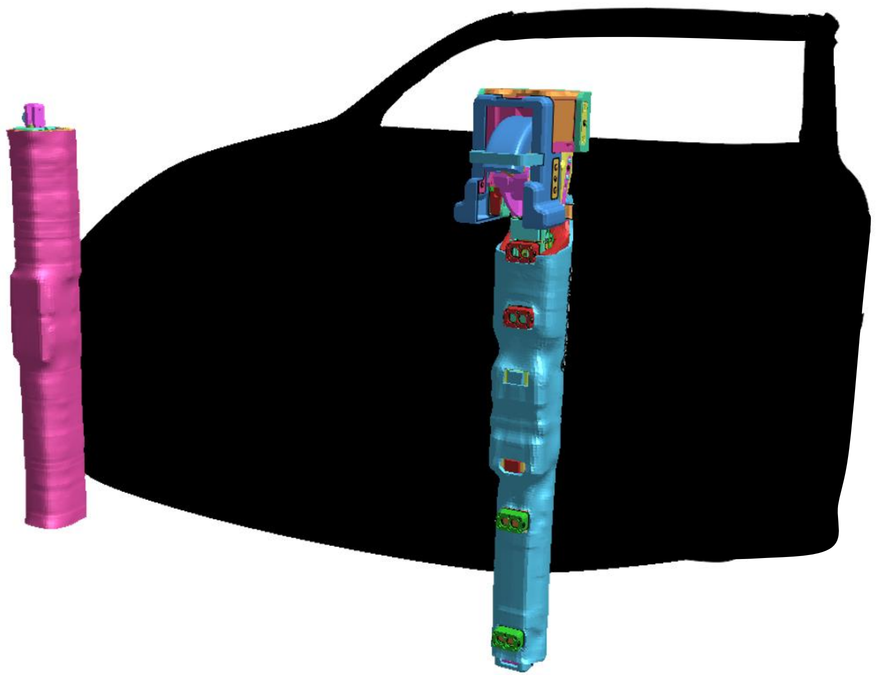
Exploration of Asymmetric Ligament Behaviours of Lower Leg Injury in Automotive Pedestrian Impact

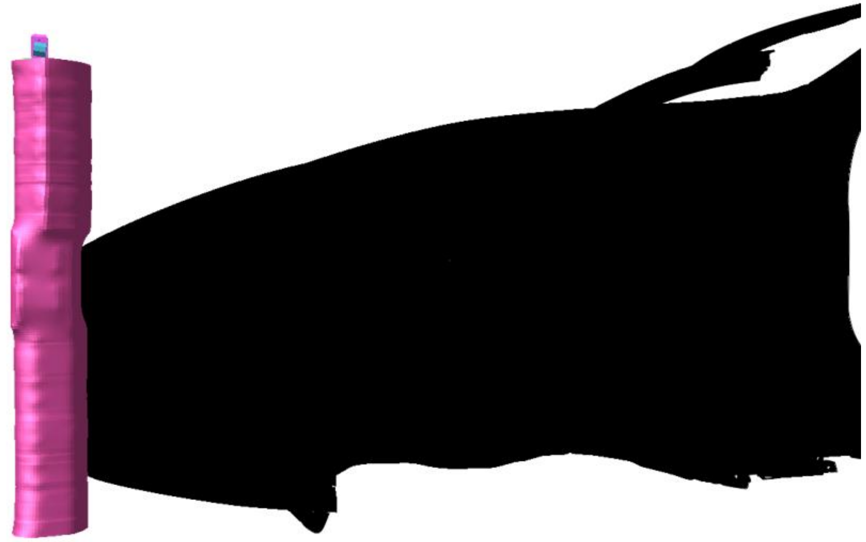
Ben Crone (Arup) , Jean Bout (Arup)

Oasys LS-DYNA Environment | ARUP

A Recent Project…

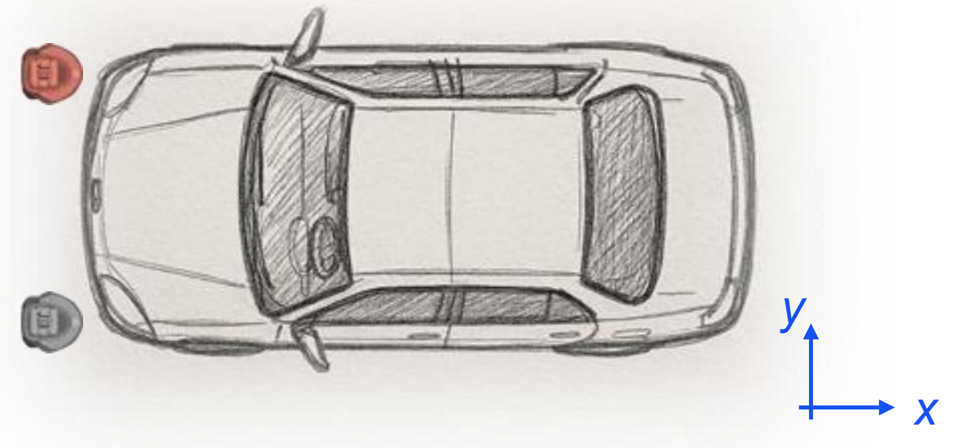
- Pedestrian impact assessment for UN ECE R127 and NCAP loadcases.
- Sports geometry such that upper portion of legform does not contact vehicle bumper system.
- The impactor models in use are:
  - Humanetics Flex-PLI v1.5.1
  - Humanetics aPLI v1.2

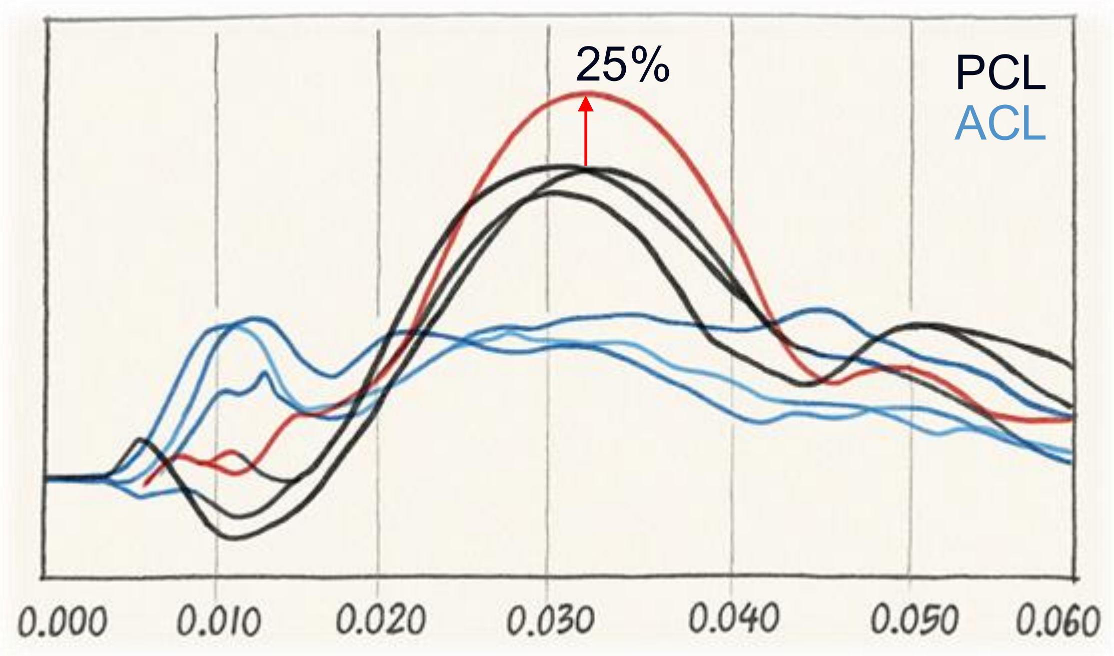




An Unexpected Result…

- During Flex-PLI physical testing, an anomalous result was recorded at the most outboard positive *y* side (RHS).
- >25% greater PCL elongation than the negative side and other RHS repeats.
- Additionally, no comparable anomaly was observed for ACL elongation.
- Only noticeable difference was small degree of impactor in-flight yaw.



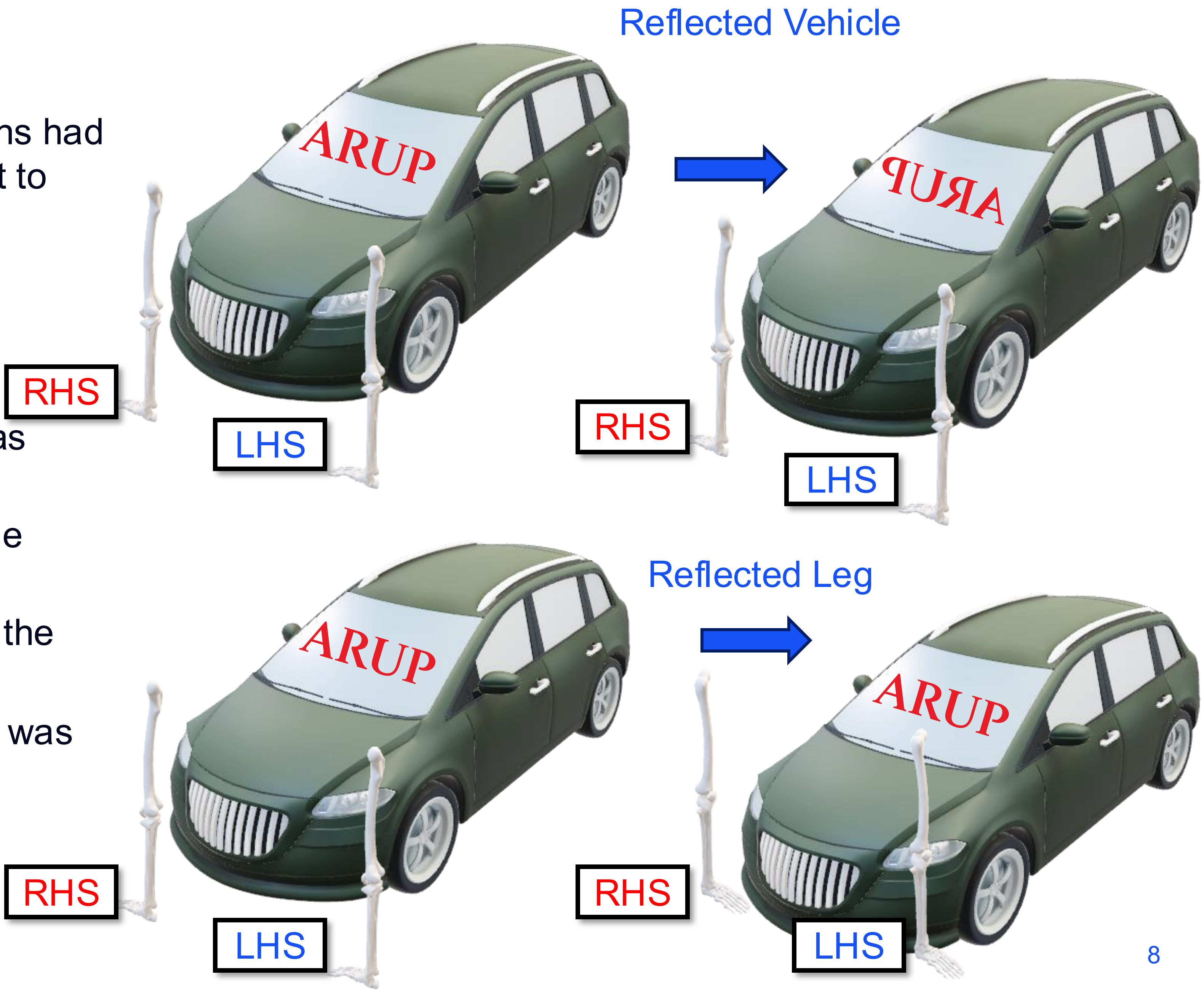


Images produced by Microsoft Copilot

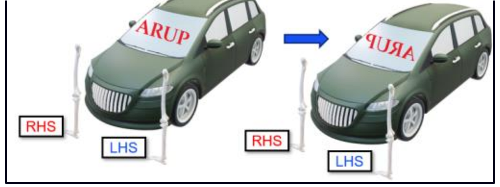
Initial Study

- Prior to physical testing, CAE predictions had not detected a *significant* difference left to right. Small differences in injury were attributed to vehicle asymmetry and/or analysis variability.

- However, through various studies, it was determined that:
    1. A side-to-side difference could be repeatedly reproduced in CAE.
    2. The difference was attributed to the impactor not the vehicle.
    3. The magnitude of the difference was sensitive to impactor yaw.

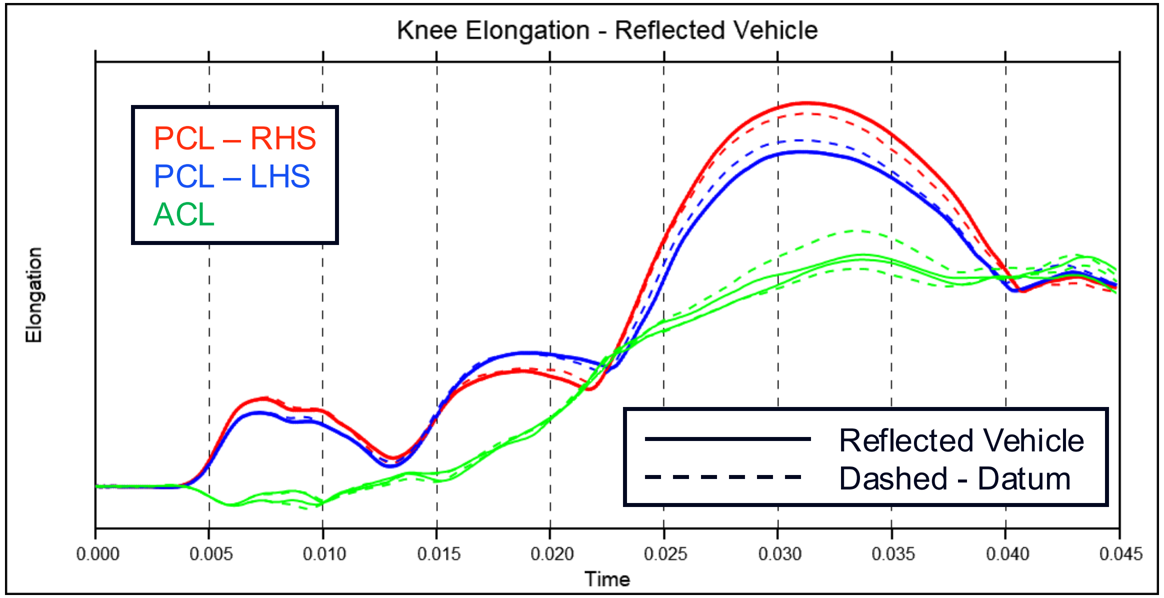


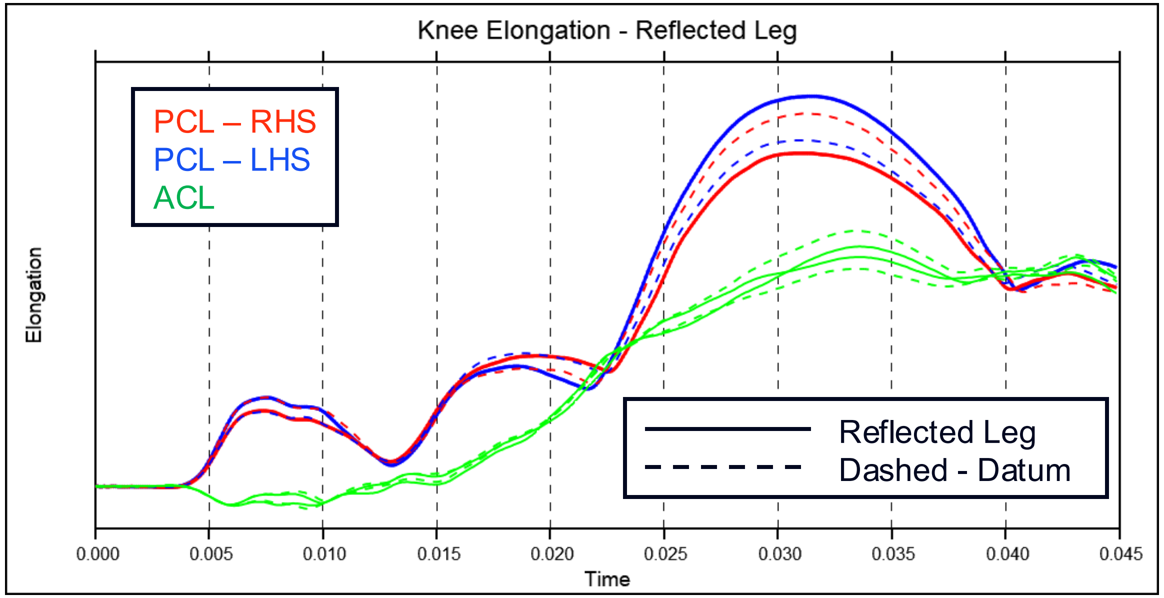
Initial Study

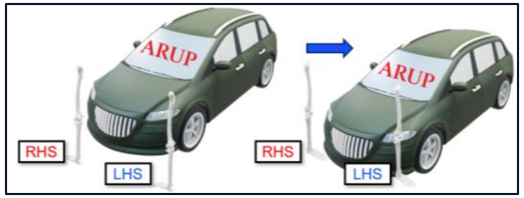


- Prior to physical testing, CAE predictions had not detected a *significant* difference left to right. Small differences in injury were attributed to vehicle asymmetry and/or analysis variability.

- However, through various studies, it was determined that:
    1. A side-to-side difference could be repeatedly reproduced in CAE.
    2. The difference was attributed to the impactor not the vehicle.
    3. The magnitude of the difference was sensitive to impactor yaw.



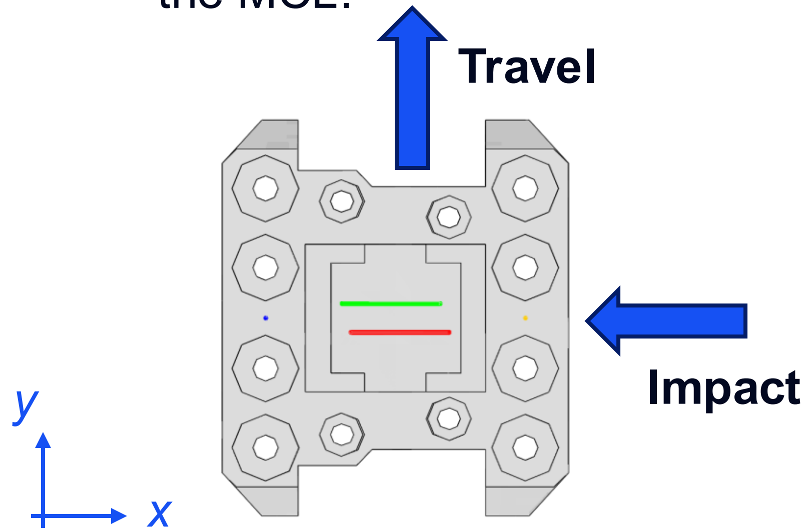


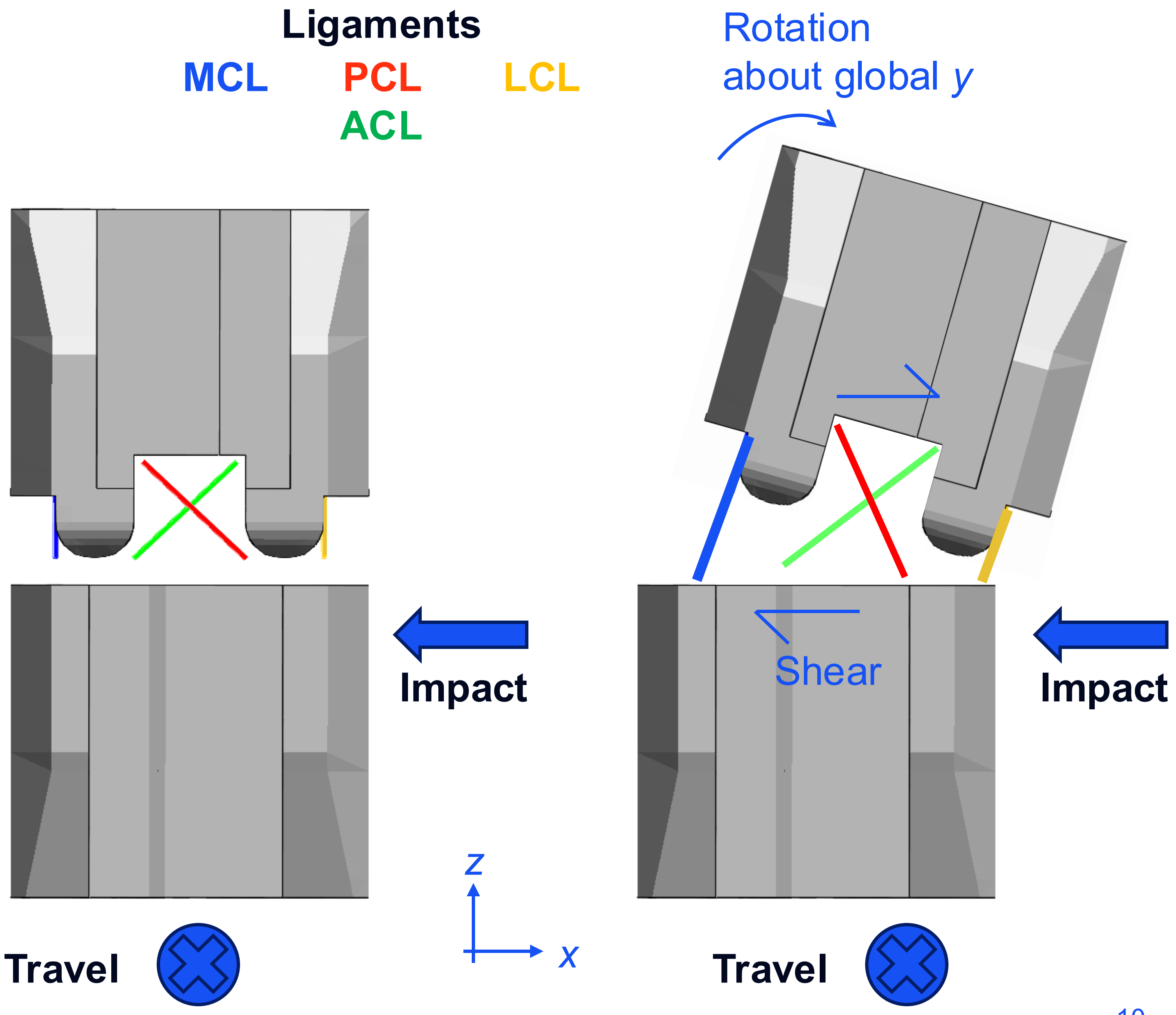


Oasys LS-DYNA Environment | ARUP

Normal Injury Mechanism

- For low vehicles, the lack of upper leg interaction encourages two primary injury mechanisms:
  - Knee/tibia shear generated by the bumper loading only the lower leg.
  - Valgus rotation/bending caused by the unopposed upper leg displacement – tending to elongate the MCL.

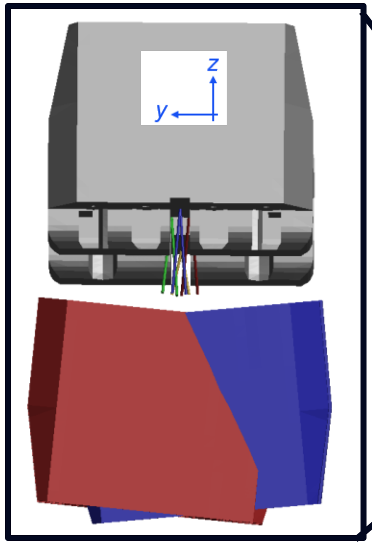




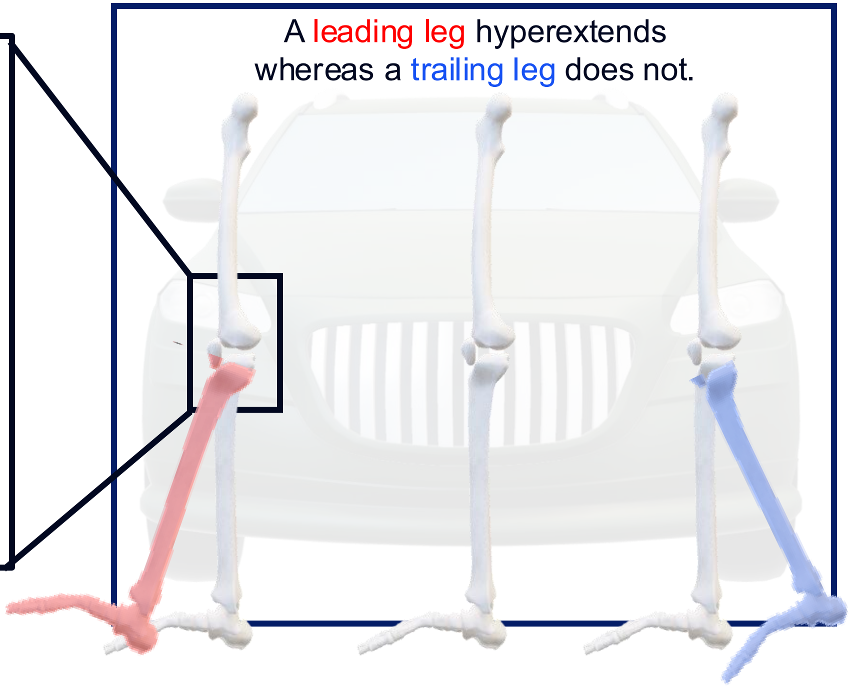
Oasys LS-DYNA Environment | ARUP

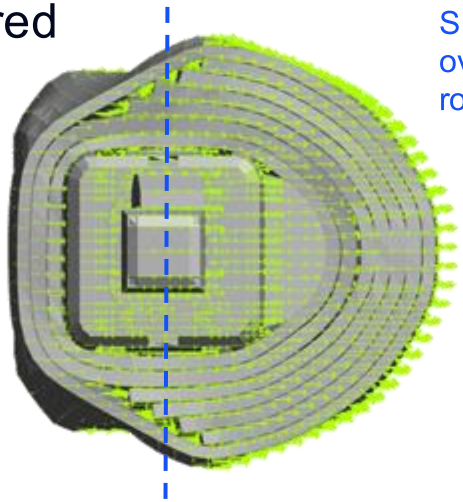
Injury Mechanism

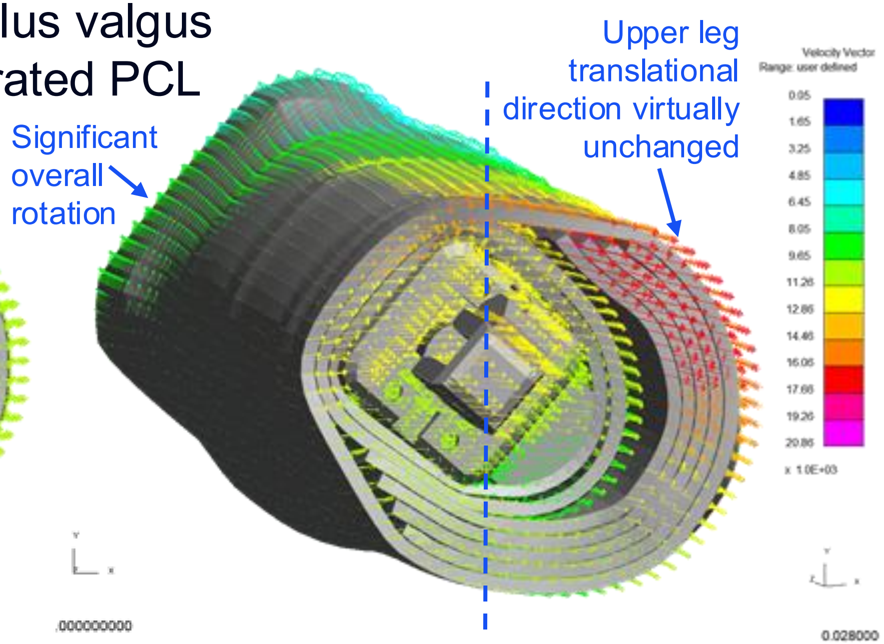
- For corner impacts, the angled A-surface acts to rotate the tibia, which in turn rotates the upper leg, but not its trajectory.
- The consequence is that the upper leg rotates *globally* as normal, but about a *rotated legform local axis*.
- The shift manifests as hyperextension of the tibia, relative to the upper leg.
- The compound behaviour (extension plus valgus rotation and shear) causes an exaggerated PCL elongation compared to baseline.

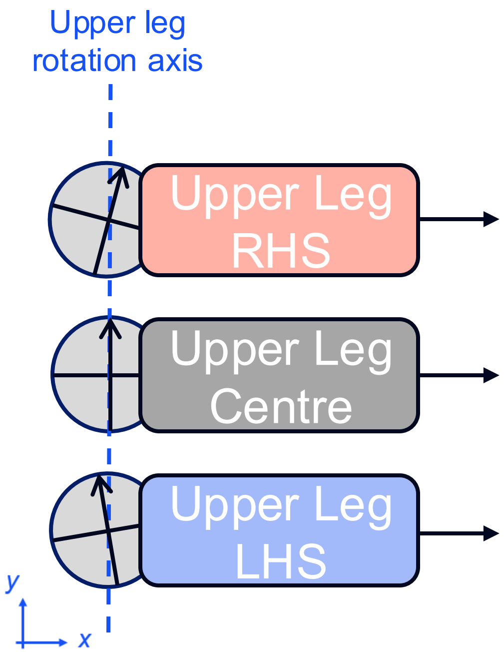


RHS and LHS impacts at time of max injury, with femurs aligned.



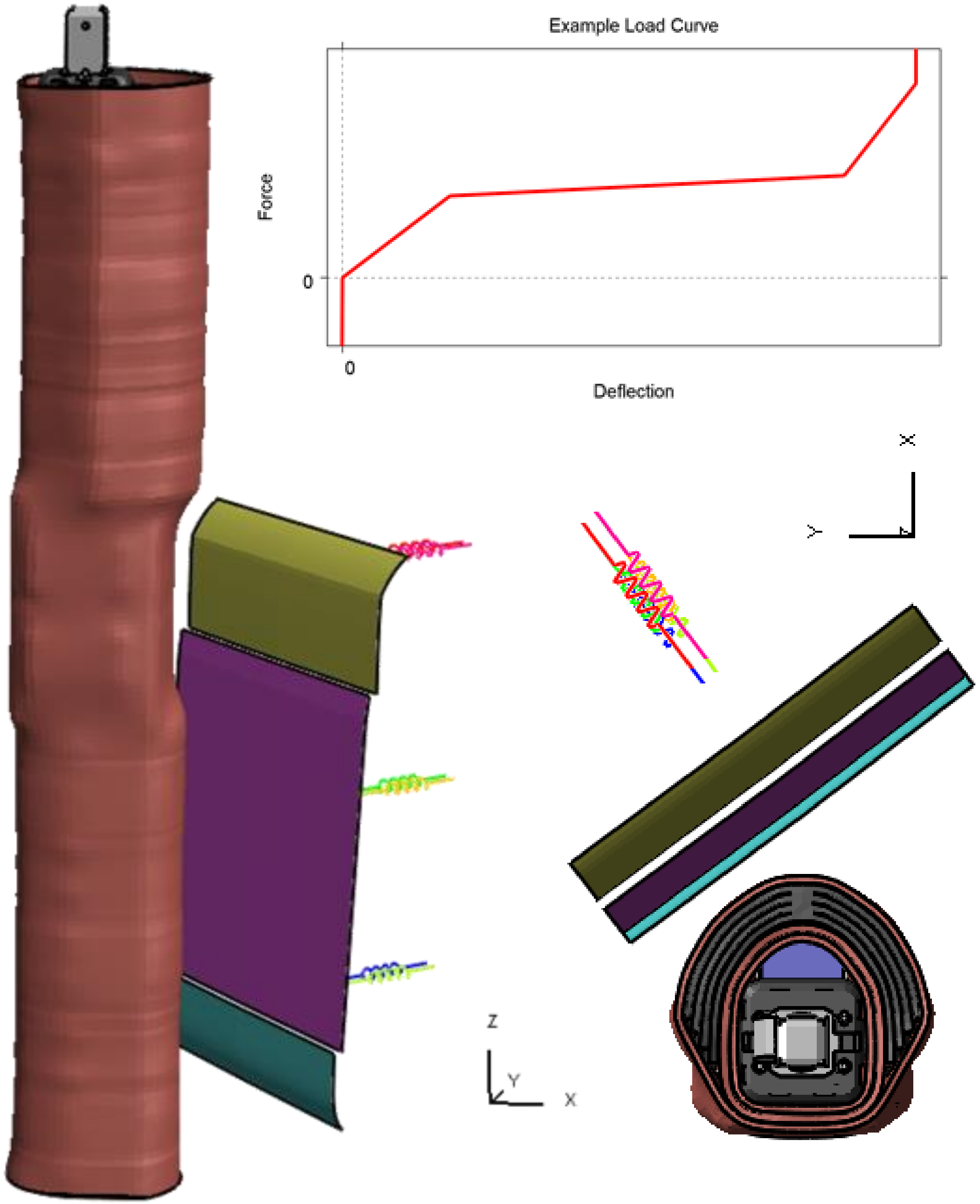






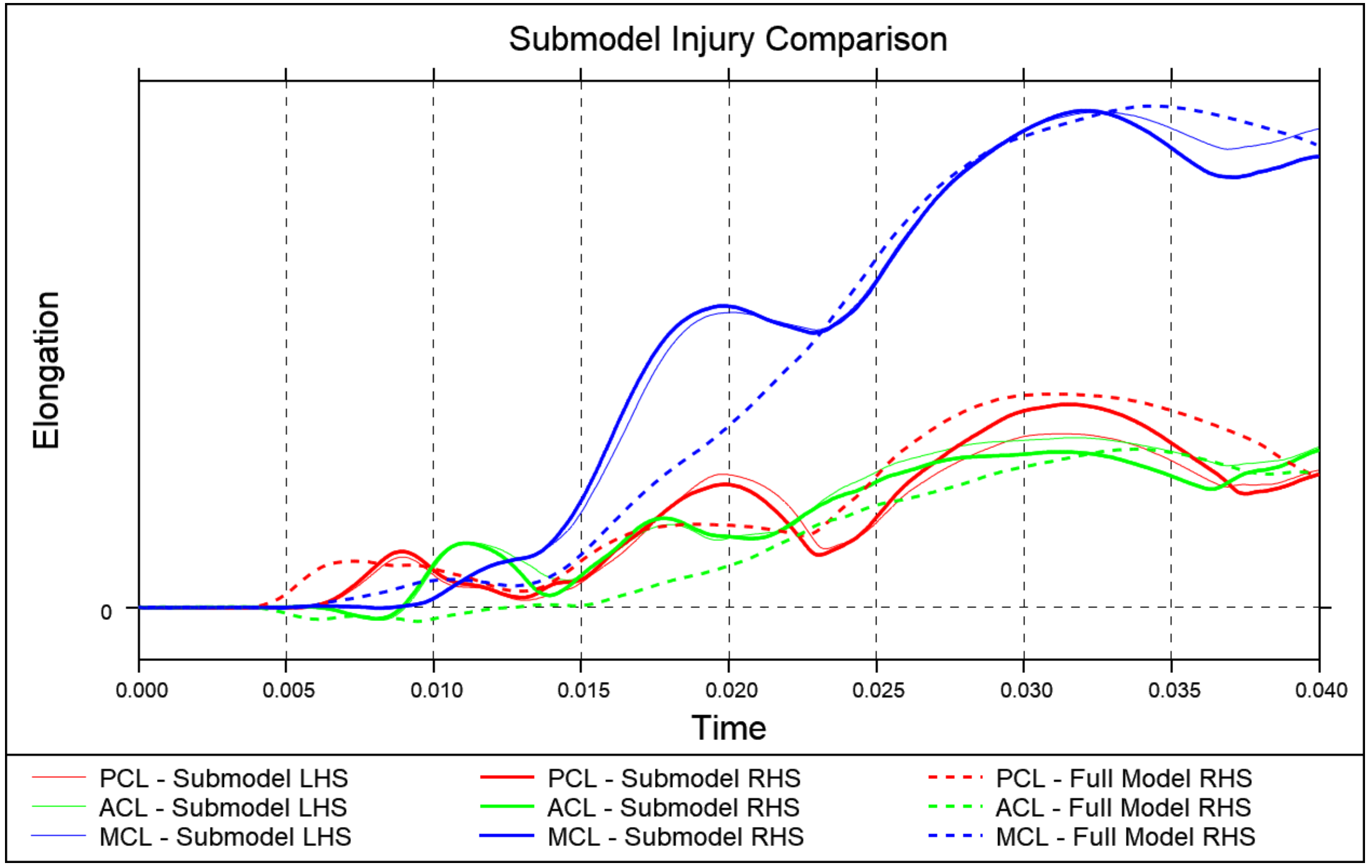
Submodel

- To assess the sensitivity of this behaviour to different vehicle geometries a submodel was created.
- The submodel consisted of three regions of rigid shell elements representing the vehicle A-surface.
- Rearwards of each A-surface region a pair of discrete elements act individually in the global *x* and *y*-directions. The shells were constrained such that they could only move in global *x* and *y*-directions
- The stiffness of the discrete elements was determined using force and displacement transducer output taken from the full vehicle model; implemented using `MAT_S04: SPRING_NONLINEAR_ELASTIC` and one-way curves.



Submodel Validation

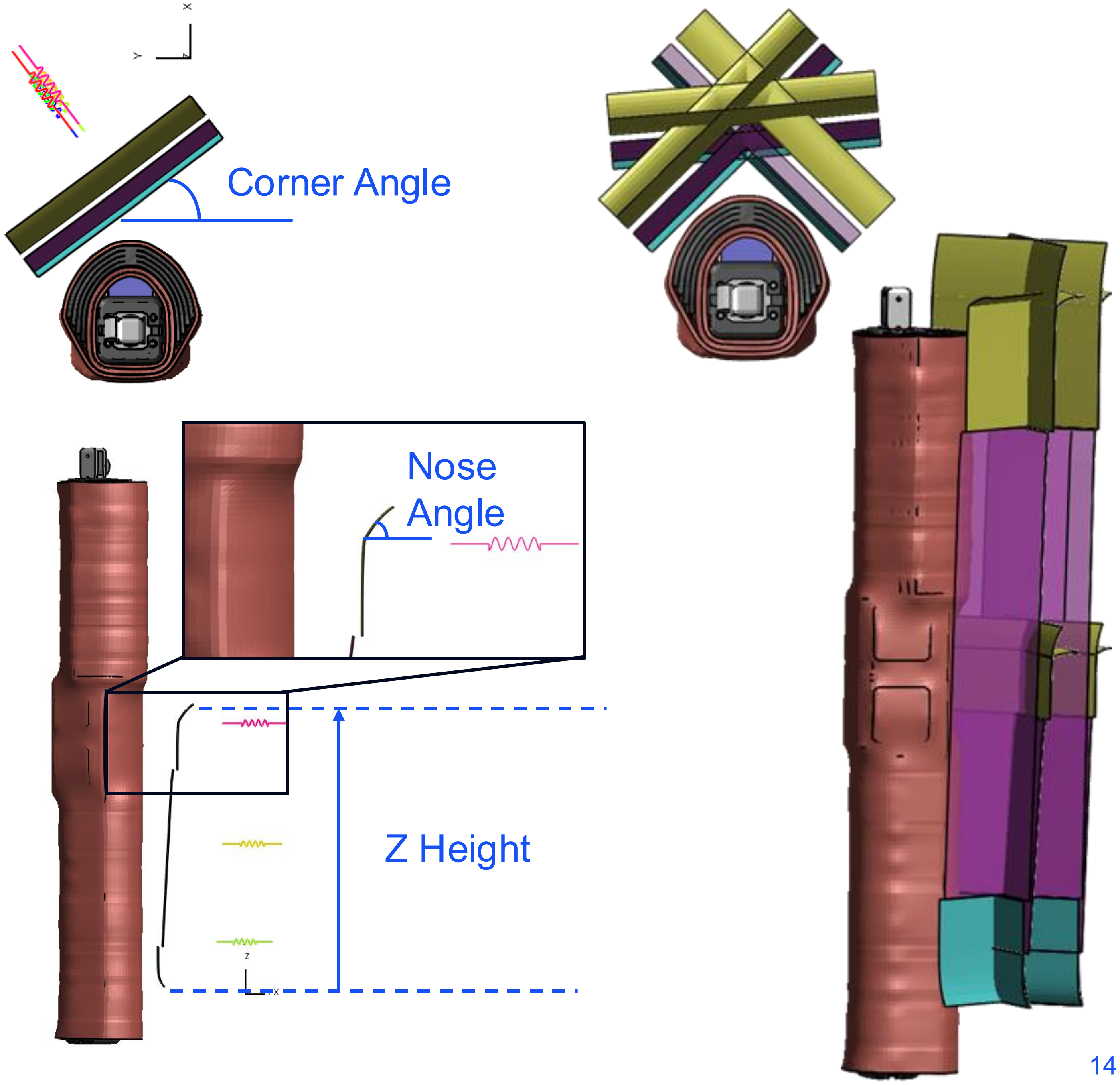
- Comparing the submodel and full model injuries:
- The submodel has good agreement between peak MCL elongations suggesting similar upper leg kinematics.
- PCL broadly follows the same timing and shape as the full model however it is noted that the submodel slightly underpredicts peak PCL injury.
- ACL has good agreement with full model peak injury but the shape of the curve is not exact.
- Submodel LHS PCL is lower than RHS PCL, as expected.
- Comparison was also made between contact forces to ensure similar loadpath distribution.



Vehicle Morphology DOE

- The submodel was parameterised to generate a vehicle morphology DOE.
- The parameters were:
  - Corner angle
  - Z height (scale factor)
  - Nose angle
- The overall design space was defined to represent typical vehicle geometries from sports to SUV.
- LHS and RHS versions of each model were analysed.

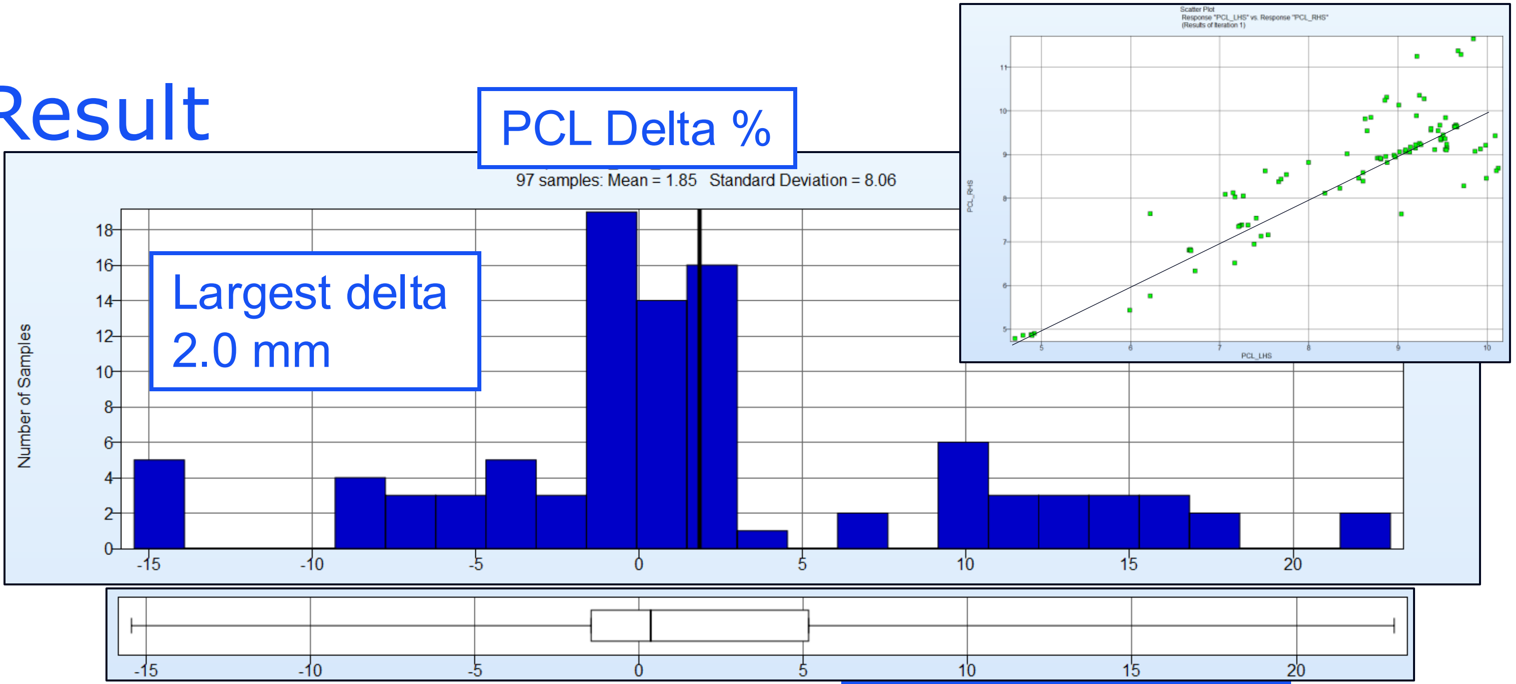
	Min	Max
Angle	+/- 5	+/- 45
Z Height	1.0	2.0
Nose Angle	0	60



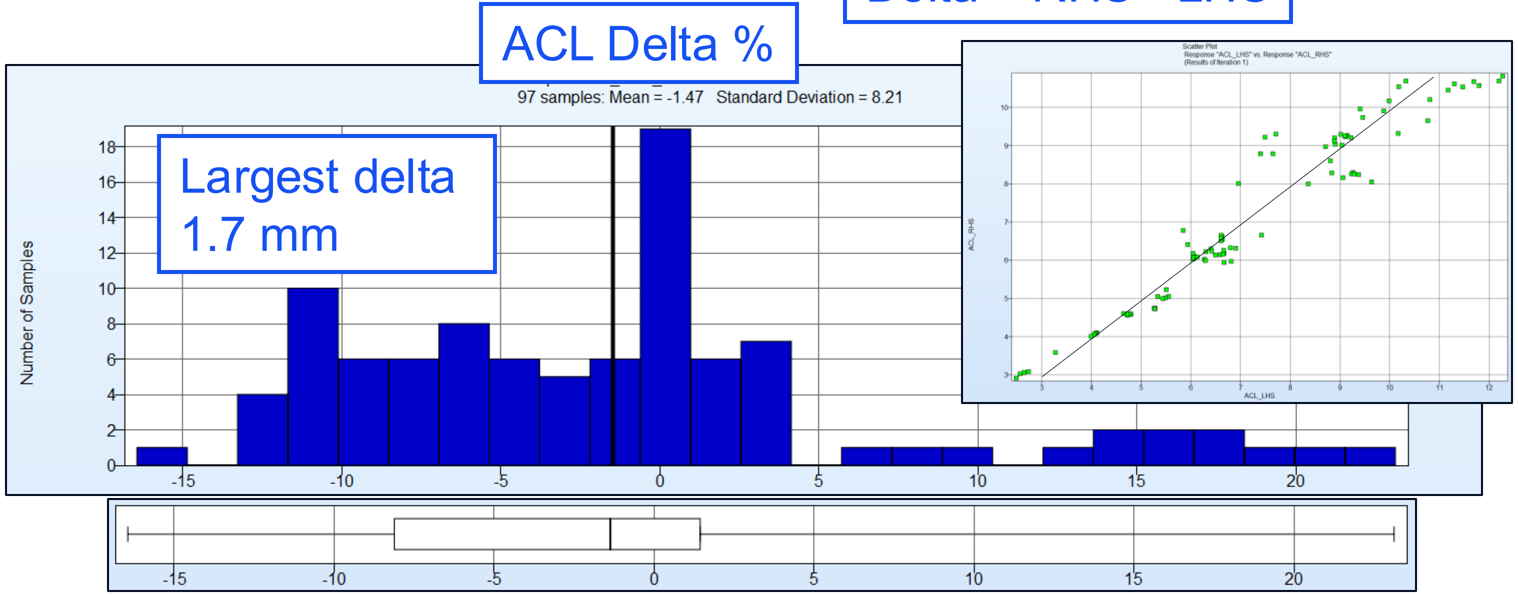
Vehicle Morphology DOE Result

- Considering ~100 result pairs, key takeaways from the vehicle morphology study include:
- A bias towards RHS being worse case for PCL.
- Conversely, ACL tended to be worse LHS but noting that absolute elongations were on average greater than ACL.
- MCL largely insensitive to impact side – consistent with D Isemann et al, IRCOBI 2023.

(mm)	LHS Mean	LHS Max	RHS Mean	RHS Max
PCL	8.4	10.1	8.6	11.7
ACL	7.2	12.3	7.0	10.8
MCL	12.0	30.0	12.1	29.8

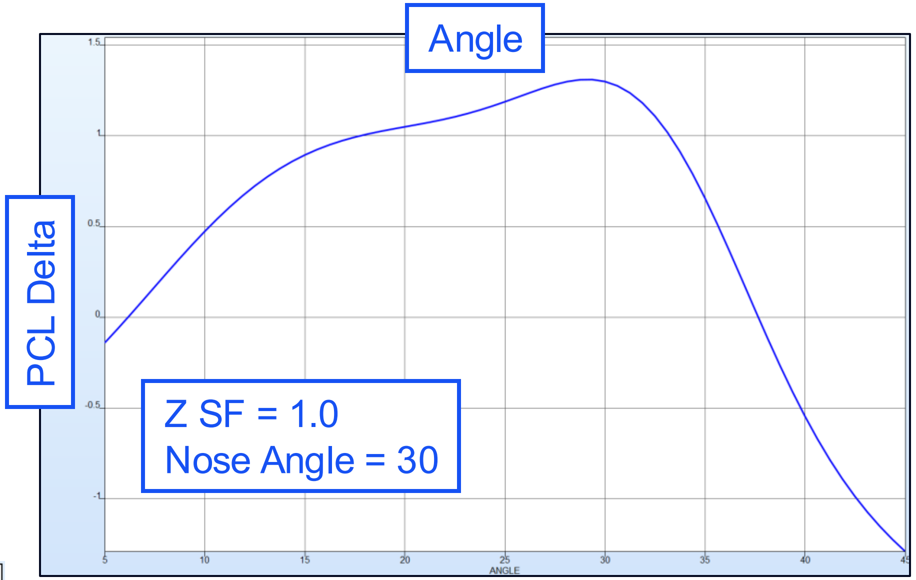


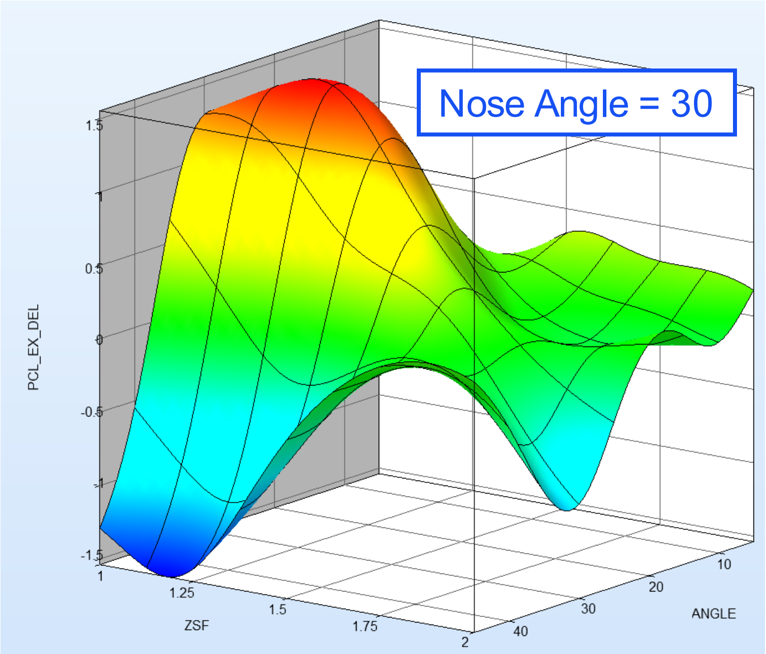
Delta = RHS - LHS

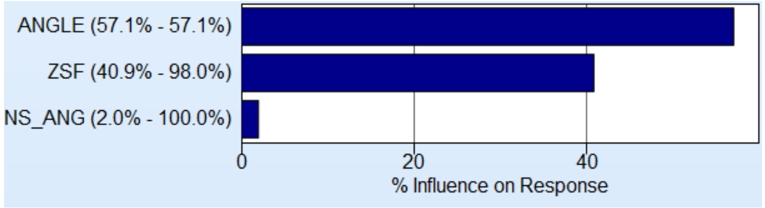


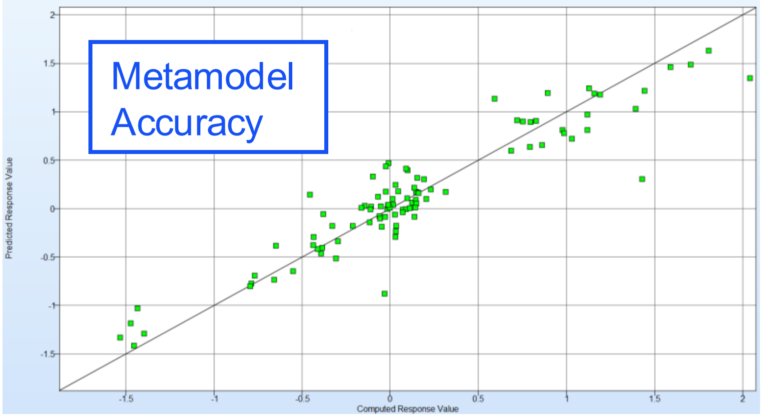
Vehicle Morphology DOE Result

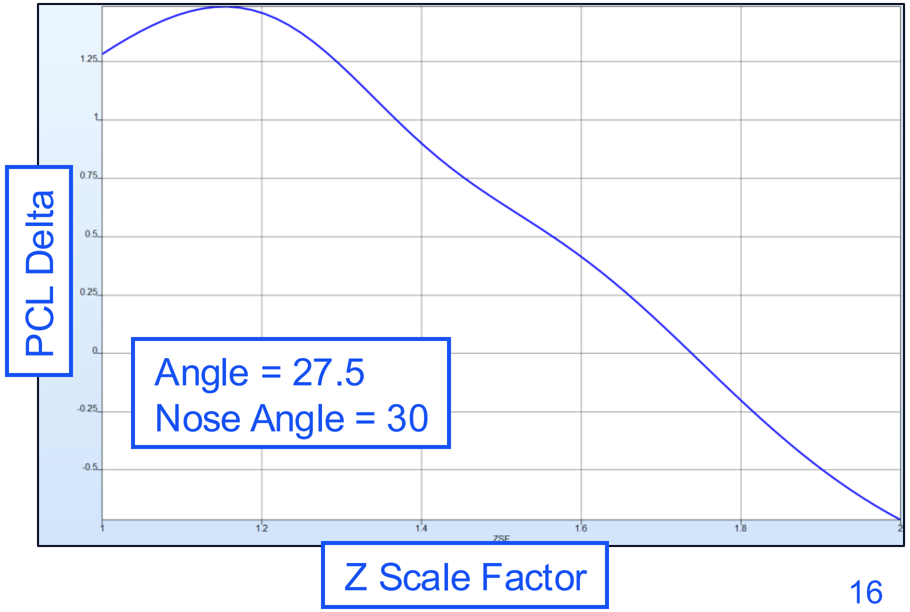
- Regarding the specific vehicle parameters, more interesting results emerge.
- PCL asymmetry is most sensitive to corner angle, increasing up to ~25-30°, before reducing again.
- Asymmetry reduces with z height.
- Nose angle largely inconsequential.







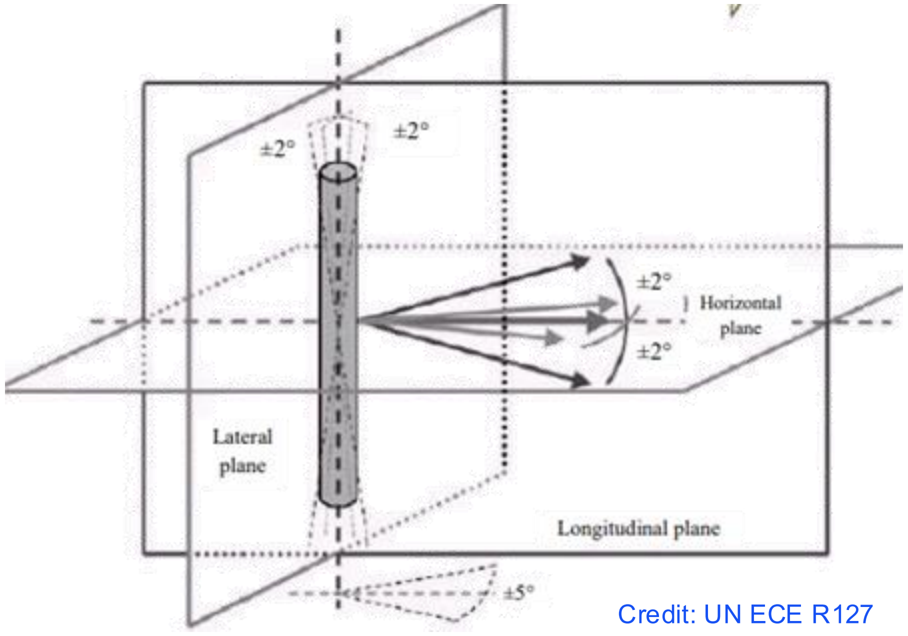




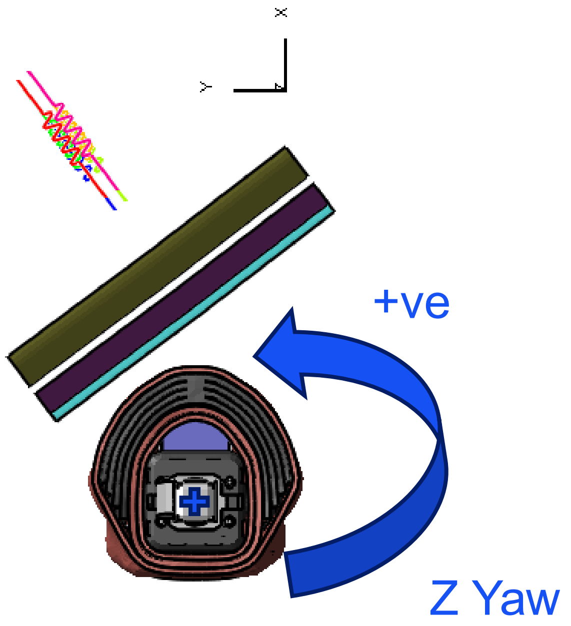
Oasys LS-DYNA Environment | ARUP

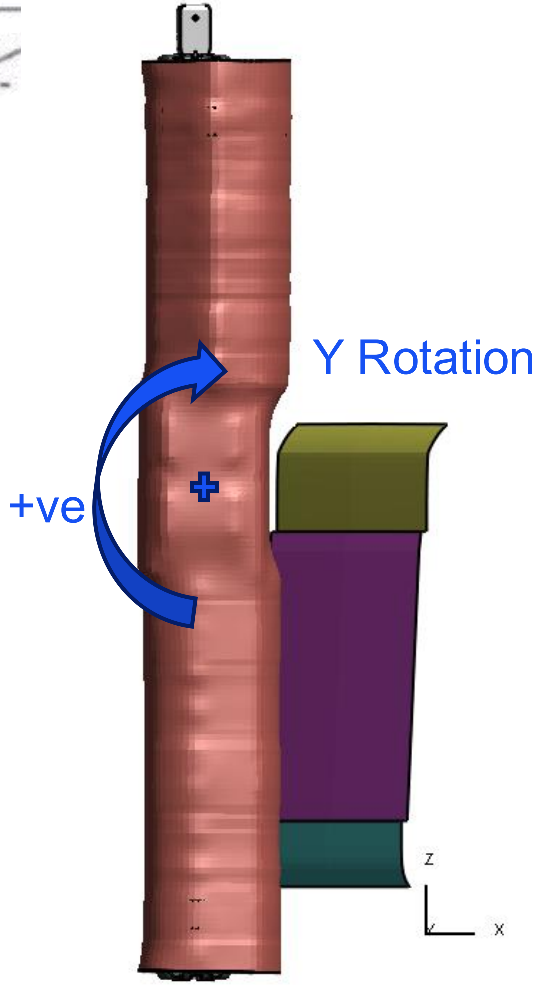
Flex-PLI Impactor DOE

- Following the vehicle morphology DOE, a further Flex-PLI study was conducted to understand the sensitivity to impactor rotation.
- Rotation about the global *y* and *z* axes were considered.
- UN ECE R127 permits these to deviate from nominal by +/- 2.5° and +/- 5.0° respectively.
- A selection of vehicle morphologies were chosen, based on the previous study results, as the basis for the impactor study.



Credit: UN ECE R127





Oasys LS-DYNA Environment | ARUP

Flex-PLI Impactor DOE Result

- 12 vehicle configurations considered.
- LHS and RHS impacts analysed for varying Y and Z impactor rotations.
- Linear correlation factors calculated as:

Delta = difference between RHS and LHS injury.

Vehicle			Linear Correlation %			
			Y Rotation		Z Rotation	
Angle	ZSF	Nose	PCL Delta	ACL Delta	PCL Delta	ACL Delta
5	1.33	45	0	38	-15	-88
15	1	0	0	5	-91	-86
25	1.33	60	13	41	-91	-74
37	1	20	11	9	-93	89
15	1.33	45	-19	0	-87	-90
25	1	0	5	-1	-99	-75
25	1.33	30	52	23	-78	-55
35	1	60	8	-9	-96	-16
35	2	45	-56	-19	33	54
45	1	0	12	-6	96	12
45	1.66	15	18	41	63	52
45	1.66	45	44	13	-53	63

15 analysis pairs per vehicle

Reduced dataset (9 pairs)

Strong sensitivity to *z* rotation, for vehicle types already showing asymmetric injury behaviour.

More investigation is required to understand this ACL anomaly.

Dataset is noisier than others, possibly skewing simple linear correlation.

Behaviour changes at high angles/heights

Low Sensitivity to *y* rotation

Flex-PLI Impactor DOE Result

- 12 vehicle configurations considered.
- LHS and RHS impacts analysed for varying Y and Z impactor rotations.
- Linear correlation factors calculated as:

Delta = difference between RHS and LHS injury.

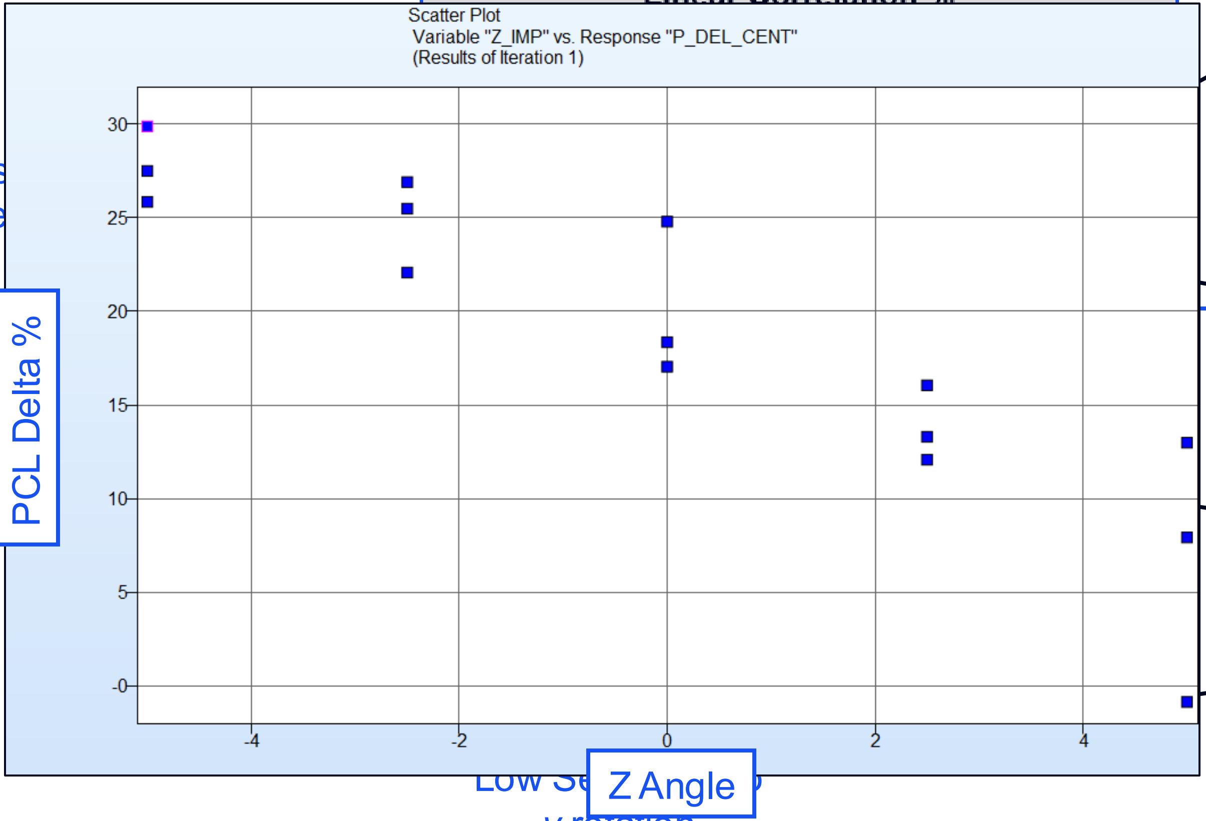
Linear Correlation %

More asymmetry

15 analysis pairs pe vehicle

Reduce dataset (9 pairs

Less asymmetry



Low Se
y rotation

Strong sensitivity to *z* rotation, for vehicle types already showing asymmetric injury behaviour.

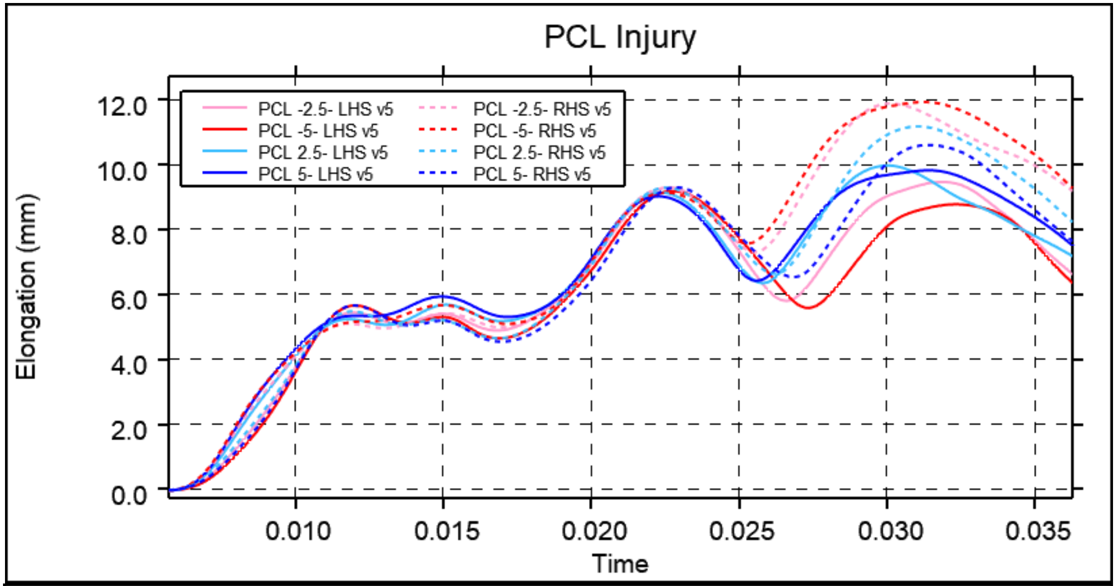
More investigation is required to understand this ACL anomaly.

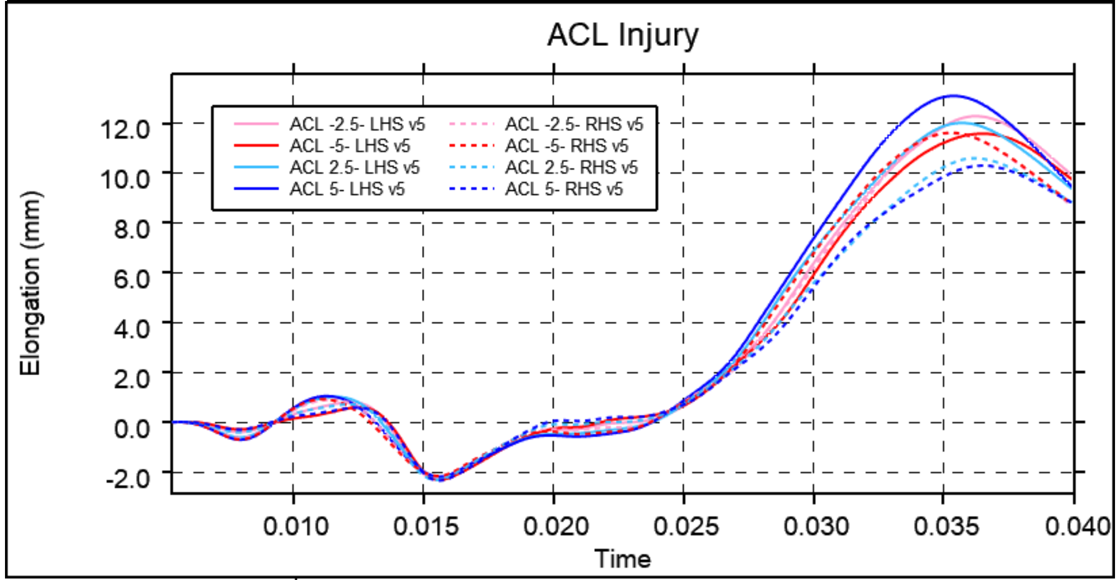
Dataset is noisier than others, possibly skewing simple linear correlation.

Behaviour changes at high angles/heights

Oasys LS-DYNA Environment | ARUP

Flex-PLI Impactor DOE Result

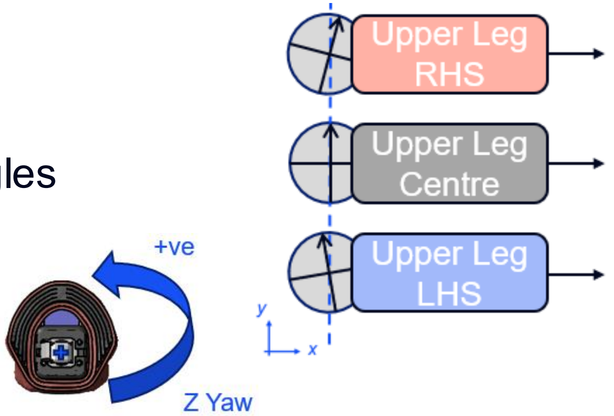




Vehicle			Linear Correlation %			
			Y Rotation		Z Rotation	
Angle	ZSF	Nose	PCL Delta	ACL Delta	PCL Delta	ACL Delta
5	1.33	45	0	38	-15	-88
15	1	0	0	5	-91	-86
25	1.33	60	13	41	-91	-74

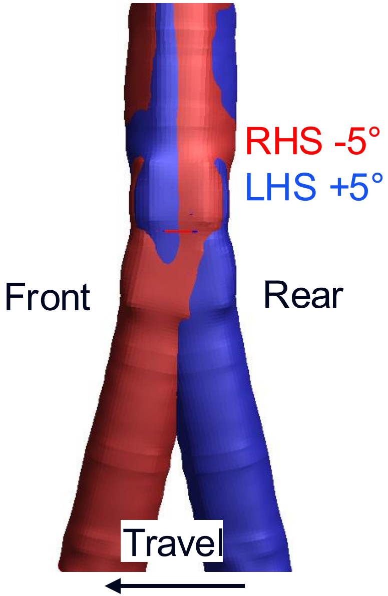
For PCL:

- RHS is worse case (dashed lines).
- Asymmetry is greatest at –ve *Z* angles (red lines).This is when impactor is rotated towards vehicle.
- Large spread: ~3.1 mm.



For ACL:

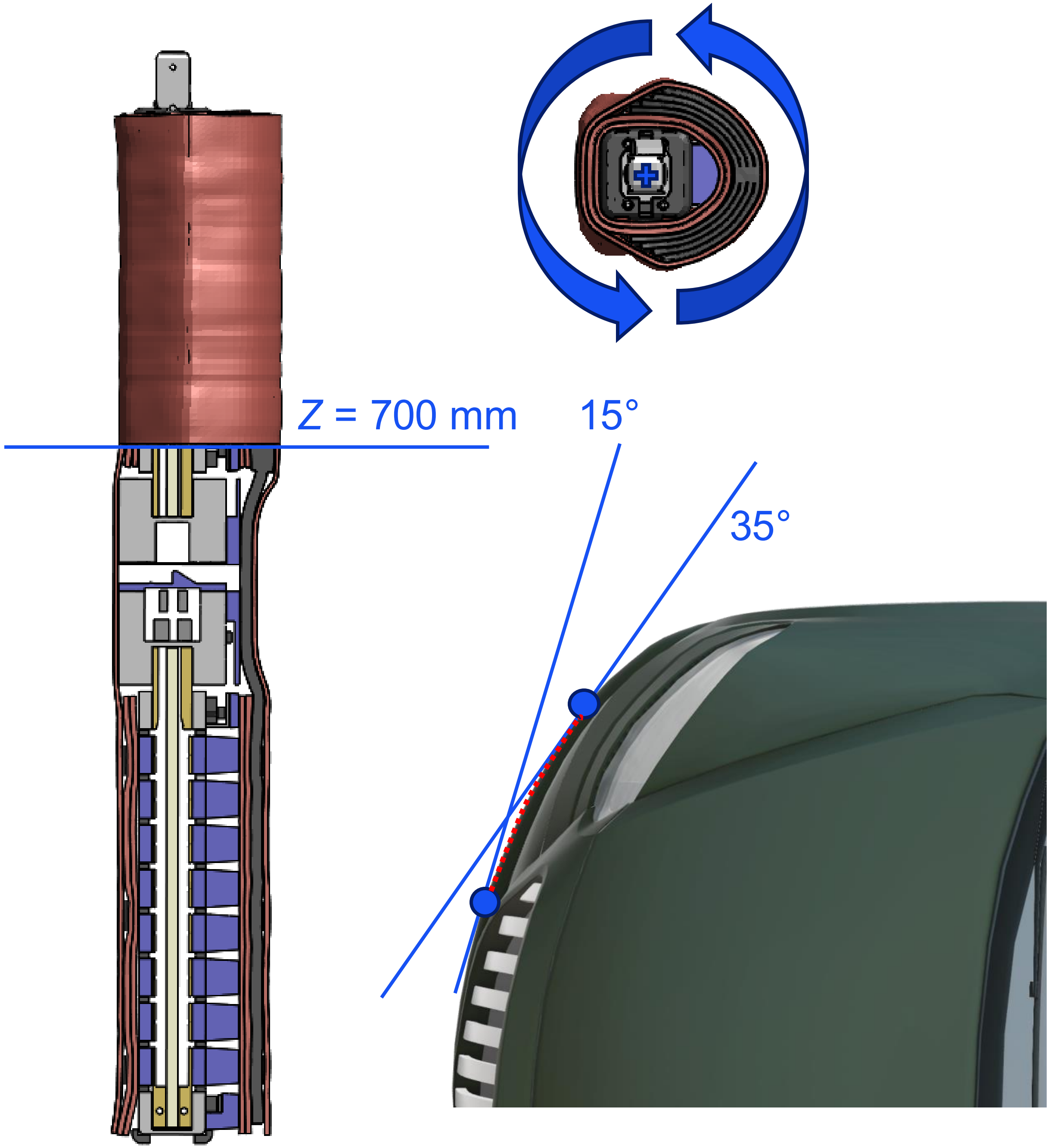
- LHS is worse case (solid lines).
- Asymmetry is greatest at +ve *Z* angles (blue lines). This is when impactor is rotated away from vehicle.
- Less Spread: ~2.7 mm.



Oasys LS-DYNA Environment ARUP

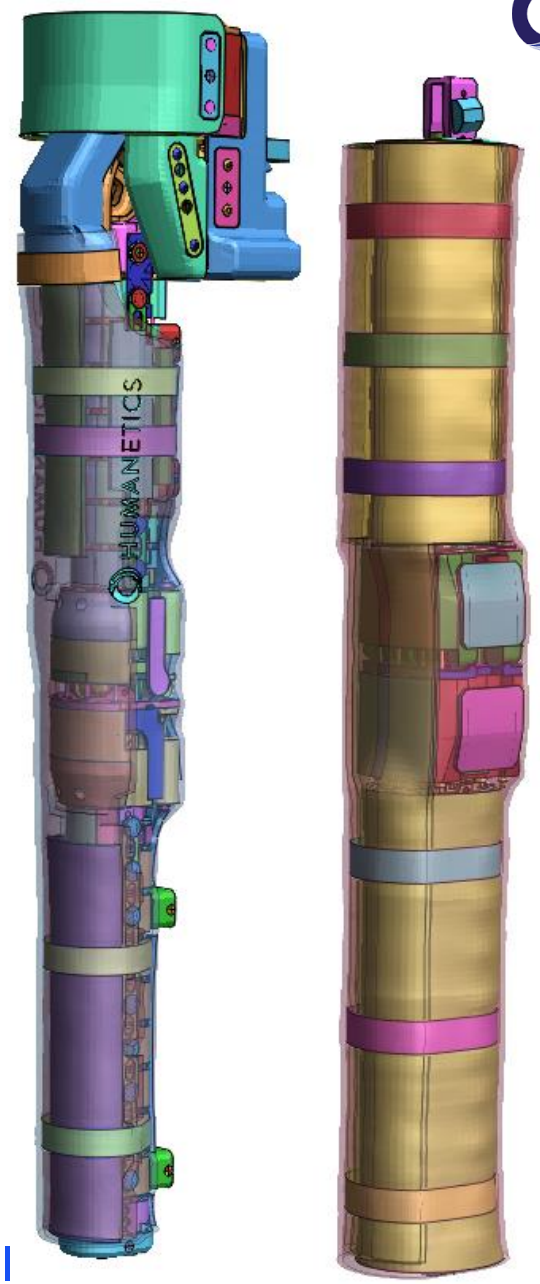
Flex-PLI Results

- RHS worse case for PCL, due to hyper extension.
- LHS worse case for ACL.
- Largest injury asymmetry observed for PCL.
- Angles between 15-35° most sensitive, above this *y*-axis loading tends to 'kick' leg out and overall rotation reduces.
- Bumper heights below ~700 mm most sensitive. Above this the upper leg is supported by vehicle.
- MCL is not sensitive LHS versus RHS.
- Asymmetry sensitive to impactor yaw as it can exaggerate the degree of local rotation.



aPLI Impactor DOE

- Having assessed the sensitivity of Flex-PLI, a further study was conducted using the aPLI impactor.
- This study was a repeat of part 2 of the Flex-PLI study (selected morphologies + impactor rotations).
- aPLI and Flex-PLI are similar but have some differences in construction and geometry.
- The most notable difference between aPLI and Flex-PLI is the inclusion of the upper body mass, which dramatically changes the kinematics of the aPLI impactor in comparison.

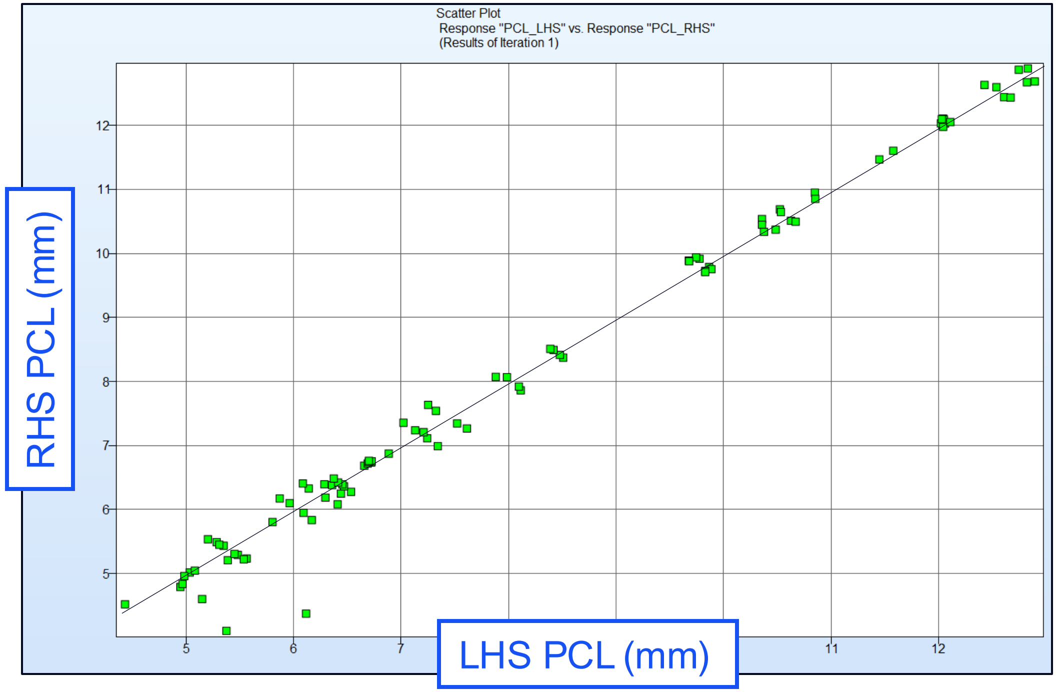


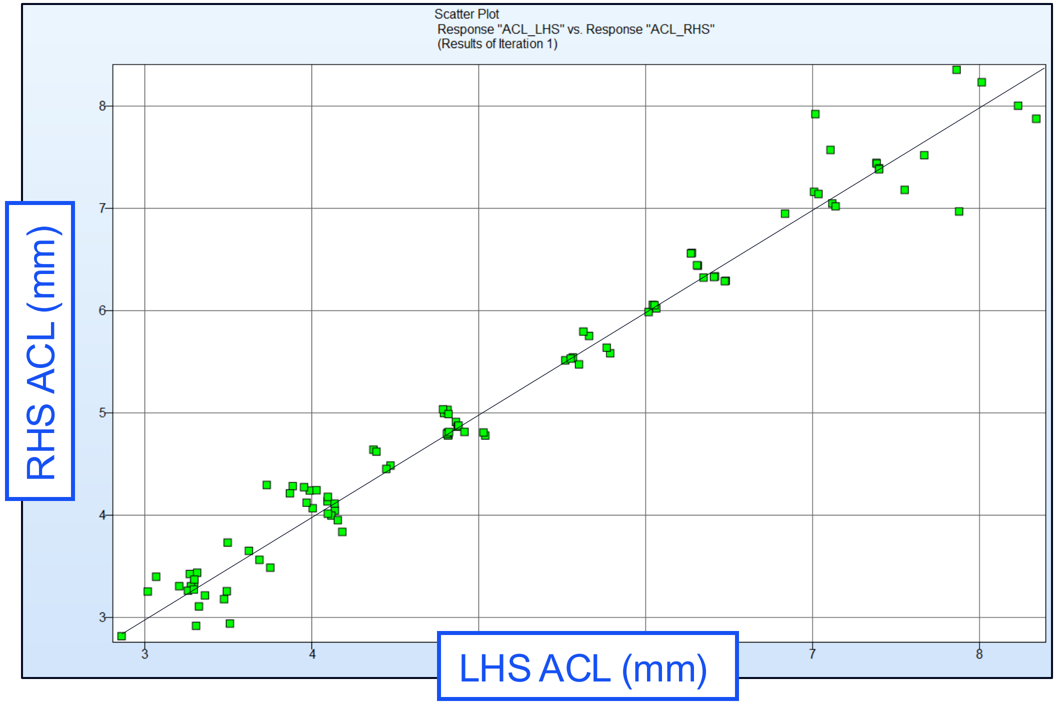
aPLI

Flex-PLI

aPLI Impactor DOE Result

- Across all of the selected vehicle morphologies and different impactor *y* and *z* angles (95 sample pairs), aPLI showed very little RHS to LHS variation.
- 85 of the 95 pairs where within 5% for PCL injury.
- More investigation is required to establish whether the lack of sensitivity is entirely due to the upper body mass or some other mechanism.

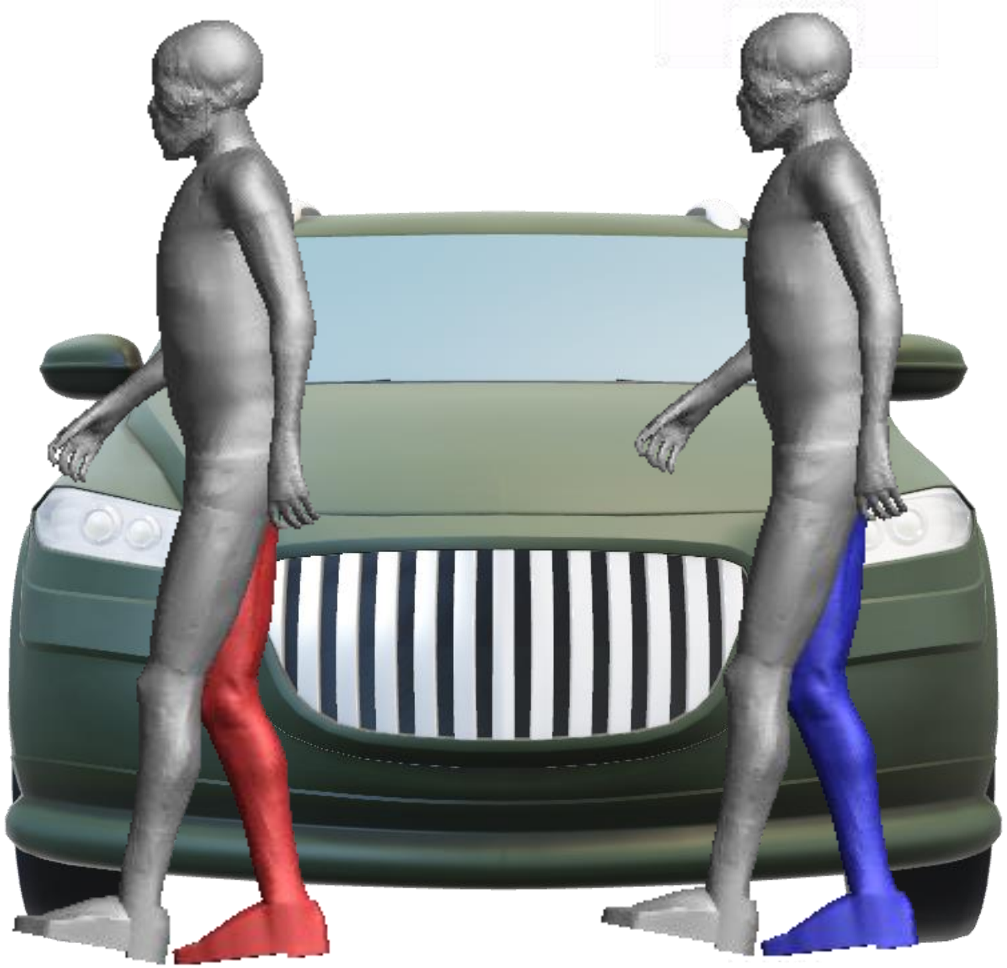




THUMS Study

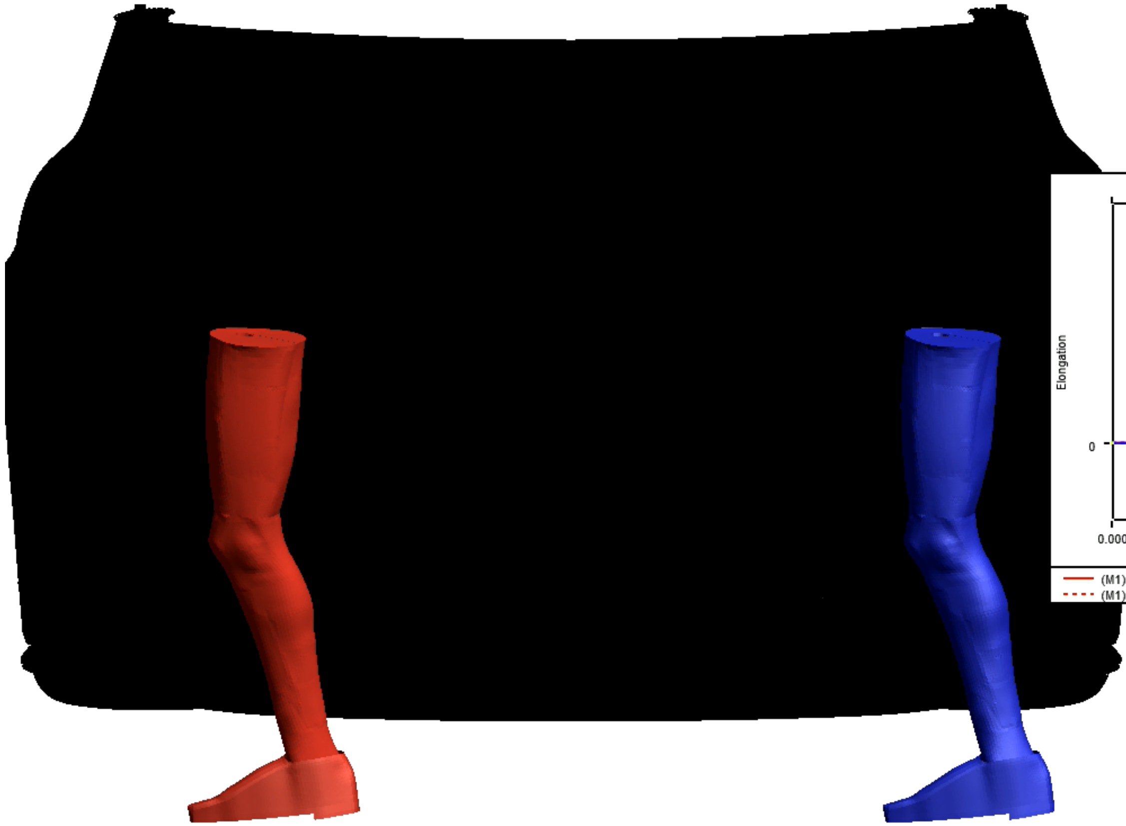
- As a final investigation, THUMS was used with the full vehicle model to establish whether the hyperextension / increased PCL injury was observable during impact with the Human Body Model.

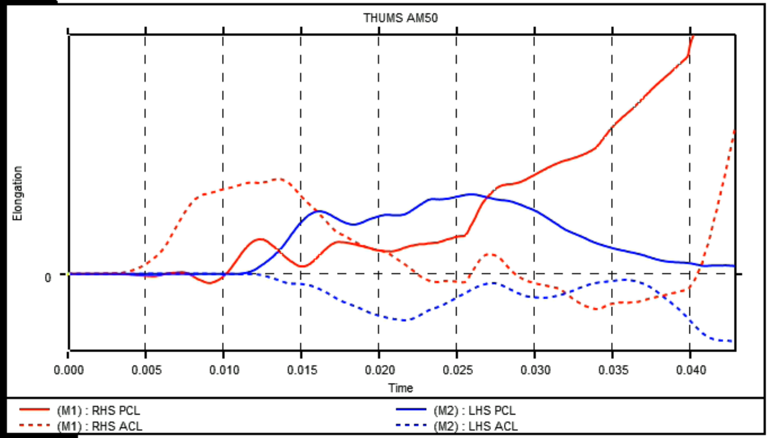
- Each model was positioned so that the right knee aligned with the vehicle at the same location as the ATD impactors.



THUMS Result

- The THUMS result is inconclusive.
- Peak ACL and PCL are higher for the RHS impact, however the mechanism is very different.
- For THUMS, the large RHS injuries are driven by significant tibia torsional rotation.





Conclusion

- Following an anomalous result during physical testing that was attributed to impactor yaw, a large DOE study was conducted to assess the sensitivity of Flex-PLI knee elongation to impacted vehicle side.
- The results have shown that for vehicles with a bumper height < 700mm a consistent asymmetry is predicted, consistent to physical test result, caused by rotation of the impactor on the vehicle A-surface.
- The sensitivity is greatest at impact angles between 15-35°.
- Impactor yaw can further exaggerate the effect when the local rotation is compounded.
- RHS impacts are worst-case for PCL and LHS impacts are worst-case for ACL.
- PCL is most sensitive.
- MCL was not sensitive.
- aPLI did not experience the same asymmetry as Flex-PLI.
- THUMS assessment was inconclusive.
- **Recommendation:** for low vehicles, +/- 5° degree yaw angles should be introduced to 'worst-case' impacts with high roll-off angles. Additionally, both vehicle sides should be routinely analysed, since RHS is worse for PCL and LHS is worse for ACL.

Acknowledgements

- The authors would like to thank Humanetics, who have generously supported this study; providing their time and access to leg impactor models.

HUMANETICS

Thank you!