# Risk Assessment of road networks in Central Chile


Eduardo Allen Binet

*PhD Student University of Auckland*

*Supervisors: Seosamh Costello & Theuns Henning*


*08 November 2021*

I was born in Viña del Mar, grew up in Quillota, but I am currently living in Santiago, Chile

Structural Engineer (2017)

Master of Science (2019)

Researcher (2017 – to date)

Amateur Padel Player

Board games

# Research

## Papers:

- [1] **Allen, E**. Amaya, T. Chamorro, A. Santa María, H. Baratta, F. Echaveguren, T. De Solminihac, H. (2021) **Development and comparison of seismic fragility curves for bridges based on empirical and analytical approaches**. Structure and Infrastructure Engineering. Doi: http://dx.doi.org/10.1080/15732479.2021.19939373
- [2] **Allen, E.** Chamorro, A. Poulos, A. Castro, S. De la Llera, J. Echaveguren, T. (2021) **Sensitivity analysis and uncertainty quantification of a seismic risk model for road networks**. 1-15. Doi: https://doi.org/10.111/mice.12748
- [3] Chamorro, A.; Echaveguren, T.; **Allen, E.;** Contreras, M.; Dagá, J.; de Solminihac, H.; Lara, L.E. (2020). **Sustainable Risk Management of Rural Road Networks Exposed to Natural Hazards: Application to Volcanic Lahars in Chile**. Sustainability 2020, 12, 6774. Doi: https://doi.org/10.3390/su12176774
- [4] Cartes, P.; Echaveguren, T.; Chamorro, A., **Allen, E.** (2020). **A cost-benefit approach to recover the performance of roads affected by natural disasters**. International Journal of Disaster Risk Reduction, Vol 53. Doi: https://doi.org/10.1016/j.ijdrr.2020.102014
- [5] Contreras, M. Echaveguren, T. **Allen, E**. Chamorro, A. Vargas, J. (2021). **Flood risk to road networks: a case study in the 'Aconcagua bajo' watershed in Central Chile. Journal of Flood Risk Management**. Submitted.

## International Assessments:

- [1] ECLAC-IADB (2020) **Assessment of the Effects and Impacts of Hurricane Dorian in The Bahamas** (LC/TS.2020/31), Washinghton D.C. Doi: http://dx.doi.org/10.18235/0002582
- [2] ECLAC (2021) **Damage and Losses Assessment of 2021 Flood in Guyana**. Submitted Work

# Risk assessment of road networks

How to **quantify** and **mitigate** those effects?

- Risk Conceptualization (Bil et al., 2014; Lowrance, 1976; Renn, 2008; Jayaram & Baker, 2010)
- Hazard Modeling (Jayaram & Baker, 2010)
- Performance indicators (Argytoudis et al., 2015; Faturechi & Miller-Hooks, 2015)
- Losses (Kiremidjian et al., 2007)
- Resilience (Geo et al., 2019)
- Optimal evacuation process (Nahum et al, 2017)

Christchurch, New Zealand, 2011

Chiloé, Chile, 2016

The objective of this research was to **assess risk** in an interurban road network with an operational indicator, **analyze the sensitivity of each parameter** and quantify the **model uncertainty**

## How to assess risk with an operational indicator on a spatially distributed network and quantify the model uncertainty?

# Risk model application in Central Chile


DOI: 10.1111/mice.12748

INDUSTRIAL APPLICATION

COMPUTER-AIDED CIVIL AND INFRASTRUCTURE ENGINEERING WILEY

## Sensitivity analysis and uncertainty quantification of a seismic risk model for road networks

Eduardo Allen[1] | Alondra Chamorro[1,2] | Alan Poulos[1] | Sebastián Castro[1] | Juan Carlos de la Llera[1,3] | Tomás Echaveguren[1,4]

[1] Research Center for Integrated Disaster Risk Management (CIGIDEN), ANID/FONDAP/15110017, Santiago, Chile
[2] Department of Construction Engineering and Management, School of Engineering, Pontificia Universidad Católica de Chile, Santiago, Chile
[3] Department of Structural and Geotechnical Engineering, School of Engineering, Pontificia Universidad Católica de Chile, Santiago, Chile
[4] Civil Engineering Department, Faculty of Engineering, Universidad de Concepción, Concepción, Chile

**Correspondence**
Alondra Chamorro, Department of Construction Engineering and Management, School of Engineering, Pontificia Universidad Católica de Chile, Santiago, Chile.
Email: achamorro@ing.puc.cl

**Funding information**
National Research and Development Agency (ANID), Grant/Award Numbers: Fondef Project ID14I20309, Fondecyt Projects ID181754, ID1170836; Research Center for Integrated Disaster Risk Management ANID/FONDAP, Grant/Award Number: 15110017

**Abstract**
Natural hazards may cause significant disruptions to road infrastructure, subsequently affecting road agencies, users, and productive activities. Despite the existence of infrastructure fragilities to seismic hazard and some operational consequences on network mobility, previous research has not modeled risk in terms of traffic disruptions and consequent travel time delays in subduction environments, analyzing the sensitivity to model parameters and quantified model uncertainty. This study proposes a risk framework to evaluate operational consequences in interurban road networks exposed to seismic hazard using travel time delays and propagate uncertainty in the model. Risk values are evaluated using Monte Carlo simulations, and uncertainty is propagated using a polynomial chaos expansion meta-model. The framework was applied to a very critical interurban network in central Chile. Results demonstrate that the parameters that most significantly influence risk are fragility, loss of road capacity, and traffic volume.

### 1 | INTRODUCTION

Natural hazards may produce physical and subsequent operational effects on the road network, such as travel time delays, speed reductions, or traffic congestion. According to Bil et al. (2014), these effects can be categorized as (1) destruction of the infrastructure and permanent traffic interruption until the affected structures are restored; (2) partial structural damage that limits operation; and (3) traffic interruption without structural damage. The main purpose of transportation networks is to supply mobility, accessibility (American Association of State Highway Transportation Officials, 2011), and also to facilitate recovery after disruptive events (Duwadi & Pagán-Ortiz, 2013).

Network topology has been studied to assess the operational effects of natural events in terms of redundancy level and network complexity (e.g., Downer, 2009; Gao et al., 2019). Also, Javanbarg et al. (2008) highlighted the importance of redundancy from the perspective of optimal traffic assignment, its relation with operational impacts in unexpected events, and the optimal evaluation of mitigation strategies. Several indicators have been proposed to address this phenomenon in terms of travel capacity (Lee et al., 2011), connectivity (Bocchini & Frangopol, 2013), reliability of travel times (Zhang et al., 2015), flexibility of the capacity (Morlok & Chang, 2004), network coverage (S. E. Chang & Nojima, 2001), and redundancy indexes (Ip & Wang, 2011), among others. Nevertheless, most authors





## Infrastructure management team

Alondra Chamorro

Eduardo Allen

Tomás Echaveguren

## Seismic analysis team

Juan Carlos de la Llera

Sebastián Castro

Alan Poulos

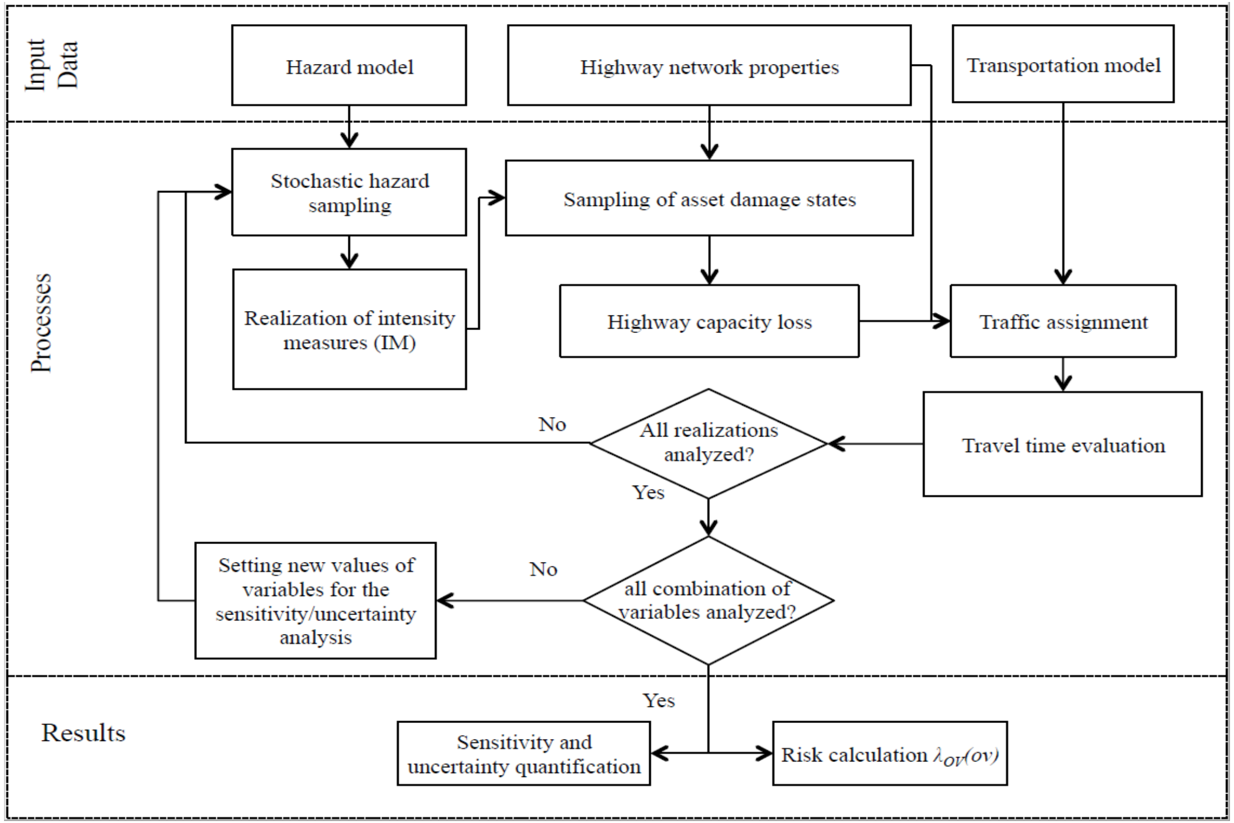
Acknowledgement:

**Fondef ID 14I20309:**
Development of risk model to quantify and mitigate the efffects of Natural Events in the National Road Network

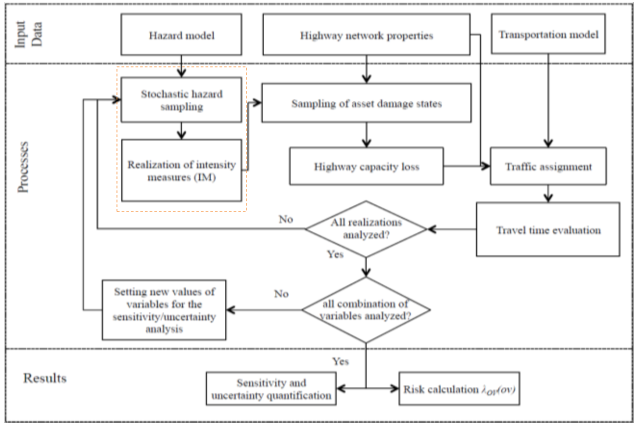
CONICYT Ministerio de Educación Gobierno de Chile
FONDEF Fondo de Fomento al Desarrollo Científico y Tecnológico

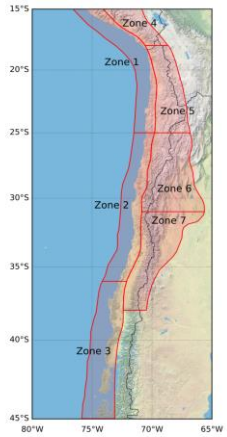
Download here:

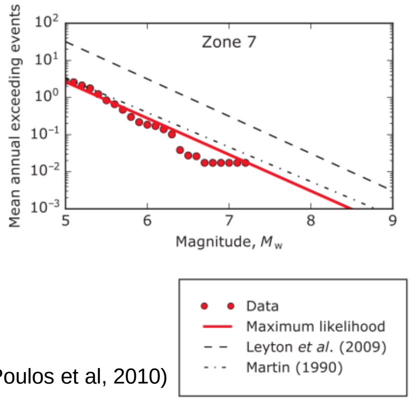
# Risk modeling of road networks exposed to seismic hazards



# Risk modeling of road networks exposed to seismic hazards




(Poulos et al, 2010)

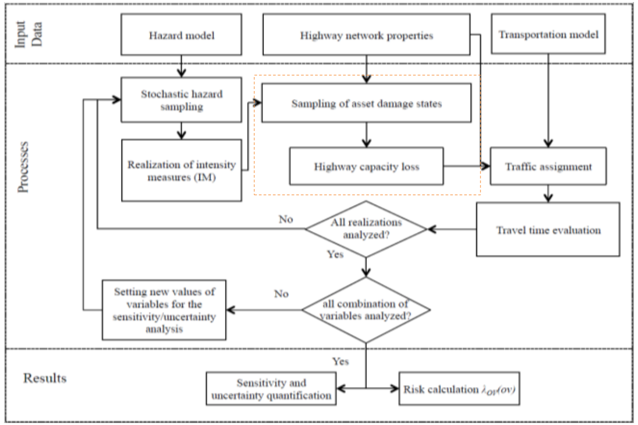
Generation of 50,000 seismic scenarios

**Once earthquakes sources are sampled, the hazard intensity of each system component are sampled using the following equation:**

$$\ln(PGA_{ij}) = \ln(\overline{PGA_{ij}}) + \sigma_{ij}\varepsilon_{ij} + \tau_{ij}\eta_{ij}$$

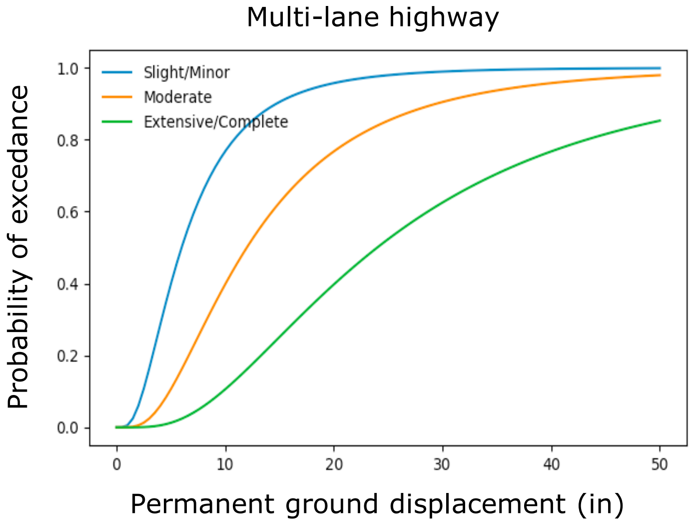
- Sampled PGA for component i during earthquake j
- Median PGA using GMPE
- Intraevent desviation and residual
- Interevent desviation and residual

# Risk modeling of road networks exposed to seismic hazards




| Damage State | Reduction for Multi-lane highway | Reduction for two-lane highways |
| --- | --- | --- |
| No damage | 0% | 0% |
| Slight damage | 25% | 55% |
| Moderate damage | 50% | 55% |
| Severe damage | 100% | 100% |

(Shiraki et al, 2007; Hua et al, 2019)




(NIBS, 2004)

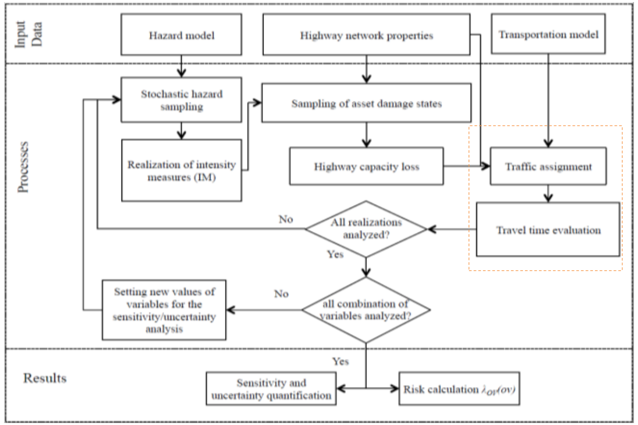
$$F(im, \mu, \theta) = \phi\left(\frac{\ln(im) - \mu}{\theta}\right)$$

$\mu$: *mean value*

$\theta$: *Standard deviation*

$\phi$: *PDF of a standard normal distribution*

# Risk modeling of road networks exposed to seismic hazards




**Traffic assignment model:**

$$\min \sum_{a \in A} \int_0^{f_a} t_a(u)du$$

$$t_a(f_a) = \begin{cases} t_a^0 \left[1 + \alpha \left(\frac{f_a}{c_a}\right)^{\beta}\right] & , multilane \\ \frac{d_a}{FFS_a - 0.0125 f_a - f_{np}} & , two-lane \end{cases}$$

Time travels as function of link flow $f_a$; link capacity $c_a$; free-flow traffic conditions $t_a^0$ and $FFS_a$; distance $d_a$; and adjustment factor for non-passing zones $f_{np}$

**Constraints:**

$$\sum_{p \in P_W} h_p = T_W \,, \forall w \in W$$

$$f_a = \sum_{p \in P} \delta_{ap} \cdot h_p \,, \forall a \in A$$

$$h_p \geq 0 \,, \forall p \in P$$

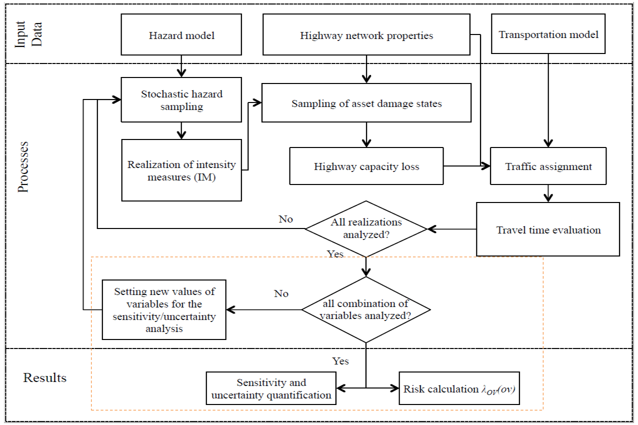
$$f_a \geq 0 \,, \forall a \in A$$

Demand $T_w$ in origin-destination pairs w $\in W$, with flow $h_p$ in route $p \in P$

Relationship between route $(h_p)$ and link $(f_a)$ flows

Positive flows $h_p$ and $f_a$

# Risk modeling of road networks exposed to seismic hazards




## Sensitivity Analysis:
## (Polynomial Chaos Expansion)

$$\lambda_{DV}(dv, \boldsymbol{X}) = \sum_{\alpha \in \mathbb{N}^M} y_\alpha(dv)\varphi_\alpha(\boldsymbol{X})$$

(Sudret, 2010)

- Probability of exceedance of decisión variable λ(dv) given the random input vector X
- Coefficients of the polynomial function
- Basis functions of the polynomial

## Risk:

$$\lambda_{DV}(dv) = \nu \int_{\Omega \in R^n} P(DV > dv | \overline{IM} = \overline{im})\, f_{\overline{IM}}(\overline{\boldsymbol{im}})\, d\overline{im}$$

(Baker et al, 2010)

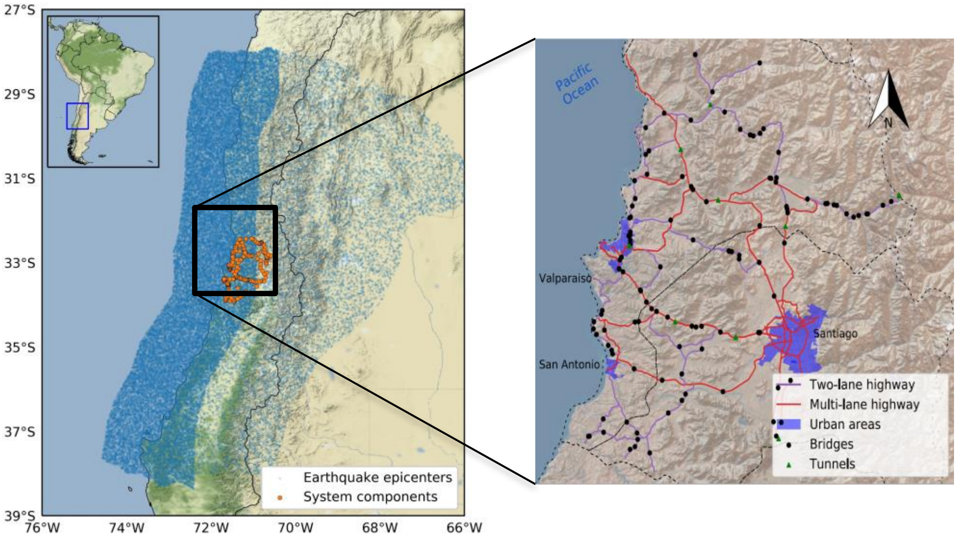
- Probability of exceedance of decision variable λ(dv)
- Evaluation of a set of Hazard scenarios Ω
- Probability of exceedance of decision variable given an intensity measure *im*
- Probability of a Intensity measure *im*

# Risk model application in Central Chile

- It corresponds to the **interurban road network** in the Metropolitana and Valparaíso regions
  - 1962 km of roads
  - 115 bridges
  - 10 tunnels

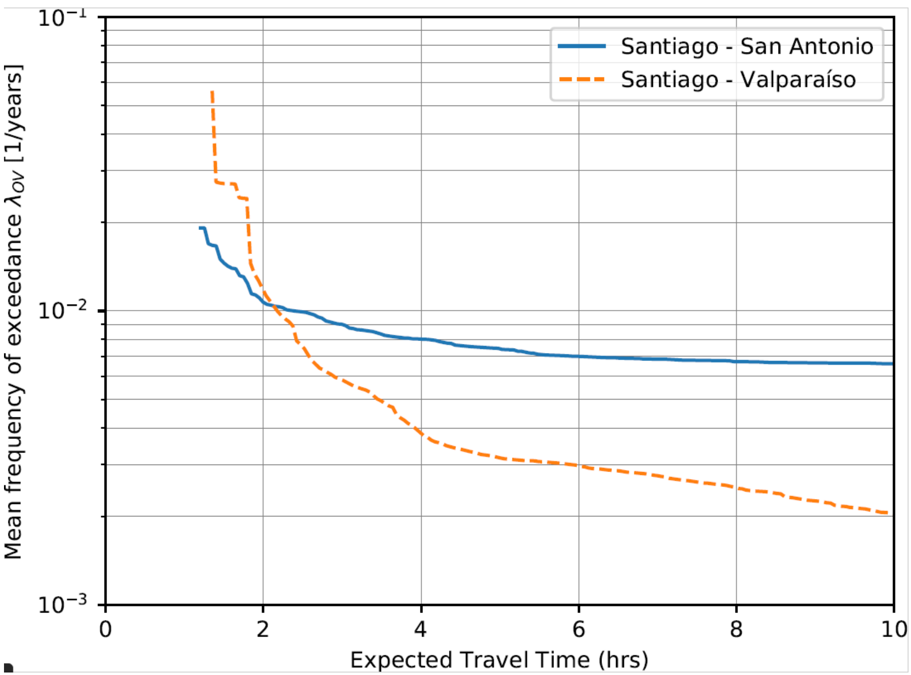
- **Travel times** between Santiago and Valparaíso/San Antonio

- Assessment of network performance considering seismic hazard
  - Earthquakes affect the road capacity
  - 50,000 PGD maps considering liquefaction
  - $5.5 < M_w < 9.6$, with *Importance sampling*
  - GMPE of Abrahamson (2016)

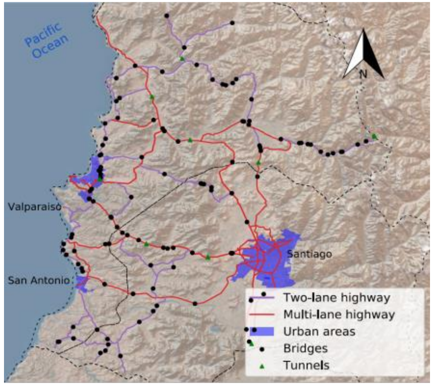


# Risk model application in Central Chile

- Expected travel time is controlled by:
  - Network redundancy (routes $P$)
  - Infrastructure fragility (effect on capacities $c_a$ and $f_{np}$)
  - Traffic levels (flows $f_a$)
- Santiago-Valparaíso connection has:
  - More independent paths
  - More redundancy
- Hence, it is less susceptible to time travel delays due to earthquakes



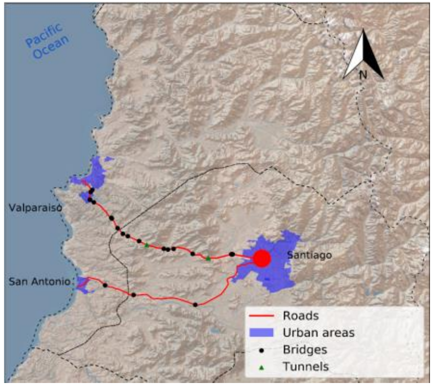
# Risk model application in Central Chile

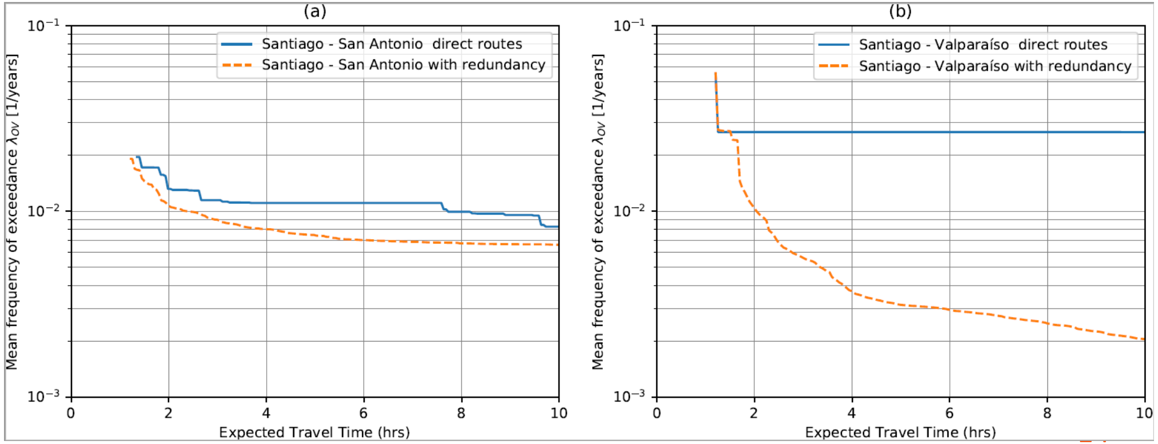



- Direct roads are considered to a new risk assessment to analyze the differences

- Santiago – San Antonio is more susceptible to increase travel time considering the whole network. However, it is less susceptible when considering the direct route. This may be explained by the number of fragile infrastructures the different routes present

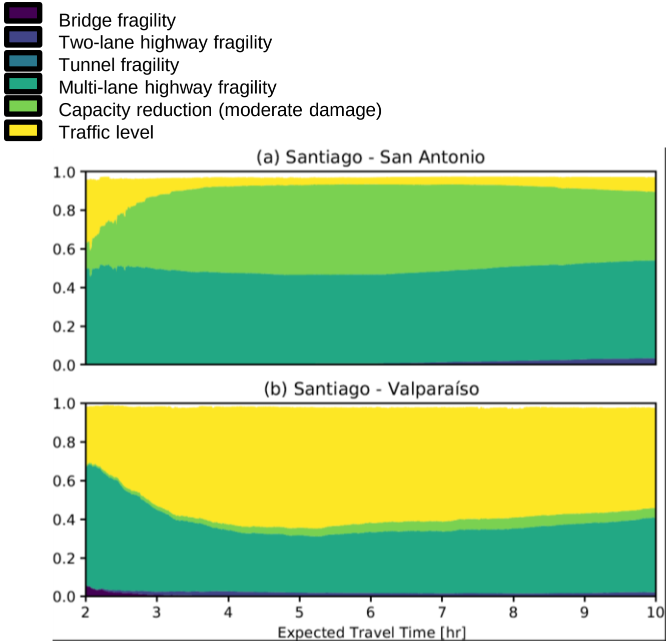
VS



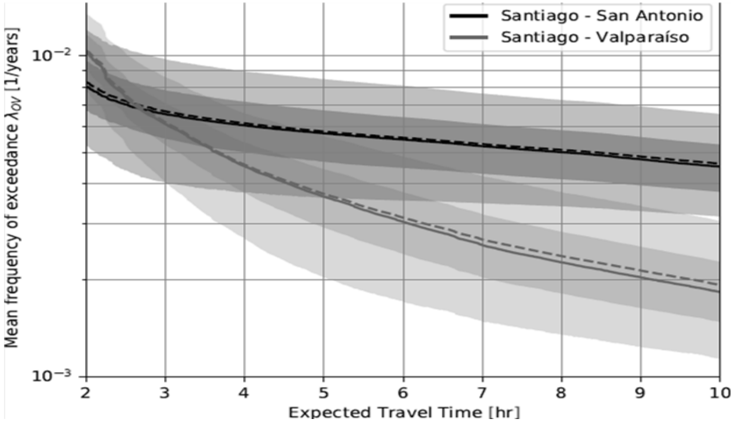



# Risk model application in Central Chile

- The most important parameter is the **fragility curve for multi-lane highway**




**First order Sobol index. Each color represents the contribution of each parameter to the total variance**




- Direct policy implications:
  - **Santiago-San Antonio**: need to reinforce the infrastructure and network redundancy, because fragility and capacity have greater relevance
  - **Santiago-Valparaíso**: should focus on controlling traffic levels
- The risk analysis could support the feasibility of a new project in order to reduce the impact of natural hazards

# Conclusions and further research

- The sensitivity analysis and the uncertainty quantification indicate the influence of each parameters and variables on the total risk. This can lead to different policies depending on each influence

- The model can evaluate risk of new transportation infrastructure projects. For example, the impact (in terms of risk reduction) of a new highway that connects two locations

- Future research in the area involves the development of optimization models for the allocation of mitigation strategies to reduce risk, the integration of this model to a social project methodology and the development of new calibrated models for other infrastructures

THE UNIVERSITY OF AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
NEW ZEALAND

“The ”

# Risk Assessment of road networks in Central Chile

Eduardo Allen Binet
*PhD Student University of Auckland*
*Supervisors: Seosamh Costello & Theuns Henning*

*08 November 2021*

# Appendix

| Variable | Description | Distribution | Polynomial basis |
|---|---|---|---|
| $\alpha_1$ | Multiplier factor of the median value | $U(0.5, 1.5)$ | Legendre |
| | for bridge fragility curves | | |
| $\alpha_2$ | Multiplier factor of the median value | $U(0.5, 1.5)$ | Legendre |
| | for single lane fragility curves | | |
| $\alpha_3$ | Multiplier factor of the median value | $U(0.5, 1.5)$ | Legendre |
| | for tunnel fragility curves | | |
| $\alpha_4$ | Multiplier factor of the median value | $U(0.5, 1.5)$ | Legendre |
| | for multilane fragility curves | | |
| $D_{mod}$ | Capacity reduction factor | $U(0.25, 0.75)$ | Legendre |
| | for moderate damage state | | |
| $V$ | Traffic volume ratio with respect to the mean annual volume | $N(1, 0.08^2)$ | Hermite |