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Applicable schemes for the Vehicle-Bridge Interaction System Identification method

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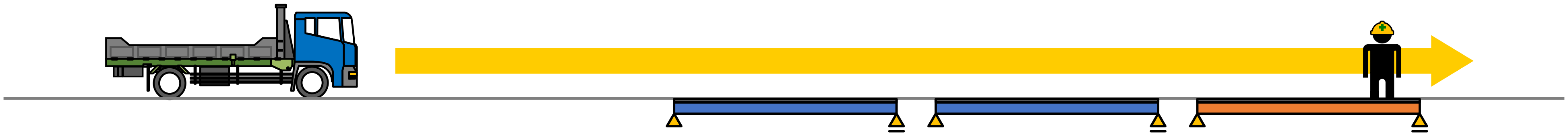
Introduction | The latent demand of our society

- Bridge Screening for determining priorities and necessities of inspections
  - The vase number of bridges scattered over the wide area > the number of engineers
  - We need to allocate personnel and budget to damage-suspected bridges with a focus

Solution | How to realize the bridge screening

- Drive-by bridge monitoring can be an option for bridge screening
  - Sensors are installed only on traveling vehicles (Not in bridges)
  - Swift and cost-effective bridge diagnostics by passing sensor-equipped vehicles over bridges



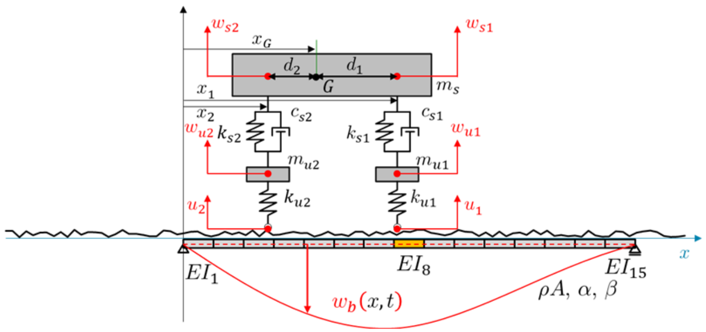
Sensors are installed on traveling vehicles

Engineers inspect only "damage-suspected" bridges

Reviews | Development of Drive-by bridge monitoring

- Measuring vehicle vibrations to extract **bridge feature values**
  - The first natural frequency of a bridge can be identified as a peak in Fourier's power spectra of vehicle vibrations. (**Yang et al**, Sound and Vibration, **2004**)
  - The mode shapes are also identified by using a multi-trailer system. (**Yamamoto et al**, JSCE journal paper, **2012**), (**Yang et al**, Mechanical Systems and Signal Processing, **2021**)
  - The bridge damages can be detected / estimated by monitoring the variations of these bridge feather values. However, you need to measure the intact values.
- Measuring vehicle vibrations to identify **vehicle parameters** and **road profile**
  - Drive-by monitoring for road pavement inspections
  - The vehicle parameters and road profiles can be simultaneously estimated. (**Xue et al**, Mechanical Systems and Signal Processing, **2020**), (**Keenahan et al**, Str. and Inf. Eng., **2020**)
  - The parameters are optimized to decrease the road profile residual of front and rear wheels.
  - This idea can be extemded to estimate vehicle and bridge parameters. (**Yamamoto et al**, Applied Sciences, **2023**), (**Shin et al**, Sensors, **2023**)

Existing Studies | The VBI system identification method



Measure Vehicle Vibration （$\ddot{w}_v$）

Assuming the Mechanical Parameters
（Vehicle：$\mathbf{M}_v, \mathbf{C}_v, \mathbf{K}_v$、 Bridge：$\mathbf{M}_b, \mathbf{C}_b, \mathbf{K}_b$ ）

Repeat random-assuming

Substitution

Substitution as the traffic loads

$$\mathbf{M}_v \ddot{w}_v + \mathbf{C}_v \dot{w}_v + \mathbf{K}_v w_v = f_v$$

（Input Estimation Problem of Vehicle）

$$\mathbf{M}_b \ddot{w}_b + \mathbf{C}_b \dot{w}_b + \mathbf{K}_b w_b = f_b$$

（Dynamic Response Simulation of Bridge）

Estimate Input Profile （u）

Estimate Bridge Deflection （w_b）

Estimate Road Profile （r）

Do road roughness estimated between the front and rear wheels match?

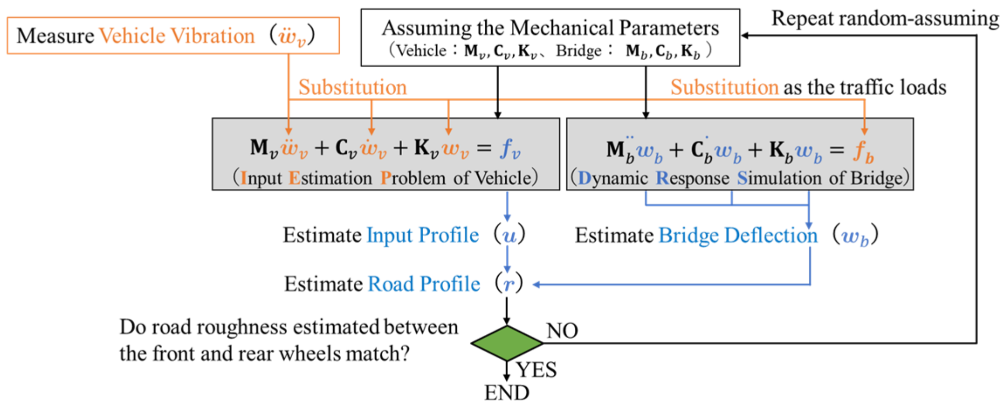
NO

YES

END

Existing Studies | The VBI system identification method

- The proposed method
  1. Measure the vehicle vibration data
  2. Assume the system paramters randomly
  3. Equation of Motion of VBI system
  4. Estimate the road profile
  5. Evaluate the likelihood on road roughness
  6. Repeat from 2



- VBI (Vehicle-Bridge Interaction) system can be identified
  - Vehicle parameters: m_{si}, c_{si}, k_{si}, m_{ui}, k_{ui} (i: front/rear wheels)
  - Bridge parameters / responses: ρA, $EI(x)$, α, β, $w_b(x, t)$
  - Road surface unevenness: $R(x)$ from $r_i(t) = R\left(x_i(t)\right)$

Technical Issue | Efficient Optimization Algorithm

- To search the optimal solution (combination of vehicle-bridge paramters) that minimizes road unevenness residuals, we have several options:
- **MCMC** (Monte Carlo Markov chain)
  - Randomly vary the candidate parameters incrementally
- **PSO** (Particle Swarm Optimization)
  - Directionally vary the candidate parameters
- **Nelder-Mead** method
  - Geometrically vary the candidate parameters

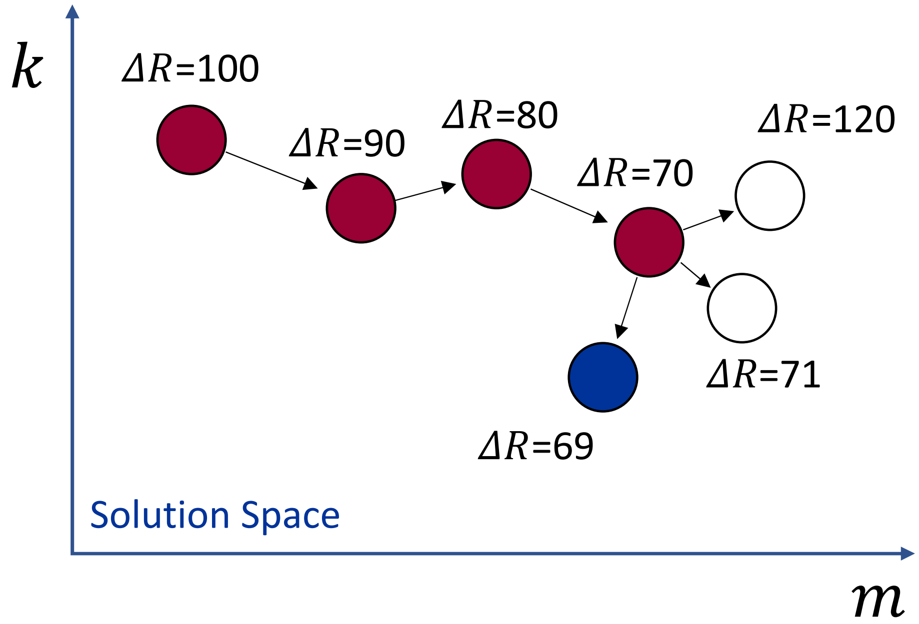
Study Purpose | Optimization Algorithm

- This study compares the MCMC, PSO and Nelder-Mead methods and discusses the applicability of these algorithms to the proposed scheme.
  - The vehicle vibration data are numerically simulated

MCMC method | Monte Carlo Markov chain

- Randomly varying the parameters
  - wide range search
  - simplicity in implementation

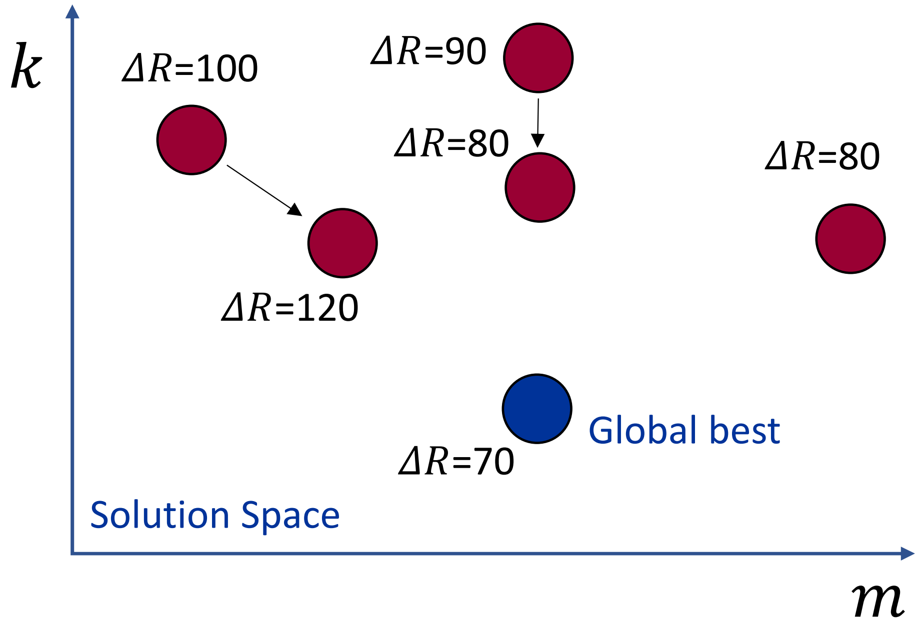
  However…
  - high computational cost
  - low efficiency



PSO method | Particle Swarm Optimization

- Directionally varying the parameters
  - efficient search

  However…
  - high computational cost
  - prone to local optima



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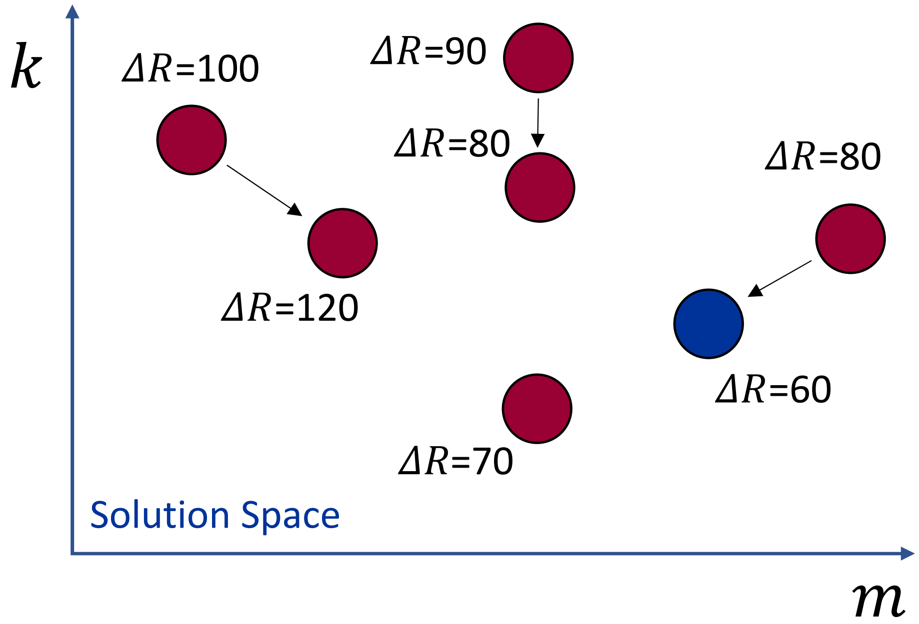
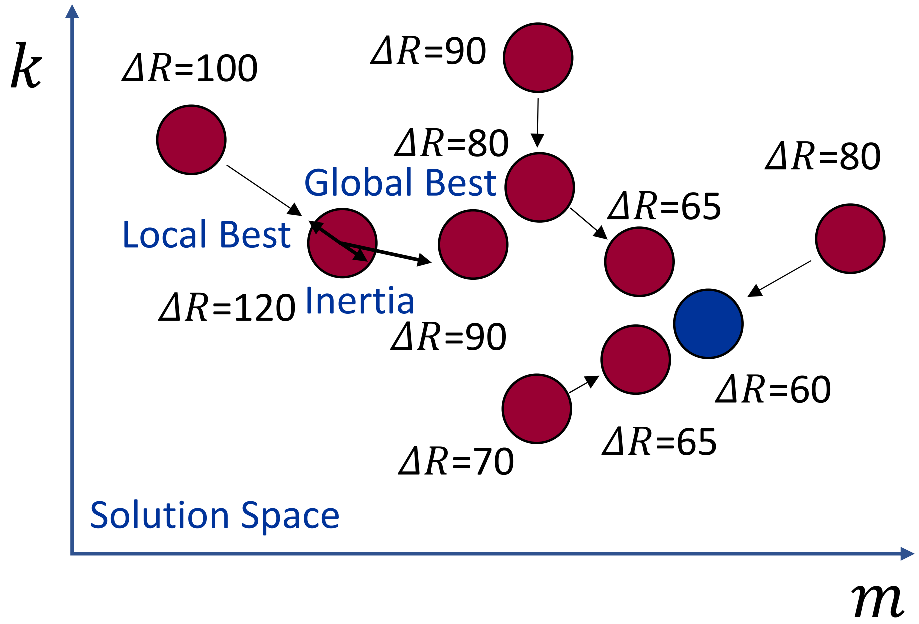


PSO method | Particle Swarm Optimization

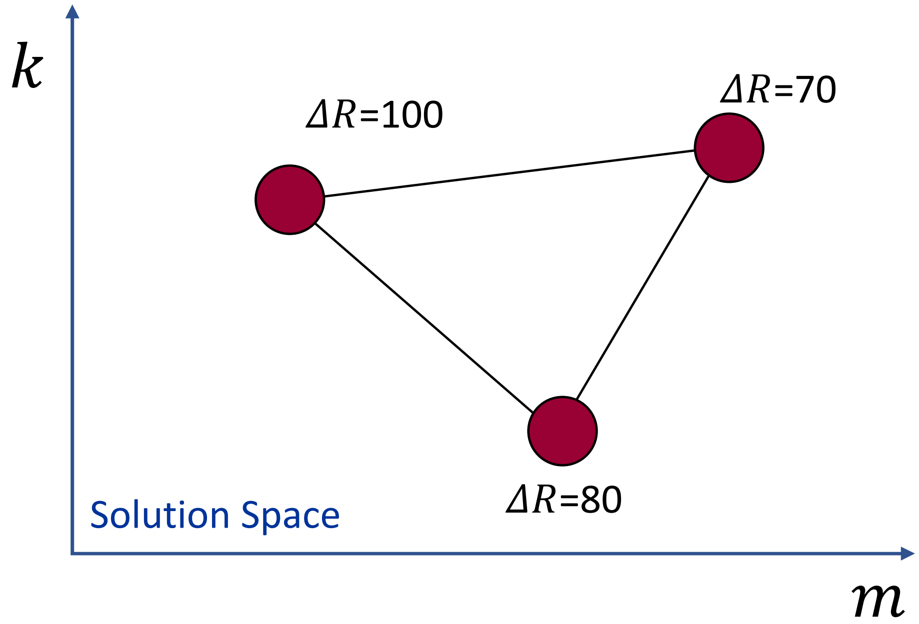
- Directionally varying the parameters
  - efficient search

  However…
  - high computational cost
  - prone to local optima
    - dependent on the initial values



Nelder-Mead method | Adaptive scheme

- Geometrically varying the parameters
  - efficient search
  - low computational cost
  - applicable even for small gradients



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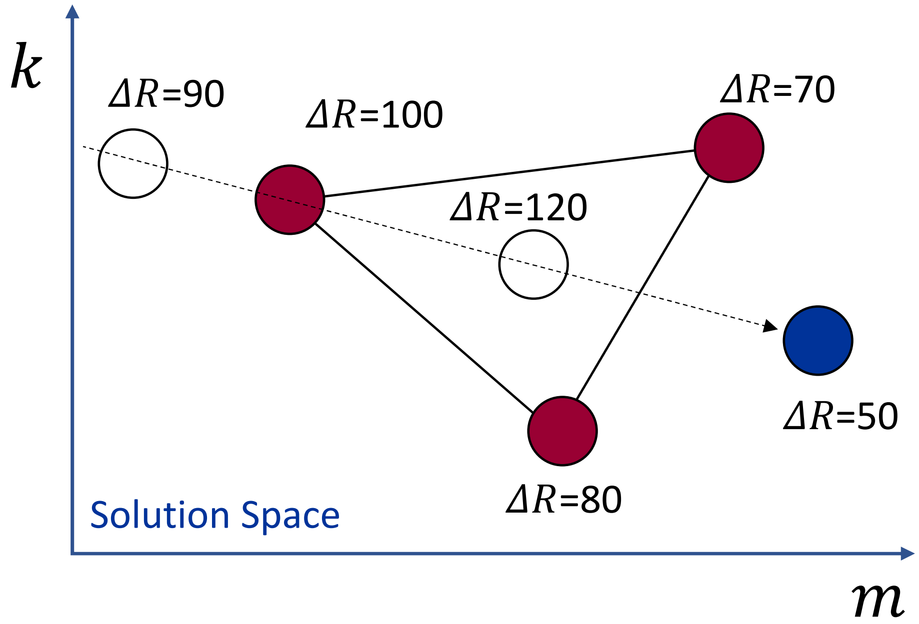

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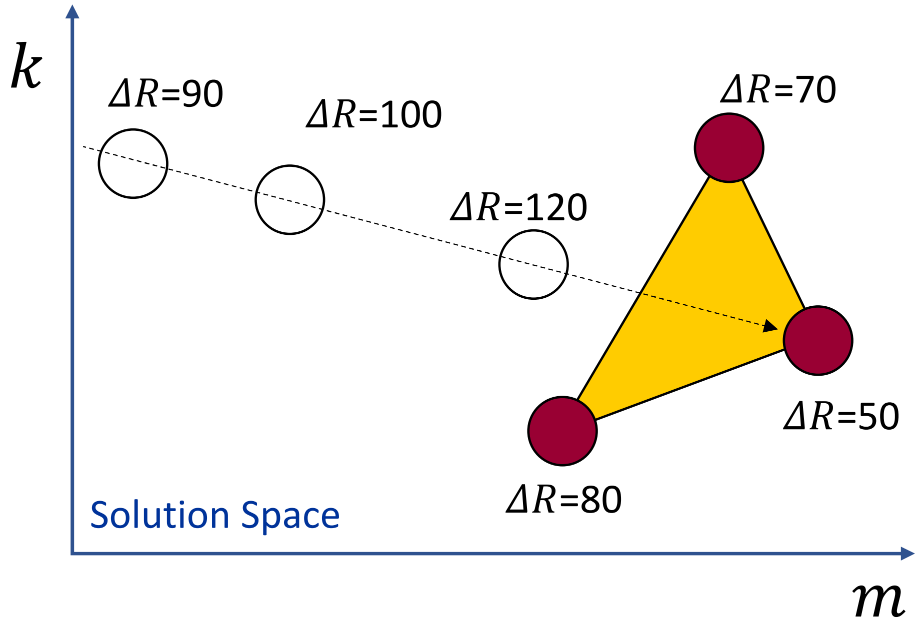
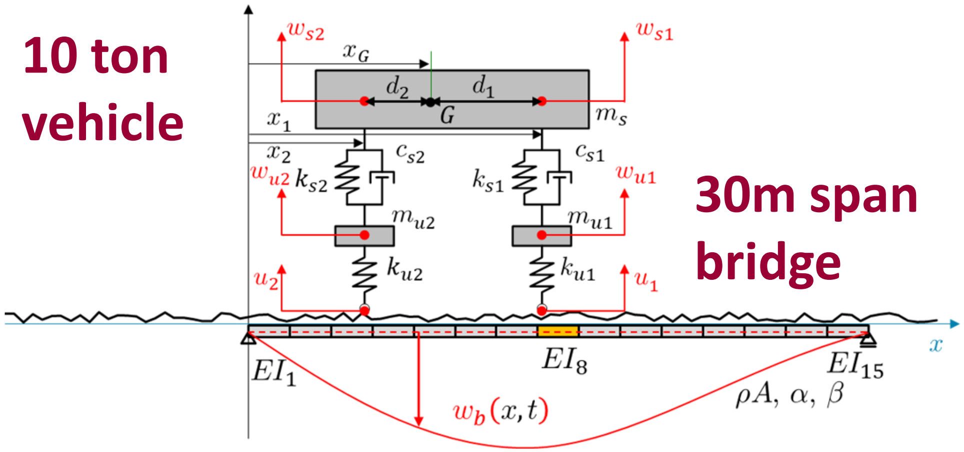


Numerical Simulation | to simulate vehicle vibrations

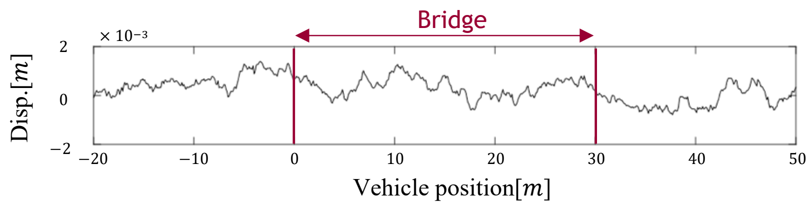
- VBI system is modeled as Multibody-Continuum interaction system
  - Vehicle: Rigid-body and Suspension
  - Bridge: FE model using 1D finite beam elements

10 ton vehicle



30m span bridge

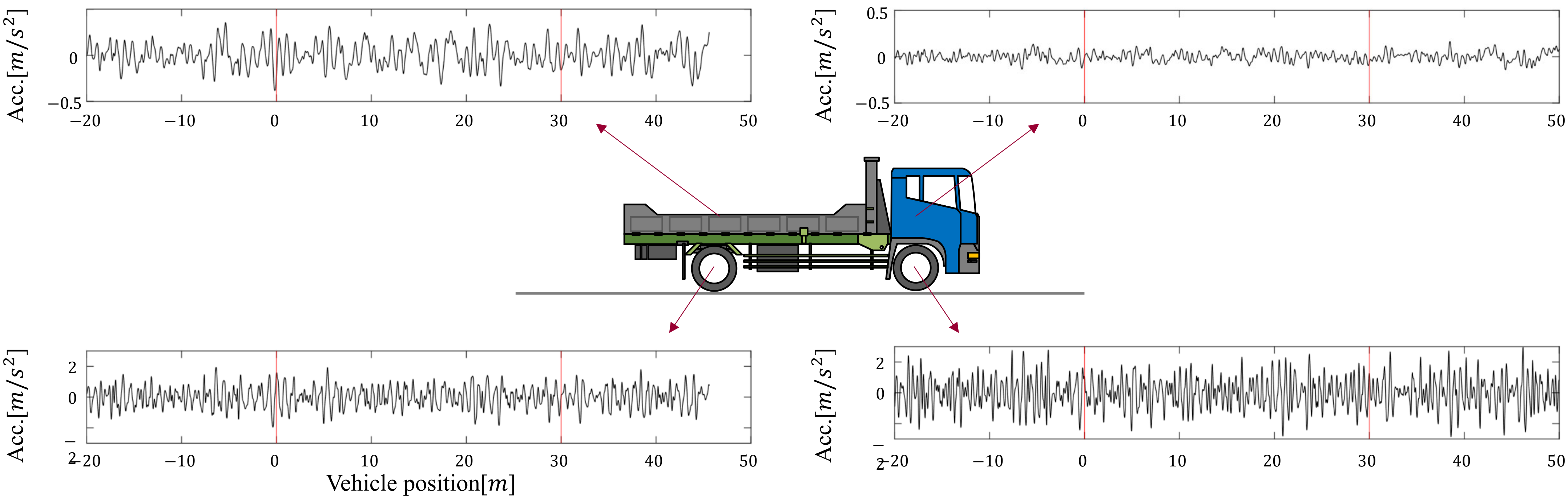
	Mass	m_s	8310 [kg]	Front Tire	Mass	m_{u1}	469 [kg]
Body	Front from G	d_1	1.215 [m]		Stiffness	k_{u1}	4,790,000 [kg/s^2]
	Rear from G	d_2	2.175 [m]	Rear Tire	Mass	m_{u2}	751 [kg]
Front	Damping	c_{s1}	24,200 [kg/s]		Stiffness	k_{u2}	4,310,000 [kg/s^2]
Suspension	Stiffness	k_{s1}	456,000 [kg/s^2]	Mass per unit length		ρA	4400 [kg/m]
Rear	Damping	c_{s2}	29,000 [kg/s]	Flexural Rigidity		EI_i	1.56×10^{11} [Nm^2]
Suspension	Stiffness	k_{s2}	431,000 [kg/s^2]	Rayleigh Damping		α	0.7024
						β	0.0052



Road Unevenness

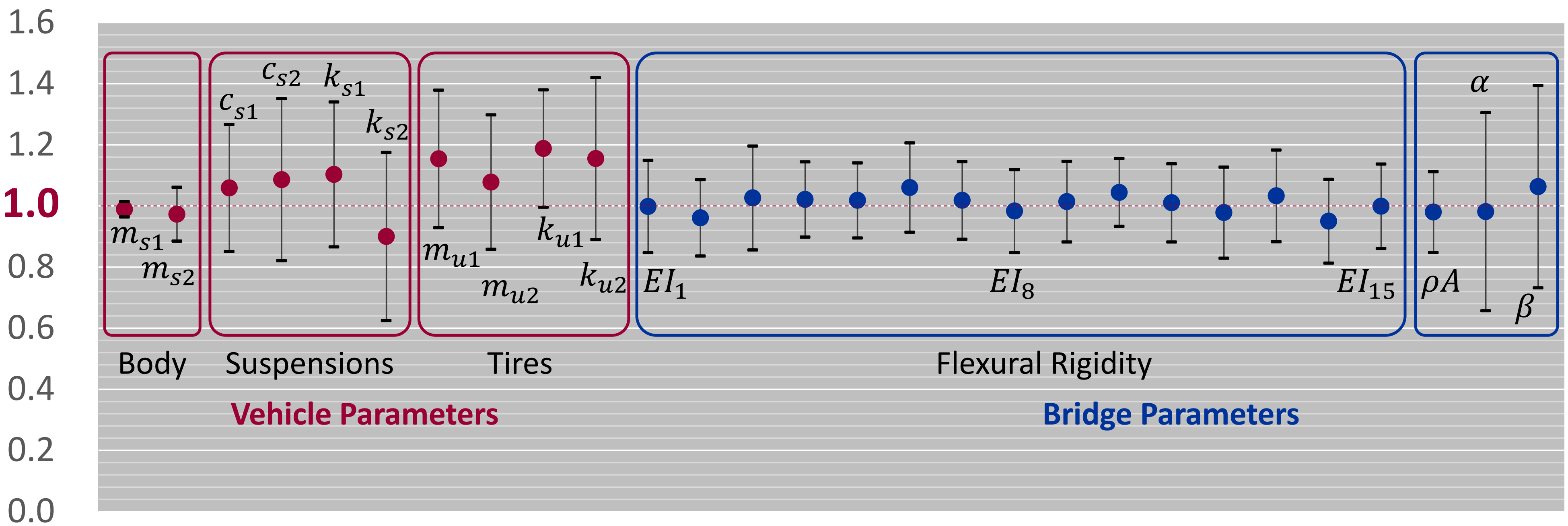
Simulated Data | vehicle vibrations

- Vehicle vibration data are simulated:



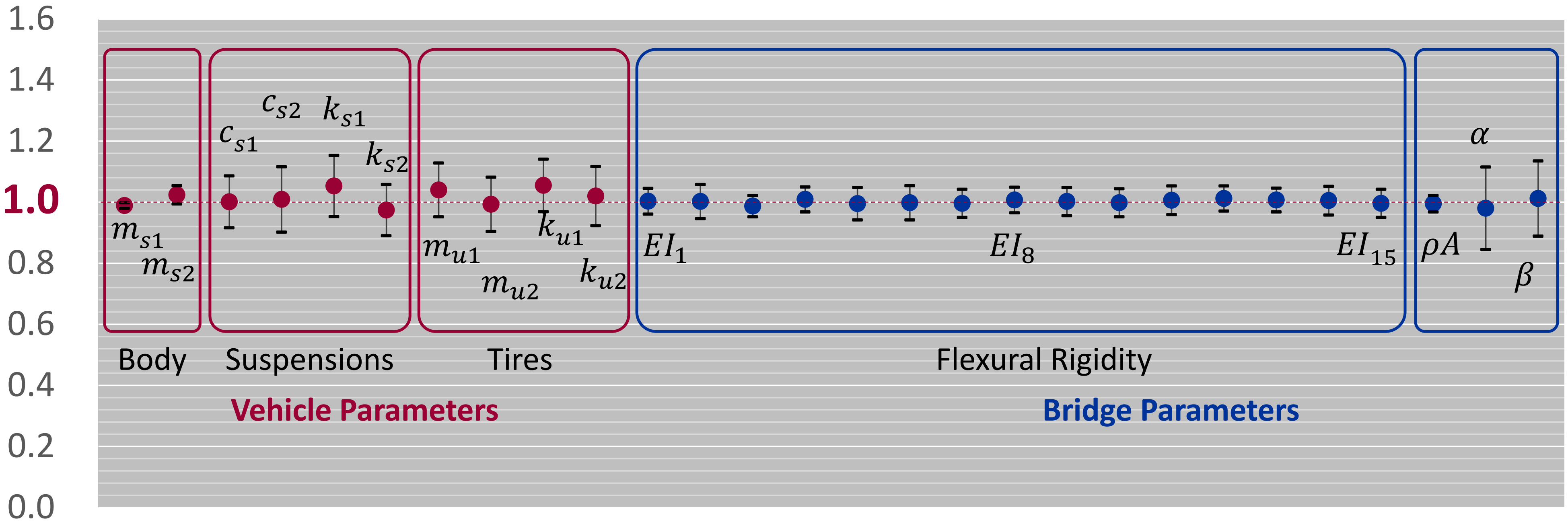
Results | Appllying the proposed method with MCMC to the data

- Implementing the optimization process using **MCMC** method



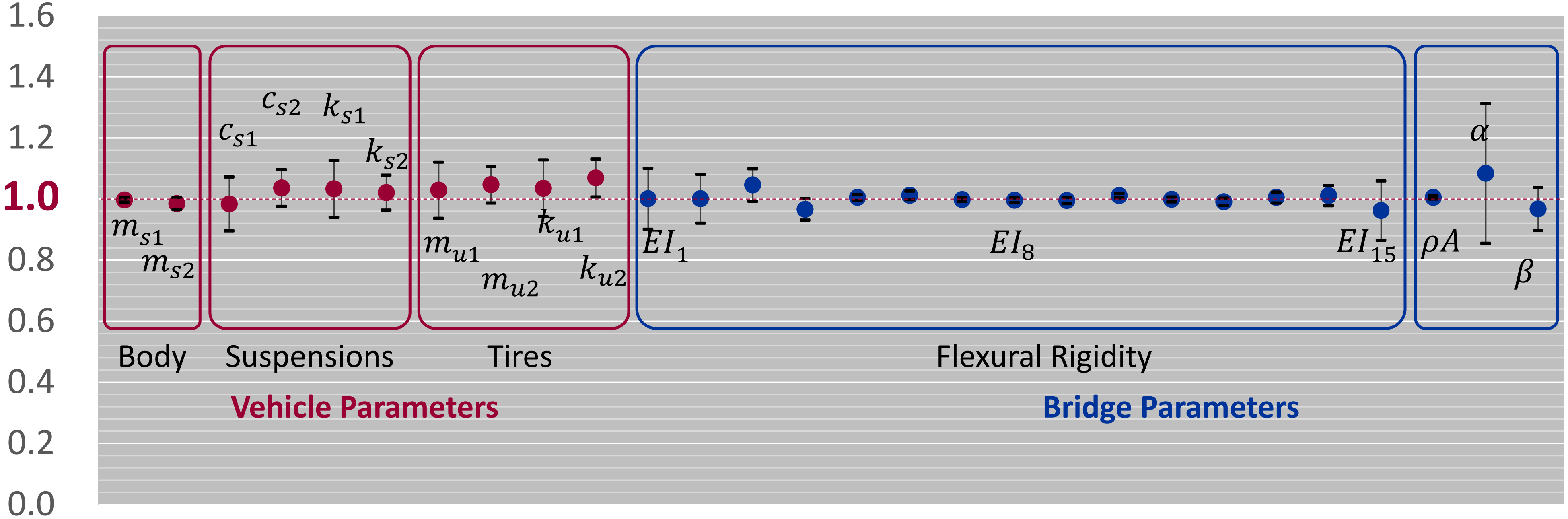
Results | Apllying the proposed method with PSO to the data

- Implementing the optimization process using **PSO** method



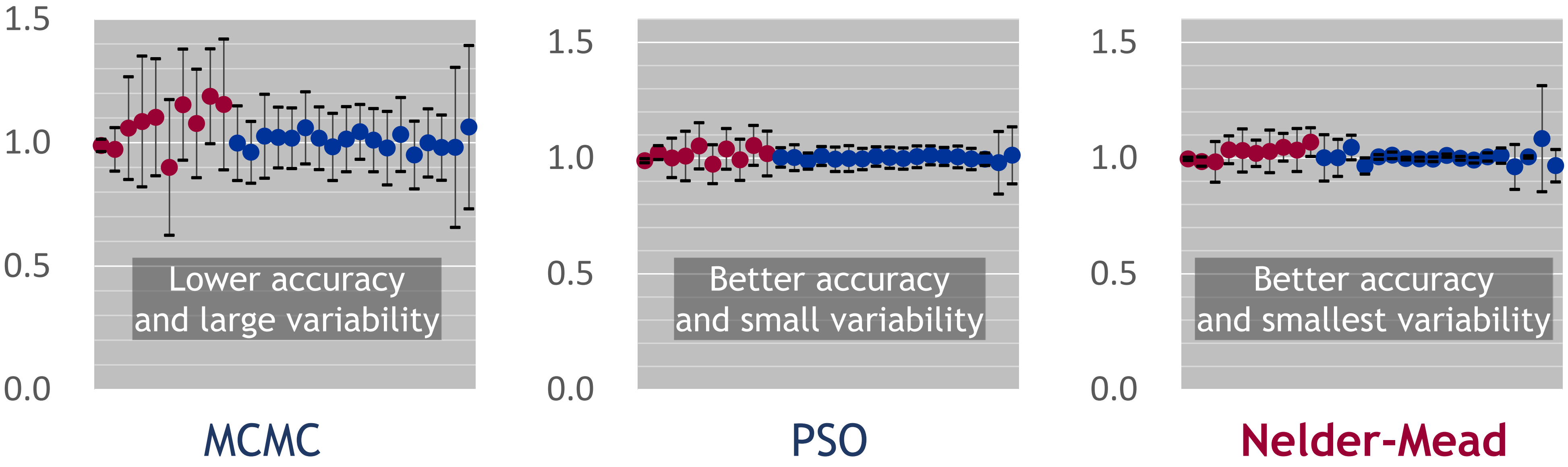
Results | Apllying the proposed method with NM to the data

- Implementing the optimization process using **Nelder-Mead** method



Discussion | Comparison of three algorithms

- **Nelder-Mead** is recommended for the optimization process
  - MCMC is costly and less accurate than both PSO and Nelder-Mead
  - PSO presents high accuracy but much more costly than Nelder-Mead



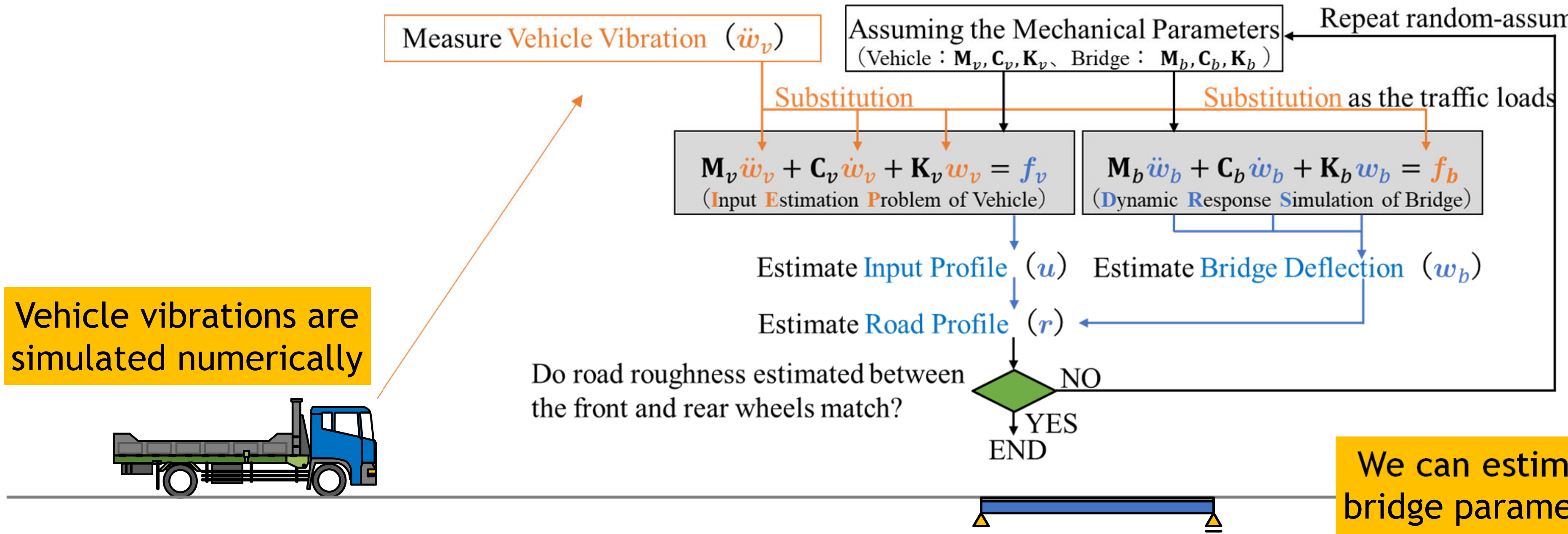
Conclusion | Applicability of Existing Optimization Schemes

- The proposed method aims to simultaneously estimate vehicle and bridge parameters and road unevenness only from vehicle vibration data.
- This method includes random search process for minimizing estimated road unevenness residual.
  - significant computational cost due to the curse of dimensionality
- **Nelder-Mead method** is recommended to use for the optimization process.
  - Note that this validation is just based on numerical simulation
  - Necessary to validate this method through experiment

Summary | Thank you for your attention

Nelder-Mead method is recommended

the proposed Drive-by Bridge Monitoring method:



Vehicle vibrations are simulated numerically

We can estimate bridge parameters and responses