Evaluation of the expected costs of nuclear accidents

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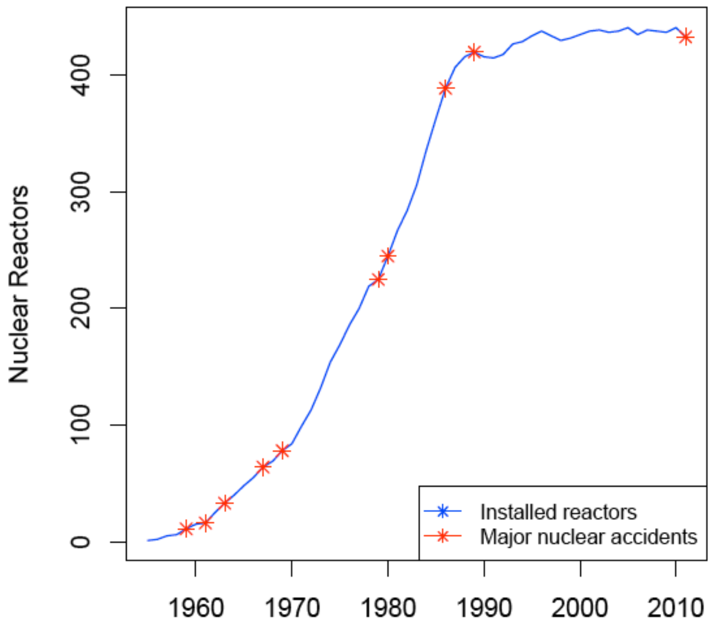
Introduction

- Why have costs to be estimated?
  - To compensate victims after the accidents
  - To make better ex ante decisions (location of nuclear power plants, nuclear phase-out, nuclear versus other non-carbon technologies, …)
- The main differences between ex ante/ex post assessments
  - Economics/cost accounting and cost auditing
  - Uncertainties on future/past
  - Probability x damage/damage
- My paper focuses on the challenges in estimating probabilities of nuclear accidents and on the gap between probabilities of nuclear accidents as calculated by experts and as perceived by people
- On costs of damages see the companion paper by Romain Bizet

The economic perspective

- Calculating the ex ante social cost
  - Private costs + external costs = social costs
  - Expected cost of accident = probability of accident x cost of accident
- Illustration: car accidents in New Zealand
  - Expected costs of a fatal car crash/vehicle/year: NZD1000 ($2.1 \times 10^{-4} \times 4.5 \times 10^{6}$$), or NZD$0.1/km twice less than gas price (Ministry of Transport, 2014)
- Application to nuclear accident
  - Expected cost of a nuclear accident/reactor/year : US$ 15,000 ($3 \times 10^{-8} \times 5.10^{11}$$) or US$0.0015/MWh less than 1 hundredths of fuel costs (Congressional Budget Office, 2008)
  - Even $1/MWh would not change nuclear competitiveness vis-à-vis other technologies
- But insuperable differences between nuclear accidents and car crashes
  - Lack of data
  - Unknows unknows
  - Dreadful event

A small number of observations



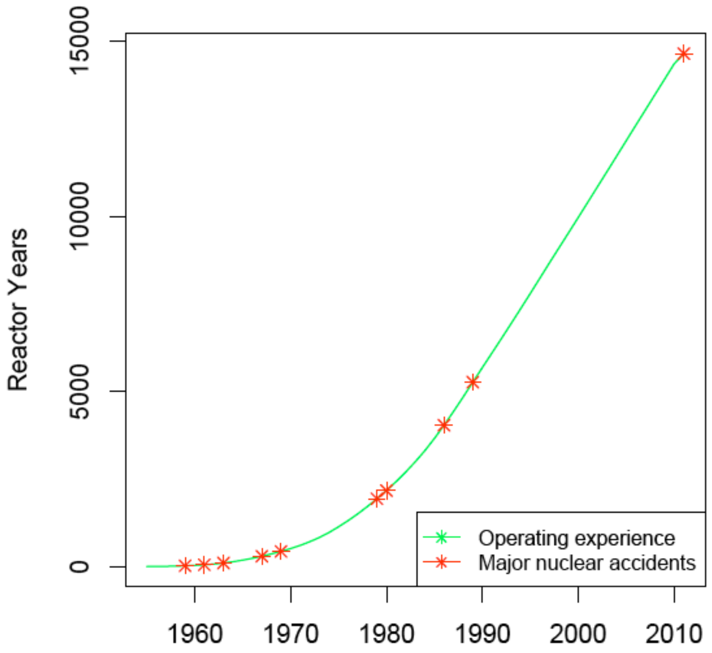


Table : Core melt downs from 1955 to 2011 in Cochran (2011)

Year	Location	Unit	Reactor type
1959	California, USA	Sodium reactor experiment	Sodium-cooled power reactor
1961	Idaho, USA	Stationary Low Reactor	Experimental gas-cooled, water moderated
1966	Michigan, USA	Enrico Fermi Unit 1	Liquid metal fast breeder reactor
1967	Dumfreshire, Scotland	Chapelcross Unit 2	Gas-cooled, graphite moderated
1969	Loir-et-Cher, France	Saint-Laurent A-1	Gas-cooled, graphite moderated
1979	Pennsylvania, USA	Three Mile Island	Pressurized Water Reactor (PWR)
1980	Loir-et-Cher, France	Saint-Laurent A-1	Gas-cooled, graphite moderated
1986	Pripyat, Ukraine	Chernobyl Unit 4	RBKM-1000
1989	Lubmin, Germany	Greifswald Unit 5	Pressurized Water Reactor (PWR)
2011	Fukushima, Japan	Fukushima Dai-ichi Unit 1,2,3	Boiling Water Reactor (BWR)

INES	3	4	5	6	7
Observations	20	13	5	1	2

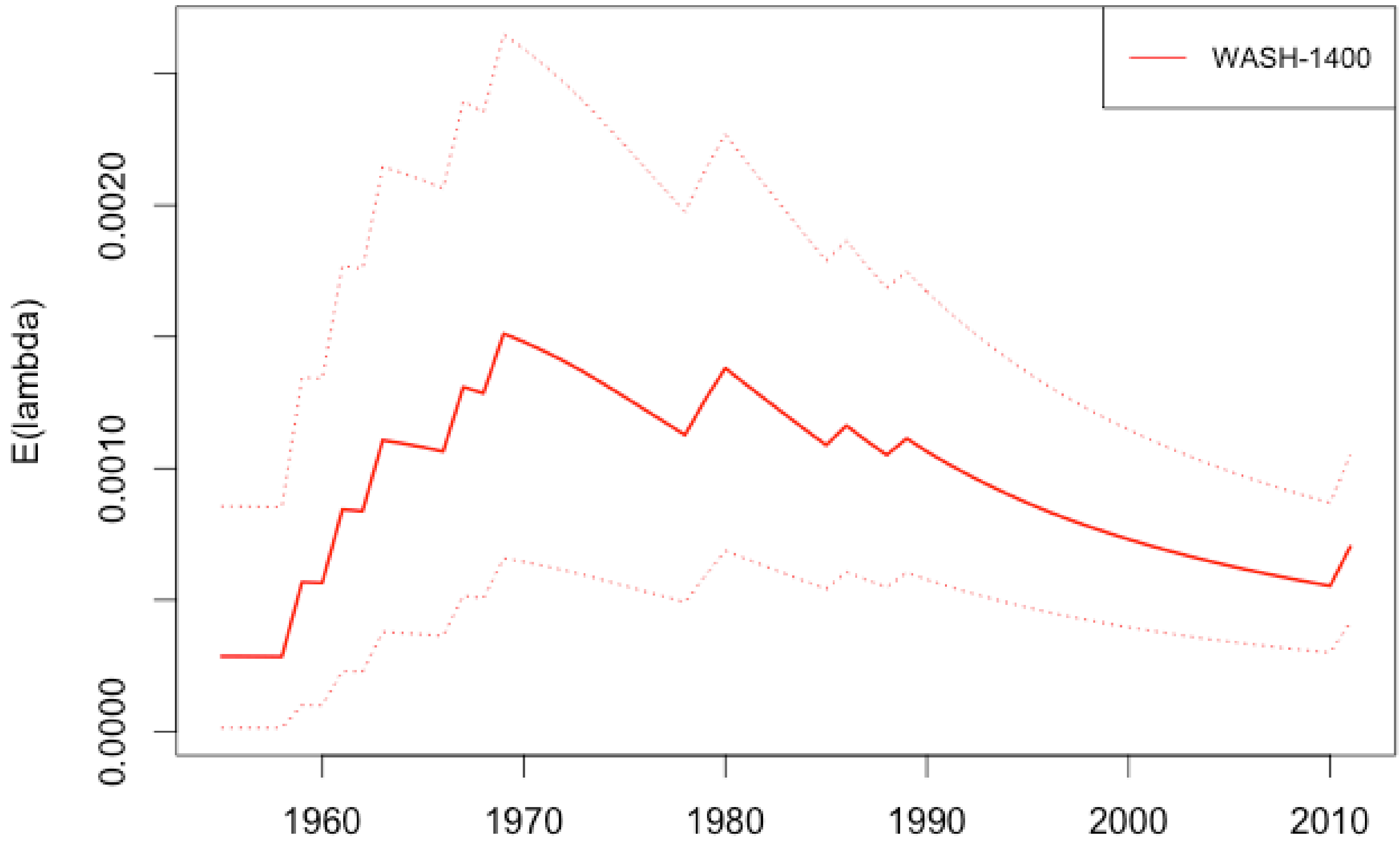
Estimating probabilities of nuclear accident from frequencies is a nonsense

- Observed frequencies
  - INES>3: 1,6 10^{-3} per reactor.year
  - Core meltdowns: 8.3 10^{-4} per reactor.year
  - INES 7: 2.7 10^{-4} per reactor.year
- Is 0,11 the probability of an INES7 in 2015 on the planet? ($[1-(1-2.7x10^{-4})^{435}]$; Poisson distribution)
- No! We cannot assume that observed events are representative, that reactors (models and locations) are identical, that events are independent, that safety is time-invariant, etc…

What abouts PSAs?

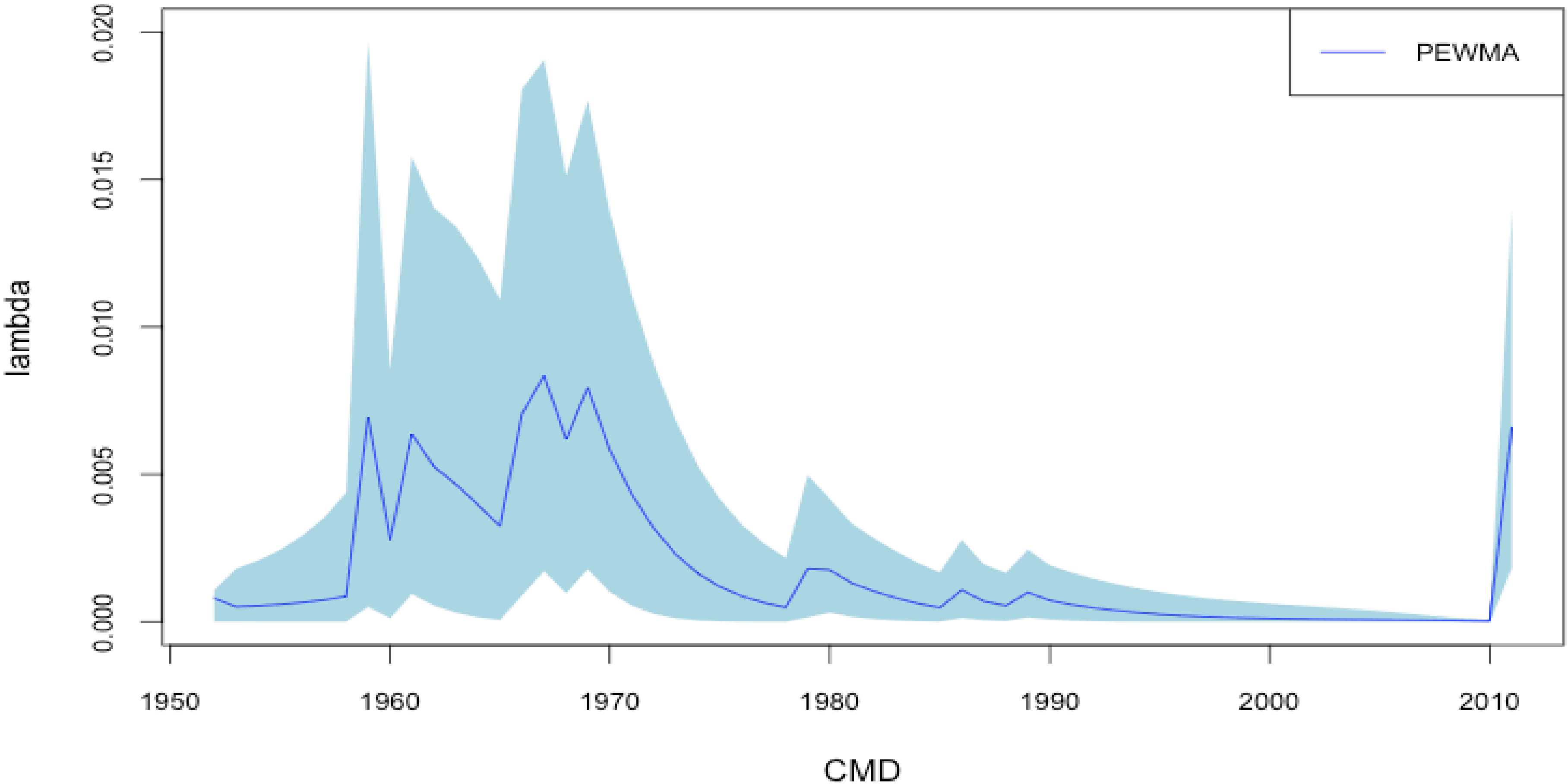
- Knowledge on nuclear accidents is not limited to the observation of past accidents
- Probabilistic Safety Assessments: for instance, the Core meltdown frequency of the UK EPR is estimated to 10^{-6} per year and the Core damage with early containment failure to 3.9×10^{-8}
- PSAs aggregate a huge amount of knowledge that can complement observed frequencies of accidents
- But PSAs have strong limitations
  - Limited scope (specific initiating events, specific cascade of failures)
  - They are not designed to obtain a single number and its confidence interval but to pinpoint local safety weaknesses and remedies
  - They assumed perfect compliance with safety standards and regulatory requirements
- PSAs figures are much more lower than observed frequencies (CDF $8.3\ 10^{-4}$ versus 10^{-5})

An attempt to combine observations of accidents and PSAs 1/2



Bayesian Poisson Gamma model, Escobar-Rangel and Lévêque, *Safety Science,* (2014)

An attempt to combine observations of accidents and PSAs 2/2



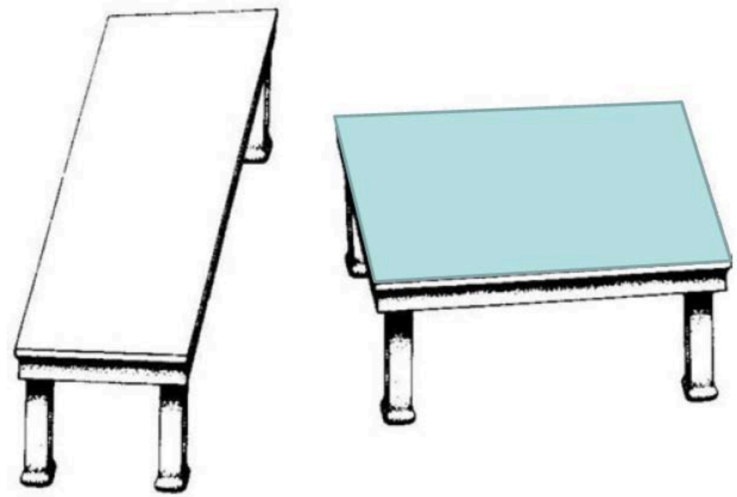
Poisson Exponentially Weighted Moving Average (independence parameter: 0,82)
Escobar-Rangel and Lévêque, *Safety Science,* (2014)

Uncertainties prevail

- There is no magic number to make a rationale decision (as in car crashes)
  - No means can be inferred from observed frequencies
  - The probability of a nuclear accident differs according to the design and the location of reactors but also according to institutional characteristics (independent regulator, liability rules, experience of operators, etc.)
  - We do not know the probability distribution of nuclear accident
- Probabilistic analysis requires to know the unknowns
  - New theories of probabilities could shed some light

Data are also required on perceived probabilities

- Experimental psychology studies (e.g., D. Kahneman, 2011) show that our perception of probabilities is biased
- For instance, the probability of a 0,0001 loss is perceived lower than a probability of 1/10.000 (the so-called denominator neglect heuristic)



Theory of decision under uncertainties and human behavior

- Historically, the economic theory of decision has progressed in complexifying the utility function to take observed behavior into consideration
- Concave utility function to explain risk-aversion (Bernouilli, 1738)
- Allais paradox (1955) can be explained with a weighted utility that is non linear in probabilities: overestimation of low probabilities and underestimation of high probabilities
- Ellsberg paradox (1961) shows that people are averse to ambiguity (i.e., they prefer risk to uncertainties)

How to balance probabilities as calculated by experts and as perceived by people in decision-making? 1/2

- How to take the perception biases into consideration in estimating the nuclear social cost of accident?
- Nuclear accident is a
  - Rare event, hence perceived probability is overestimated
  - Ambiguous event, hence our minds select on the highest value of probability and damages
  - Dread event, hence we neglect the denominator and focus on the event itself which leaves a strong footprint
- Consequently, whenever decision making is based on *perceived probabilities*
  - Overinvestment in nuclear safety
  - Premature phase-outs (e.g., German decision after Fukushima-Daiichi)
  - Distorted choice between alternative power technologies (coal or hydro are perceived less dangerous)

How to balance probabilities as calculated by experts and as perceived by people in decision-making? 2/2

- Conversely, whenever decision-making is based on *calculated probabilities*, people may fight against new plants and whenever they succeed investments would have been made for nothing and a huge amount of money would have been lost (e.g., the shut down of the Superphénix reactor in France)
- How to balance perceived probabilities and calculated probabilities in estimating the expected cost of nuclear accident?
  - Institutional design: NSAs deliver calculations and Government and Congress integrate perceptions through the policy process
  - Quantifying risk aversion and probabilities biases

Conclusive research suggestions

- Progress in ex ante estimating the costs of nuclear accidents to nurture nuclear policy decisions (new builds, phase-out, NPPs location, etc.) requires new approaches
- Elaborating and applying methods to combine
  – Pure observations on accidents and other pieces of knowledge
  – Probabilities as calculated by experts and as perceived by people

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The Economics and Uncertainties of Nuclear Power

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