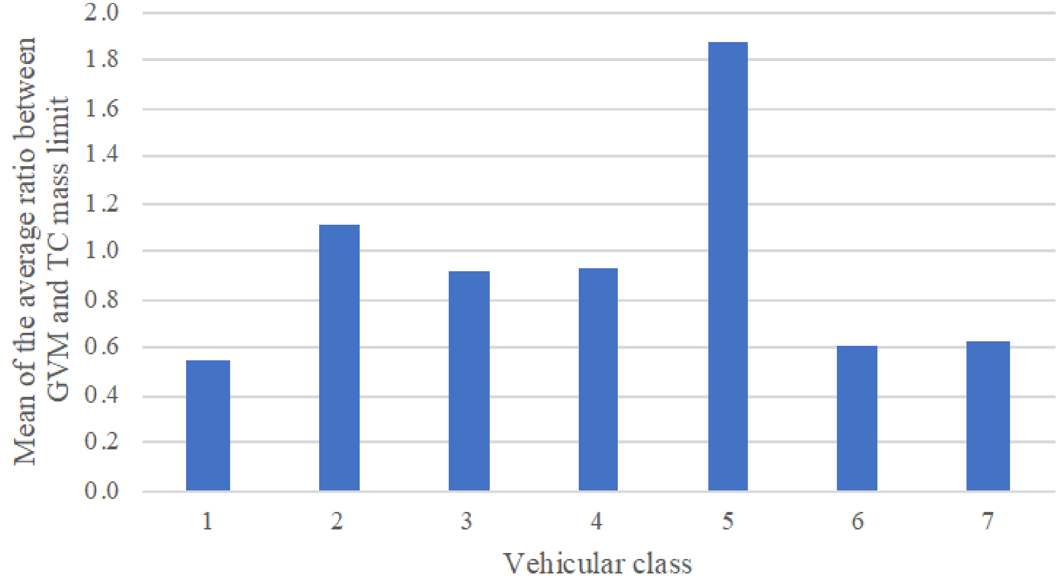
- **2M+ vehicles** sampled by a **WIM system** during a **five months monitoring period** were considered.

Source: Authors elaboration (2023)

Class ID	Class name	Symbolic illustration	Fraction [%]
1	Cars and vans		92.889%
2	Single unit trucks and buses		0.597%
3	Articulated trucks up to 6 axles		5.733%
4	Road trains up to 6 axles		0.469%
5	More than 6 axles vehicles		0.309%
6	Isolated trailers		0.003%
7	Unknown vehicles	?	< 0.001%

Source: Authors elaboration (2023)





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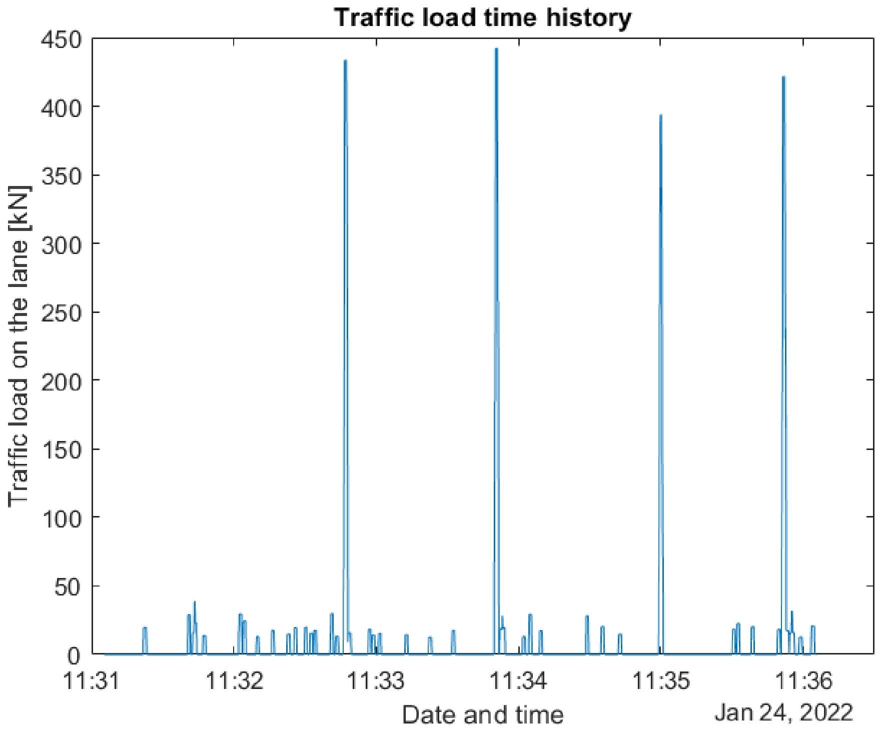
4. Real world experiment: Block 1

- The computation procedures were implemented into a **MATLAB© script**.
- The **traffic load time history** and the number of **design load overcoming events** associated to each threshold were determined.



Parameter	Symbol	Unit	Statistic	Value
Number of design load overcoming events related to FuC threshold in each $s \in S$ (ULS)	$\lvert DLO(th_{FuC_1}, s)\rvert$	-	Mean	0.000
			Standard dev.	0.000
			Minimum	0
			Maximum	0
			Sum	0
Number of design load overcoming events related to ChC threshold in each $s \in S$ (ISLS)	$\lvert DLO(th_{ChC_1}, s)\rvert$	-	Mean	0.005
			Standard dev.	0.075
	$T_r \cong 8\ days$		Minimum	0
	$(\ll 1'000\ years)$		Maximum	2
			Sum	14
Number of design load overcoming events related to FrC threshold in each $s \in S$ (RSLS)	$\lvert DLO(th_{FrC_1}, s)\rvert$	-	Mean	5.298
			Standard dev.	8.056
	$T_r \cong 11\ min$		Minimum	0
			Maximum	57
			Sum	15’132

Source: Authors elaboration (2023)

4. Real world experiment: Block 2

- The **Generalized Linear Regressions** models for predicting the two risk components were determined:

Frequency model (GLR)

Source: Authors elaboration (2023)

Item	Description	Est.	p-val	Item	Description	Est.	p-val
$\log(\alpha)$	Natural logarithm of the constant	-1.920	0.516	γ_8	Mean interaxle	1.084	0.085
β	Exponent of the exposure factor	0.400	**<.001**	γ_9	Maximum GVM length ratio	0.00043	**<.001**
γ_1	Weekend (wrt weekday)	-0.510	**<.001**	γ_{10}	Mean GVM overload ratio – Class 1 (*Cars and vans*)	3.910	**0.005**
γ_2	Class 2 (*Single unit trucks and buses*) fraction	-8.390	0.158	γ_{11}	Maximum GVM overload ratio – Class 2 (*Single unit trucks and buses*)	-0.151	0.111
γ_3	Class 5 fraction (*More than 6 axles vehicles*)	6.950	0.242	γ_{12}	Maximum GVM overload ratio – Class 4 (*Road trains up to 6 axles*)	0.403	**<.001**
γ_4	Mean speed	-0.042	**<.001**	γ_{13}	Overloaded vehicles fraction – Class 3 (*Articulated trucks up to 6 axles*)	1.711	**<.001**
γ_5	Minimum length	-2.094	**0.017**	γ_{14}	Overloaded vehicles fraction – Class 4 (*Road trains up to 6 axles*)	0.271	**0.018**
γ_6	Mean axle imbalance ratio	-1.426	**0.011**	γ_{15}	Extremely loaded vehicles following one another	0.150	**0.043**
γ_7	Maximum axle imbalance ratio	0.438	**0.045**	γ_{16}	Overloaded axles fraction	19.260	**<.001**

Summary statistics

Source	Degree of freedom	Deviance	Mean deviance	Parameter	Value
Regression	17	4’303.1	253.13	d.r.	253.13
Residual	2’139	569.5	0.266	χ^2	.001
Total	2’156	4’872.7	2.260		

Compliance with Traffic Code prescriptions are strong predictors!

Severity model (GLR)

Source: Authors elaboration (2023)

Item	Description	Estim.	OR	p-val.	Item	Description	Estim.	OR	p-val.
δ	Constant	-188.9		**0.027**	η_4	Minimum axle imbalance ratio	-38.7	1.56E-17	**0.029**
η_1	Maximum length	0.464	1.590	0.061	η_5	Maximum GVM overload ratio	55.8	1.71E+24	**0.019**
η_2	Maximum axle mass	0.00212	1.002	0.091	η_6	Maximum GVM overload ratio – Class 1 (*Cars and vans*)	-23.48	6.35E-11	**0.018**
η_3	Mean axle imbalance ratio	50.4	7.73E+21	0.091					

Summary statistics

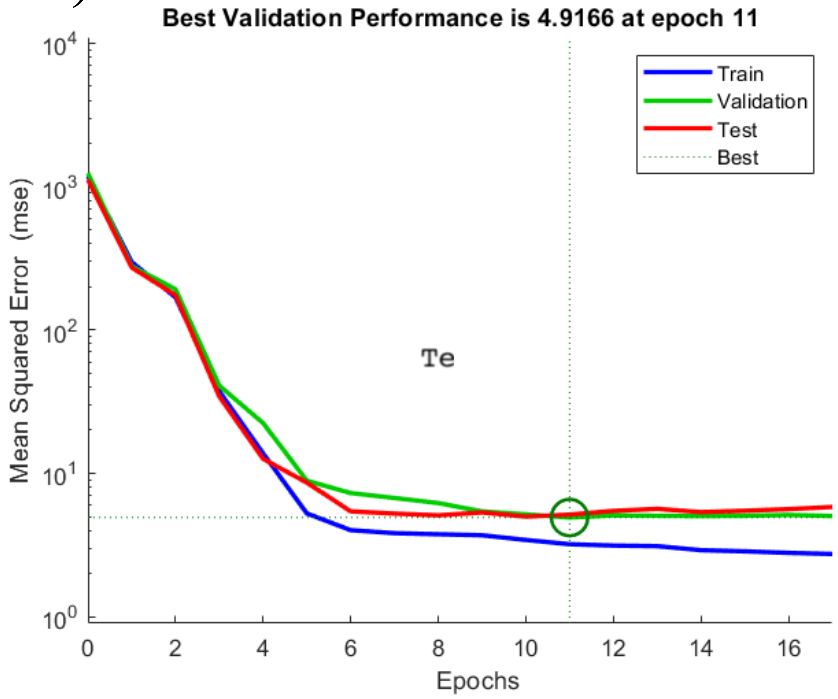
Source	Degree of freedom	Deviance	Mean deviance	Parameter	Value
Regression	6	101.02	16.836	d.r.	16.84
Residual	1’224	15.16	0.012	χ^2	<.001
Total	1’230	116.18	0.094		

4. Real world experiment: Block 2

- The **Artificial Neural Networks** models for predicting the two risk components were determined:

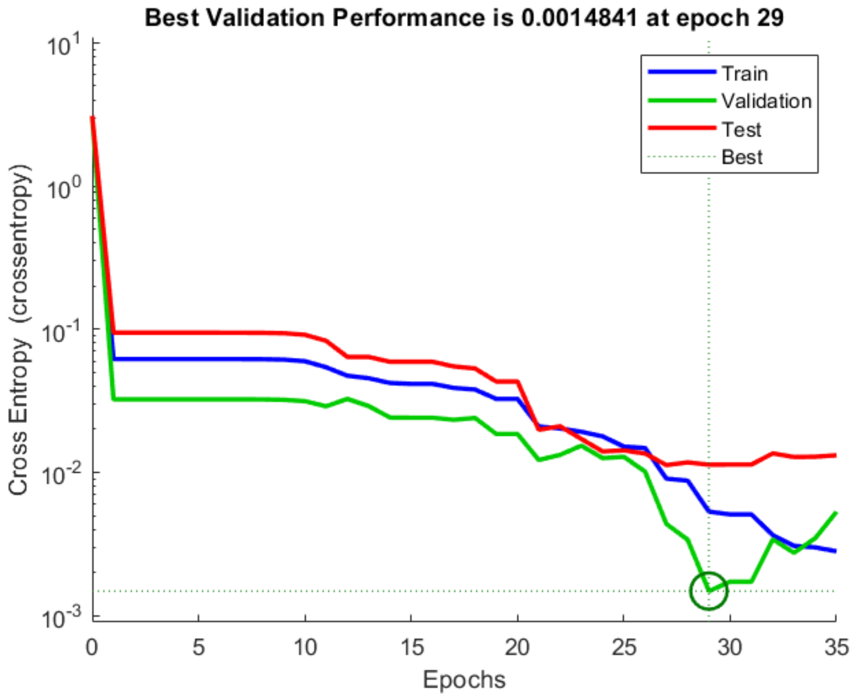
Source: Authors elaboration (2023)

Frequency model



- **2 layers feed-forward**
- **10 perceptrons** in hidden layer
- **Sigmoidal** activation functions
- **Levenberg-Marquardt** training algorithm

Severity model



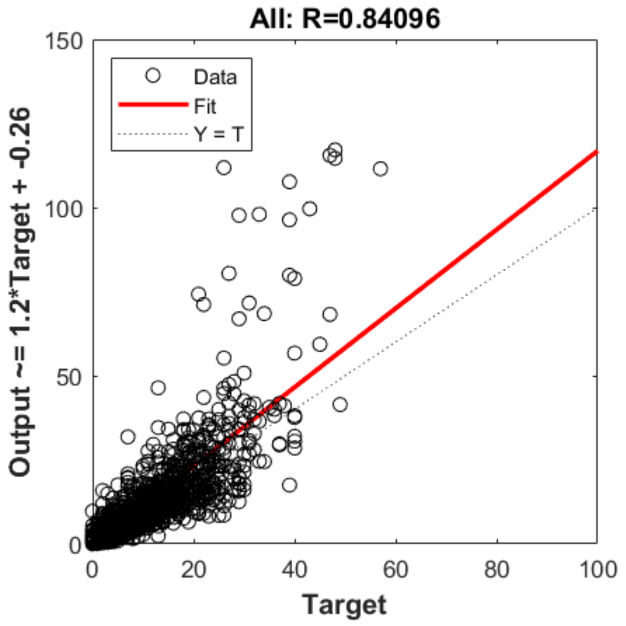
- **2 layers feed-forward**
- **10 perceptrons** in the hidden layer
- **Sigmoidal** activation functions
- **Scaled Conjugate Gradient** training algorithm

4. Real world experiment: Block 2

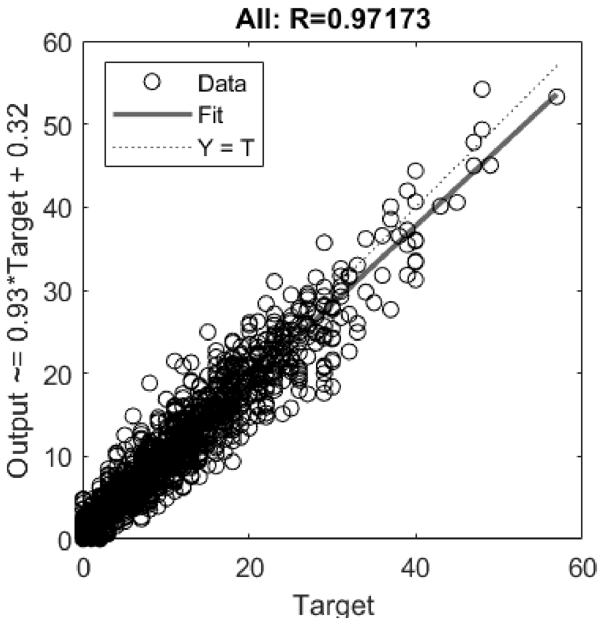
- The **performances** of the alternative models were **compared**:

Model	*R* (train)	*R* (test)	*R* (all)	π	*S* (train)	*S* (test)	*S* (all)	*CE*
Freq - GLR	0.838	0.859	0.841	1.120	na	na	na	na
Freq - ANN	0.977	0.961	0.972	0.999	na	na	na	na
Sev - GLR	na	na	na	na	80.0%	66.7%	76.9%	0.0077
Sev - ANN	na	na	na	na	88.9%	100.0%	92.3%	0.0034

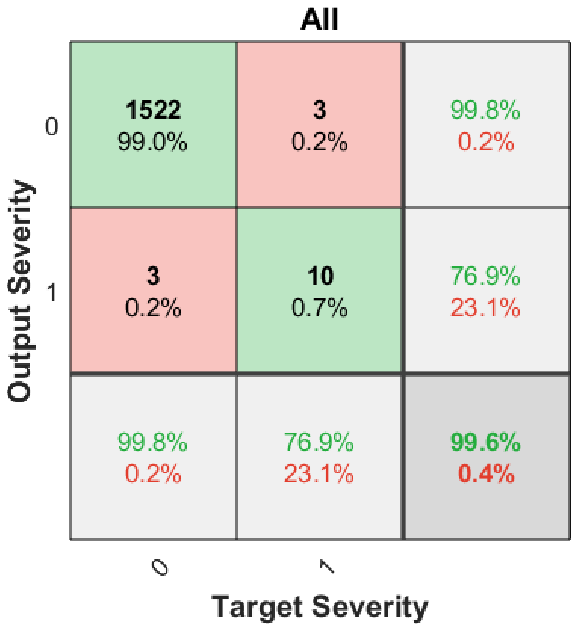
Freq - GLR



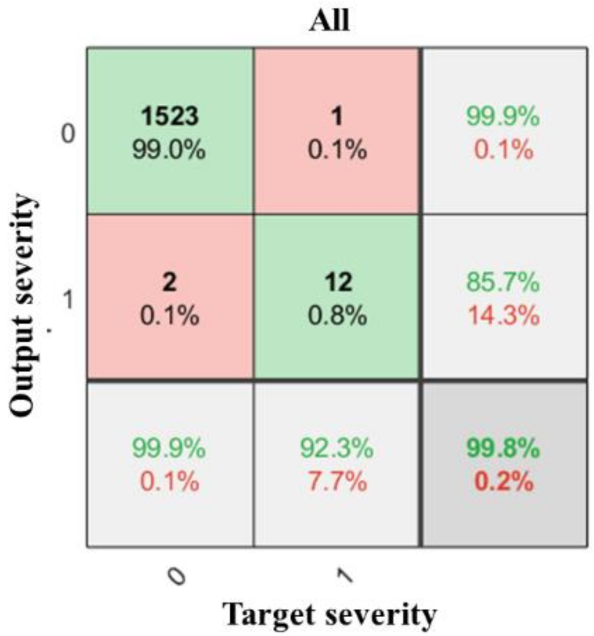
Freq - ANN



Sev - GLR



Sev - ANN

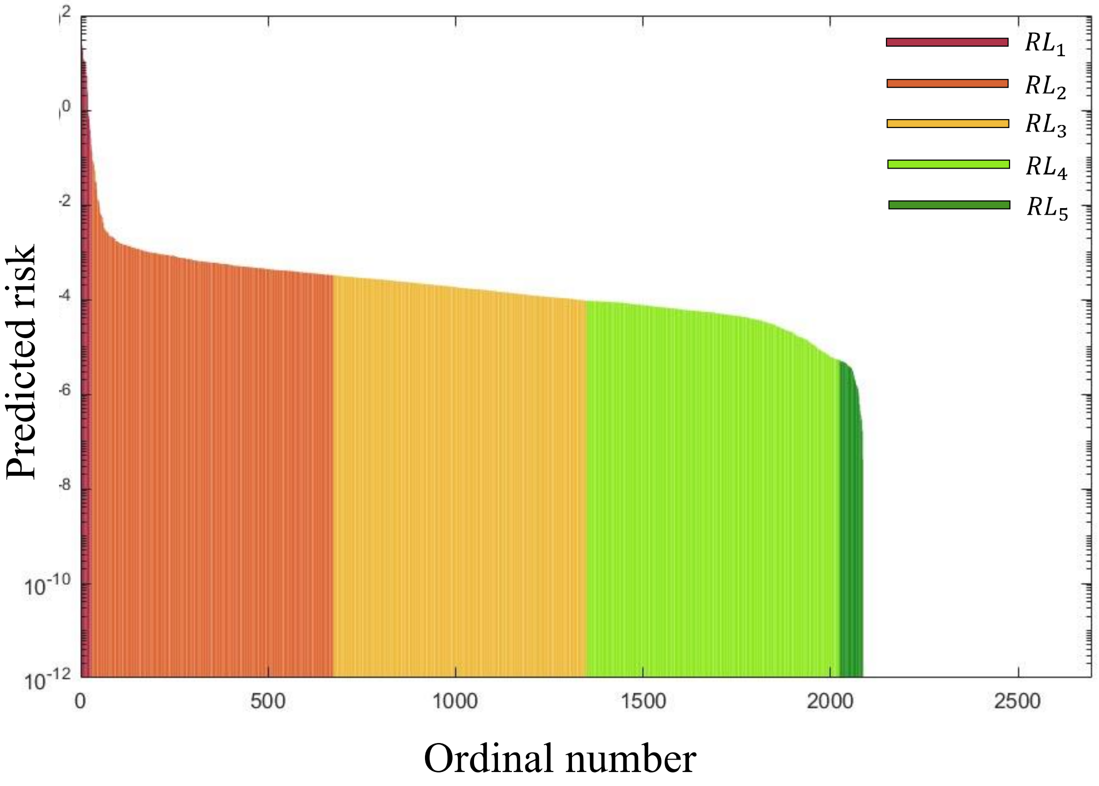


Source: Authors elaboration (2023)

4. Real world experiment: Block 2

- The **timeslots were classified** according to the predicted risk by adopting the **five-level risk scale**:

Risk predicitons distribution



Source: Authors elaboration (2023)

Timeslots weekly distribution

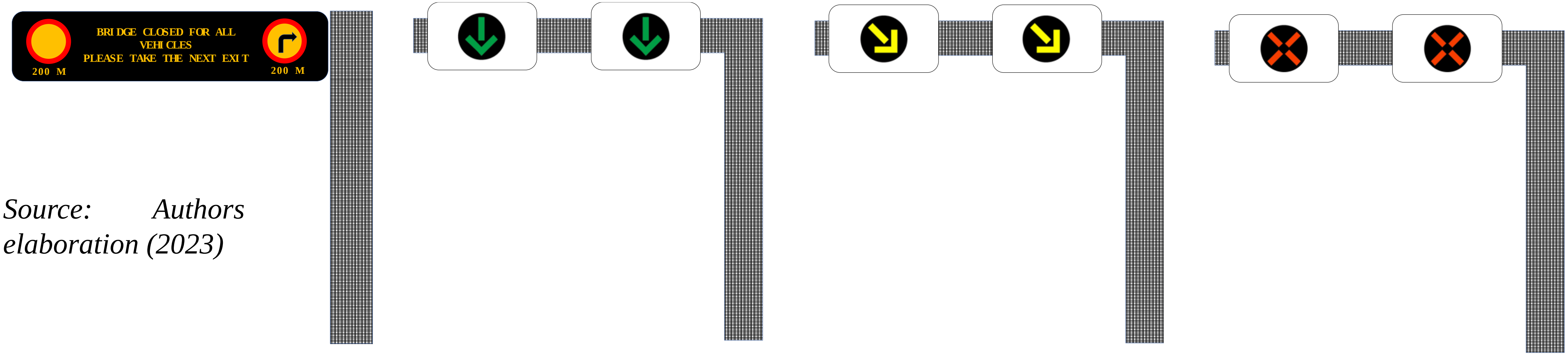
Day of the week	RL_1	RL_2	RL_3	RL_4	RL_5
1	0.00%	0.46%	1.34%	19.44%	33.23%
2	3.70%	21.33%	16.47%	10.98%	8.01%
3	14.81%	19.47%	18.84%	12.61%	7.86%
4	37.04%	20.56%	20.18%	12.02%	7.12%
5	22.22%	17.00%	17.21%	12.02%	9.20%
6	22.22%	19.01%	17.06%	10.53%	10.53%
7	0.00%	2.16%	8.90%	22.40%	24.04%
Total	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**

Timeslots daily distribution

Hour	RL_1	RL_2	RL_3	RL_4	RL_5
0	0.00%	0.46%	1.48%	3.71%	10.68%
1	3.70%	0.62%	1.04%	1.63%	12.91%
2	0.00%	2.78%	2.67%	3.26%	7.57%
3	0.00%	4.33%	2.97%	2.52%	7.27%
4	0.00%	9.89%	2.97%	1.78%	2.67%
5	0.00%	11.28%	2.97%	0.45%	2.67%
6	0.00%	10.82%	3.71%	1.04%	1.78%
7	7.41%	1.39%	6.08%	6.97%	2.23%
8	0.00%	1.70%	6.23%	7.42%	1.93%
9	7.41%	4.02%	7.57%	3.71%	1.63%
10	3.70%	7.57%	4.75%	3.12%	1.78%
11	18.52%	7.57%	4.30%	1.93%	2.52%
12	14.81%	8.04%	4.15%	3.26%	1.34%
13	11.11%	8.04%	4.45%	3.26%	1.19%
14	7.41%	5.72%	5.93%	3.41%	1.78%
15	18.52%	3.40%	6.08%	4.30%	2.37%
16	7.41%	4.64%	5.93%	3.12%	2.82%
17	0.00%	0.77%	4.90%	8.61%	2.37%
18	0.00%	2.78%	5.93%	4.75%	3.12%
19	0.00%	1.70%	4.75%	7.57%	2.23%
20	0.00%	0.31%	4.45%	8.46%	2.97%
21	0.00%	0.77%	2.67%	7.42%	5.34%
22	0.00%	0.62%	2.08%	5.49%	8.01%
23	0.00%	0.77%	1.93%	2.82%	10.83%
Total	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**

4. Real world experiment: Block 3

- The **layout of the ITS architecture** was designed and the **traffic management actions** were simulated:



Source: Authors elaboration (2023)

Risk management actions	**Number of involved monitoring windows**	**Percentage of involved monitoring windows**	**Involved vehicular flow**	**Percentage of involved vehicular flow**
Display “All vehicles must take the next exit” on the VMS **AND** Trigger a yellow-red cycle on the TL	6’923	1.34 %	7’354	3.69 %
Display "All vehicles heavier than 108t must take the next exit" on the VMS	53’155	10.25 %	22’500	11.28 %
Do nothing	458’303	88.41 %	169’621	85.03 %

5. Discussion

The **main findings** can be summarized in the following points:

- WIM data revealed a **high percentage of overloaded vehicles** on the bridge.
- Bridge design loads were exceeded with a **return period significantly shorter** than that prescribed by **Eurocode 1** ($T_r \cong 8\ days \ll 1'000\ years$ for ChC).
- **ANNs outperformed GLRs** in predicting both frequency and severity components.
- Safety factors related to the **compliance with TC mass limits prescriptions** showed a high influence on risk predictions.
- Approximately **4% passing flow** would be interested by the **more severe traffic management actions**.

6. Conclusions

The findings have at least **three practical consequences**:

- Recommend **enforcement strategies** for the **identification** and **sanctioning** of **illegal overloaded vehicles** that travel on the bridge without any authorization.

- Suggest a **greater caution** by the RAs when **permits for extremely overloaded vehicles** are issued.

- Recommend a **widespread deployment of ITS-based architectures** for the real time management of the risk posed by the traffic load hazard.

6. Conclusions

This study indicates several **future developments**:

- Considering **traffic load effects** instead of traffic load itself. Indeed, for the same total load, the internal actions can be very dissimilar for **different load configurations**.
- Integrating **new variables** based on data acquired by **other sensors** (e.g., accelerometers, strain gauges, intelligent traffic cameras, etc.).
- Prioritising **traffic management actions at network level**, taking into account the negative consequences of traffic interruptions.

7. References

- European Union. (2003). Eurocode 1: Actions on structures - Part 2: Traffic loads on bridges (Vol. 1).
- ISO (2012). ISO 39001: Road Traffic Safety (RTS) Management Systems: Requirements with Guidance for Use.
- Proske, D., & Curbach, M. (2005). Risk to historical bridges due to ship impact on German inland waterways. *Reliability Engineering and System Safety*, *90*(2–3), 261–270. https://doi.org/10.1016/j.ress.2004.10.003
- Ventura, R., Barabino, B., Vetturi, D., & Maternini, G. (2020). Bridge safety analysis based on the function of exceptional vehicle transit speed. The Open Transportation Journal, 14(1). Available at http://dx.doi.org/10.2174/1874447802014010222
- Ventura, R., Barabino, B., Vetturi, D., & Maternini, G. (2023). Bridge's vehicular loads characterization through Weight-In-Motion (WIM) systems. The case study of Brescia. European Transport/Trasporti Europei, (90), 1-12. Available at https://doi.org/10.48295/ET.2023.90.6
- Ventura, R., Barabino, B., Vetturi, D., & Maternini, G. (2023). Monitoring vehicles with permits and that are illegally overweight on bridges using Weigh-In-Motion (WIM) devices: a case study from Brescia. Case Studies on Transport Policy, 101023.. Available at https://doi.org/10.1016/j.cstp.2023.101023
- Ventura, Roberto and Barabino, Benedetto and Maternini, Giulio, Traffic Hazard on Main Road's Bridges: Real-Time Managing the Risk of Design Load Overcoming Events (March 22, 2023). Available at SSRN: https://ssrn.com/abstract=4396914 or http://dx.doi.org/10.2139/ssrn.4396914
- Ventura, Roberto and Barabino, Benedetto and Maternini, Giulio, Estimating the Frequency of Design Traffic Loads Overcoming on Road's Bridges (April 1, 2023). Available at SSRN: https://ssrn.com/abstract=4417358 or http://dx.doi.org/10.2139/ssrn.4417358
- Zanini, M. A., Faleschini, F., & Pellegrino, C. (2017). Probabilistic seismic risk forecasting of aging bridge networks. *Engineering Structures*, *136*, 219–232. https://doi.org/10.1016/j.engstruct.2017.01.029

UNIVERSITÀ DEGLI STUDI DI BRESCIA

Department Civil, Environmental, Architectural Engineering and Mathematics (DICATAM)

Roberto VENTURA

Post-Doctoral Researcher,

University of Brescia, Italy

r.ventura001@unibs.it

Benedetto BARABINO

Associate Professor,

University of Brescia, Italy

benedetto.barabino@unibs.it

Giulio MATERNINI

Full Professor, University of Brescia, Italy

University of Brescia, Italy

giulio.maternini@unibs.it

Thanks for your kind attention!

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