# Documentation of Generic Vehicle Models

Corina Klug

30.08.2023

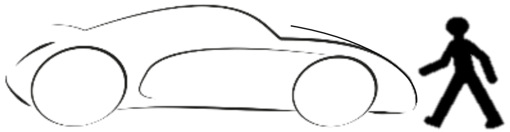
# References on GV Model Development

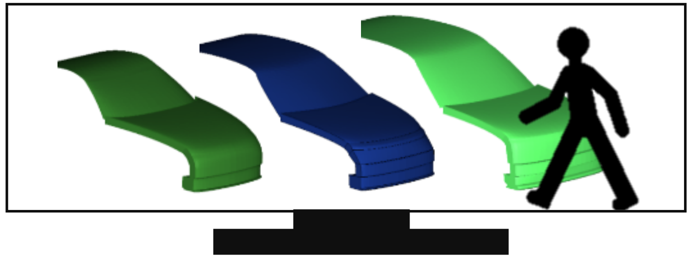

Klug, C., Feist, F., Schneider, B., Sinz, W., Ellway, J., van Ratingen, M., Development of a Certification Procedure for Numerical Pedestrian Models, In: NHTSA (Ed.), The 26th ESV Conference Proceedings (10.-13.6.2019, Eindhoven, Netherlands), 2019, 1-24. https://www-esv.nhtsa.dot.gov/Proceedings/26/26ESV-000310.pdf

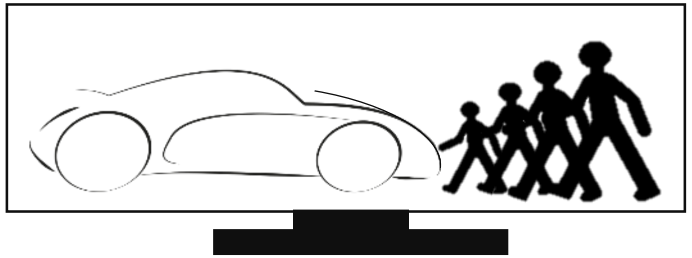
Klug, C., Assessment of Passive Vulnerable Road User Protection with Human Body Models, Doctoral Thesis, Graz University of Technology, Graz, 2018. https://repository.tugraz.at/marc21/sa2db-8q875

Klug, C., Feist, F., Raffler, M., Sinz, W., Petit, P., Ellway, J., et al., Development of a Procedure to Compare Kinematics of Human Body Models for Pedestrian Simulations, In: International Research Council on the Biomechanics of Injury (Ed.), 2017 IRCOBI Conference Proceedings (13.-15.9.2017, Antwerp, Belgium), IRCOBI, 2017, 509–530; http://www.ircobi.org/wordpress/downloads/irc17/pdf-files/64.pdf

# Abstraction levels in DPPS assessment







### 1. Real World
- Pedestrian – real car impact

### 2. Assessment
- Head form impactor – real car

### 3. HIT Determination
- HBM – simulation model of real car

GTR No. 9

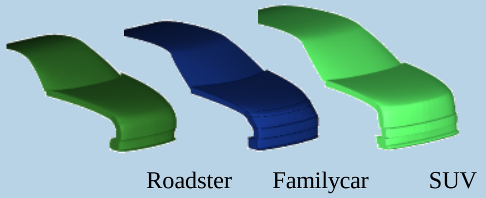
### 4. HBM Qualification
- HBM – Generic vehicle models

### 5. GV model plausibility check
- GV model – rigid impactor

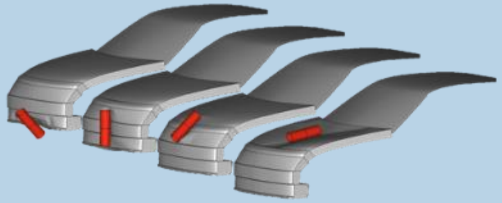
MR1

MR 1 – Addendum 5: Specifications for the Qualification of Human Body Models for Pedestrian HIT Determination for DPPS (DPPS tools)

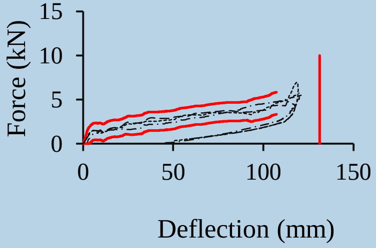
## GV Models




Specification and tools needed for GV Model plausibility check



Corridors for GV Model plausibility check




## Qualification Process of Human Body Models for Pedestrian HIT Determination

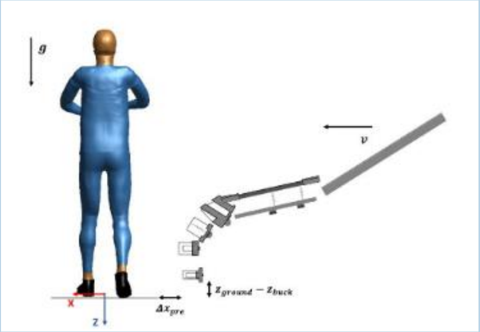
Reference to Amendment 3 of GTR No 9

Specification for HBM qualification simulations

Corridors for HBM Qualification for Use in DPPS

| GV Type | Velocity (km/h) | HIT (ms) | | HCx (mm) | | HCz (mm) | |
|---|---|---|---|---|---|---|---|
| | | Min | Max | Min | Max | Min | Max |
| FCR | 30 | 152 | 197 | -1438 | -1005 | 1019 | 1117 |
| | 40 | 127 | 150 | -1489 | -1105 | 1006 | 1158 |
| | 50 | 107 | 121 | -1504 | -1179 | 1024 | 1169 |
| RDS | 30 | 163 | 199 | -1574 | -1104 | 931 | 1125 |
| | 40 | 133 | 156 | -1659 | -1191 | 931 | 1178 |
| | 50 | 112 | 127 | -1665 | -1283 | 981 | 1183 |
| SUV | 30 | 127 | 144 | -1000 | -624 | 1092 | 1193 |
| | 40 | 101 | 116 | -1032 | -737 | 1103 | 1187 |
| | 50 | 86 | 99 | -1110 | -799 | 1109 | 1191 |

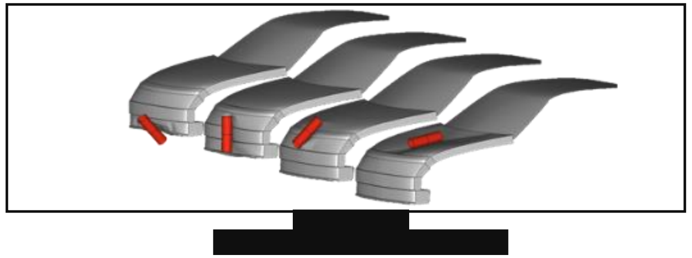
## Documentation + Guideline what needs to be done if corridors shall be revised in the future

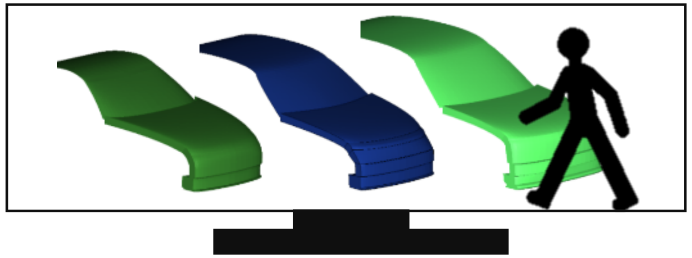


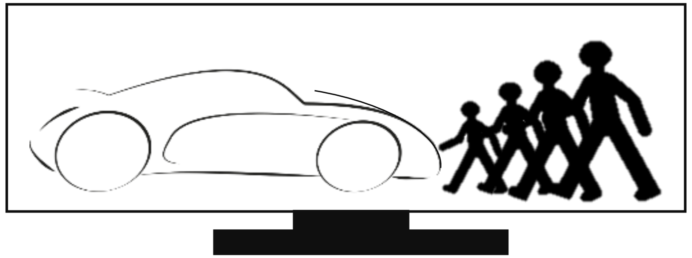
HBM Validations (comparison with PMHS tests) – „Qualification“ of Human Body Models to be used for corridor definition

| | HIT (ms) | | ΔHCx (mm) | | HCz (mm) | |
|---|---|---|---|---|---|---|
| | Min | Max | Min | Max | Min | Max |
| Reference from PMHS Tests | 117 | 159 | -1653 | -1402 | 1020 | 1271 |
| GHBMC M50-PS v5.3.4 LS-DYNA MPP R10.2 | 136.6 | | -1492 | | 1160 | |
| GHBMC M50-PS v1.5 Radioss 2019.2.5 | 139.4 | | -1614 | | 1181 | |
| GHBMC M50-PS v5.33 R1.09 VPS 2019.0.4 | 130.3 | | -1500 | | 1186 | |
| GHBMC M50-P v5.3.4 LS-DYNA MPP R10.2 | 140.7 | | -1503 | | 1182 | |
| JAMA pedestrian_AM50 ver6.2.1. LS-Dyna MPP R10.0 | 141.9 | | -1586 | | 1191 | |
| THUMS v4.02 TB024 (05/22) LS-Dyna MPP R9.3 | 141.6 | | -1622 | | 1223 | |
| THUMS v4.02 (licensed) LS-Dyna MPP R12 | 140.5 | | -1609 | | 1224 | |
| THUMS v4.02 VWG006.2 Aud165VH VPS 2020.54 | 135.6 | | -1574 | | 1219 | |

# Overall DPPS Process







## 1. GV Plausibility check

MR1

GV Models — Impactor corridors

OK

## 2. HBM qualification with GV

MR1

GV Models + HBM — HBM corridors

OK

## 3. Head Impact Time vs. WAD determination

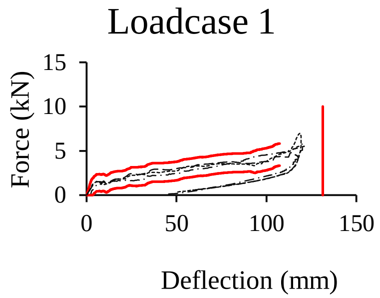
Amendement 3 of GTR No 9

DPPS vehicle + HBM — HIT vs. WAD graph

## 4. DPPS decision for tests

Amendement 3 of GTR No 9

Static test / dynamic HIT (WAD) — HIC




| GV Type | Velocity (km/h) | HIT (ms) | | HCx (mm) | | HCz (mm) | |
|---|---|---|---|---|---|---|---|
| | | Min | Max | Min | Max | Min | Max |
| FCR | 30 | 152 | 197 | -1438 | -1005 | 1019 | 1117 |
| | 40 | 127 | 150 | -1489 | -1105 | 1006 | 1158 |
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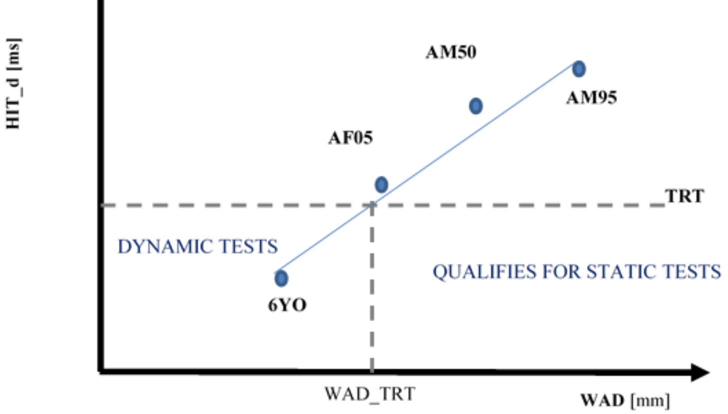
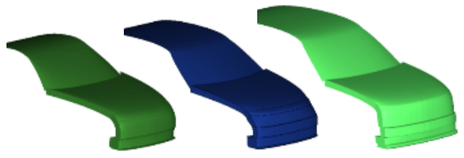
Tables A



# Building Blocks




**Generic Vehicle Models**
available on UNECE website – MR1

UNECE

**Human Body Models**
(openly available or by suppliers)

**Vehicle Simulation Models with DPPS** of Vehicle Manufacturer

**Finite Element Software**

(supplied by code-houses to Industry)

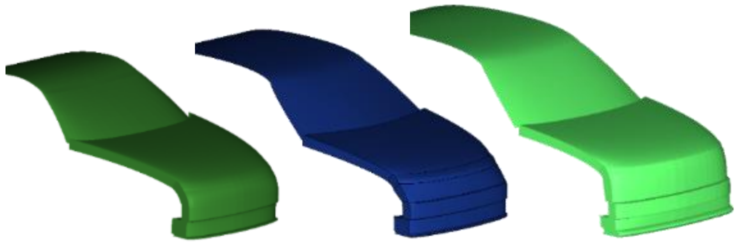
**1. GV Plausibility check**

2. **Human Body Model qualification**

**3. HIT vs. WAD determination**

**4. Use HIT for DPPS decision**

# History of GV Models




- Generic Vehicle Models have been developed in 2015/2016 within CoHerent project
- First version has been shared with CoHerent group (consisting of HBM developers, Car Manufacturers, Code Houses, Research Institutes and Universities) in 2016
- Models have been made publicly available via Euro NCAP website end of 2017 (R1.0 from 17.11.2022) for use of TB024 which is valid since 2018
- R2.0 update in 2019 (adaptation of mesh, which was causing issues in Abaqus)
- R3.0 update in 2022 to improve robustness and comparability between codes

# Updated GV Models (R3)

Aim: Make GV Models ready for regulation

- address issues identified since the introduction of the models in 2016 with as little updates as possible
    - Improved BLE response (to avoid instabilities with child models caused by vertical metal sheet)
        - Interface layer between bonnet leading edge and bonnet (red) deleted
        - nodes of neighbour parts set coincident
        - ble foam tuned to achieve similar response compared to R2 GV models
    - Improved comparability between codes
        - Earlier hard stop for bonnet (as differences in maximum deflection were observed in between codes)
        - Spoiler foam adjusted (original implementation required different versions of GV models in VPS depending on solver version)
    - Improve stability of foams (smooth curves instead of parameters to avoid that curves might be interpreted differently by solvers in the future)
    - Cosmetic improvements (Model cleaning without any effect on the models)

# Development of GV Models

The shape of the GV models are based on the geometries of nineteen European passenger cars with year of market introduction between 2009-2017. Details on the parametrisation of the geometries and resulting shapes in comparison to other vehicle models are documented in Klug et al. (2017) and Klug (2018).

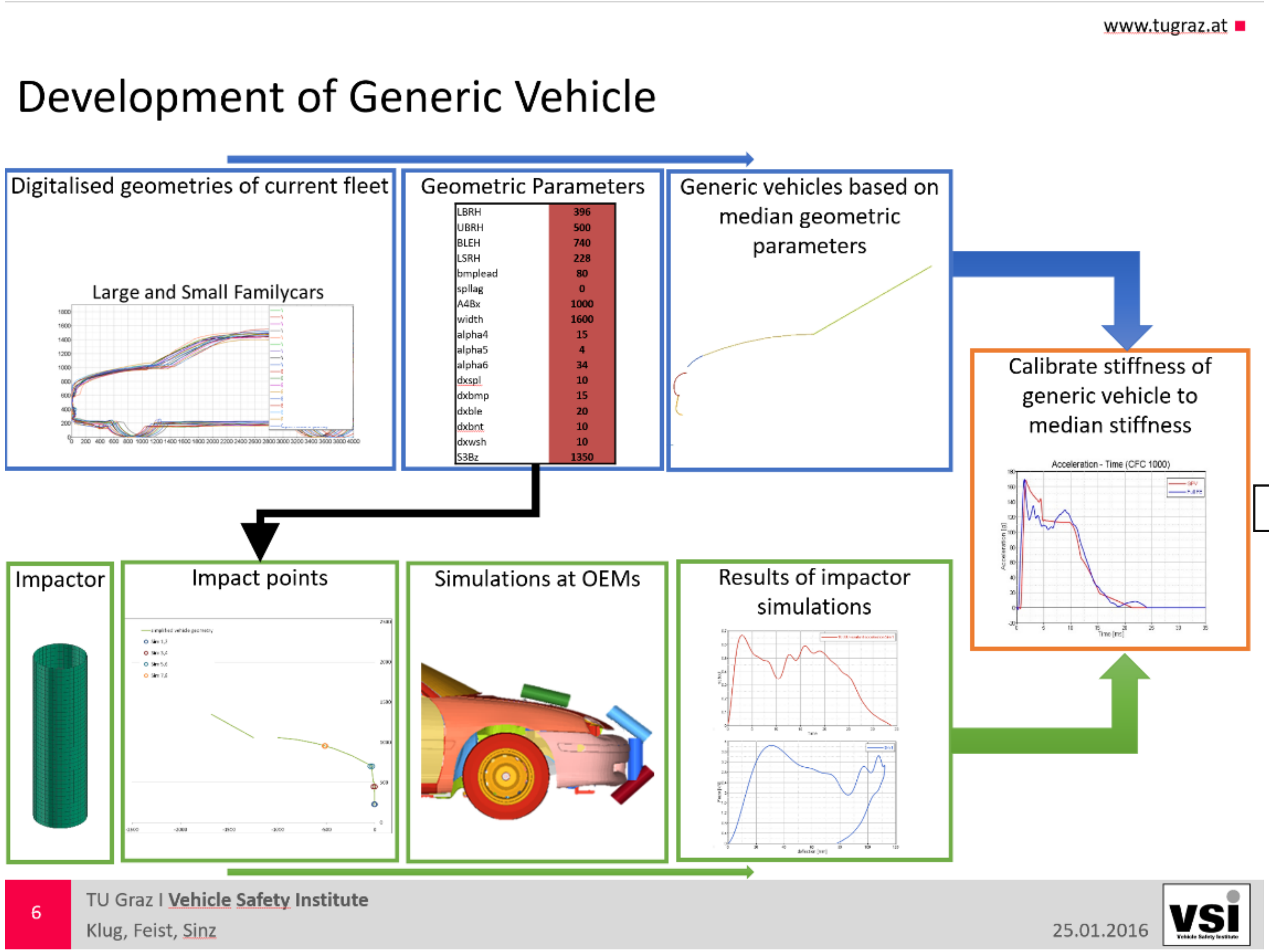
The stiffness of the GV models was calibrated to achieve a robust stiffness behaviour close to a median response derived from FE simulations on serial cars using a cylindrical rigid impactor. The impactor has a mass of 5.95 kg, diameter of 120 mm and length of 400 mm. The impactor was modelled as a rigid structure to minimise code-specific effects, as impactor simulations were performed with four different FE software packages. The energy level of the impactor was selected as an overall compromise of the different body parts impacting the vehicle in angles and speeds depending on the shape and stiffness of the vehicle. With an initial kinetic energy of nearly 400 J even severe contact conditions such as elbow contact on the bonnet are covered.

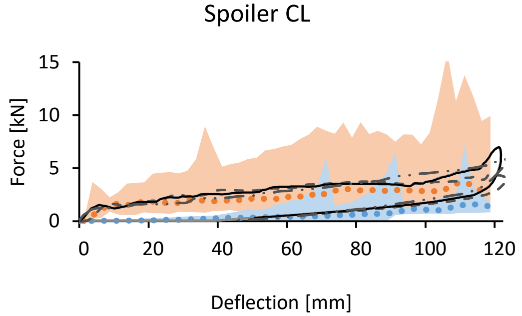
A comparison of the internal energies of the foam between impactor and HBM simulations (with 50$^{th}$ percentile male at 50 km/h) showed an equal energy level for the spoiler area. In the bonnet area, energies were 1.4 times higher for the impactor simulations compared to the HBM.

Force-Displacement curves were derived from accelerations and displacements of the centre of the impactor for each load case. Displacements were discretised (2.5-mm steps) and separated into loading and unloading curves (based on the maximum deflection) for each load case and vehicle. The median, maximum and minimum force values were derived for each discretised displacement over all vehicles and within grouped vehicle categories. The variation between the median values for each vehicle category was smaller than the variation within one category. Therefore, the median force-deflection curve was derived over all vehicle categories. The only exception was the roadster bonnet impact (RDS), which is why a hard bonnet stop was introduced earlier for this type of vehicle. The detailed results are available in Klug (2018).

The result of the impactor simulations on the GV models are documented in MR1 and available as part of the auxiliary files for the plausibility check. The impact conditions in the plausibility check are the same as the impactor simulations on the full FE car models for the original corridor development. This enables a comparison to the median responses derived from serial cars. The corridors for the plausibility check are based on the responses of the GV models in the 3 different FE codes at the time of development. The force displacement curves were resampled with a step size of 0.1 mm. Mean and standard deviation were calculated from the resampled curves. To the mean value the maximum value of 3 standard deviations up to the considered displacement was added and subtracted at each displacement (to avoid implausible narrowing of the corridors at higher displacements). The corridor was created up to the mean value of the maximum displacement of the 3 responses, subtracted by the maximum of 3 standard deviations of the maximum displacements and 10% of the mean maximum displacements. The vertical line in the corridor, which shall not be exceeded, is the mean value plus the maximum of 3 standard deviations of the maximum displacements and 10% of the mean maximum displacements. This approach was chosen iteratively to achieve a compromise of a plausible, but not too wide corridor neglecting numerical oscillations. A hard stop is implemented as contact between the outer and inner layer to avoid instabilities of the foam and increase the robustness and comparability between codes of the GV models. The foam material’s stiffness is exponential increasing after ~80% compression to additionally avoid negative volumes within the foam in case of high local deformation. All foam material curves have been tuned to get as close as possible to the median curves from the corridors and as close as possible to each other in between the different FE codes.

# Development of GV Models (in 2016)



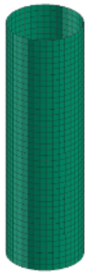



# Development of GV Models (in 2016)

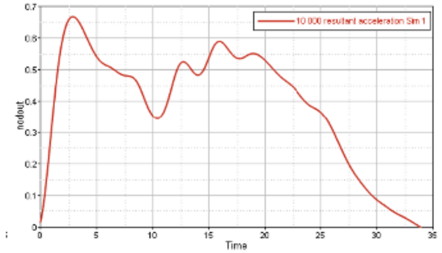


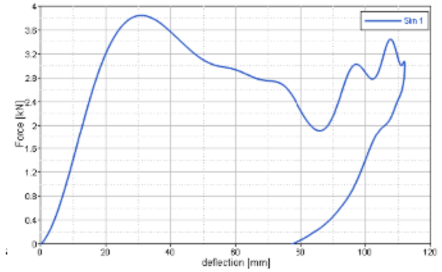
## Impactor

- Cylindrical Impactor
  - Material: Elastic plastic steel
  - Diameter: 120 mm
  - Height: 400 mm
  - Shell thickness: 5 mm
  - Density: 7.89E-6kg/$mm^3$
  - Mass: 6 kg
  - Element size: 10 mm
  - CoG of Cylinder = origin of local coordinate system
  - Initial transformation :
    - 65 mm in x-direction + offset (if needed)
  - Initial velocity: 40 km/h in local x-direction of impactor
  - Other degrees of freedom constraint
  - Contact: Shell thickness not considered, soft contact, $\mu=0.3$
- Output:
  - Node history of node 10 000 = CoG of Cylinder, use local coordinate system (acceleration- time curve)
  - Contact forces (Force deflection curve)



High energy to ensure intrusion (to engine block)






The stiffness of the GV models was calibrated to achieve a robust stiffness behaviour close to a median response derived from FE simulations on serial cars using a cylindrical rigid impactor. The impactor has a mass of 5.95 kg, diameter of 120 mm and length of 400 mm. The impactor was modelled as a rigid structure to minimise code-specific effects, as impactor simulations were performed with four different FE software packages. The energy level of the impactor was selected as an overall compromise of the different body parts impacting the vehicle in angles and speeds depending on the shape and stiffness of the vehicle. With an initial kinetic energy of nearly 400 J even severe contact conditions such as elbow contact on the bonnet are covered.
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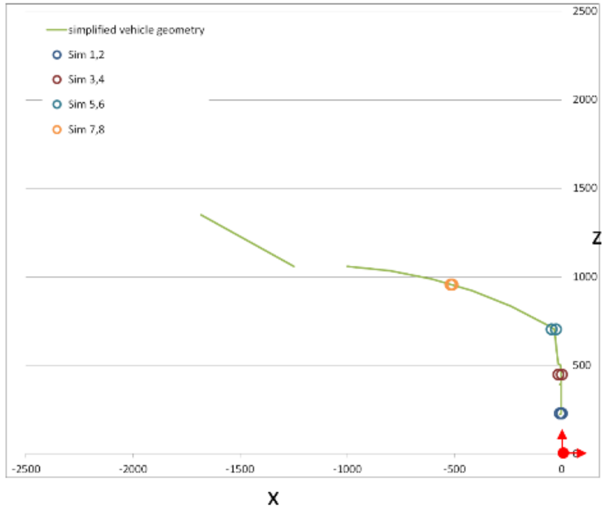
# Development of GV Models (in 2016)

www.tugraz.at

## Calculation of Impact Points – Output Example

- Impact points are calculated based on the geometry input
- Please check for initial penetrations (especially at bonnet impact) and adapt parameter “offset” slightly if needed
- Run 8 simulations
- Initial transformation of vehicle:
  - **most frontal point of vehicle at ground level = origin**
  - **x-direction= driving direction**

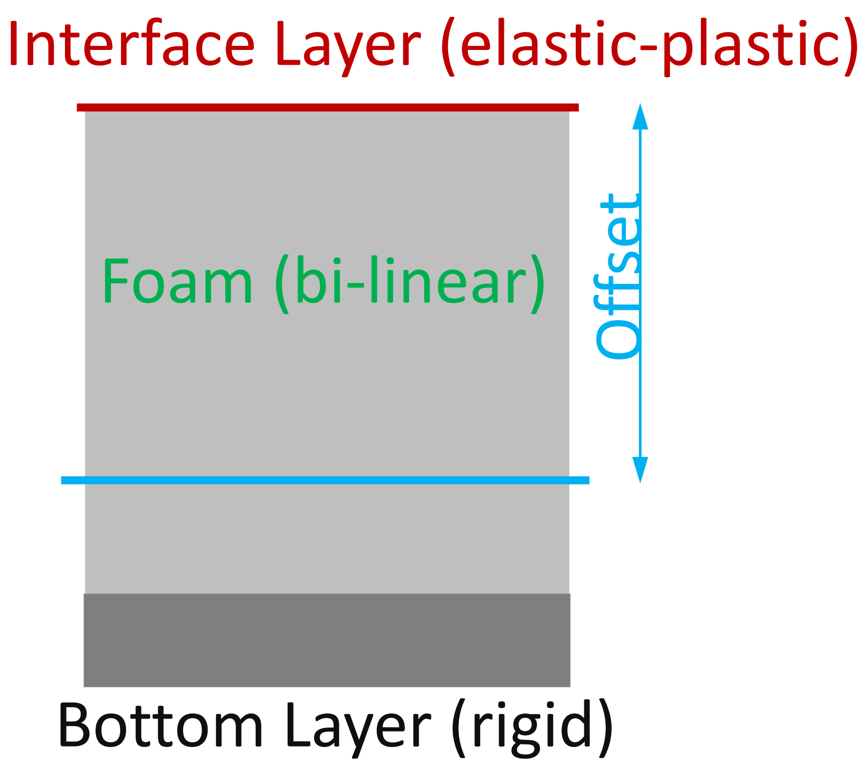
| | Impactor Position | | | | |
|---|---|---|---|---|---|
| Simulation ID | orient | x | y | z | offset |
| 1 | 45 | 0 | 0 | 228 | 0 |
| 2 | 45 | -10 | 800 | 228 | 0 |
| 3 | 90 | 0 | 0 | 448 | 0 |
| 4 | 90 | -15 | 800 | 448 | 0 |
| 5 | -50 | -28 | 0 | 703 | 0 |
| 6 | -50 | -48 | 800 | 703 | 0 |
| 7 | -75 | -567.1 | 0 | 927.5 | 0 |
| 8 | -75 | -577.1 | 800 | 927.5 | 0 |

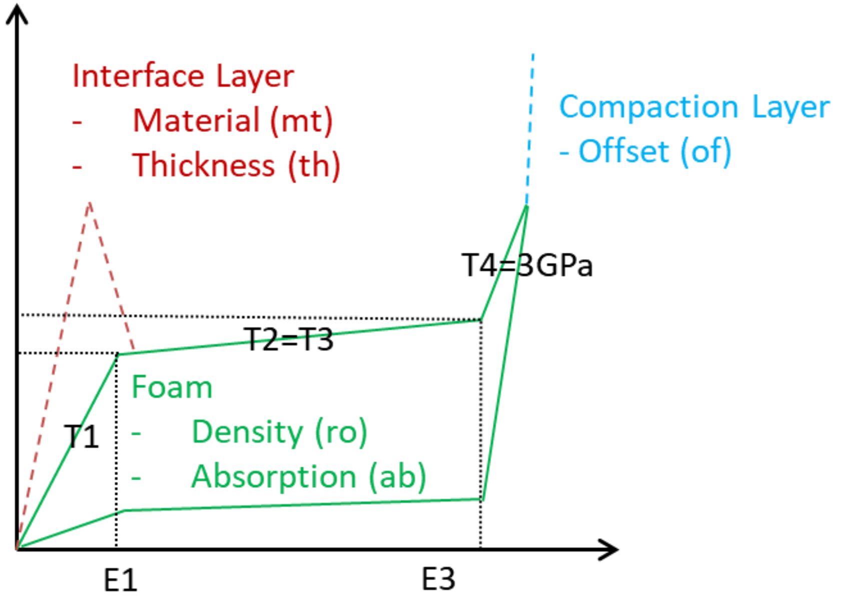


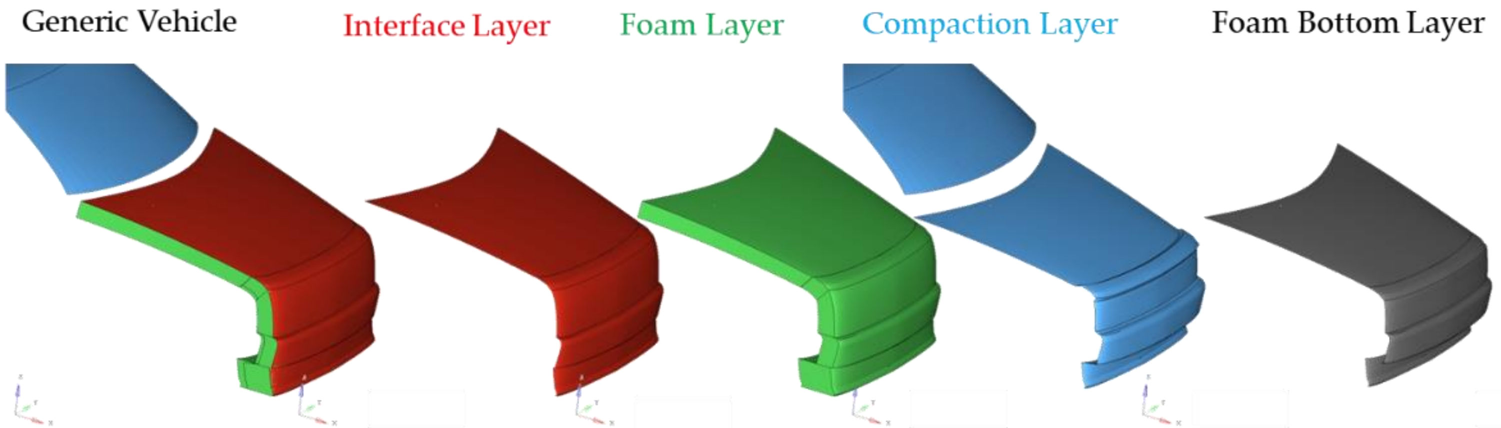



A detailed protocol and calculation tool was provided to ensure comparable impact points on the different vehicle shapes.

# Generic Vehicle Models



# Evaluation criteria for GV Model Development

1.) Robust design of GV models (no error terminations, problems in code updates).

2.) Response as close as possible to the Median curve.

3.) Response in different codes as close as possible.

**If 2) causes a problem for 1) or 3), 2 was given lower priority as the aim is not to replicate one specific car, but have GV models which behave as consistent as possible within one and within different solvers (<u>reproducibility & repeatability</u>)**

All foam material curves have been tuned to get as close as possible to the median curves from the corridors and as close as possible to each other in between the different FE codes. The same foam material models are used for all GV shapes.

# Comparison of GV Model response and responses from serial cars in impactor simulations

Corridors have been created from FE simulations on serial cars using a cylindrical rigid impactor. The impactor has a mass of 5.95 kg, diameter of 120 mm and length of 400 mm. The impactor was modelled as a rigid structure to minimise code-specific effects, as impactor simulations were performed with four different FE software packages. The energy level of the impactor was selected as an overall compromise of the different body parts impacting the vehicle in angles and speeds depending on the shape and stiffness of the vehicle. With an initial kinetic energy of nearly 400 J even severe contact conditions such as elbow contact on the bonnet are covered.

Force-Displacement curves were derived from accelerations and displacements of the centre of the impactor for each load case. Displacements were discretised (2.5-mm steps) and separated into loading and unloading curves (based on the maximum deflection) for each load case and vehicle. The median, maximum and minimum force values were derived for each discretised displacement over all vehicles and within grouped vehicle categories. The variation between the median values for each vehicle category was smaller than the variation within one category. Therefore, the median force-deflection curve was derived over all vehicle categories. The only exception was the roadster bonnet impact (RDS), which is why a hard bonnet stop was introduced earlier for this type of vehicle. The detailed results are available in Klug (2018).

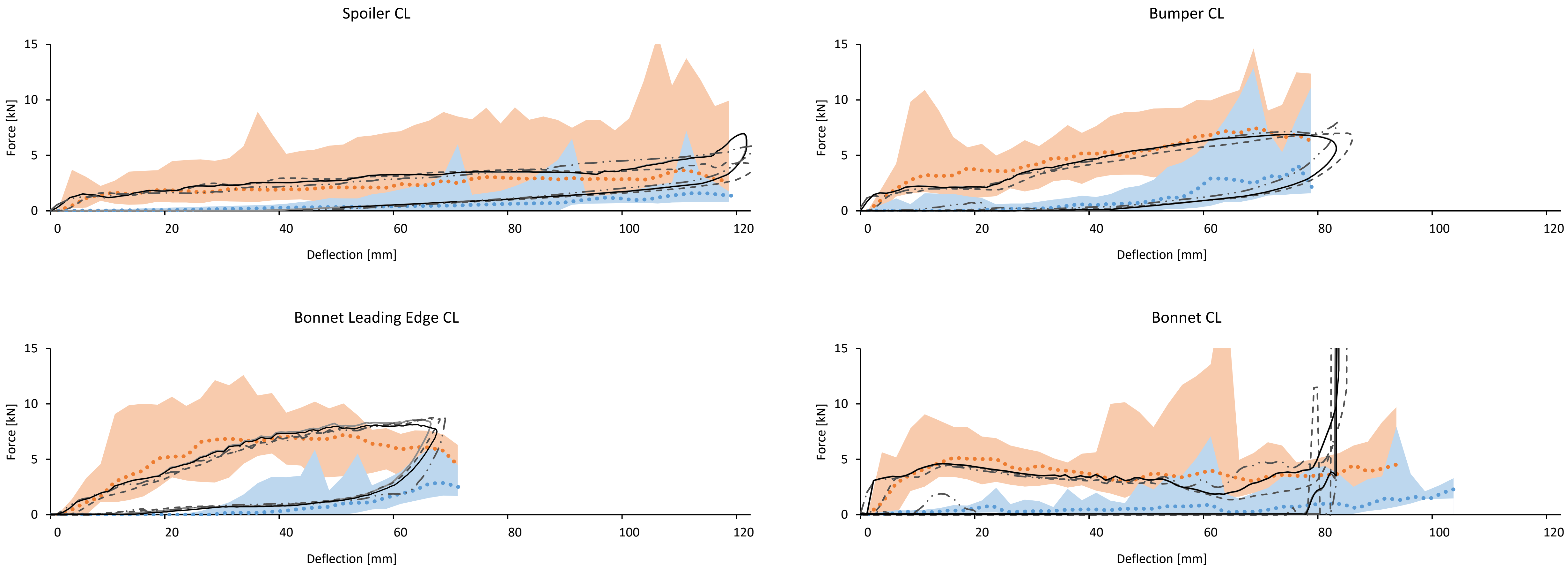
The median responses were used for optimization of the foam material models and interface layer thickness. The same material models are applied throughout all vehicle shapes for easier maintenance and because no significant differences in steiffness in between the vehicle categories form the serial cars have been observed. The force-deflection response of the GV models was qualitatively compared with the derived corridors to check if the response is within the range of serial cars.

# Evaluation of the GV Models

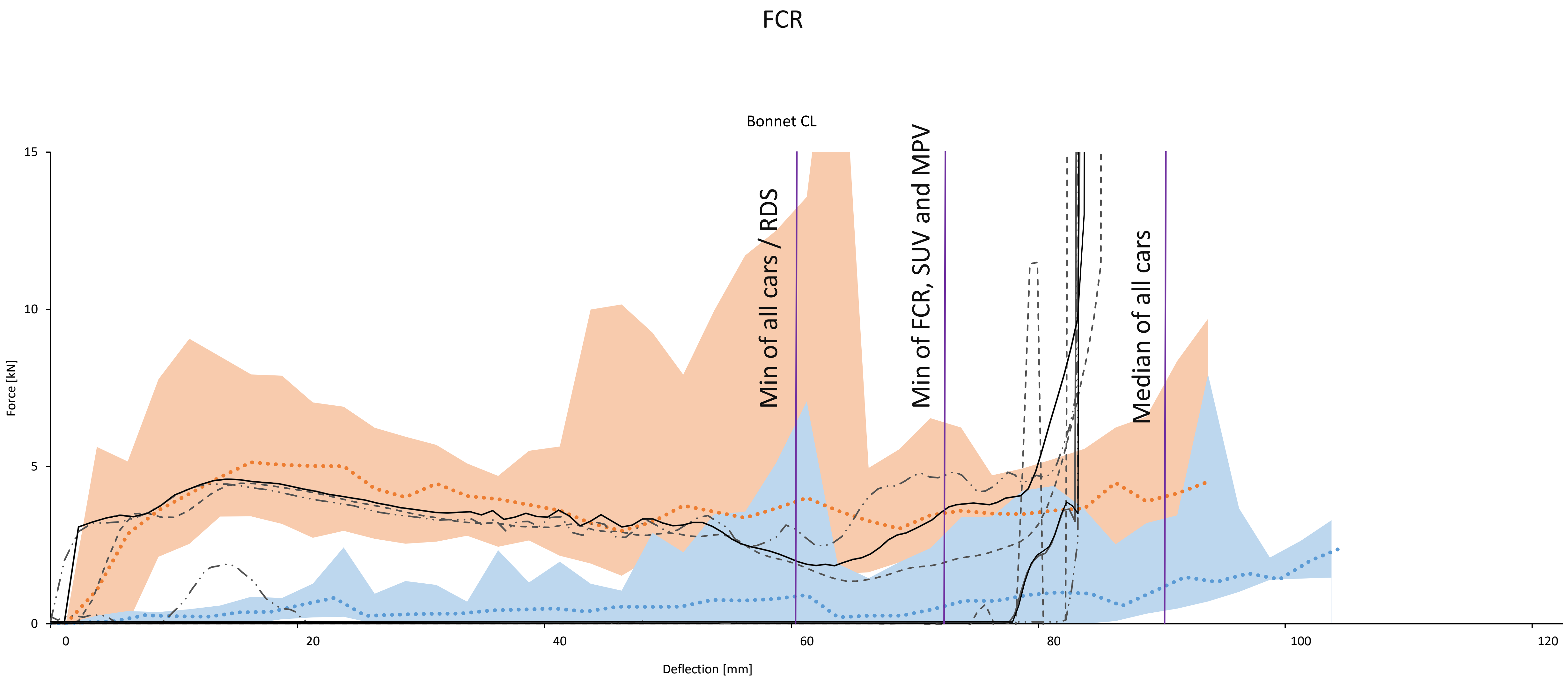
The possibilities for quantitative evaluation are limited, as the corridors do not represent time series. To make the results from different cars with different geometries comparable, Force-Deflection corridors are used. The comparison of the GV models with the corridors does not represent a validation. The GV models have no physical counterpart. The comparison with the corridor is done to check if the response is within the range of real cars and therefore not unrealistic.

# Comparison of GV R3 response with original corridors from Klug et al., 2017

FCR

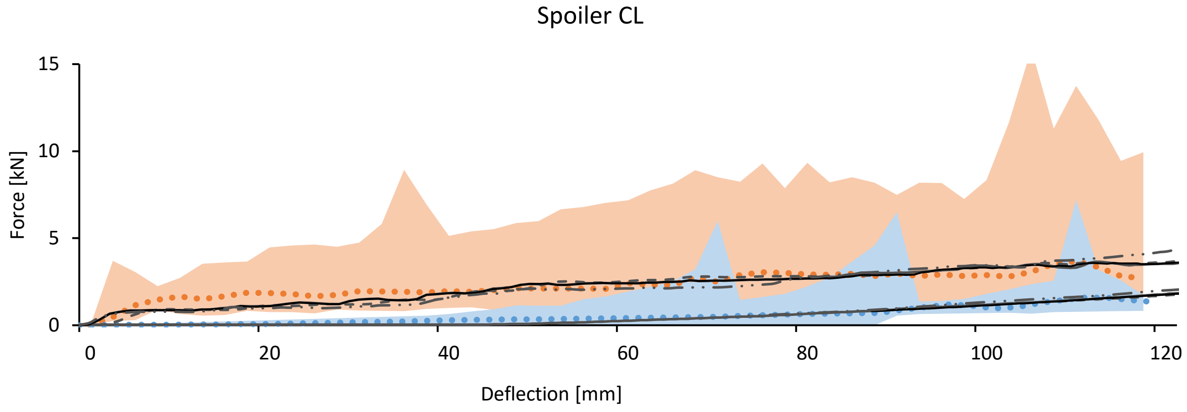


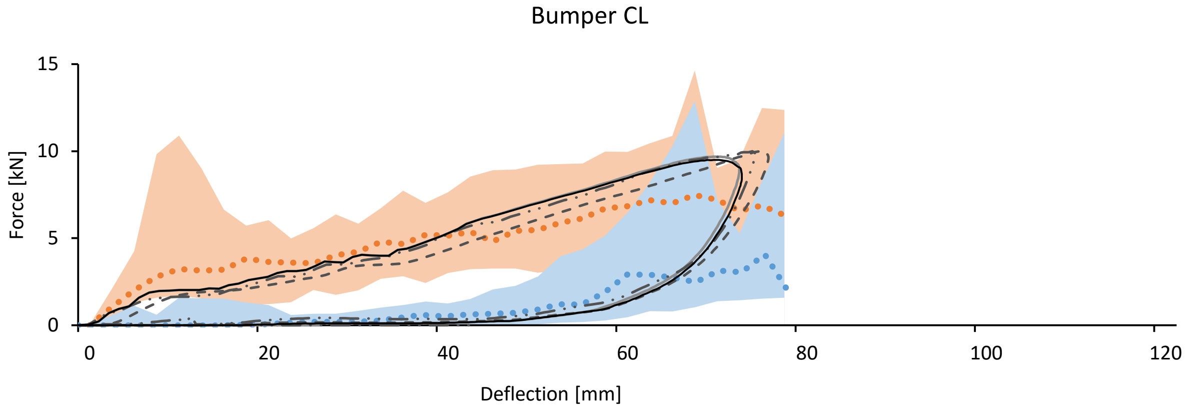
# Comparison of GV R3 response with original corridors from Klug et al., 2017

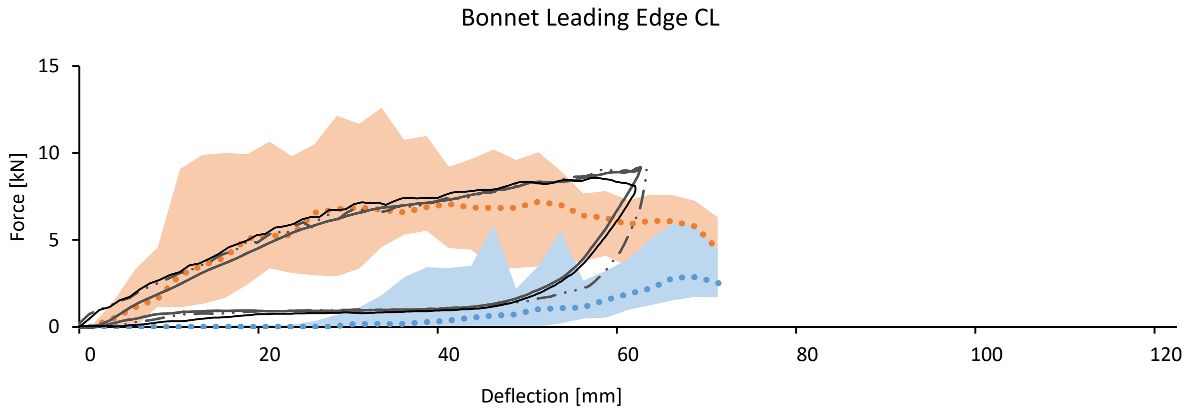


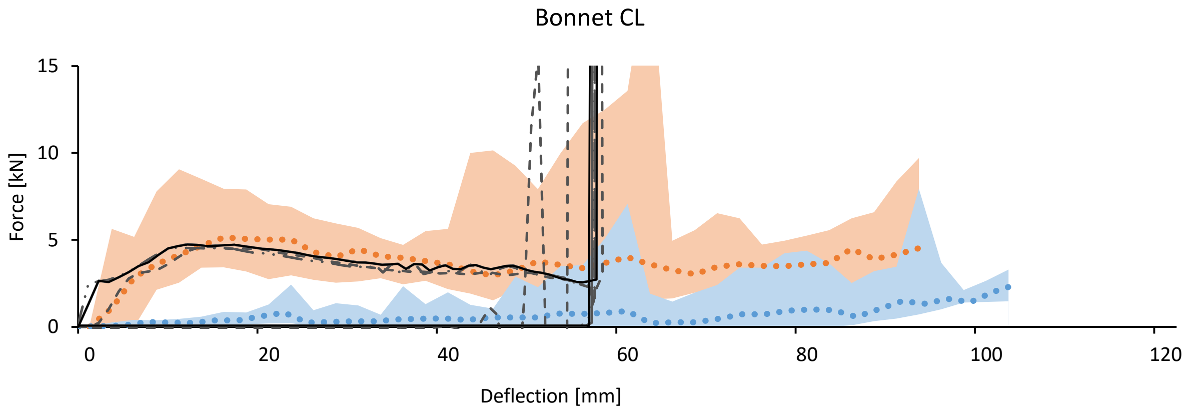
# Comparison of GV R3 response with original corridors from Klug et al., 2017

RDS



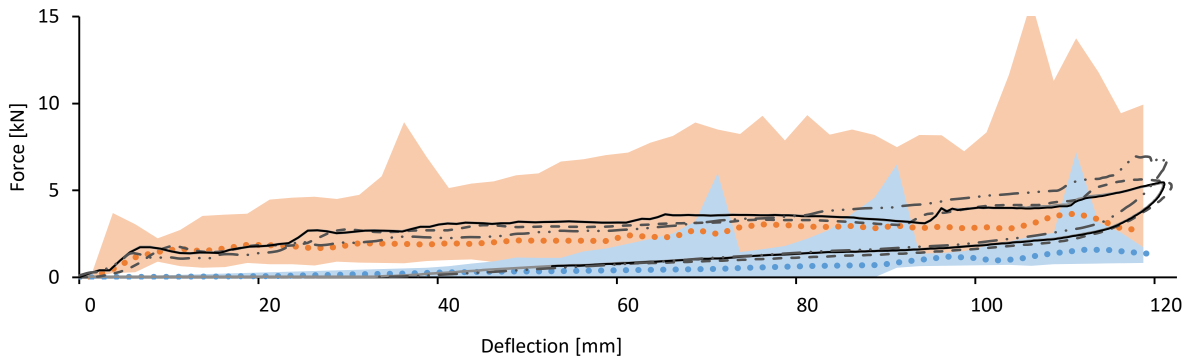



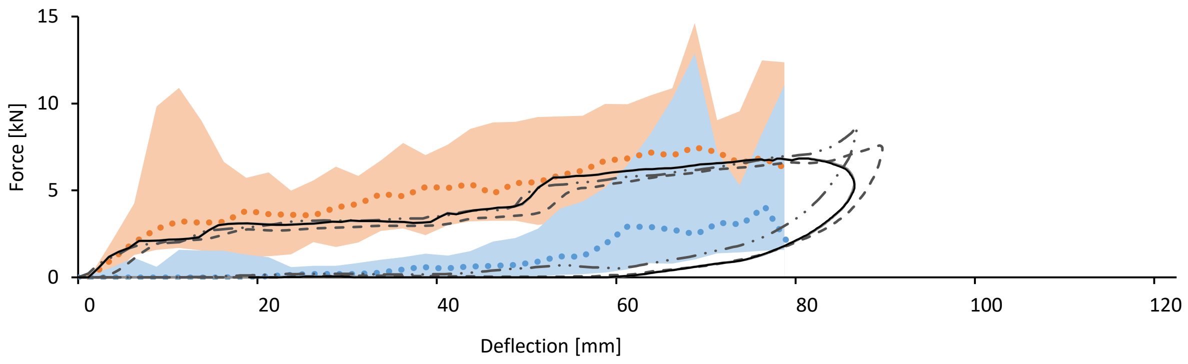
# Comparison of GV R3 response with original corridors from Klug et al., 2017

SUV

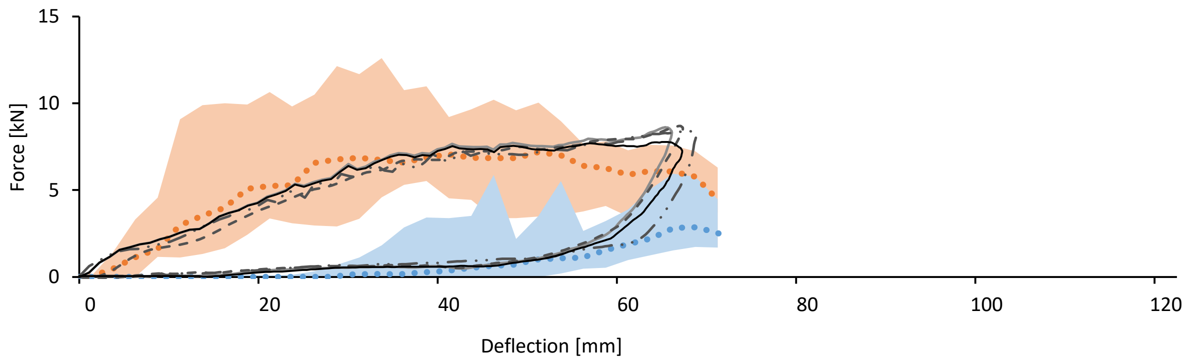
Spoiler CL



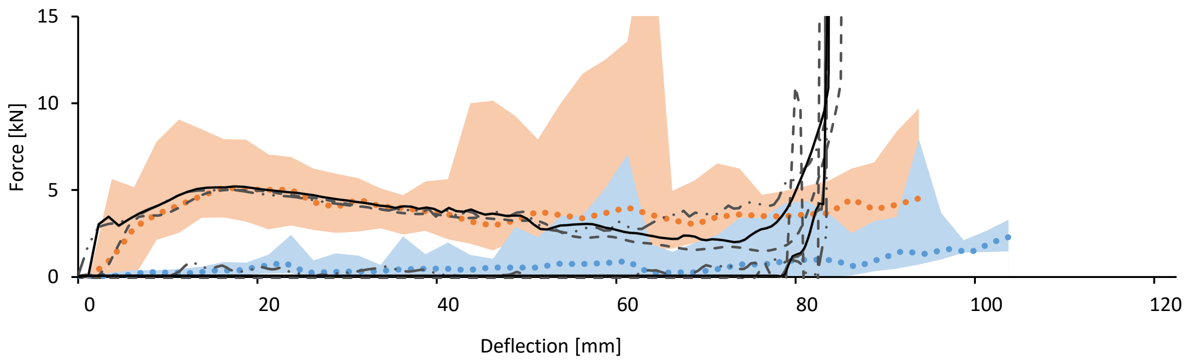

Bumper CL



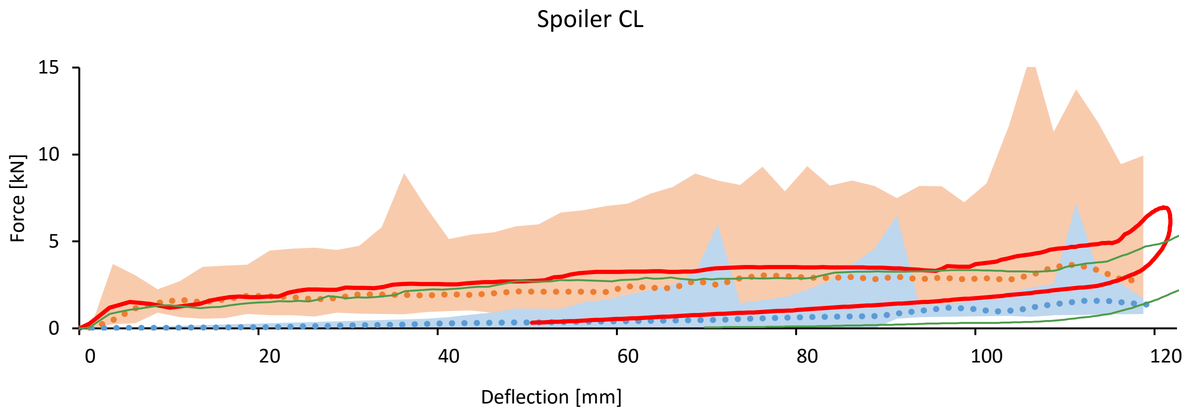

Bonnet Leading Edge CL

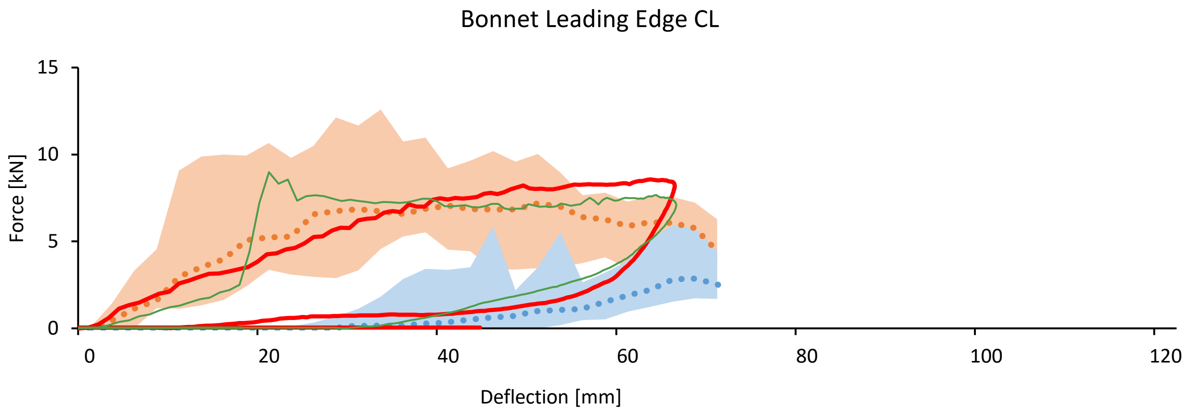


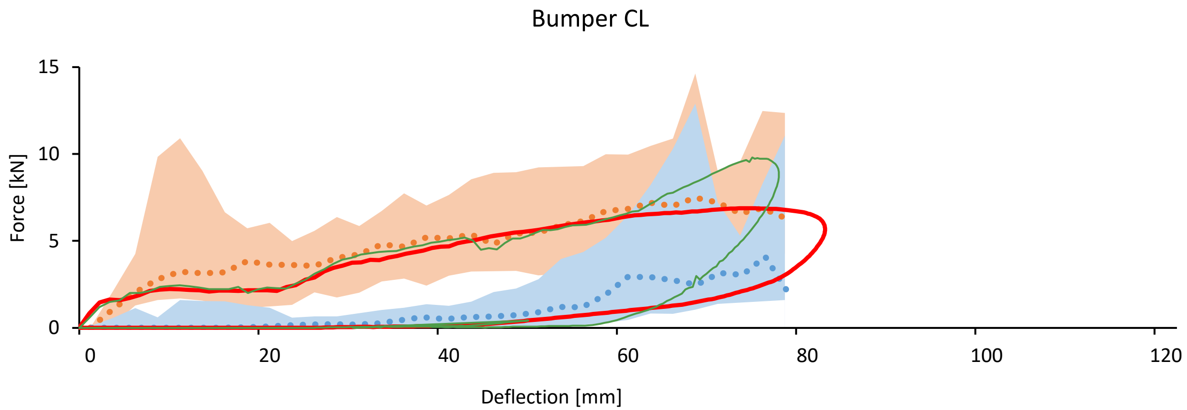

Bonnet CL

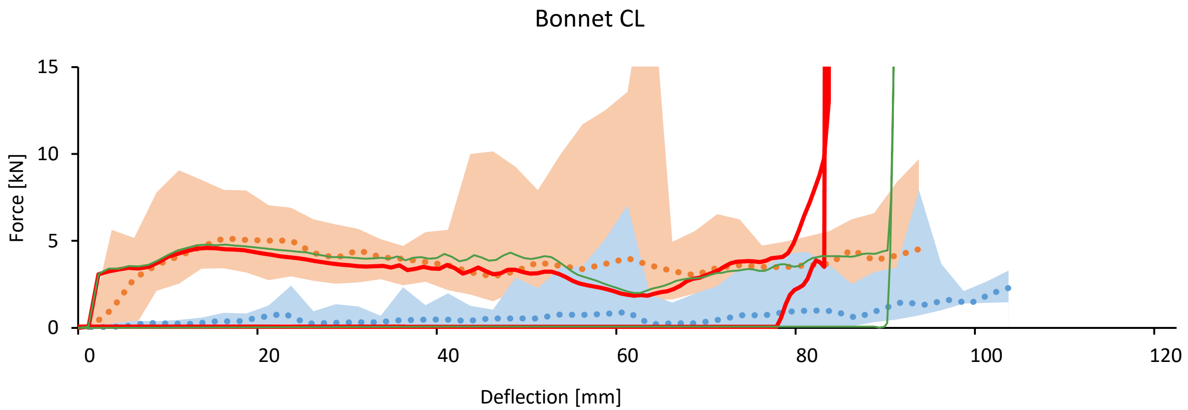


# GV Models- Comparison of GV Models R2 vs. R3 (FCR)



# Summary of GV model Updates

## Previous releases of GV models (R1+R2)

- had stability issues in BLE area (causing error terminations in some child models)
- showed differences in behavior in different codes in some areas (spoiler and bonnet)
- required to differentiate between code versions in VPS

## New GV model release (R3)

- are an update and address only these issues;
- had only minor effects on HBM responses
- have been tested by different users globally since June 2022 (internal tests at code houses and TU Graz already before) and showed to be very robust
- Were used to establish reference corridors for HIT & head impact location (HCx & HXz @ HIT) presented in Addendum 4 of MR1

# Why is a hard stop included in the GV models?

A hard stop is implemented as contact between the outer and inner layer to avoid instabilities of the foam and increase the robustness and comparability between codes of the GV models. The foam material's stiffness is exponential increasing after ~80% compression to additionally avoid negative volumes within the foam in case of high local deformation. All foam material curves have been tuned to get as close as possible to the median curves from the corridors and as close as possible to each other in between the different FE codes.

- also in a serial car, stiff structures (engine) can be reached
- robust foam model needs increase of the force too avoid 100% compression → negative volumes

- Even if hard stop occurs, so far no problem with the HBM kinematics observed although implemented since the beginning in the GV models and all animations nad overall contact forces are always checked.
- Sensitivity study to investigate the effect of different stiffness areas of the GV has been performed → Negligible effect of the bonnet stiffness on HIT, sensitive to stiffness of BLE, bumper and spoiler  (Klug et al., 2018)

# Why to perform impactor simulations up to the hard stop?

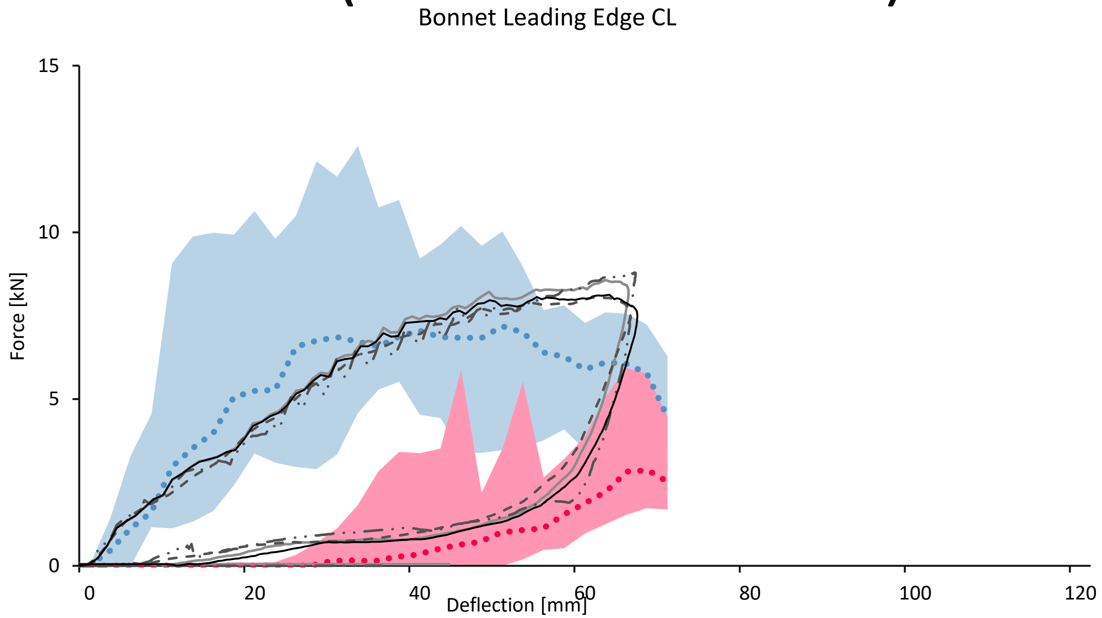
The corridors and impactor simulations are only there to check if updates of the models are still robust. One important criterion to check the robustness is that the bottoming out is working properly and the foam can not compress after a certain stage to avoid negative volumes in simulations.

Even if the thickness would be increased, an increase of force before reaching 100% of strain is needed, because the strain in single elements can be higher than the overall displacement divided by the original thickness.

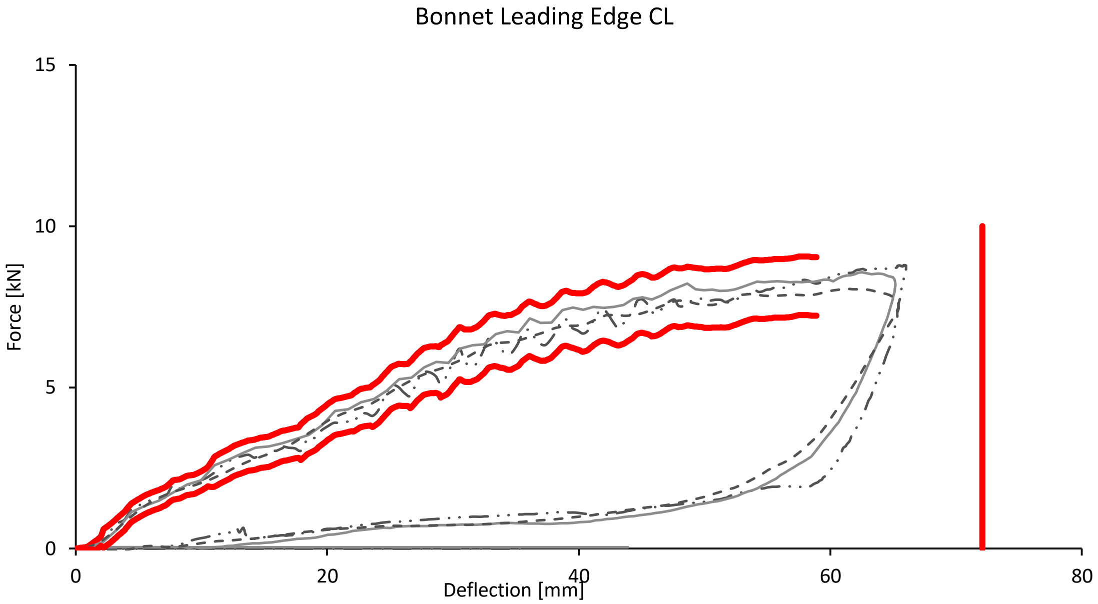
# Corridors for plausibility check

(are the GV models behaving as they should in new solver versions?)

old (Euro NCAP TB024)



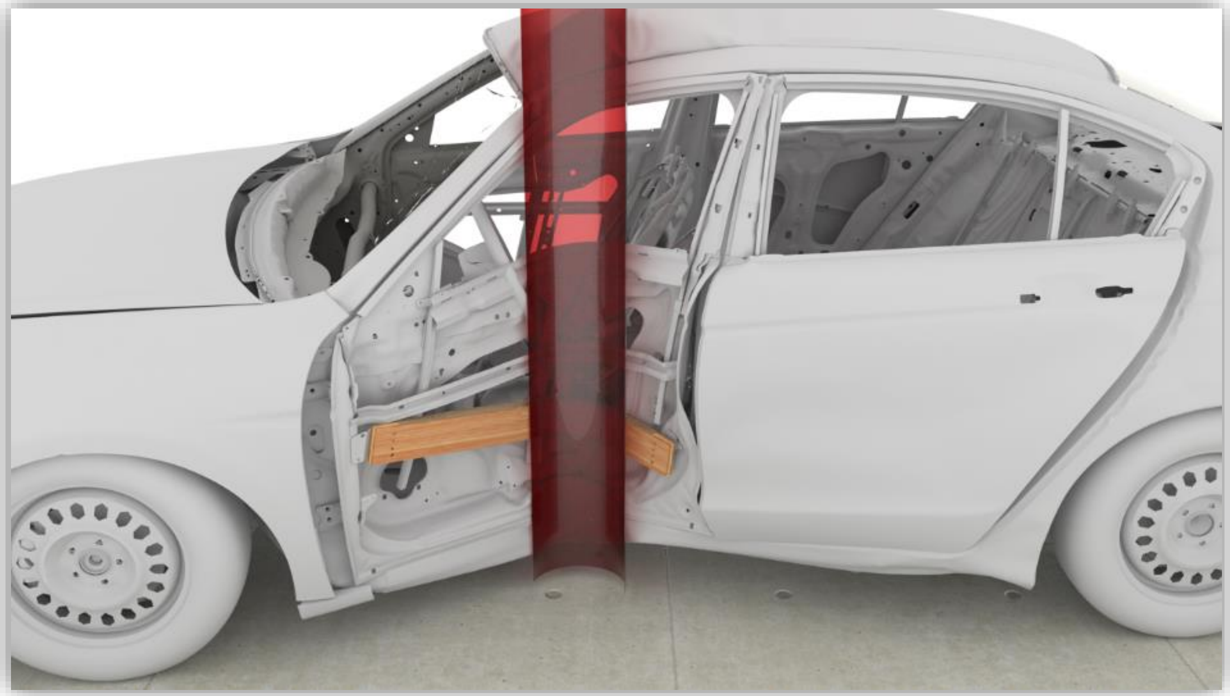

new




The result of the impactor simulations on the GV models are documented in MR1 and available as part of the auxiliary files for the plausibility check. The impact conditions in the plausibility check are the same as the impactor simulations on the full FE car models for the original corridor development. This enables a comparison to the median responses derived from serial cars. The corridors for the plausibility check are based on the responses of the GV models in the 3 different FE codes at the time of development. The force displacement curves were resampled with a step size of 0.1 mm. Mean and standard deviation were calculated from the resampled curves. To the mean value the maximum value of 3 standard deviations up to the considered displacement was added and subtracted at each displacement (to avoid implausible narrowing of the corridors at higher displacements). The corridor was created up to the mean value of the maximum displacement of the 3 responses, subtracted by the maximum of 3 standard deviations of the maximum displacements and 10% of the mean maximum displacements. The vertical line in the corridor, which shall not be exceeded, is the mean value plus the maximum of 3 standard deviations of the maximum displacements and 10% of the mean maximum displacements. This approach was chosen iteratively to achieve a compromise of a plausible, but not too wide corridor neglecting numerical oscillations.

# Summary

The GV models were developed to be robust and repeatable enough to be used for reference simulations with HBMs to derive head impact times and locations for the qualification of HBMs. **They shall not be used for any other purposes.**



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