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Quantifying Nonlinear Risk Factor Interactions in Type 2 Diabetes

NFBR: A Bayesian Network Framework Using Real-World Data



Speaker: Cinzia Carrodano, PhD

22nd October 2026

Papers published in Nature Portfolio (Scientific Reports) :

Carrodano, C. (2024). Data-driven risk analysis of nonlinear factor interactions in road safety using Bayesian networks. *Scientific Reports*, 14(1), 18948. *https://doi.org/10.1038/s41598-024-69740-6*

Carrodano, C. (2025). General framework of nonlinear factor interactions using bayesian networks for risk analysis applied to road safety and public health. Scientific Reports, 15(1), 29934. *https://doi.org/10.1038/s41598-025-13572-5*

Demonstration → Conceptualization → Validation and generalization

Demonstration of risk nonlinearity using BN
(Paper published in 2024, Scientific Reports)

General NFBR Framework
(Paper published in 2025, Scientific Reports)

NFBR Framework
Validation and generalization mobility and public health, Ongoing-Environmental risk



Ongoing: A dynamic NFBR Framework
Upcoming: A multi-level hierarchical NFBR Framework
Conceptualization, validation and generalization

Contributions NFBR Framework

- Demonstration of risk nonlinearity using BN applied to Mobility
- 2 risk factors

- Formalization of NFBR framework
- Nonlinear effect factor
- Multi-factor interactions

- Generalization of NFBR
- Mobility and public health

Why NFBR Framework ? *(Problem – Question - Objective)*

Problem

In complex systems, risk factors rarely act independently.

Their combined effect may be nonlinear, amplifying or attenuating risk beyond what additive models predict

Research question

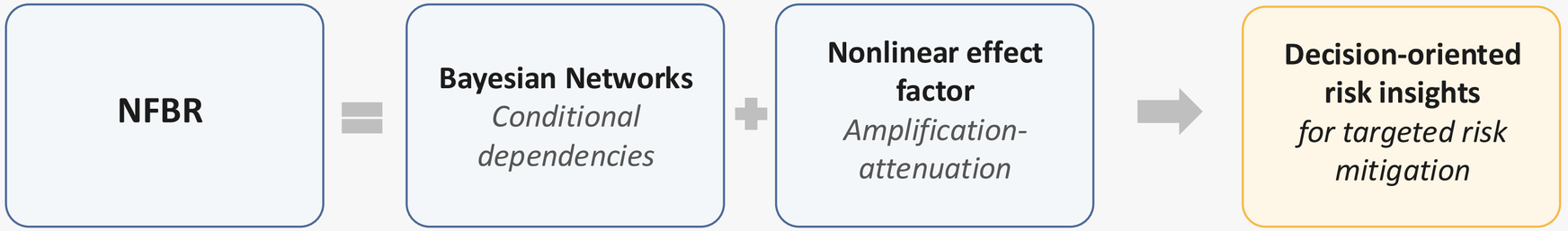
How do multiple risk factors interact, and
how can we quantify the nonlinearity of their combined effects ?

Objective

NFBR provides a probabilistic framework
to identify, quantify and interpret
nonlinear risk interactions using Bayesian Networks.

What is NFBR Framework ? *(Methodology)*

Method



NFBR = General framework of **N**onlinear **F**actor Interactions based on **B**ayesian Networks for **R**isk Analysis

Nonlinearity refers to an analysis in which the combined impact of multiple risk factors on outcomes cannot be accurately predicted by merely summing their individual effects.

What is NFBR Framework ? *(Methodology)*

Method

Define Outcome & identify Risk Factors

Human, Environmental, Technical, …

$X_1, X_2, \ldots, X_n$

Bayesian Network

Probabilistic graphical model

Scenarios Comparison

Normal Situation (baseline)

Individual additive effects – Combined effects

Nonlinear effect factor γ

Deviation from additive effect

Risk interpretation

$\gamma > 1$ amplification ; $\gamma < 1$ attenuation

$\gamma = 1$ additive effect

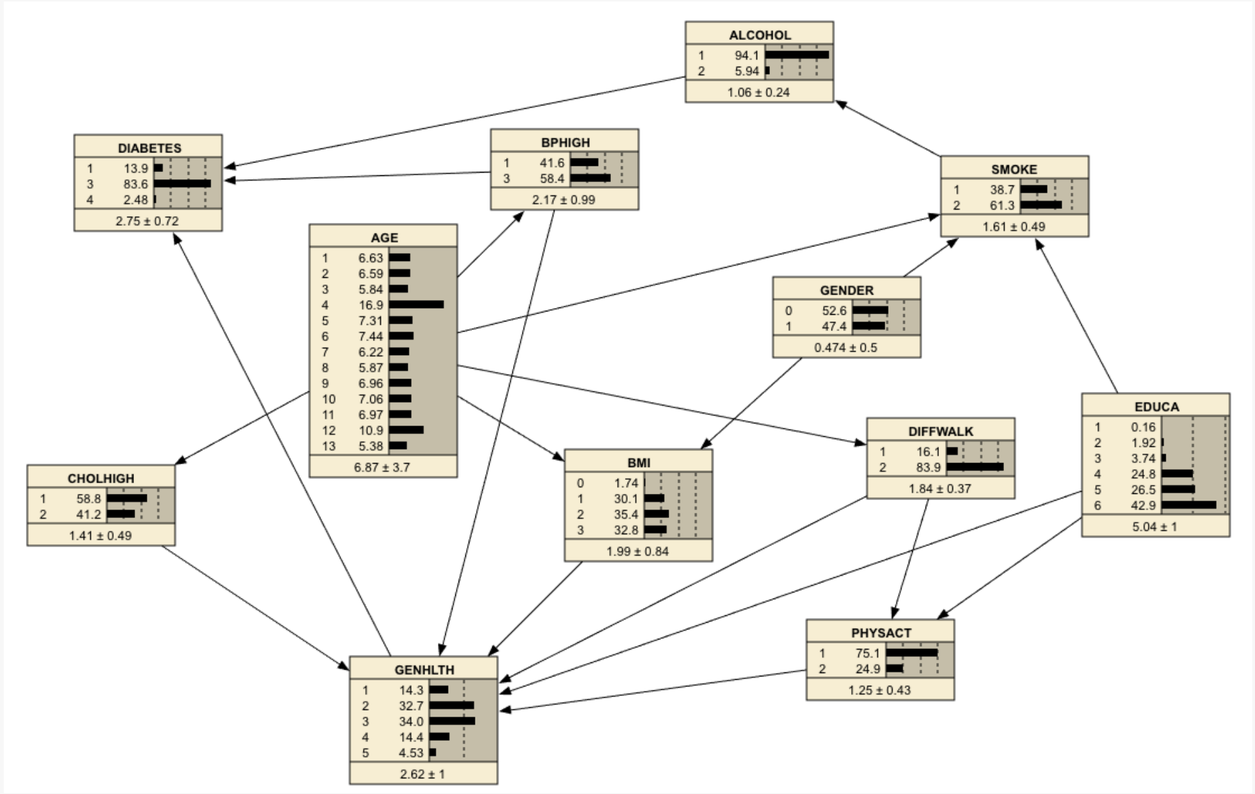
Nonlinear effect factor

$$\gamma = \frac{\Delta(combined\ effect)}{\Delta(additive\ effect)}$$

γ quantifies how much the combined effect deviates from the additive effect.

NFBR applications *(Results)*

Results



Carrodano, C. (2025). General framework of nonlinear factor interactions using bayesian networks for risk analysis applied to road safety and public health. Scientific Reports, 15(1), 29934. *https://doi.org/10.1038/s41598-025-13572-5*



Diabetes Type 2

429’086 observations, 12 variables (CDC BRFSS, 2023)

Outcome:
Type 2 diabetes Risk

Risk factors:
Blood pressure • Physical activity • Smoking

NFBR output:
Nonlinear effect of diabetes risk

NFBR compares the combined BN-estimated effect with the additive baseline.

NFBR applications *(Results)*

Results

Scenario #1 BP High / No phys. Act. Node	Code	Description	**A** Normal situation	**B** BP High	**C** No phys. activities	**D** Combined factors	**E***(computed)* Added factors
Diabetes	1	**Diabetes**	**5.648**	**22.838**	**8.208**	**29.210**	
	4	Pre-diabetes	1.600	3.458	2.019	3.876	
	3	No diabetes	92.752	73.704	89.773	66.914	
Blood pressure (BP)	3	Normal	100		100		
	1	High		100		100	
Phys. activities	1	Yes	100	100			
	2	No			100	100	
		Blood pressure	Normal	High	Normal	High	High
		Phys. Activities	Yes	Yes	No	No	No
		Diabetes Risk	**5.648**	**22.838**	**8.208**	**29.210**	**25.398**
		Delta vs. normal sit (A)		***17.190***	***2.560***	***23.562***	***19.750***

Table 5. Nonlinear risk factor results for Scenario #1 (BP High and No physical activities) – Diabetes risk

$$Nonlinear\ effect\ factor = \gamma = \frac{\Delta(Combined\ effect)}{\Delta\ (Additive\ effect)} = \frac{23.562}{19.750} = 1.193 \qquad (15)$$

Scenario #2 BP High/No phys. act. / Smoke Node	Code	Description	**A** Normal situation	**B** BP High	**C** No phys. Act.	**D** Smoke	**E** Combined 3 factors	**F** Added factors
Diabetes	1	**Diabetes**	**5.566**	**22.773**	**8.056**	**5.810**	**29.220**	
	4	Pre-diabetes	1.586	3.450	1.999	1.629	3.890	
	3	No diabetes	92.848	73.777	89.945	92.561	66.890	
Blood pressure (BP)	3	Normal	100		100	100		
	1	High		100			100	
Phys. activities	1	Yes	100	100		100		
	2	No			100		100	
Smoke	2	No	100	100	100			
	1	Yes				100	100	
		Blood press.	Normal	High	Normal	Normal	High	High
		Phys. Act.	Yes	Yes	No	Yes	No	No
		Smoke	No	No	No	Yes	Yes	Yes
		Diabetes Risk	**5.566**	**22.773**	**8.056**	**5.810**	**29.220**	
		Delta vs. normal sit (A)		*17.207*	*2.490*	*0.244*	***23.654***	***19.941***

Table 6. Nonlinear risk factor results for Scenario #2 (BP High, No physical activities and Smoke) – Multifactor

$$Nonlinear\ effect\ factor = \gamma = \frac{\Delta(Combined\ effect)}{\Delta\ (Additive\ effect)} = \frac{23.654}{19.941} = 1.186$$

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NFBR applications – Diabetes Type 2

Clinical and behavioral risk factors interact nonlinearly, increasing type 2 diabetes risk beyond the additive baseline..

Two factor interaction

High blood pressure × No physical activity

Additive effect Δ : **19.750**

Combined BN effect Δ : **23.562**

γ = 1.193

Interpretation: **+19.3% amplification**

Multifactor: three factor interaction

High blood pressure × No physical activity x Smoking

Additive effect Δ : **19.941**

Combined BN effect Δ : **23.654**

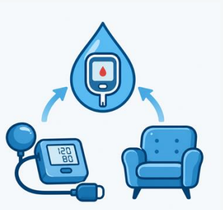
γ = 1.186

Interpretation: **+18.6% amplification**

The NFBR framework captures synergistic effects among clinical and behavioral risk factors.

NFBR applications – Synthesis *(Results)*

From case studies to risk insights



Diabetes Type 2: 2 factors

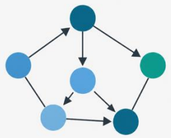
- High blood pressure
- No physical activity



Diabetes Type 2: 3 factors

- High blood pressure
- No physical activity
- Smoking

NFBR
Framework



γ

Risk insights

2 factors	3 factors
$\gamma = 1.193$	$\gamma = 1.186$
+ 19.3%	**+ 18.6%**

- Nonlinear effect of the outcome *(Case studies: $\gamma > 1$ amplification)*
- Consider a cross-domain comparison
- Identify high risk combinations for targeted risk mitigation

NFBR transforms complex factor interactions into interpretable nonlinear risk effect metrics.

NFBR applications – Conclusion

- NFBR formalizes nonlinear risk interactions using Bayesian Networks
- The nonlinear effect factor quantifies amplification or attenuation beyond additive assumptions
- Applications show transferability to other complex domains
- Future work: dynamic and spatiotemporal hierarchical NFBR framework

Thank you for your attention

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