Risk analysis of bridges using a new reliability-based robustness assessment methodology

Current Status

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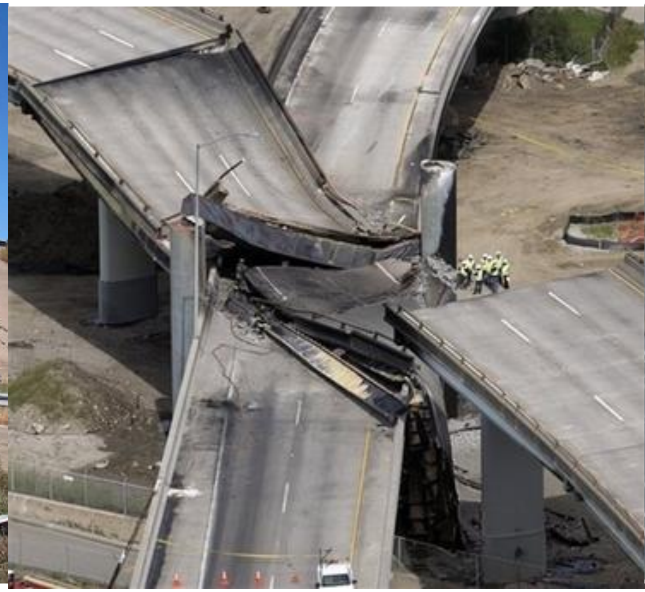


Outline

- **Robustness as a performance indicator**
  - Assessment framework
- **Performance under sudden extreme event**
  - Notional removal of failed elements
  - Reliability Analysis
- **Performance under service conditions**
  - Influence of creep, shrinkage and corrosion on serviceability
  - Model validation based on literature findings
- **Normalized risk-based indicator**
  - Costs model based on literature survey
  - Normalization of direct and indirect consequences based on utility functions
- **Criticality**
  - Criticality assessment based on risk matrixes using utility indifference curves

Robustness assessment

… Proposed measures

Most complete measure

	Frangopol and Curley (1987) Fu and Frangopol (1990)	***Lind (1995)***	***Ghosn and Moses (1998)***	***ISO (2007)***	***Starossek (2008)***	***Baker et al. (2008)***	***Biondini and Restelli (2008)***	***Cavaco (2013)***
Nature	Probabilistic	Probabilistic	Probabilistic	Deterministic	Deterministic	Risk-based	Deterministic	Det. or Prob.
Atribute	Redundancy	Vulnerability Damage Tolerance	Redundancy	Performance indicator	Stiffness-based Damage-based Energy released	Robustness index	Performance indicator	Performance indicator
Range	$[0,\infty]$ ← $[0,\infty]$ →	$[1,\alpha]$ ← $[\alpha^{-1},1]$ →	Target Reliabilities verification	$[0,1]$ →	- $[0,1]$ → -	$[0,1]$ →	$[0,1]$ →	$[0,1]$ →
Scenario	Damaged vs Intact	Damaged vs Intact	Limit states	Damaged vs Intact	Damaged vs Intact	Multi hazard	Damaged vs Intact	Spectrum of Damage States

$$I_{rob} = \frac{R_{dir}}{R_{dir} + R_{ind}}$$

→ Increasing robustness

Robustness assessment methodology

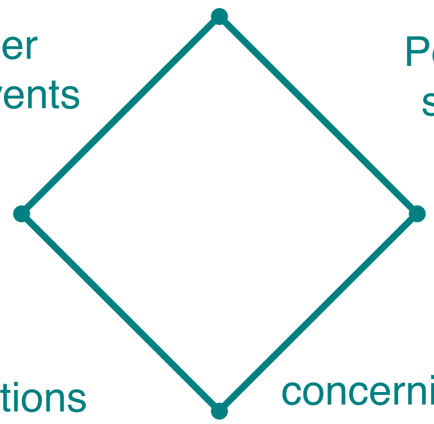
... Robustness computed as equal to the area of a quadrilateral, whose sides' lengths represent a *performance indicator*

Reliability analysis of notional removal of elements

Reliability analysis of long-term performance considering effects of corrosion

Performance under extreme sudden events

Performance under service conditions



Risk indicator based on utility functions

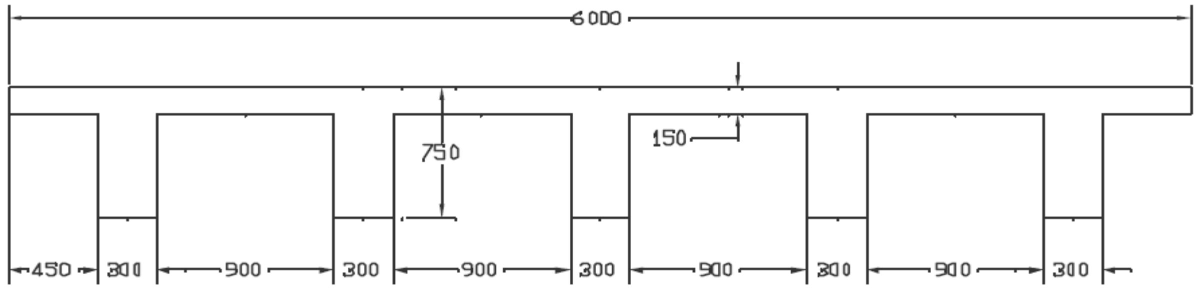
Criticality level concerning transportation network

Normalized risk indicator based on utility functions

Criticality level based on risk ranking using utility indifference curves

Application example

… Short-span RC bridge studied by Wong et al. (2005)



1. Several numerical difficulties were encountered using traditional RSM (Wong et al. 2005)

2. Prove efficiency of the developed RSM when dealing with nonlinear FE

3. Typical configuration of a highway overpasses

Reliability analysis considering sudden damage

FE model

- 3D nonlinear grillage model using TNO DIANA

Constitutive models

- Concrete and steel behaviour based on CEB-FIP (1993)

Damage Scenarios

- Failure of each girder shattered due to an unexpected event [Goshn et al. (2010), Saydam & Frangopol (2014)]

Live load model

- HB abnormal vehicle (BS 5400 1978)

Time-dependent performance

- General uniform corrosion due to chloride ingress

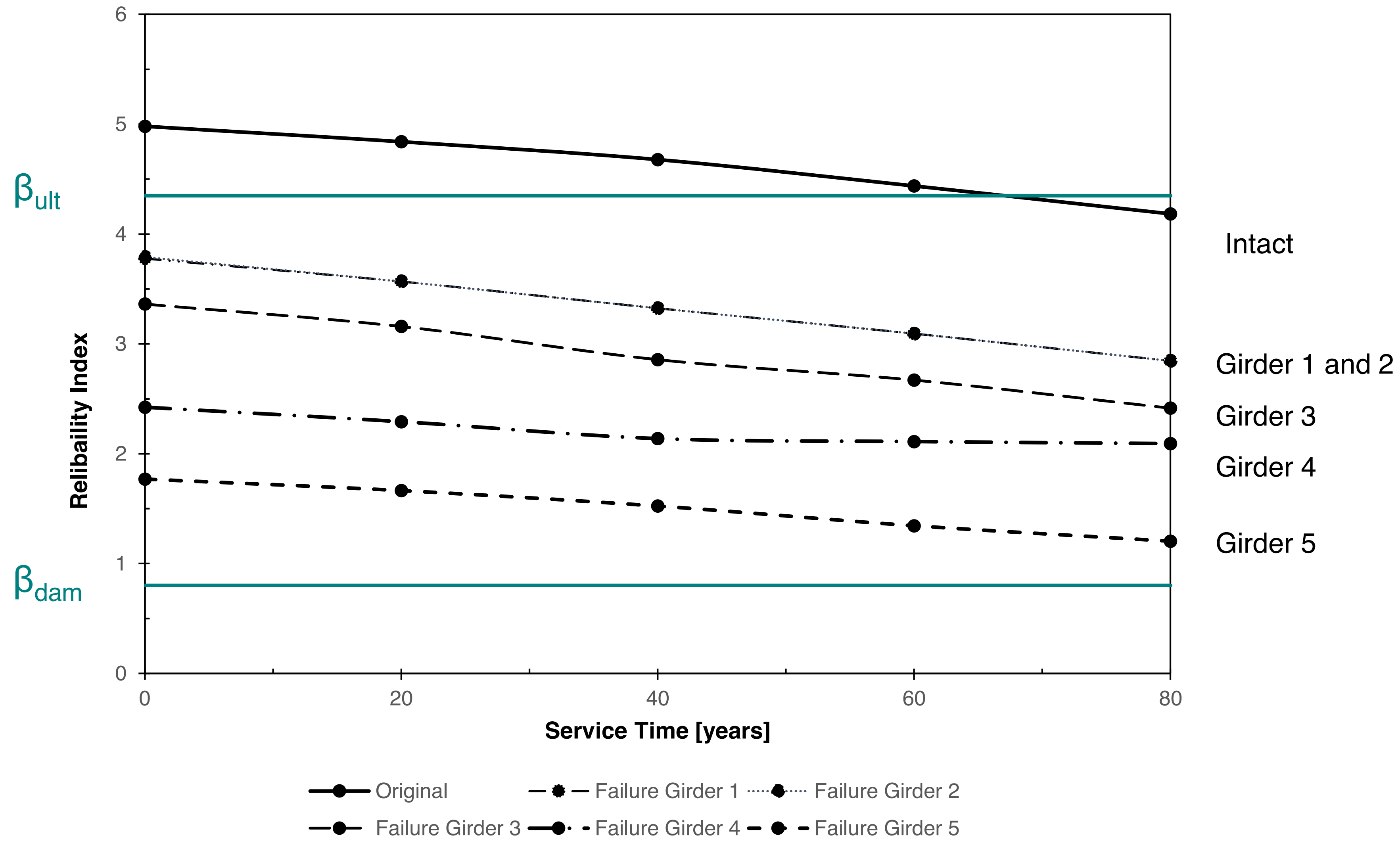
$$D(t) = D_0 - 0.0232(t - t_i)i_{corr}$$

Val & Robert (1997)

Reliability analysis under sudden damage

$$G(X) = LF(X) - LL$$

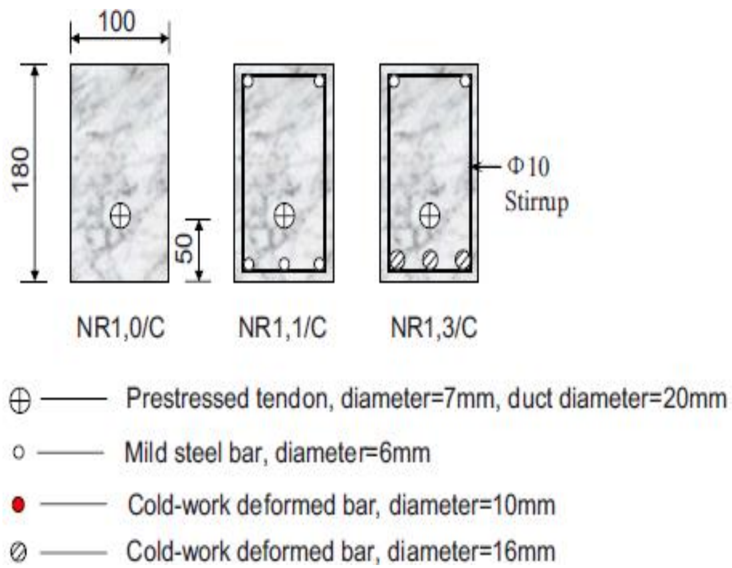
Target reliability based on Ghosn and Moses (1998)

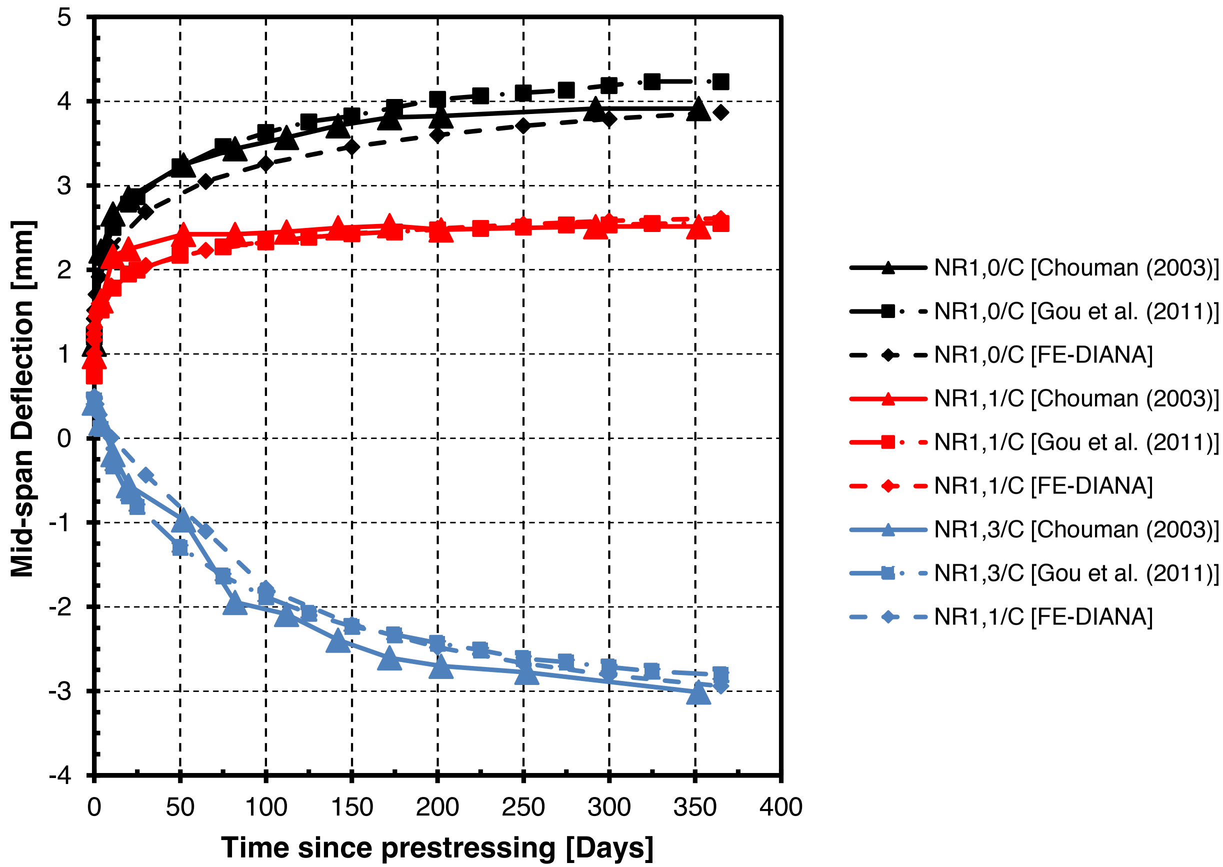


Serviceability reliability analysis

… Model validation for creep, shrinkage and prestress

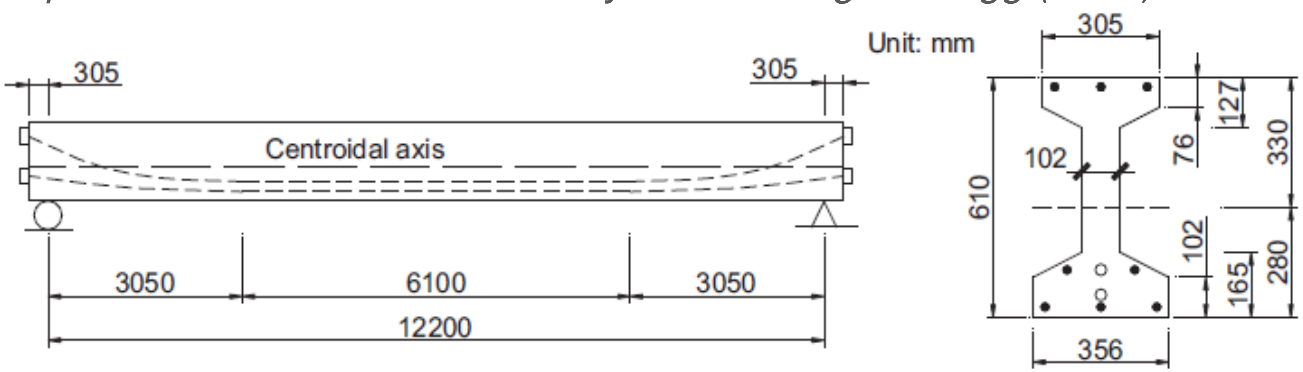
1. *Experimental results from Chouman (2003a,b)*

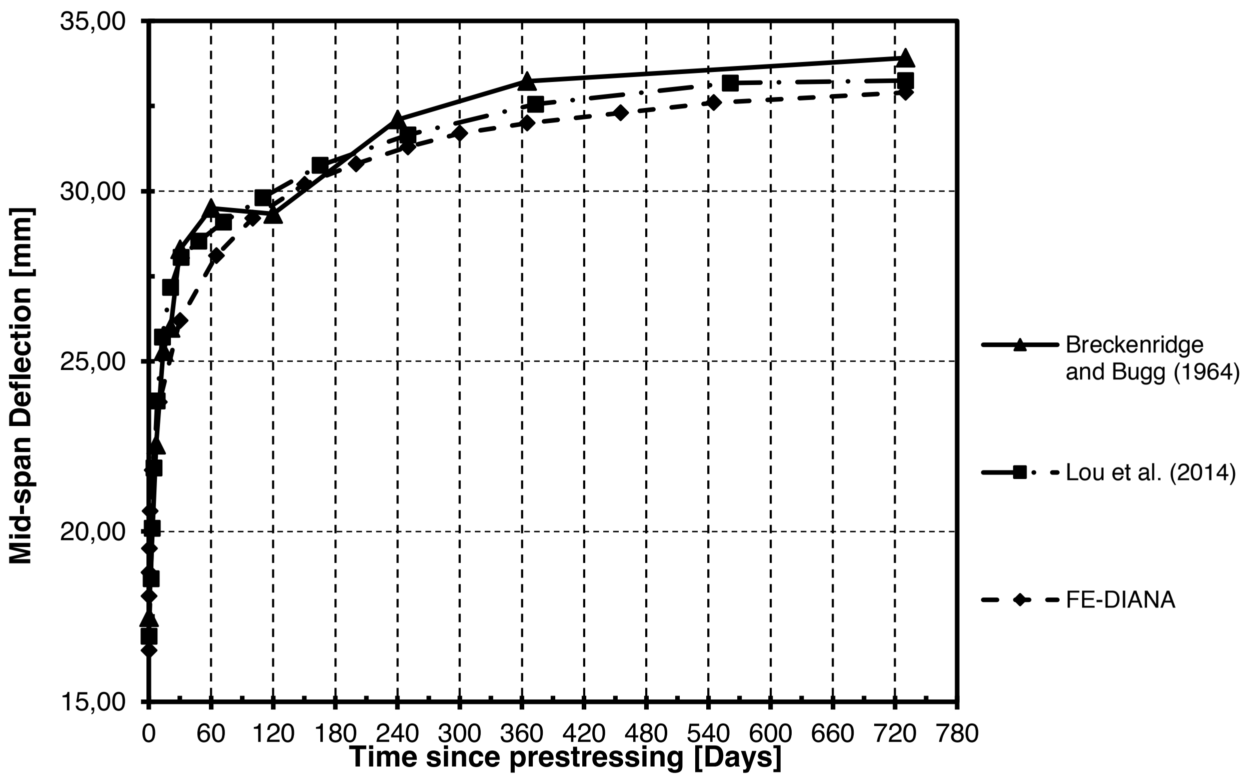




Serviceability reliability analysis

2. *Experimental results conducted by Breckenridge & Bugg (1964)*





Serviceability reliability analysis

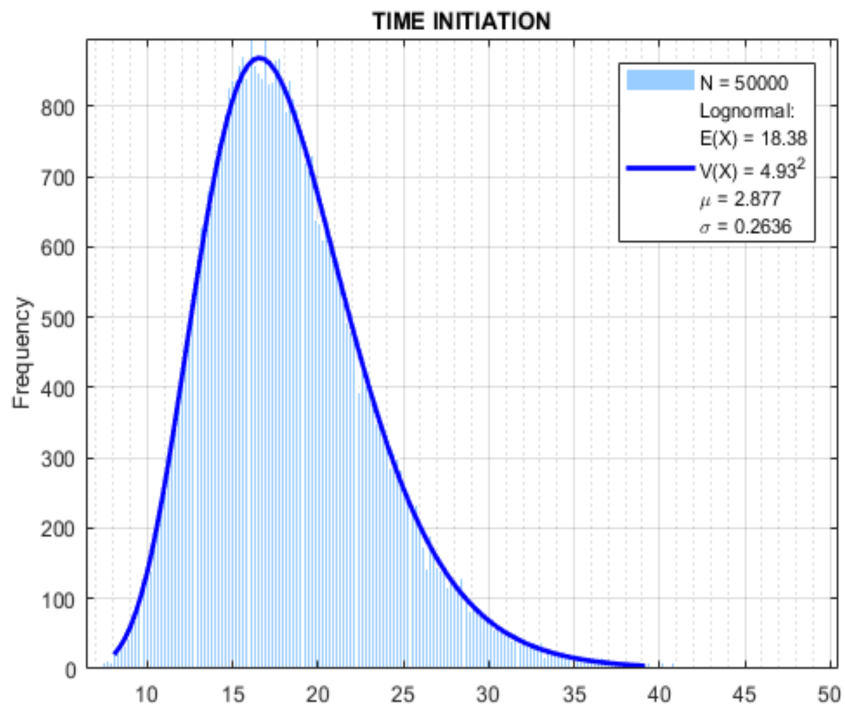
Application Example

$$G(X) = \delta_{\lim} - \delta(X) = \frac{L}{360} - \delta(X)$$

Corrosion initiation time due to chloride diffusion process

$$t_i = \frac{c^2}{4D_c}\left[erf^{-1}\left(\frac{C_0 - C_{cr}}{C_{cr}} \right) \right]^{-2}$$

Enright & Frangopol (1998)



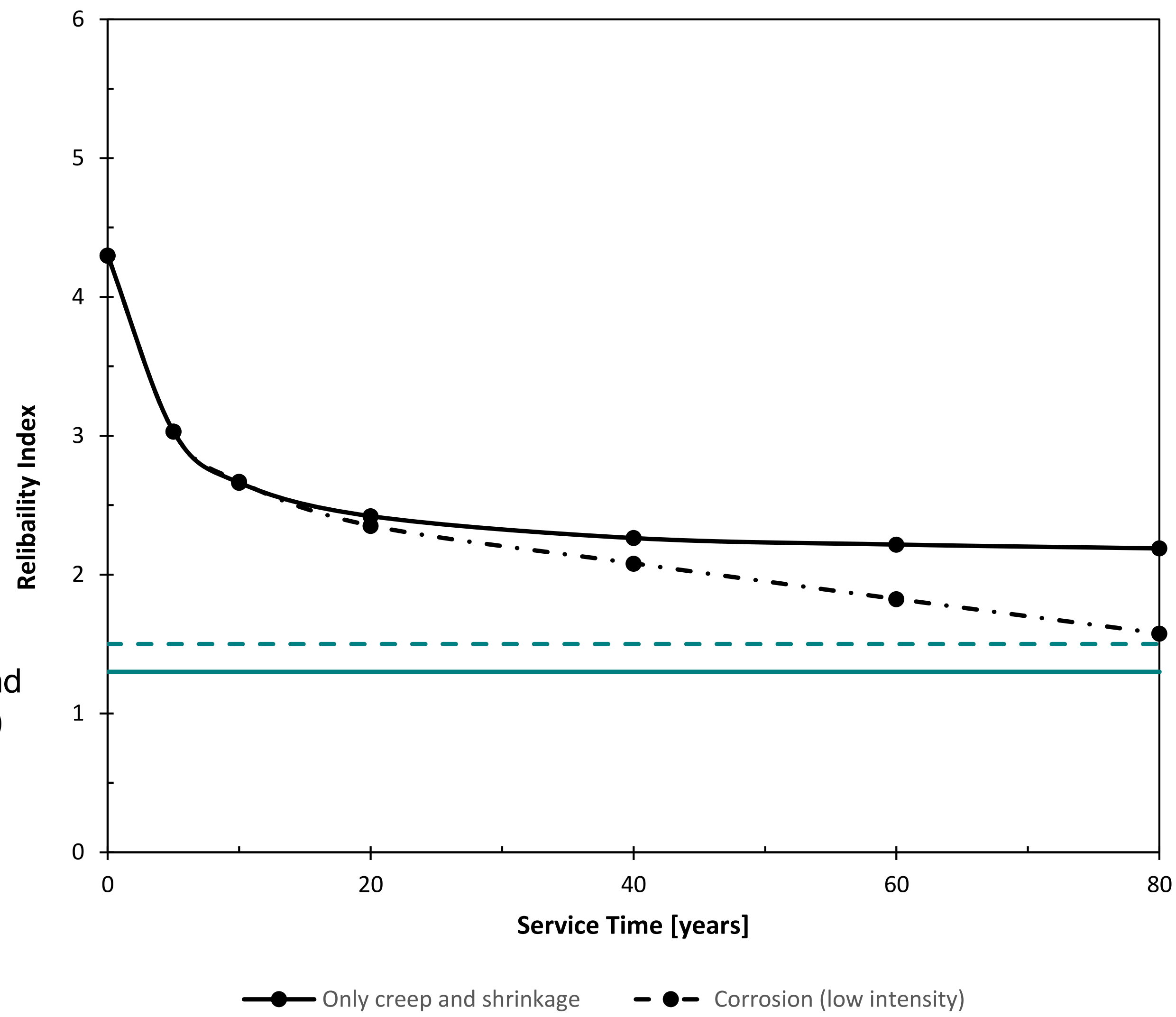
Variable	Label	Distr. Type	Nominal	Bias	COV	References
Concrete cover	c	Lognormal	3.5	1.00	10%	Wong et al. (2005)
Chloride concentration at surface	C_0	Lognormal	0.10	1.00	10%	Enright & Frangopo (1998)
Critical chloride concentration	C_{cr}	Lognormal	0.03	1.00	10%	Enright & Frangopo (1998)
Chloride diffusion coefficient	D_c	Lognormal	0.32	1.00	10%	Enright & Frangopo (1998)

Serviceability reliability analysis

Application Example

$\beta_{serv} = 1.3$

JCSS (2001) and ISO2394 (2015)



$\beta_{serv} = 1.5$

EN-1990 (2002)]

Performance assessment based on target reliability

Reference	***Scope***	***Level***	***Reference Period***	**Limit State**			***Consequences Levels***	***Additional Criteria***
				ULS	***SLS***	***Fatigue***		
NKB-36 (1978)	Design	Member	n/a	X			3[(1)]	Failure Type
EN-1990 (2002)	Design	Member	50 y. (1 y.)	X	X	X	3	n/a
AASHTO (1994)	Design	Member	n/a	X			n/a	
ISO2394 (1998)	Design	Member	life-time	X	X	X	4[(2)]	Cost of safety
CAN/CSA (2000)	Design	Member	n/a	X			3[(3)]	System and Element behavior
ISO13822 (2001)	Design/Assessment	Member	50 y. or remaing life	X	X	X	4	Reference Period
JCSS (2001)	Design	Member	1 y.	X	X		3	Cost of safety
ISO2394 (2015)	Design/Assessment	Member	1 y.	X	X		3	Cost of safety, Optimization, LQI

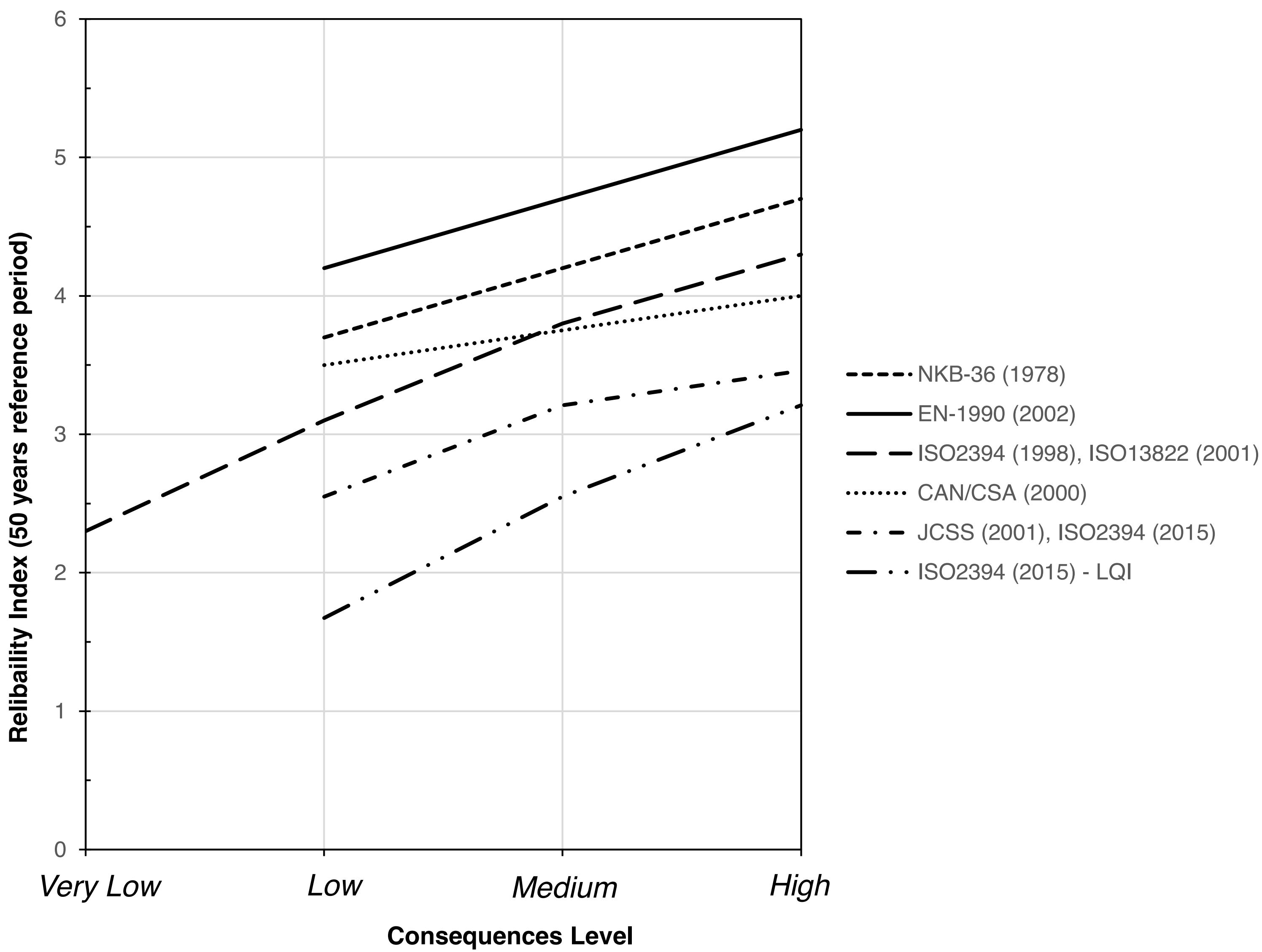
(1) Consequences level: Low, Medium, High.

(2) Consequences level: Very Low, Low, Medium, High.

(3) System behavior vs consequences level: Local failure (Low), Local failure with alternative load paths (Medium), Global collapse (High)

Performance assessment based on target reliability

Ultimate Limit States



Consequences – literature survey

- **Direct consequences**
  - Rebuilding costs for road administrator
- **Indirect consequences**
  - Extra travel time costs for users (due to detour) – time loss costs
  - Extra travel distance costs for users (due to detour) – running costs

Crucial factors

- Network redundancy – alternatives for detour
- Duration of repair
- Average Daily Traffic (ADT) and % of trucks
- Type of vehicles: car and truck
- Location and affected area

Consequences – literature survey

Direct costs: rebuilding costs

Rebuilding cost parameter [USD /m²]							
Reference	**based on**	**Country**	**Value**	**Reference Year**	**Proj. Value[1] [€]**	**Conv. Factor[2]**	**Conv. Value [€]**
Stein et al. (1999)	Assumed	USA	646	1999	801	2.0	*400*
Deco et al. (2011)	Stein et al. (1999)	USA	894	2010	1027	2.0	*514*
Dong et al. (2014), Sabatino et al. (2015a,b)	Deco et al. (2011)	USA	1292	2012	1426	2.0	*713*

(1) Updated/projected values (year 2017) assuming a constant anual discount rate equal to 2% and the actual currency converter between USD and €.

(2) Conversion factor to Portugal context according to international relative construction costs reported in [Moore & Riley (2012)]

Rebuilding cost parameter [€ /m²]							
Reference	**based on**	**Country**	**Value**	**Reference Year**	**Proj. Value[1] [€]**	**Conv. Factor[2]**	**Conv. Value [€]**
COST 345 Report (2004)	Inventory	10 EU Countries	800 - 2200	2002	1077 - 2960	1.5	*1077 - 2000*
Noortwijk & Klatter (2004)	Inventory	the Netherlands	2000 - 2130	2000	2800 - 2980	1.5	*1892 - 2014*
Setra (2008)	Inventory	France	2250 - 2634	2006	2800 - 3275	2.1	*1308 - 1530*
Radowitz et al. (2008)	Inventory	Germany	1735 - 2245	2003	2290 - 2683	2.0	*1168 - 1369*
Adey & Hajdin (2011)	Expert Judgment	Switzerland	2100	2008	2510	2.6	*973*
Orcesi & Cremona (2011)	Inventory	France	2265	2006	2816	2.1	*1316*
Almeida (2013)	**Inventory**	**Portugal**	**700 - 2550**	**2012**	**773 - 2816**	**1.0**	***773 - 2816***

(1) Updated/projected values (year 2017) assuming a constant anual discount rate equal to 2%.

(2) Conversion factor to Portugal context according to international relative construction costs reported in [Moore & Riley (2012)]

Consequences – literature survey

Indirect costs: running costs due to detour

Running cost due to detour [USD/km]

Reference	based on	Vehicle	Value	Reference Year	Projected Value [1] [€]
Frangopol (2014a,b)	Assumed	Average	0.16	1999	0.20
Deco et al. (2011)	Assumed	Car	0.08	2010	0.08
		Truck	0.38	2010	0.37
Dong et al. (2014)	Deco et al. (2011)	Car	0.40	2012	0.38
		Truck	0.56	2012	0.54

(1) Updated/projected values (year 2017) assuming a constant anual discount rate equal to 2% and the actual currency converter between USD and €.

Running cost due to detour [€/km]

Reference	based on	Vehicle	Value	Reference Year	Projected Value [€]
Santos (2006), Santos et al. (2011)	Portuguese data	Car	0.16	2006	0.20
		Truck	0.60	2006	0.75
Rodrigues (2007)	Portuguese data	Car	0.12 - 0.16	2001	0.17 - 0.22
		Truck	0.53 - 0.67	2001	0.73 - 0.92

Consequences – literature survey

Indirect costs: time cost due to detour

Time cost due to detour [USD/h]					
Reference	**based on**	**Vehicle**	**Value**	**Reference Year**	**Projected Value[(1)] [€]**
Stein et al. (1999), Barone & Frangopol (2014a,b)	AASHTO (1997)	Car	7.05	1999	8.74
		Truck	20.56	1999	25.48
Deco et al. (2011)	AASHTO (2003)	Car	22.82	2010	22.75
	AASHTO (2003)	Truck	26.97	2010	26.89
	Assumed	Cargo	4	2010	3.99
Dong et al. (2014)	Deco et al. (2011)	Car	23.36	2012	22.38
		Truck	29.28	2012	28.06

(1) Updated/projected values (year 2017) assuming a constant anual discount rate equal to 2% and the actual currency converter between USD and €.

Time cost due to detour [€/h]					
Reference	**based on**	**Vehicle**	**Value**	**Reference Year**	**Projected Value [€]**
Santos (2006), Santos et al. (2011)	Portuguese data	Car	6.00	2006	7.46
		Truck	9.06	2006	11.27
Rodrigues (2007)	UNITE	Car	14.42	2006	17.93
		Truck	37.57	2006	46.71

Consequences – literature survey

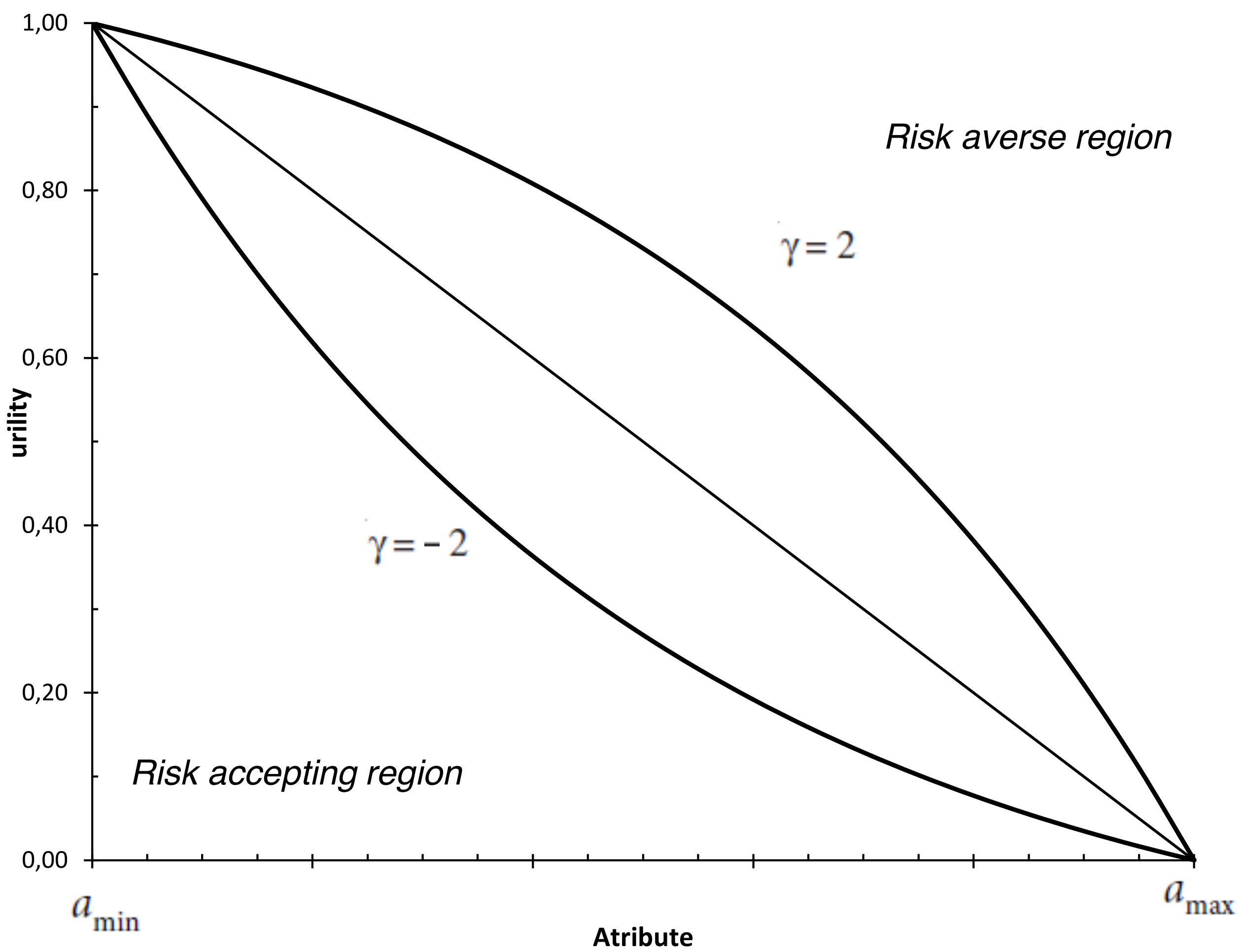
Indirect costs: occupancy rate for vehicles and ADT

Occupancy rate for vehicles			
Reference	**based on**	**Vehicle**	**Value**
Stein et al. (1999), Barone & Frangopol (2014a,b), Sabatino et al. (2015a,b)	AASHTO (1997)	Car	1.56
		Truck	1
Santos (2006), Santos et al. (2011)	Portuguese data	Car	2[(1)]
		Truck	1
Deco et al. (2011)	Assumed	Car	1.5
		Truck	1.05
Dong et al. (2014)	Deco et al. (2011)	Car	1.5
		Truck	1.05

(1) 1 working passenger + 1 non-working passenger.

% of truck in ADT		
Reference	**based on**	**Value**
Stein et al. (1999), Barone & Frangopol (2014a,b), Sabatino et al. (2015a,b)	National Bridge Inventory	4%
Deco et al. (2011), Dong et al. (2014)	Mahmoud et al. (2005)	12%
Gervásio (2010)		12%
Almeida (2013)	Highway	10%
	Primary Road	10%
	Complementary Road	10%

Utility functions



$$u = \frac{1}{1-\exp[-\gamma]}\left(1-\exp\left[-\gamma\frac{a_{max}-a}{a_{max}-a_{min}}\right]\right)$$

Sabatino (2015a, 2015b)

Consequences and Risk

Application Example

	Parameter	Mean value	Unit	Reference
Rebuilding costs	Rebuilding cost parameter, c_{reb}	1545	€ /m^2	Almeida (2013)
	Bridge's width, W	6	m	Wong et al. (2005)
	Bridge's length, L	12	m	Wong et al. (2005)
Detour costs	Running cost for car due to detour, $c_{Run,car}$	0.20	€/km	Santos et al. (2011)
	Running cost for truck due to detour, $c_{Run,truck}$	0.75	€/km	Santos et al. (2011)
	Time loss cost for car due to detour, $c_{TL,car}$	7.46	€/h	Santos et al. (2011)
	Time loss cost for truck due to detour, $c_{TL,truck}$	11.27	€/h	Santos et al. (2011)
Detour	Duration of detour, D_d	365	days	Almeida (2013)
	Average daily traffic, ADT	100	vehicles	Almeida (2013), IMTT (2016)
	Percentage of truck traffic (% of truck ADT), TT_p	1	%	Almeida (2013)
	Average detour speed for cars, $S_{d,car}$	50	km/h	IMTT (2016)
	Average detour speed for trucks, $S_{d,ctruck}$	40	km/h	IMTT (2016)
	Detour Length, D_l	3.00	km	Google Maps

Consequences and Risk

Application Example: local road (ADT =100 vehicles)

Maximum admissible direct losses: % annual budget for maintenance

Maximum admissible indirect losses: % GDP (region)

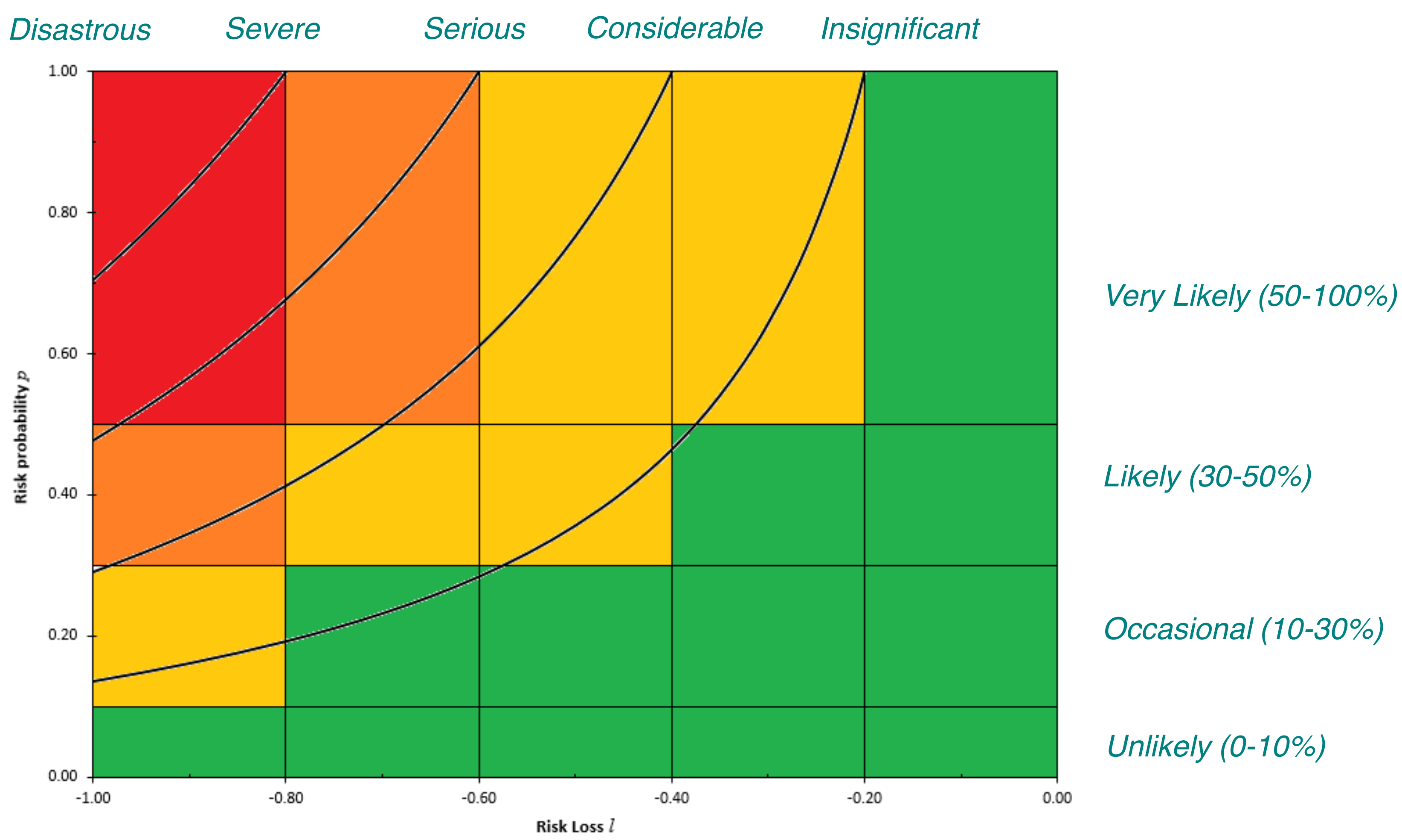
$$I_{rob} = \frac{R_{dir}}{R_{dir} + R_{ind}}$$

		t [years]				
		0	**20**	**40**	**60**	**80**
Rebuilding Costs		111,240 €	165,297 €	245,622 €	364,982 €	542,344 €
Running Costs	Car	21,681 €	39,311 €	71,276 €	129,233 €	234,317 €
	Truck	821 €	1,489 €	2,700 €	4,895 €	8,876 €
	Total	22,502 €	40,800 €	73,975 €	134,128 €	243,192 €
Time Loss Costs	Car	16,174 €	29,326 €	53,172 €	96,408 €	174,800 €
	Truck	309 €	559 €	1,014 €	1,839 €	3,334 €
	Total	16,483 €	29,885 €	54,186 €	98,246 €	178,134 €
Time Loss (h)	Car	2168	2645	3228	3939	4806
	Truck	27	33	41	50	61
	Total	2195	2679	3269	3989	4867
Direct Costs	Total	111,240 €	165,297 €	245,622 €	364,982 €	542,344 €
Indirect Costs	Total	38,985 €	70,685 €	128,161 €	232,374 €	421,327 €
Risk-based Indicator		***0.74***	***0.70***	***0.66***	***0.61***	***0.56***
Utility Direct Costs	Total	0.61	0.61	0.61	0.61	0.61
Utility Indirect Costs	Total	0.43	0.35	0.27	0.18	0.10
Proposed Indicator		***0.83***	***0.73***	***0.61***	***0.46***	***0.29***
Utility Direct Costs	Total	0.92	0.92	0.92	0.92	0.92
Utility Indirect Costs	Total	0.85	0.80	0.73	0.62	0.46
Proposed Indicator		***0.96***	***0.93***	***0.88***	***0.81***	***0.67***

Risk taking attitude

Risk averse attitude

Criticality



Negligible - 1
Acceptable - 0,8
Controllable - 0,6
Critical - 0,1
Unacceptable - 0

Ruan et al. (2015a)

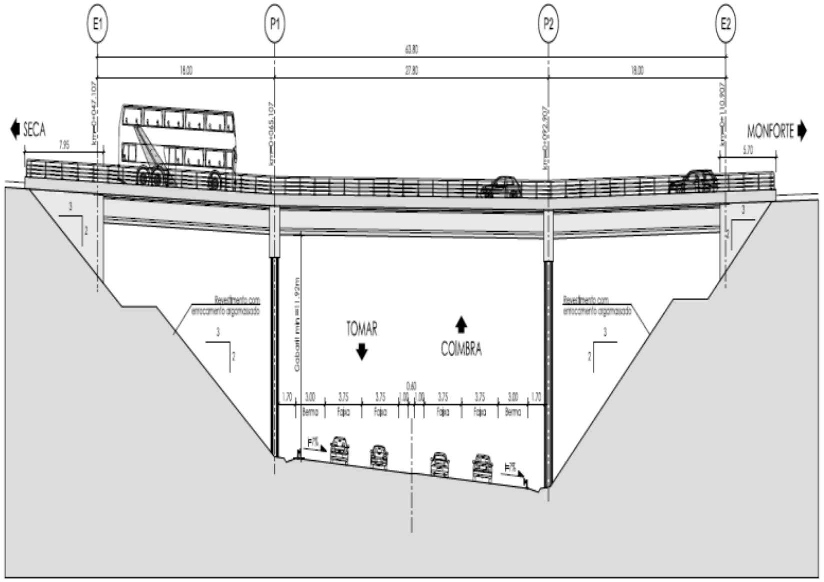
Robustness Assessment

Application Example: local road

The system performance under sudden event and service conditions meet the target requirements (PI = 1). Regarding criticality, bridge disruption does not lead to significant consequences to the transportation network.

	t [years]				
	0	**20**	**40**	**60**	**80**
Sudden Event	1	1	1	1	1
Serviciability	1	1	1	1	1
Risk	0.83	0.73	0.61	0.46	0.29
Criticality	1	1	1	1	1
Robustness Indicator	***0.90***	***0.85***	***0.77***	***0.66***	***0.59***

Case Study – Highway overpass (PS8)



This methodology has been applied to a three-span highway overpass.
Final results are close to be achieved and will be disseminated.

Conclusions

1. *A robustness assessment methodology addressed at two performance levels is presented.*
2. *A highway overpass studied by Wong et al.(2005) is introduced and used as application example.*
3. *Performance under sudden failure is assessed by reliability analysis of different damage scenarios (notional removal of failed elements).*
4. *Performance under service condition is assessed by means of serviceability reliability analysis using a deflection criteria.*
5. *Experimental results concerning long-term behaviour of RC beams are used for validation.*
6. *Failure consequences are estimated based on a literature survey.*
7. *Risk-based indicator is obtained using utility functions.*
8. *Criticality is assessed by means of a risk matrix based on expert judgment and utility indifference curves.*