HyDRA®: Design space validation for seatbelt systems combined with functional models for *real-life safety*

13.03.2024 Crash.Tech24 | K.-U. Machens

01

The normal is what you find, but rarely …

(Somerset Maugham)

in *real-life*.

The normal is what you find but rarely …

… in real-life

… in body shape

Improving safety for women requires more than a female crash test dummy (iihs.org)

- Mass/ body-fat (slack) distribution
- Skeleton (kinematics)
- Posture (slouching)
- Muscle activation (pre-crash)

… in crash pulse

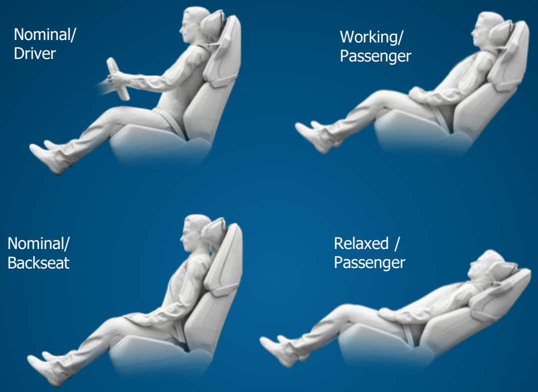
What To Do After Car Accidents? |Small Business Sense (small-bizsense.com)

Two killed in single-car accident - Plumas News

Kurioser Unfall: Auto an Auto gelehnt (stuttgarter-zeitung.de)

- Crashworthiness
- Delta velocity
- Crash scenario
- Pre-crash action

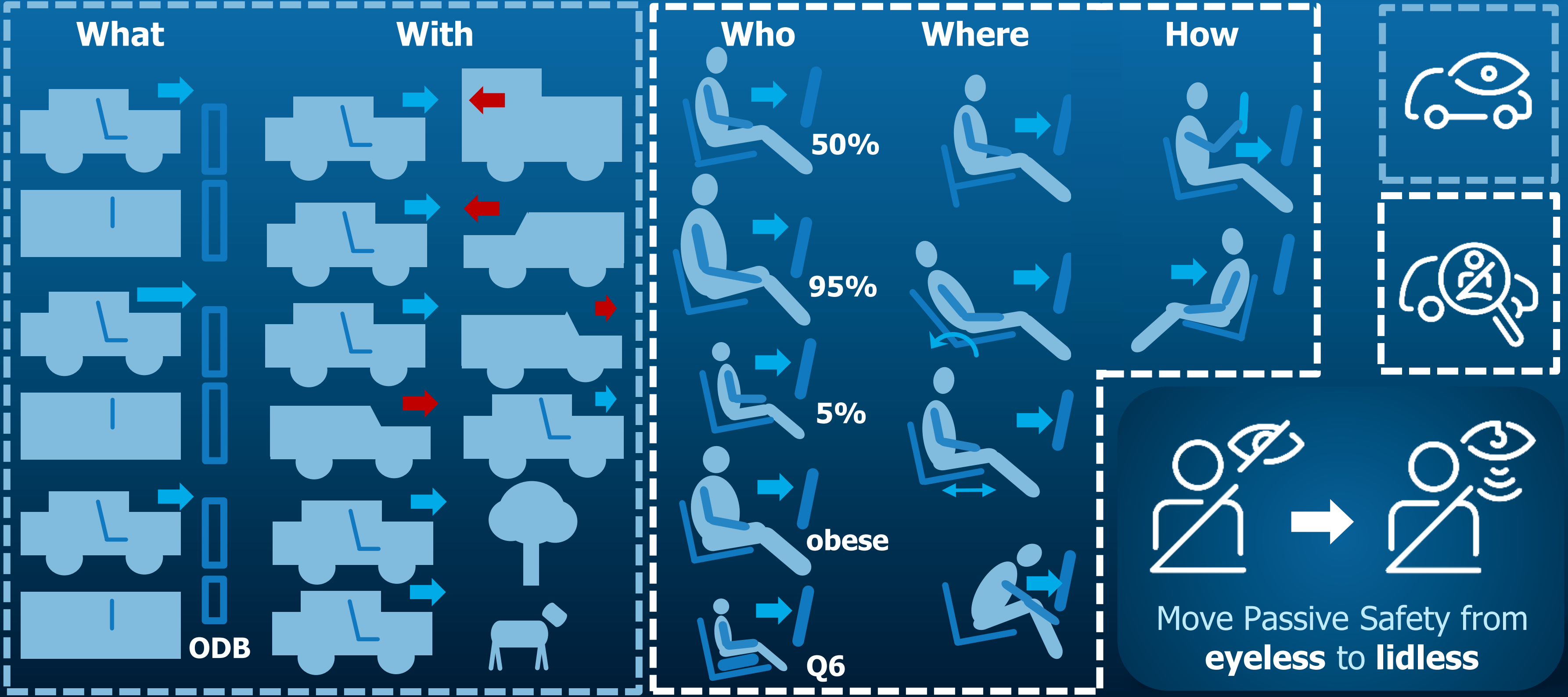
… in seating position



- Seat position / orientation
- Seat geometry/ compliance
- SBS fixation points

Adaptive safety to come …

… calls for virtual crash-safety validation



Real-Life Safety – focus of future NCAP & Insurance Testing

USA – NTHSA[1] / IIHS[2]

Frontal non-rollover crashes accounted for 50% of fatalities of belted passenger-vehicle occupant in 2019 [1]. This pro-portion is highest for the newest vehicles (Fig.1),…[2]

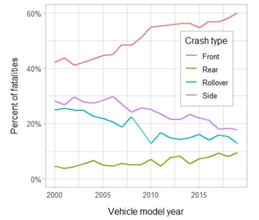


Fig. 1. 2018–2019 US fatalities of belted passenger-vehicle occupants by model year and crash type.

Improved thoracic injury protection in frontal crashes may be the single most pressing crashworthiness issue in the passenger vehicle fleet. [2]

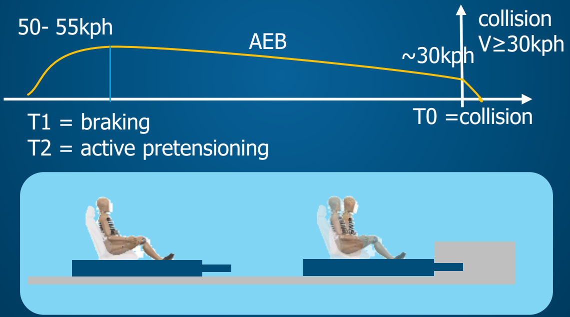
EU - NCAP
Roadmap 2030
Starting 2026

- Consider elderly
- Wider range required: 5%ile 35 kmph, 95%ile, 56 kmph
- female dummy bio fidelity, THOR 5%ile
- Virtual testing (real-life safety)

China - CNCAP / CIASI

2024 Protocol

- Active Restraints
- ACR bonus point – performance in pre-braked sled test (CATARC)



- Comfort seating „0-Gravity" draft

Adaptivity / Virtual Testing / Digital Twin / Reversible Pretensioning / Pre-Crash Validation

THOR: Test device for **H**uman **O**ccupant **R**estraint
NCAP: **N**ew **C**ar **A**ssessment **P**rogramme
AEB: **A**utomatic **E**mergency **B**raking
ACR: **A**ctive **C**ontrol **R**etractor

02

HyDRA® - Hyper Dynamic Response Actuator

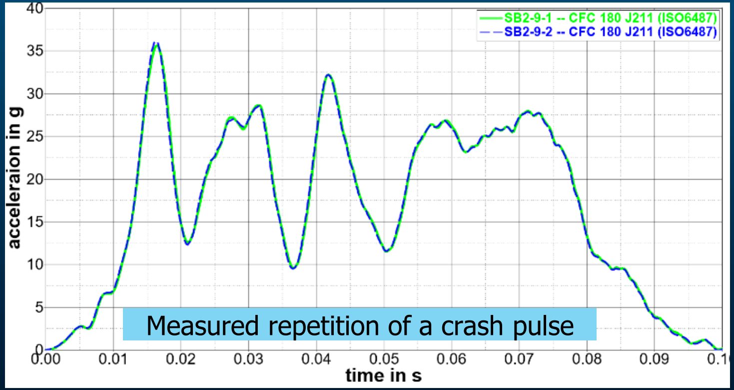
High precision setups

V10:
PHYSICAL & VIRTUAL DYNAMIC TEST-BENCH TO APPROACH INTEGRATED SAFETY

HyDRA® Propulsion System

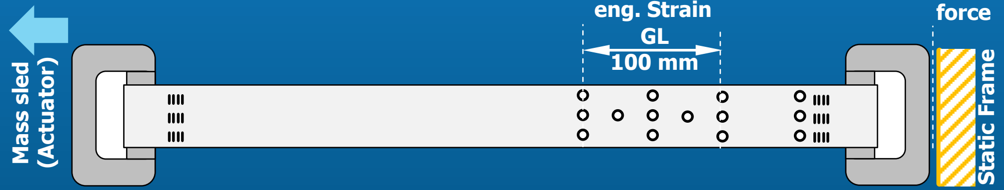
Electric linear motors with closed loop control

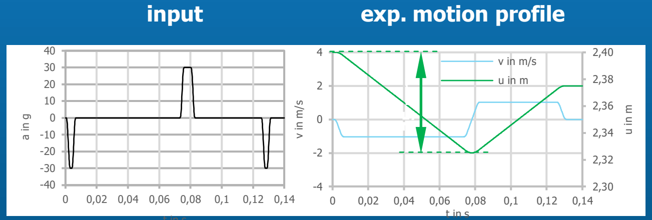
Technical data - propulsion unit	
...	
Propulsion Force	max. 120 kN
Electric Current	max. 4500 A
Control Frequency	8 kHz
Velocity	max. ± 20 m/s
Acceleration	max. ± 70 g
Jerk	max. ± 25 g/ms
...	

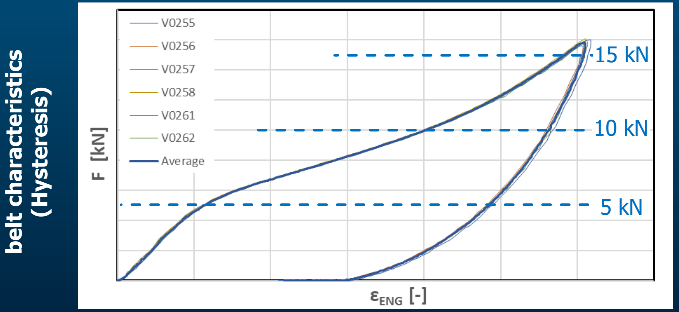


HyDRA® High precision setup – static frame

Example 1: Dynamic belt characteristics







dynamic belt tension test results with low scatter and good quality

HyDRA® High precision setup – static frame

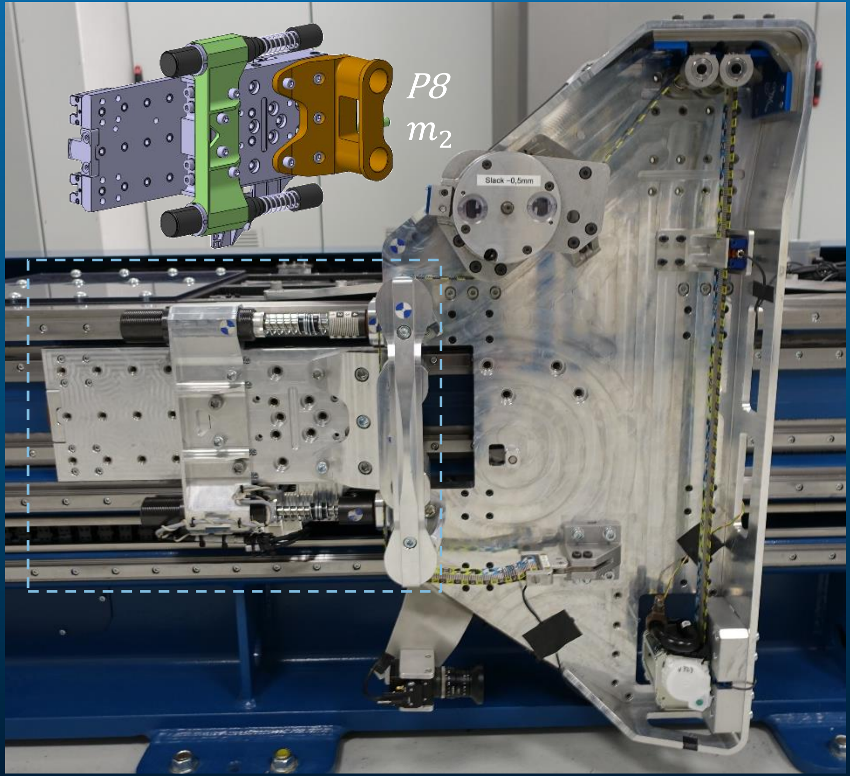
Example 2: Load Limiter characteristics - belt pull-out speed 4m/s (650 mm)

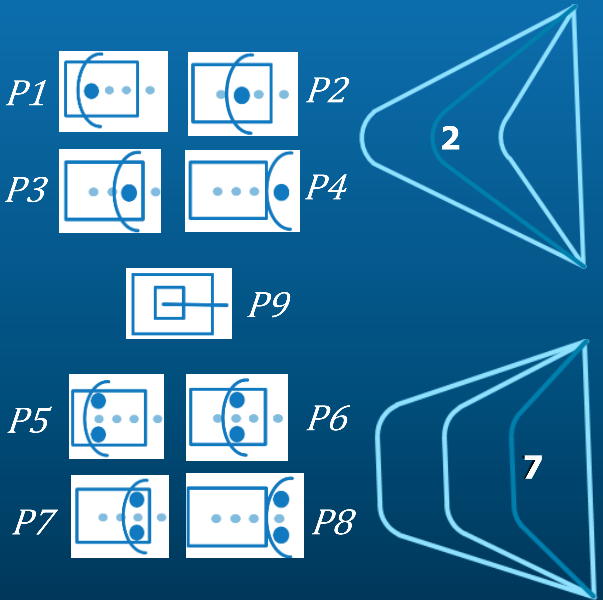
Digital Twin

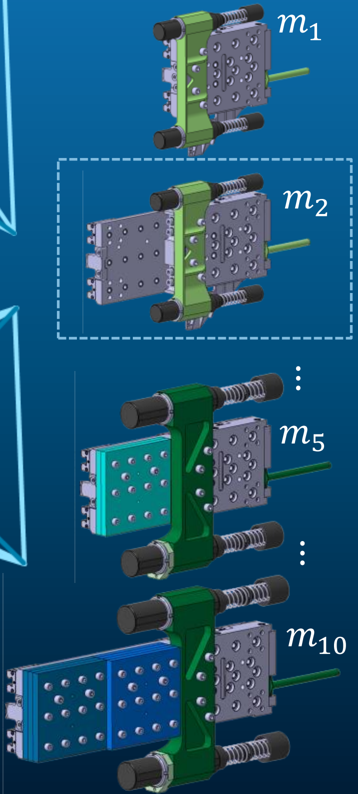
Physical Twin

HyDRA® High precision setup – moving frame

Customized generic setups







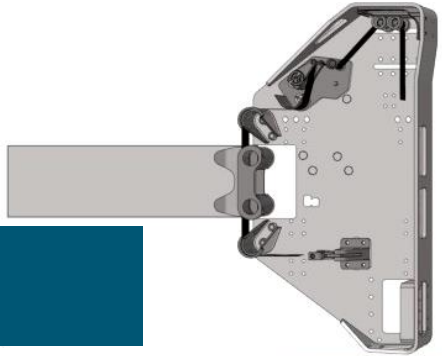
important system parameters

- dynamic onset $(1 - 8)$ / direct pull
- adjustable system-slack
- free floating mass $m_1 - m_{10}$

HyDRA® High precision setup – moving frame

Example 3: crash pulse – acceleration from rest

Digital Twin



Dynamic boundaries

- unlimited

Physical Twin

Dynamic boundaries

- Max. $\Delta v = 20\frac{m}{s}$ one-directional
- Max. $\Delta v = 40\frac{m}{s}$ two-directional
- Max acceleration: $a = 70\ g$

03

HyDRA® - Hyper Dynamic Response Actuator

Full kinematic setups

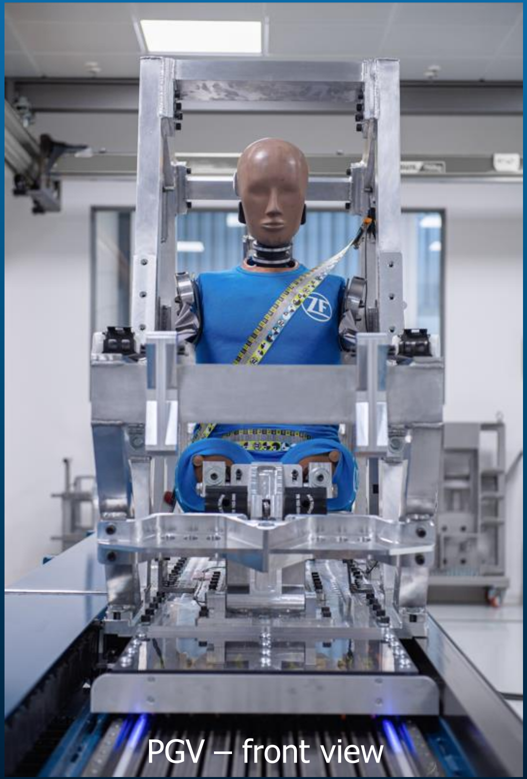
27th ESV 2023
YOKOHAMA, JAPAN
PACIFICO Yokohama North, April 3-6, 2023

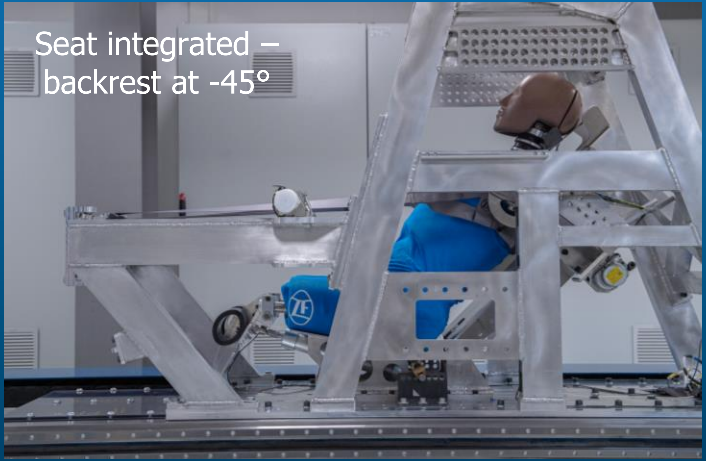
PAPER NO.23-0067-O
Dynamic testing with pre-crash activation to design adaptive safety systems
230119_ESV27_paper_Pre-Crash-Approach.docx (mirasmart.com)


Rebound Guy MkI in PGV

PGV: **P**retty **G**ood **V**ehicle

HyDRA® Torso@Seat: Physical test setup
Enabling Technology for next generation pre-crash activated and adaptive safety





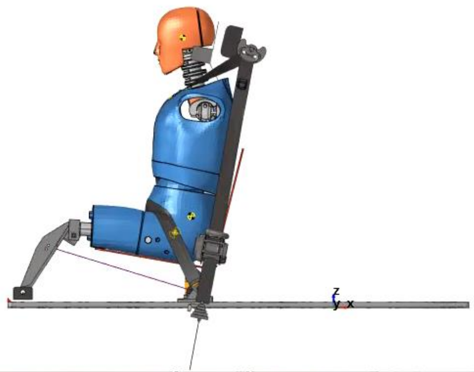
- **Physical twin** of T@S setup
- ATD H350 **chest impedance**
- **Front & rear** seat SBS installation
- **Efficient & accurate setup**
- **PGV configuration** & Fixation point **variants**
- **Inclined seat** with SBS

T@S: Torso@ Seat
SBS: Seat Belt Systems
ATD: Anthropomorphic Test Device
PGV: Pretty Good Vehicle

HyDRA® Full kinematic setup: Torso@Seat

Example 4: crash pulse – acceleration from rest

Digital Twin



Physical Twin

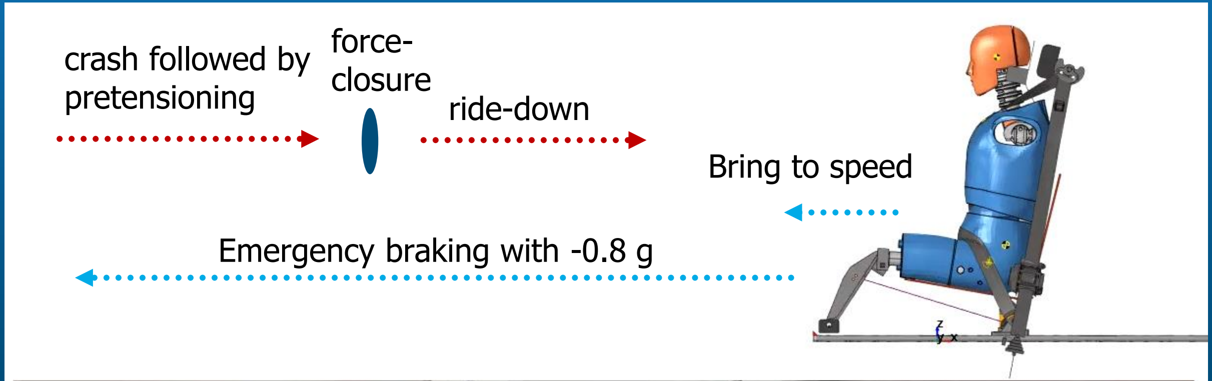
Retractor:	SPR4.1
Pulse:	Mid.Cut
TTF:	0 ms
LL:	T-bar 9 mm
WOS:	930 mm

LL: **L**oad **L**imiting
TTF: **T**ime **T**o **F**ire
WOS: **W**ebbing **O**n **S**pool
T-bar: Torison-bar LL

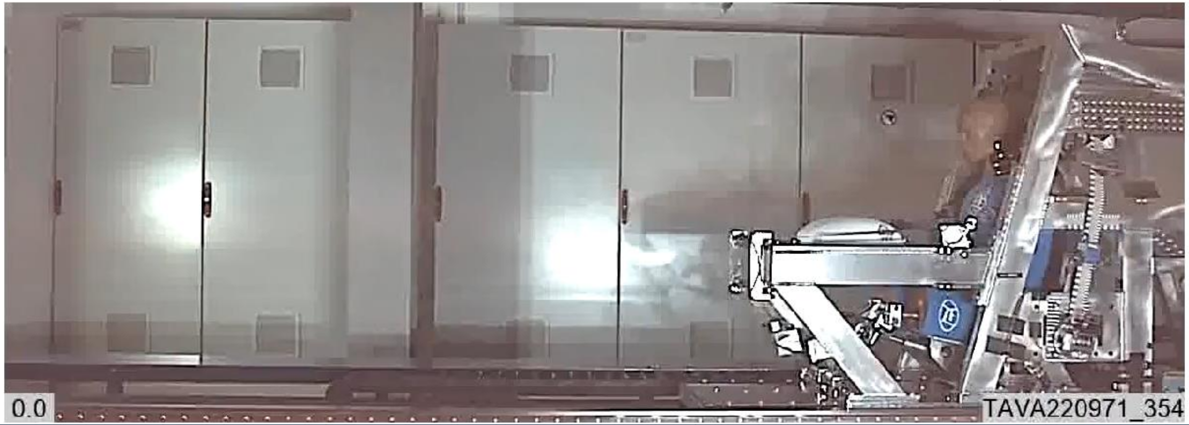
HyDRA® Full kinematic setup: Torso@Seat

Example 5: pre-crash braking followed by crash pulse

Digital Twin



Physical Twin



Retractor:	SPR4.1
Pulse:	Mid.Pre
TTF:	0 ms
LL:	T-bar 9 mm
WOS:	930 mm

LL: Load Limiting
TTF: Time To Fire
WOS: Webbing On Spool
T-bar: Torison-bar LL

04

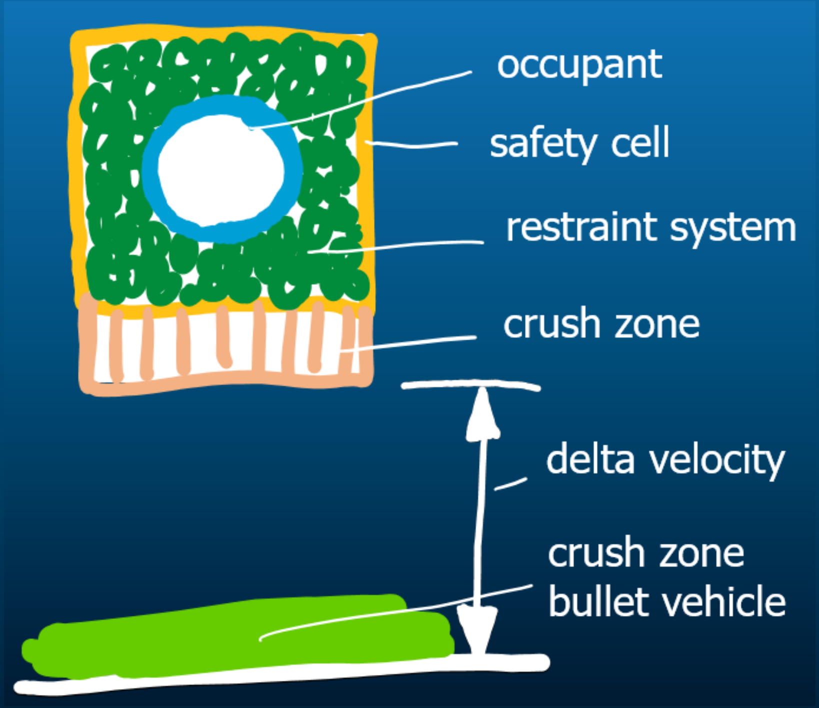
Crash injury risk factors
Dominant factors for occupant restraint

Crash injury risk factors

Visualized as padded goods in a moving box

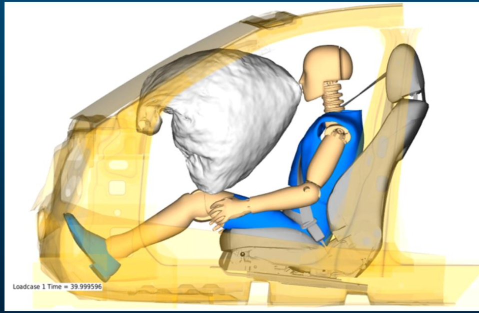
Imagine goods (occupant) bubble wrapped (restraint system) in a box (safety cell) with bottom as a bumper zone (crush zone).

Here, dropping height and floor composition (carpet present?) represent delta velocity and crush zone bullet vehicle.



SBS load case

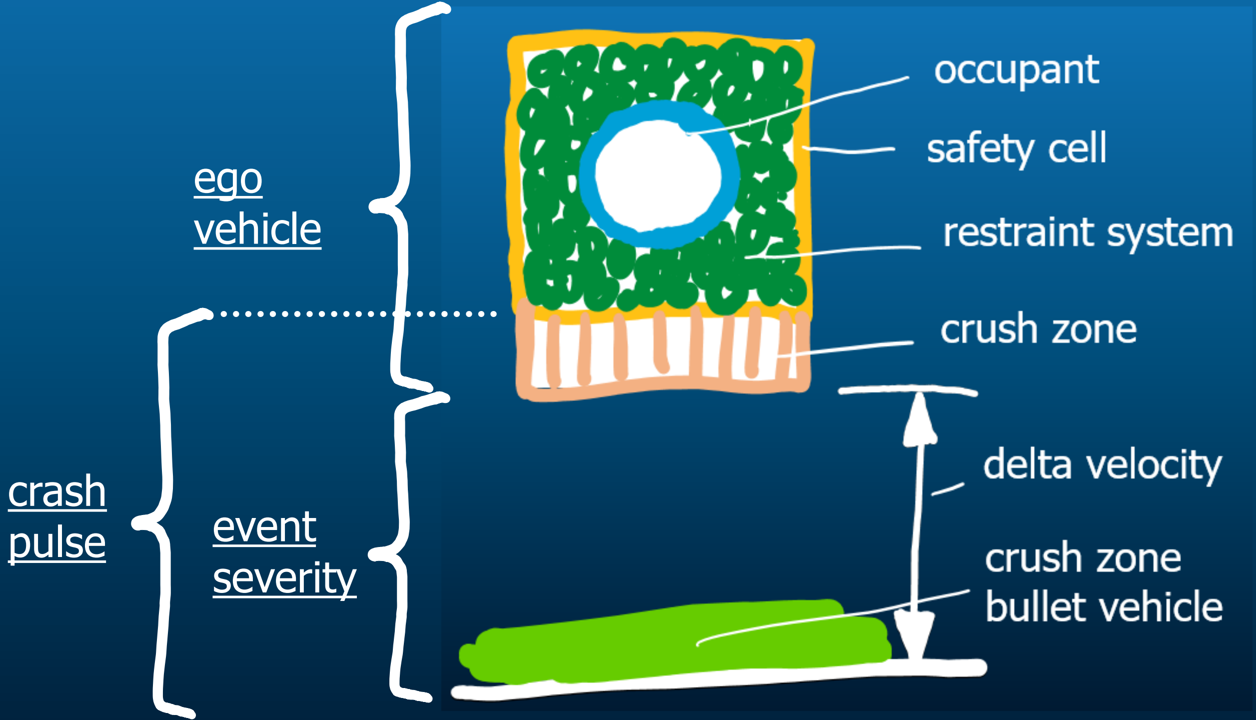
- Crash pulse acting on cell
- Safety cell not compromised
- Vehicle configuration (geometry)
- Occupant



SBS: Seat **B**elt **S**ystem

Crash injury risk factors

Visualized as padded goods in a moving box



SBS load case

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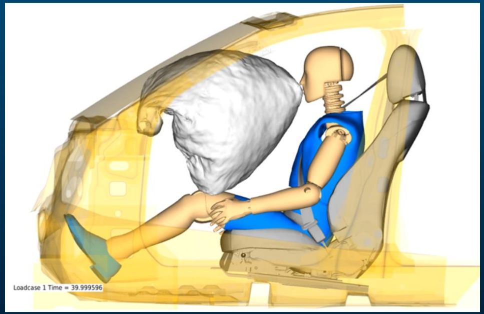
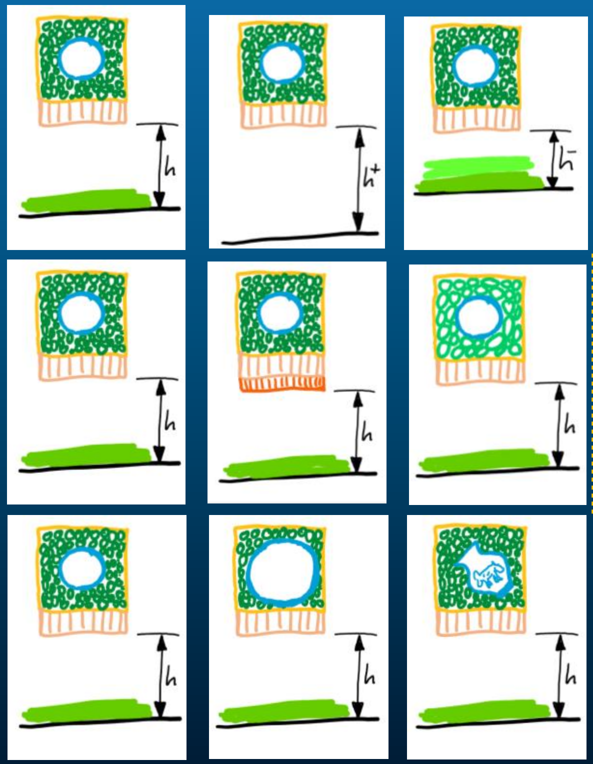


SBS: **S**eat **B**elt **S**ystem

Crash injury risk factors

Visualized as padded good in a moving box



Event severity

- delta velocity
- crashworthiness bullet vehicle / obstacle
- compatibility
- mass distribution …

fuzzy, uncontrollable, outside

Restraint performance

- crash detection (TTF)
- crashworthiness ego vehicle
- vehicle configuration
- force-closure performance SBS
- ride-down performance

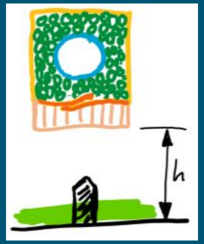
controlled subsystem

Occupant factor

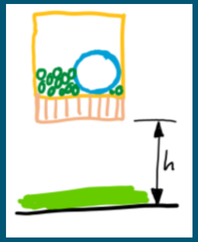
- obese,
- large
- vulnerable
- seat adjustment …

fuzzy, uncontrollable, outside

Out of scope



- intrusion
- multiple impact

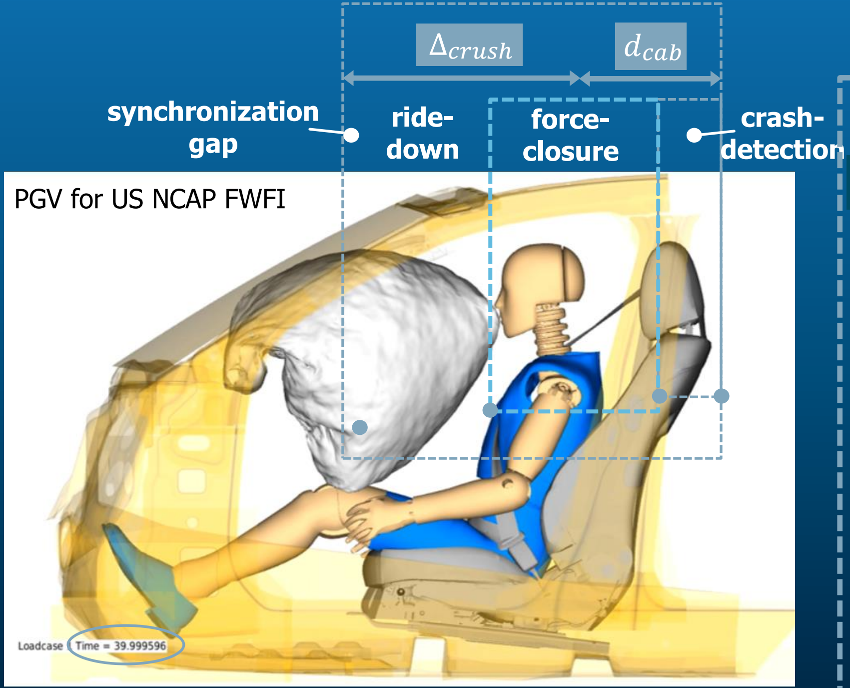


- misuse
- out of position
- (unbelted)

- extreme obesity
- post crash complications (age or heart related)

Dominant factors as a function of in-crash phases

PGV: Front Passenger US NCAP FWFI (five star rated midsize sedan)



Occupant Protection

Until *ride-down* completion
Based on Integral Scenario

1. **Seat Belt System**
2. **Crash Scenario**
3. **Vehicle Sensory System**
4. **Occupant**
5. **Vehicle**
6. **Seat & Environment**
7. **Airbag System**

SBS Performance

Force-closure generation
Based on **"The Big 8"**

1. **Vehicle pulse**
2. **Time-to-Fire delay**
3. **ATD**
4. **SBS fixation points**
5. **Initial Torso inclination**
6. **Pelvis damper force**
7. **System slack**
8. **Available safety space**

Ride-down contribution

A. **SBS-energy management**
B. **Stop (hard, soft)**

SBS Task: Establish early & efficiently force-closure and contribute to ride-down.
Airbag System and Seat & Environment do **not** interact with occupant in force-closure phase.

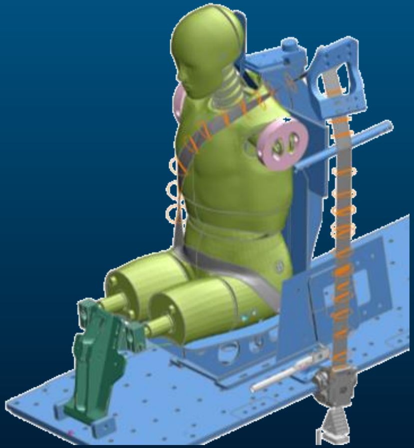
SBS: **S**eat **B**elt **S**ystem
ATD: **A**nthropomorphic **T**est **D**evice
PGV: **P**retty **G**ood **V**ehicle
FWFI: **F**ull **W**idth **F**rontal **I**mpact

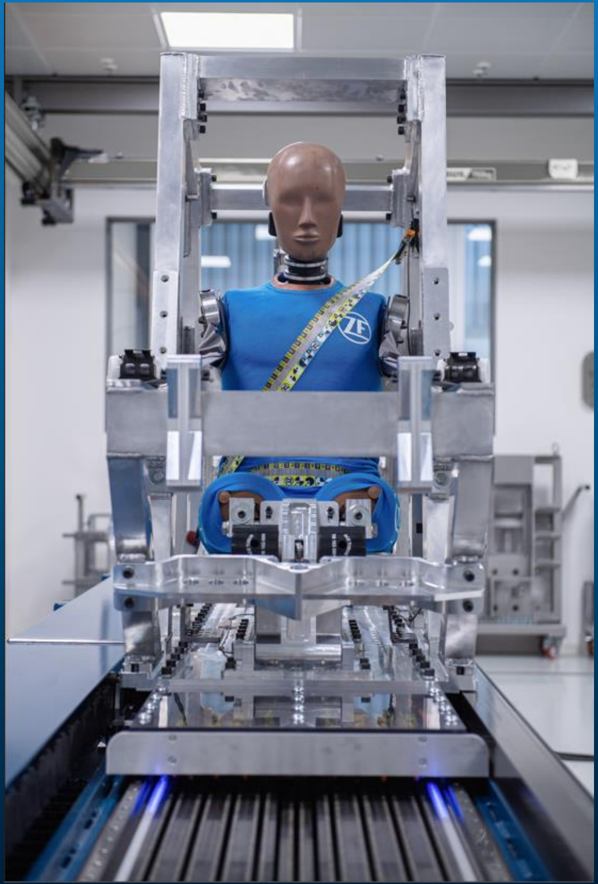
05

CFL-Metric:

- **Quantification of restraint performance**
- **Evaluation of contributing factors**

By means of
specific T@S setup
available as
physical and digital twin

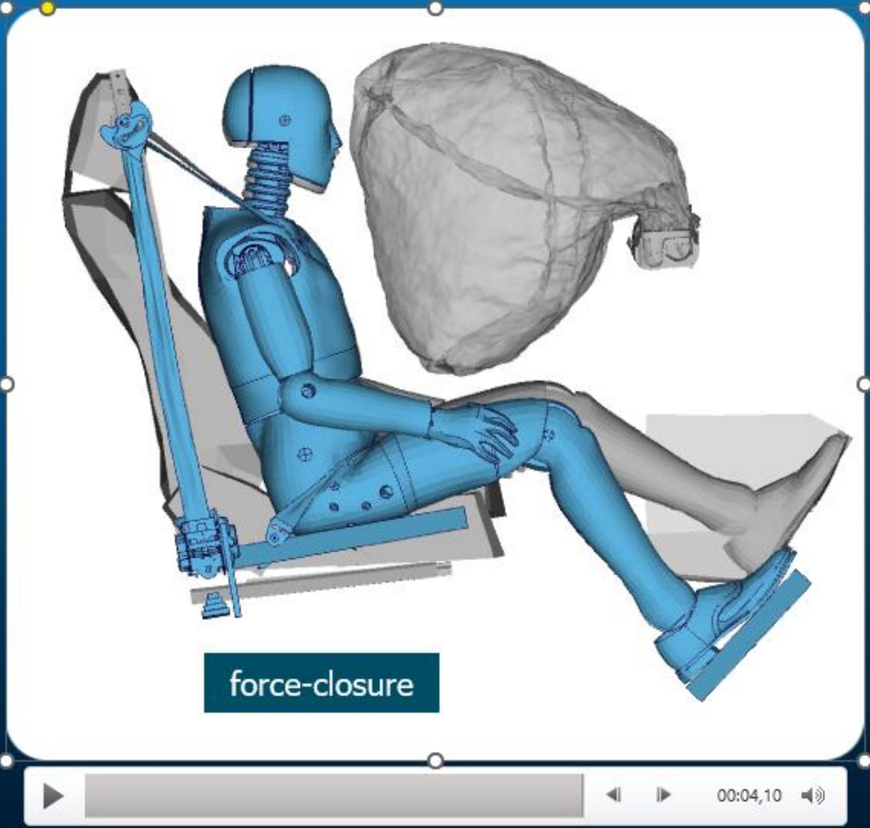


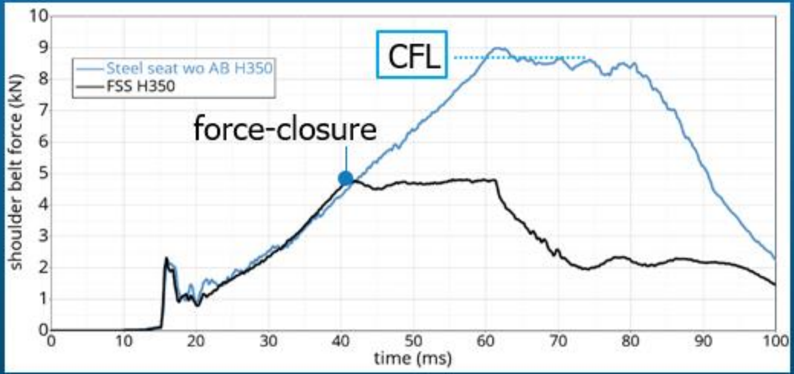


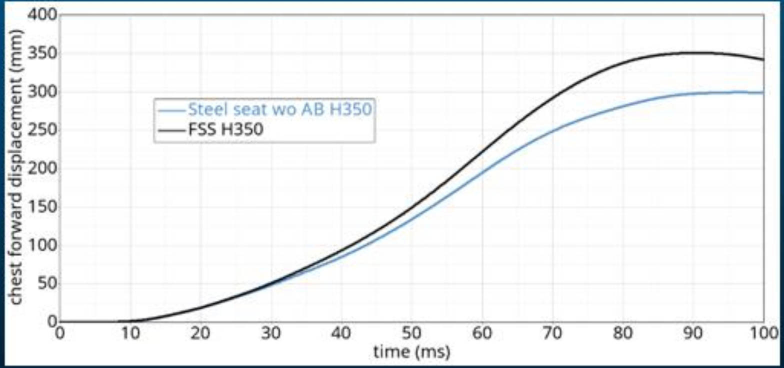
T@S: **T**orso@ **S**eat
SBS: **S**eat **B**elt **S**ystems

CFL: **C**haracteristic **s**houlder belt **F**orce **L**evel

Characteristic Shoulder Belt Force Level (CFL)

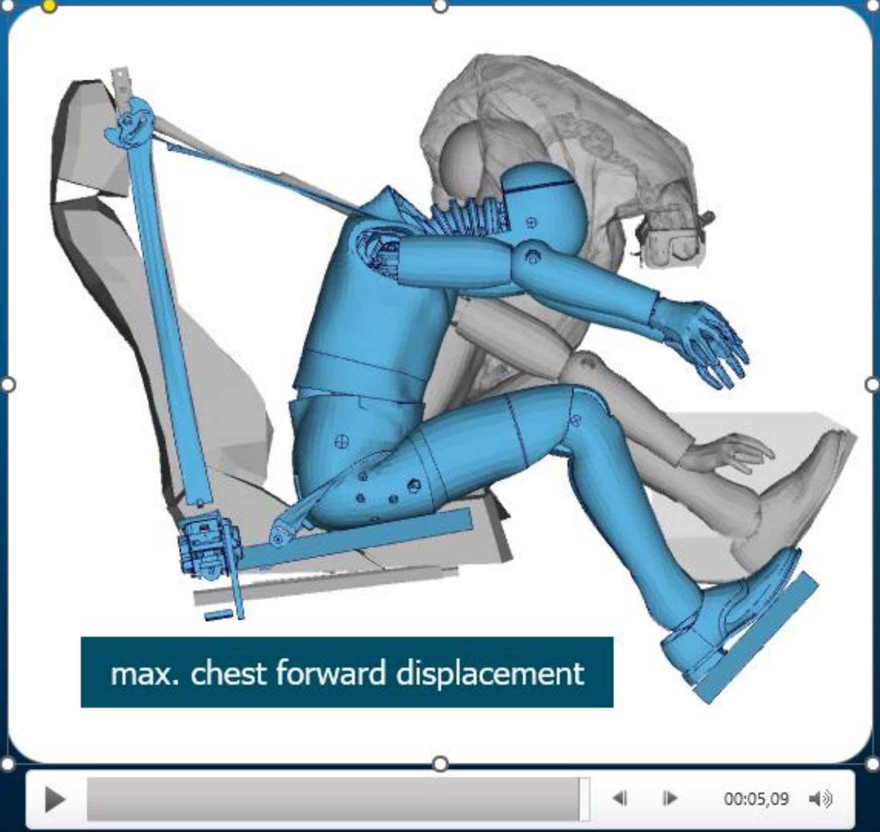


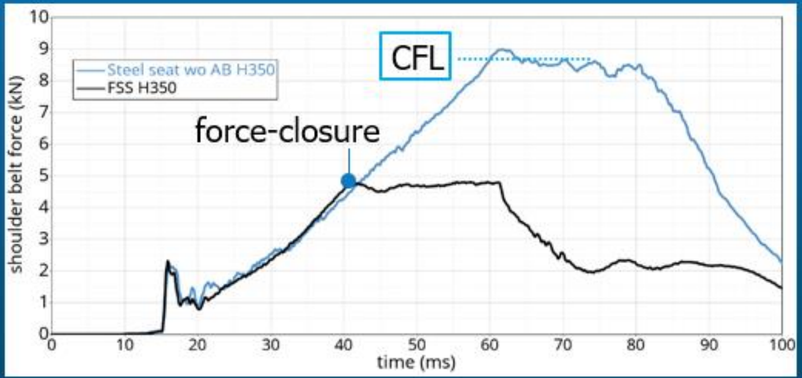


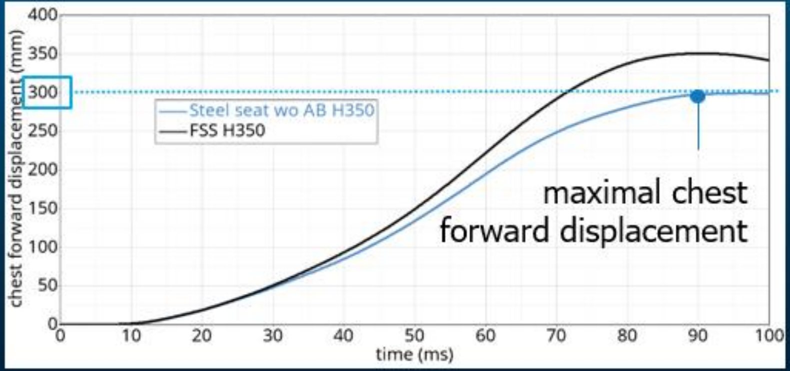


CFL: Characteristic Shoulder Belt Force Level
AB: AirBag
CLL: Constant Load Limiter
FSS: Full Safety System

Characteristic Shoulder Belt Force Level (CFL)

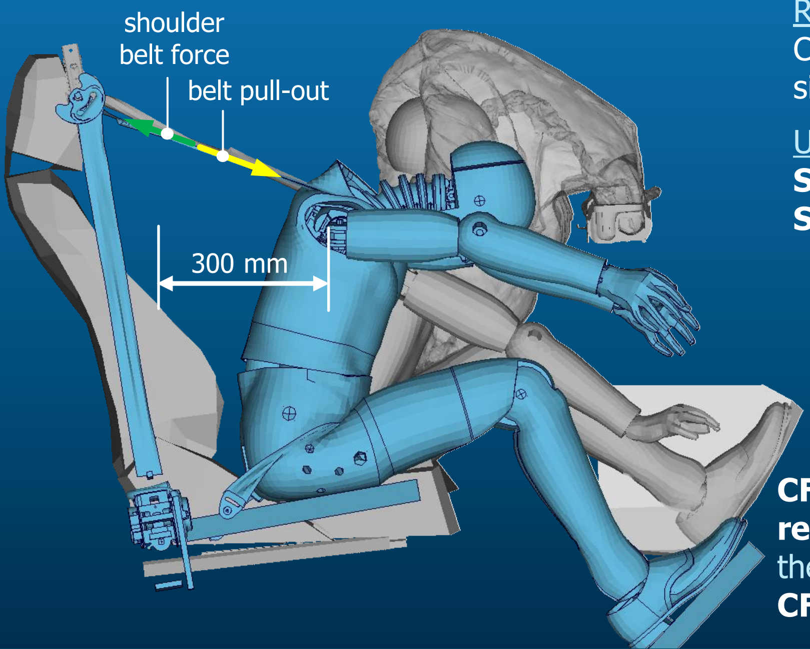






CFL: Characteristic Shoulder Belt Force Level
AB: AirBag
CLL: Constant Load Limiter
FSS: Full Safety System

Characteristic Shoulder Belt Force Level (CFL)[5][6]



Ride-down w. **CFL as CLL-level**:
CFL defined as CLL-level to stop chest forward displacement on simplified T@S setup at 300 mm $\pm 1.5\ mm$.

Until force-closure:
Steal seat and **T@S** setup behavior **corresponds** to **Full Safety System** config. for identical "The Big 8" parameter set.

CFL is higher

1.) if consumed distance is larger or

2.) if dissipated kinetic energy is lower

CFL combines shoulder belt force (~ chest deflection) **with rest energy dissipation** (work = belt force * belt displacement) therefore considering both factors in a single value.
CFL assumes ride-down with **minimal** (=constant) belt **force**

CFL (the lower the better) serves as **single value metric** to quantify the **restraint performance** in a specific load case.

[5] Machens KU, Kübler L. Dynamic testing with pre-crash activation to design adaptive safety systems. Proceedings 27th Conference on the Enhanced Safety of Vehicles, Yokohama, 2023
[6] Schöneburg R. Integrale Sicherheit von Kraftfahrzeugen, ISSN 2628-104X ISSN 2628-1058 (electronic) ATZ/MTZ-Fachbuch ISBN 978-3-658-42805-1 ISBN 978-3-658-42806-8 (eBook) https://doi.org/10.1007/978-3-658-42806-8, 2023

CFD: Chest Forward Displacement
CFL: Characteristic Shoulder Belt Force Level
CLL: Constant Load Limiter
T@S: Torso @ Seat

Quantification of restraint performance and factor benchmarking
by referencing to a state-of-the-art configuration (PGV, PGS, PGO) in a reference crash event

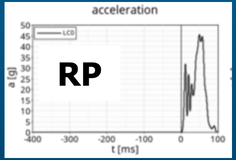
Pretty Good Seatbelt System (PGS):
SPR8-Retractor, OMPL-pilar loop, RNS4-Buckle, System Test Belt

Pretty Good Vehicle (PGV):
Fixation points, Seat Orientation, Seat Friction, WOS 900 mm

Pretty Good Occupant (PGO):
H350-ATD -> Torso@Seat (T@S)

Reference Pulse (RP):
PGV under US NCAP FWFI 56 kmph

Reference TTF (RTTF):
10 ms



The **relative deviation** from **CFL** obtained for (PGV,PGS,PGO, RP, RTTF)

- by using a vehicle specific pulse is defined as **Pulse Severity (PS)** (Pulse & TTF under a specific crash event including pre-crash dynamics)
- by using a specific occupant is defined as **Occupant Handicap (OH)**
- by using a specific vehicle configuration is defined as **V-Configuration Handicap (VCH)**
- by using a specific seatbelt system is defined as **SBS Thoracic Load (STL)**

To assess a different **event severities** a typical pulse is selected as new reference and "specific" joins the name.
Load Case Severity (LC-S) links this pulse to **RP** by applying both on PGV,PGS, PGO and calculating their relative CFL.

RNS4: **R**ast **N**ocken **S**chloss 4
CFL: **C**haracteristic Shoulder Belt **F**orce **L**evel
SPR8: **S**nake **P**retensioner **R**etractor **8**
OMPL: **O**ver**m**olded **P**ilar **L**oop

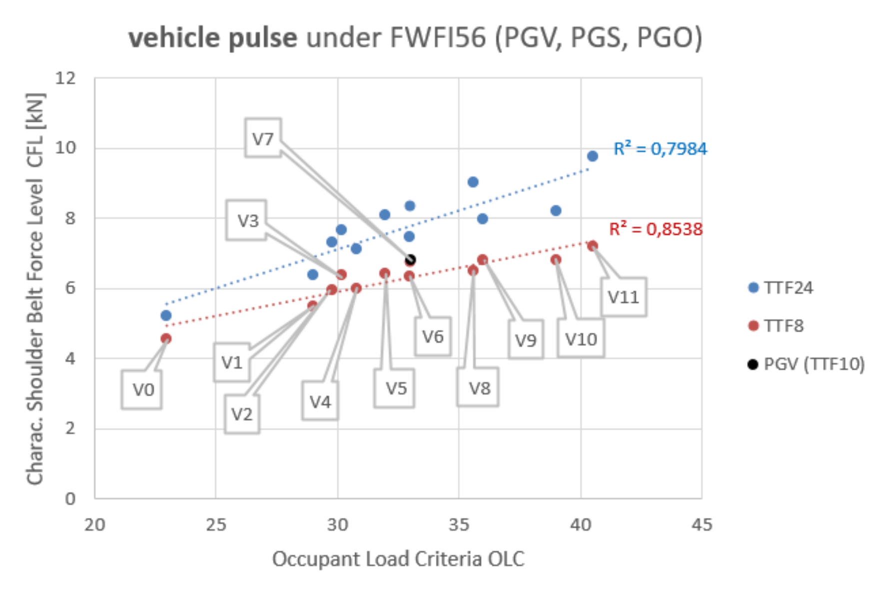
06

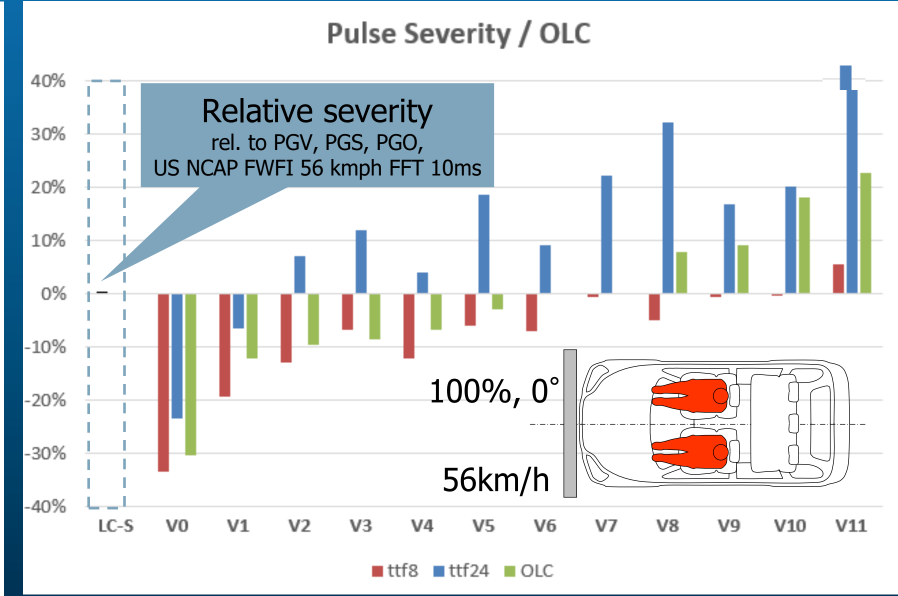
Quantification of restraint performance including factor benchmarking

Pulse Severity (Crashworthiness)
Occupant Handicap
V-Configuration Handicap
SBS Thoracic Load
specific SBS Thoracic Load (with Pre-crash activation)

SBS: **S**eat **B**elt **S**ystem

Pulse Severity (Crashworthiness rating) with CFL
Vehicle pulses under US NCAP FWFI (PGV config., PGS (TTF8, TTF24), PGO)



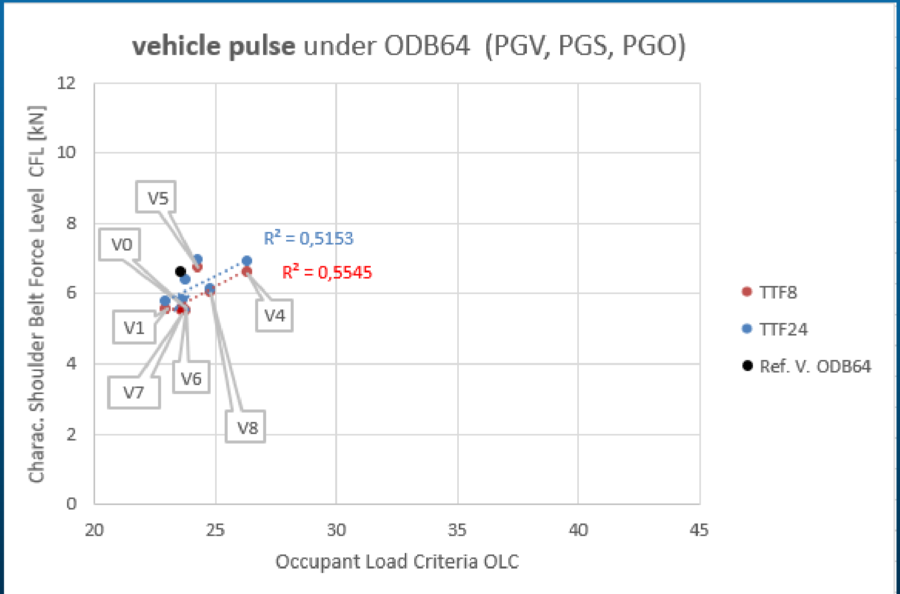


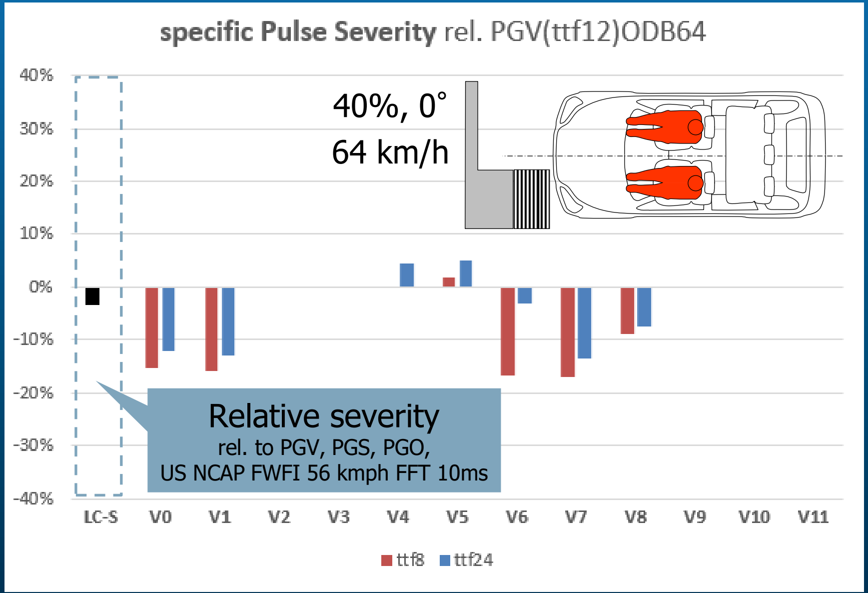
- Rough correlation between **Pulse Severity with CFL** (TTF 8ms) and pulse criterion **OLC**.
- **CFL is enriched** by ATD kinematic, TTF information and uses the **dynamic characteristics of a typical SBS** which replaces the generic assumptions used in **OLC.** Higher calculation effort results in **improved effect separation**.

OLC: Occupant Load Chriterium
CFL: Characteristic Shoulder Belt Force Level
SBS: Seat Belt System
TTF: Time To Fire

Specific Pulse Severity (Crashworthiness rating) with CFL

Vehicle pulses under EU NCAP ODB (PGV config., PGS (TTF8, TTF24), PGO)

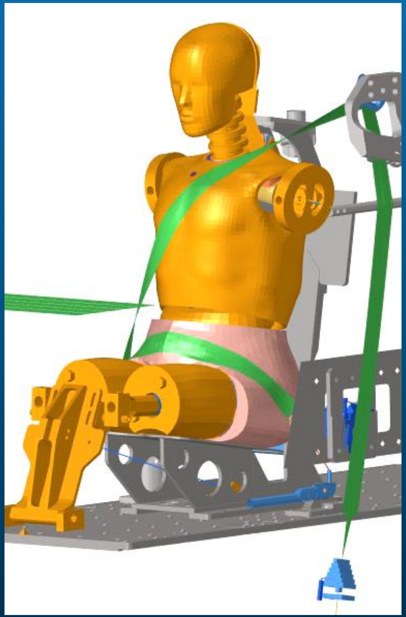


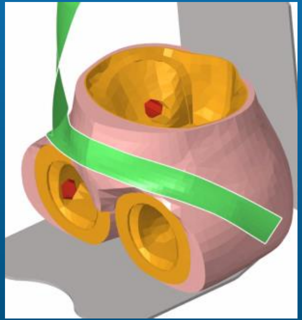


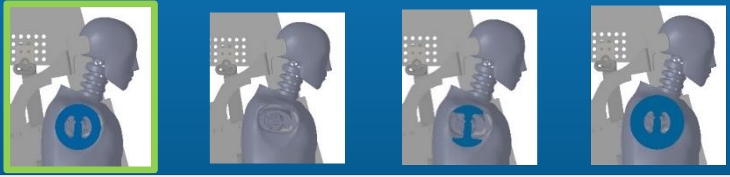
- Deformable Barrier (=crashworthiness bullet vehicle) **reduces vehicle pulse differences** for in CFL and OLC metric.
- CFL for PGV FWFI56(TTF10) and ODB64(TTF12) differs only by 3%
- **LC-S:** Average CFL under FWFI56 and ODB64 similar for **TTF8**: 6.3 /6.1 (**3%**), different for **TTF24**: 7.7 / 6.4 (**20%**)

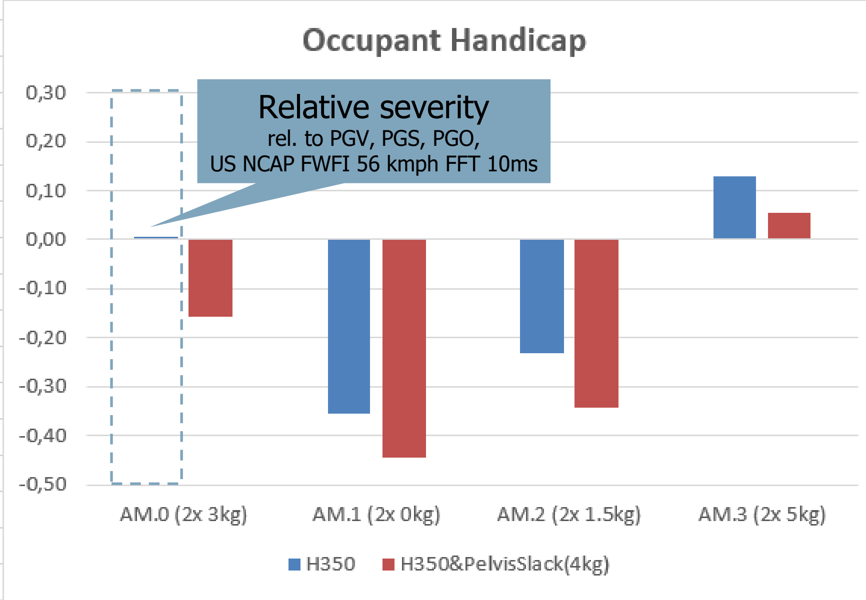
Occupant Handicap rating with CFL

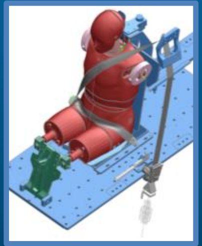
Pulse & TTF from PGV under US NCAP FWFI 56kmph for (PGV, PGS)

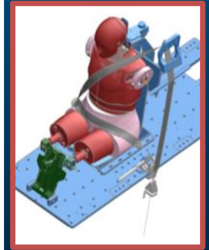








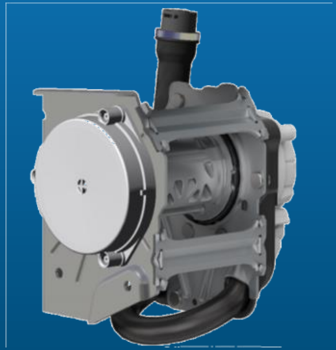




- **Occupant Handicap** grows by added mass at shoulder (0-10 kg) from **-35% to 12%**
- **Pelvis slack** (+4 kg) lowers CFL **by 9-16%**

V-Configuration Handicap / SBS Thoracic Load rating with CFL

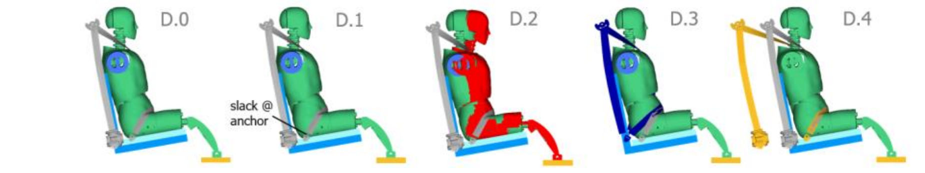
Pulse & TTF from PGV under US NCAP FWFI 56kmph for (PGS, PGO)

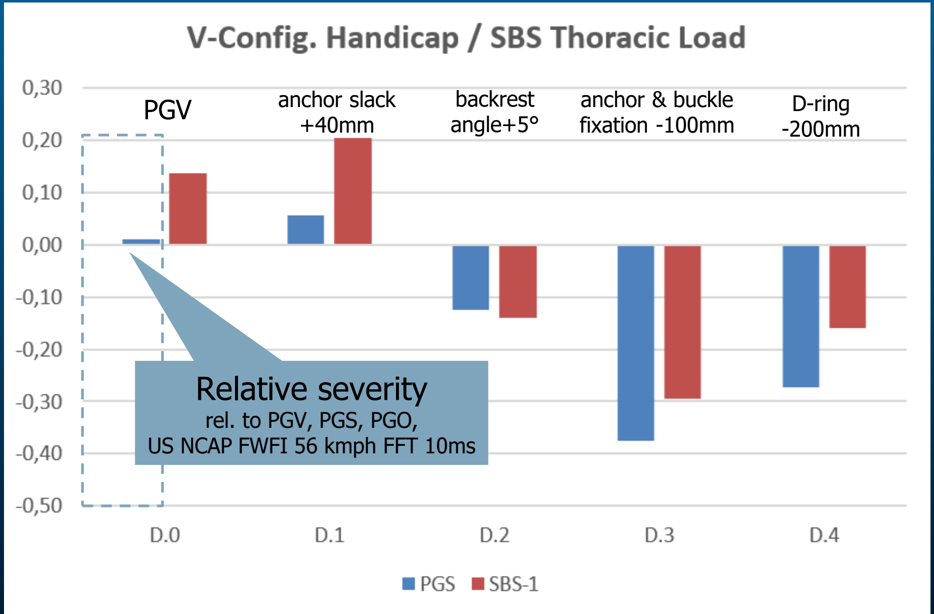


PGS

SBS-1

- **SBS-1** raises CFL **by 14%** (SBS-1 less effiicient)
- **40 mm anchor slack** raises CFL **by 6%**
- **Backrest angle +5°** lowers CFL **by 13%/14%**
- **Anchor & buckle fixation 100mm backwards** lowers CFL **by 38%**
- **D-ring fixation 200mm backwards** lowers CFL **by 27%/26%**



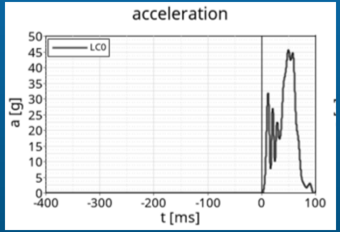


PGS: Pretty Good System
CFL: Characteristic Shoulder Belt Force Level
PGV: Pretty Good Vehicle
TTF: Time To Fire

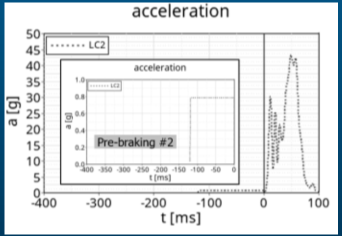
Specific SBS Thoracic Load w. pre-crash dynamics

Example: Variations of PGS activation

Load Case scenario

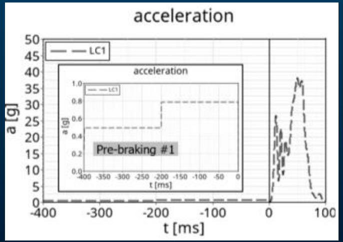


LC0



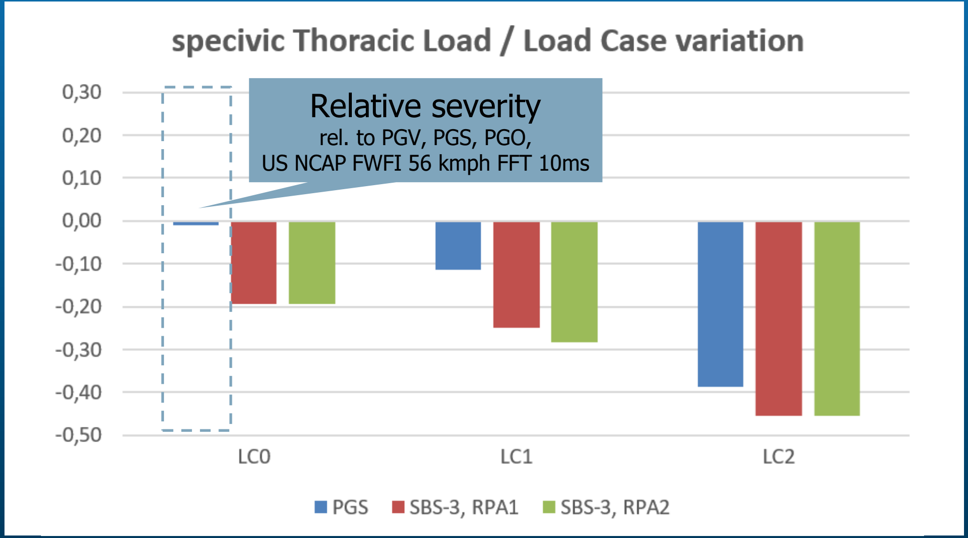
LC1

Scaling factor: 0.94



LC2

Scaling factor: 0.833



SBS activation

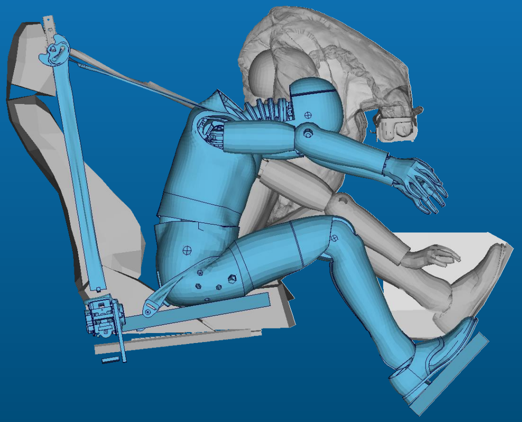
- ACR activation reduces CFL by **19% w/o braking.**
- **Pure braking** beneficial by **11%/39%**. (the longer the better)
- ACR activation reduced CFL up to **11%/14% in addition to** the effect of **short braking** and 6% in addition to long braking
- **ACR & Braking amount to 45% CFL** reduction about the effect of maximal vehicle pulse differences in the field.

PGS: Pretty Good System
CFL: Characteristic Shoulder Belt Force Level
SBS: Seat Belt System
ACR: Active Control Retractor

07

Summary & Outlook

Summary and Outlook



Matthiew Brumbelow, Jesssica S. Jermakian (IIHS)

"Improved thoracic injury protection in frontal crashes may be the single most pressing crashworthiness issue in the passenger vehicle fleet. Perhaps the quickest way to make gains in this area would be the use of a metric in crash test rating programs that is demonstrated to predict field injury risk for drivers restrained by a seat belt and airbag." [2]

[2] Brumbelow ML, et. al. (2022) Predicting Real-World Thoracic Injury Using THOR and Hybrid III Crash Tests. Proceedings of IRCOBI Conference, 2022, Porto, Portugal

1. **Characteristic shoulder belt force level (CFL)** is a potential metric to **predict SBS Thoracic Load** (Correlation to field injury risk pending).
2. **Adaptive restraint systems** regarded as important step towards **equity in occupant real-life safety**.
3. **HyDRA®** bench **enabler** to cross **link virtual** functional SBS models to **physical** testing.

SBS: Seat Belt Systems
CFL: Characteristic Shoulder Force Level

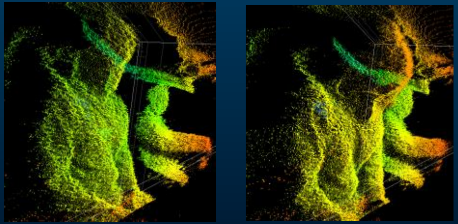
Pre-Crash (Re-)Positioning and early coupling with HyDRA®

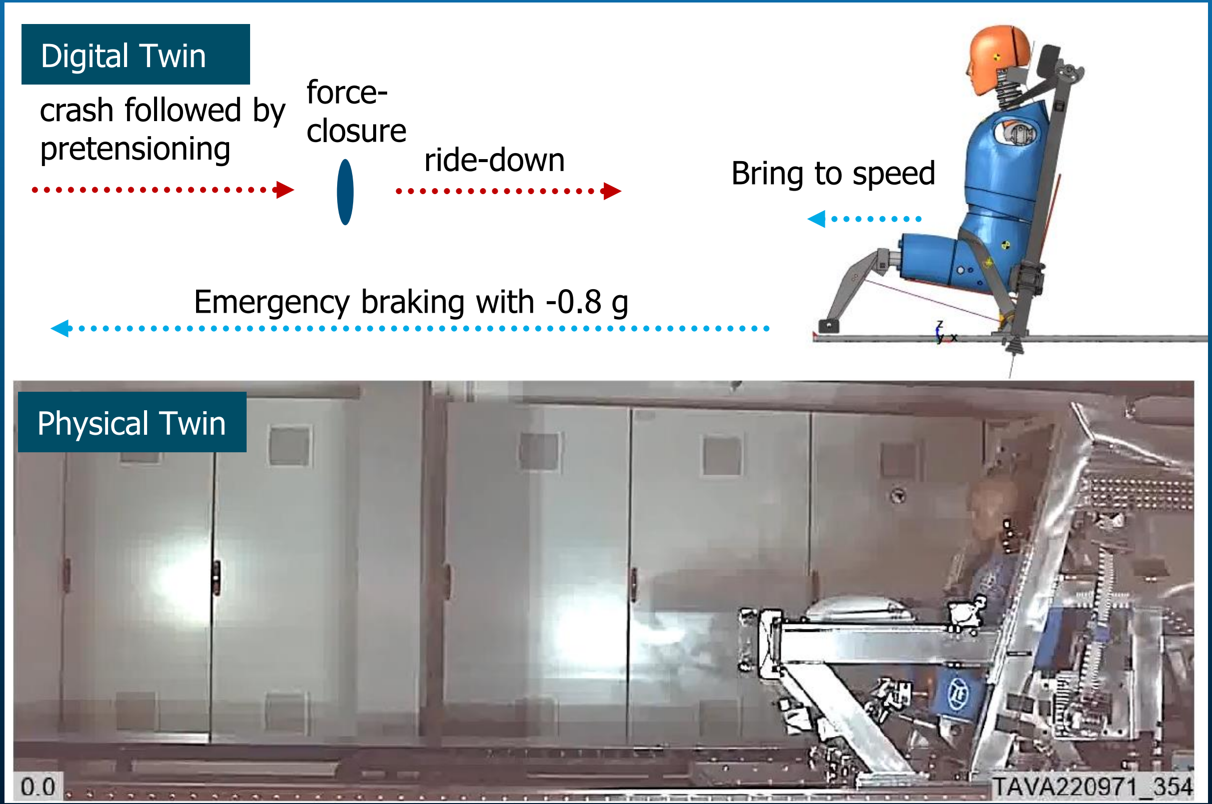
Submitted to airbag2024 Mannheim

meet us

CATARC defined braking by pedal robot

Assessment of occupant displacement by TOF camera





CATARC: China Automotive Technology & Research Center
TOF: Time Of Flight

Safety thrives when HyDRA® bites

Dr.-Ing. Kai-Ulrich Machens

Dr.-Ing. Lars Kübler

ZF Automotive Germany GmbH
Industriestr. 20,
73553 Alfdorf, Germany

Findings of IIHS and NTHSA

From National Automotive Sampling SystemCrashworthiness Data System (NASS-CDS)

- NTHSA reports that about 50% of all passenger vehicle occupants killed in 2020 were unrestrained.[1]
- Frontal non-rollover crashes accounted for 50% of fatalities of belted passenger-vehicle occupant in 2019 [1]. This proportion is highest for the newest vehicles (Fig.1),…[2]
- The estimated risk of a thoracic injury was greater than the risk of any other non-extremity injury for the two oldest age groups at all delta-Vs, with a larger difference for the oldest group.[3]

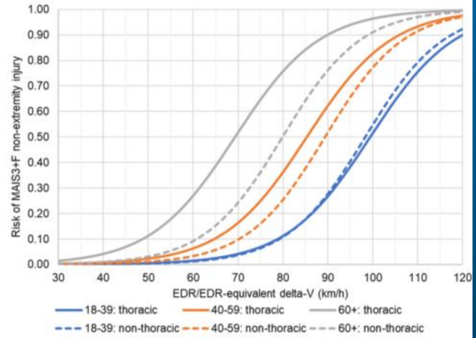


Fig. 4. Thoracic vs. non-thoracic (non-extremity) injury risk by delta-V and driver age in large overlap, moderate overlap and center impact crashes

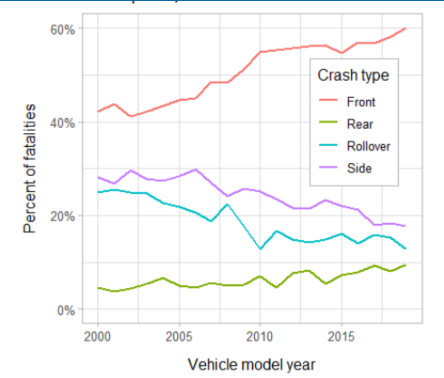


Fig. 1. 2018–2019 US fatalities of belted passenger-vehicle occupants by model year and crash type.

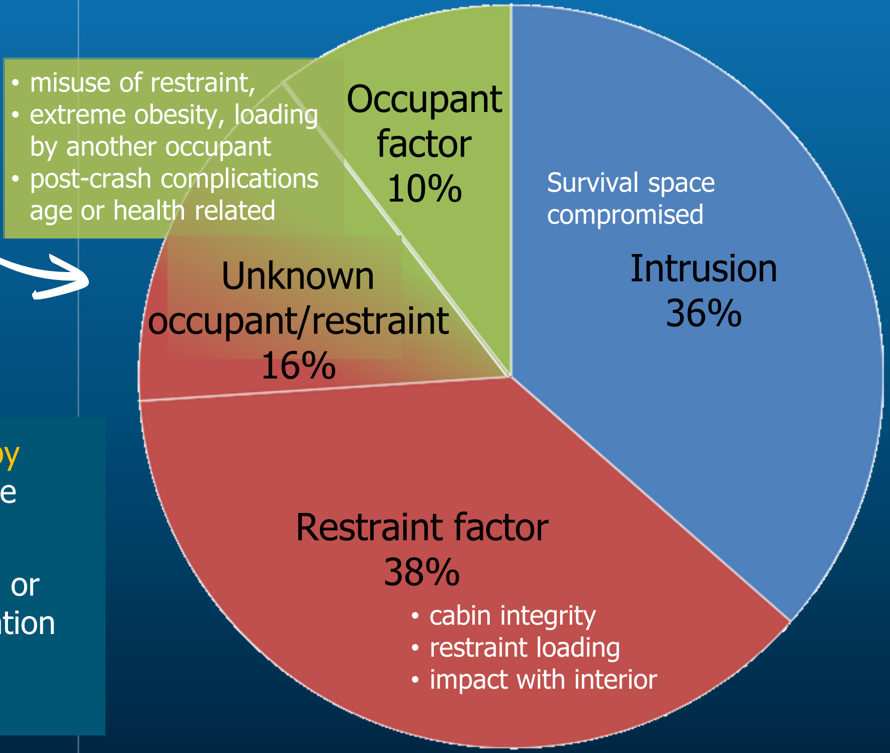
Improved thoracic injury protection in frontal crashes may be the single most pressing crashworthiness issue in the passenger vehicle fleet. Perhaps the quickest way to make gains in this area would be the use of a metric in crash test rating programs that is demonstrated to predict field injury risk for drivers restrained by a seat belt and airbag.[2]

[1] National Highway Traffic Safety Administration (2020) Fatality Analysis Reporting System
[2] Brumbelow ML, et. al. (2022) Predicting Real-World Thoracic Injury Using THOR and Hybrid III Crash Tests. Proceedings of IRCOBI Conference, 2022, Porto, Portugal..
[3] Brumbelow ML (2019) Front crash injury risks for restrained drivers in good-rated vehicles by age, impact configuration, and EDR-based delta V. Proceedings of IRCOBI Conference, 2019, Florence, Italy.

Findings of IIHS and NTHSA

From National Automotive Sampling SystemCrashworthiness Data System (NASS-CDS)

- Analysis of real-world cases with serious injuries resulting from frontal crashes of vehicles rated good for frontal crash protection.[4] (2000-06 data from NASS-CDS)
- Further restraint system improvements may require technologies that adapt to occupant and crash circumstances.[4]



- The high levels of real-world injury risk are not predicted by Hybrid III (HIII) measurements taken in the IIHS moderate overlap test, ….[2]
- ... shoulder-belt force, vehicle bumper-to-firewall distance, or the ratio between sternum deflection and thoracic acceleration often performed better in predicting injury outcomes than sternum deflection alone.[2]

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[4] Brumbelow ML., Zuby DS. Impact and injury patterns in frontal crashes of vehicles with good ratings for frontal crash protection. Proceedings of 21st Intl Tech Conf on the Enhanced Safety of Vehicles, 2009

ODB: **O**ffset **D**eformable **B**arrier

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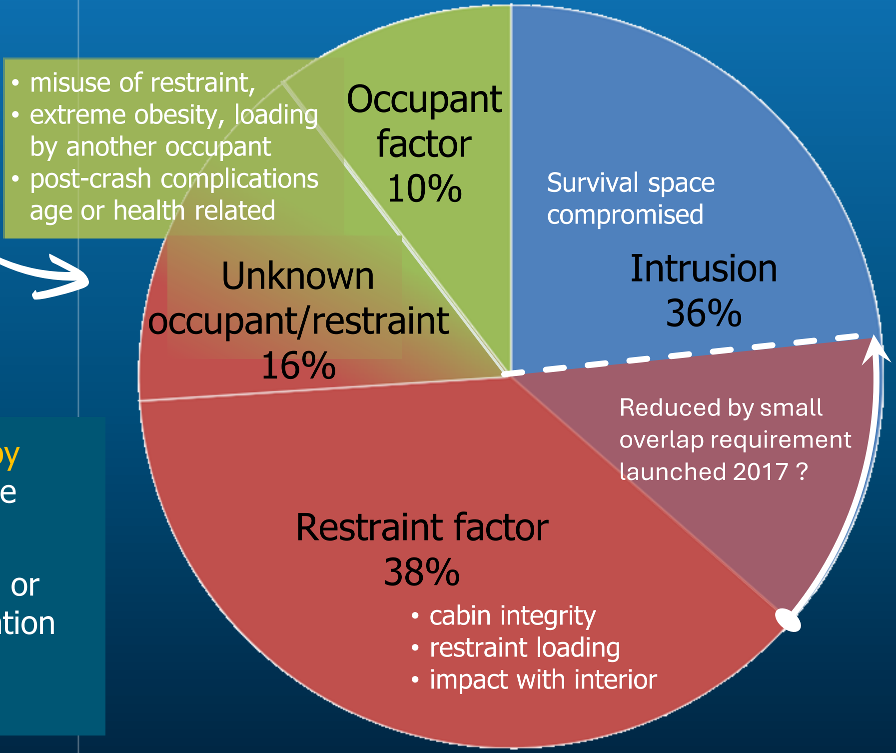

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In-Crash Phases for Passive & Integrated Safety

Passive Safety: phases in-crash

Phase 1	Phase 2	Phase 3
crash detection first contact – TTF task: reliable crash detection	**force closure** TTF – LL-level reached task: fast coupling build up belt forces	**ride-down** LL-level reached – occupant at rest task: ride-down occupant with controlled (minimal) forces

Irreversible SBS activation

Integrated Safety: phases in-crash

Phase 1	Phase 2	Phase 3
pre-crash preparation ... – collision imminent signal (TTF) task: pre-crash activity reliable crash detection	**force closure** TTF – LL-level reached task: fast coupling build up belt forces	**ride-down** LL-level reached – occupant at rest task: ride-down occupant with controlled (minimal) forces

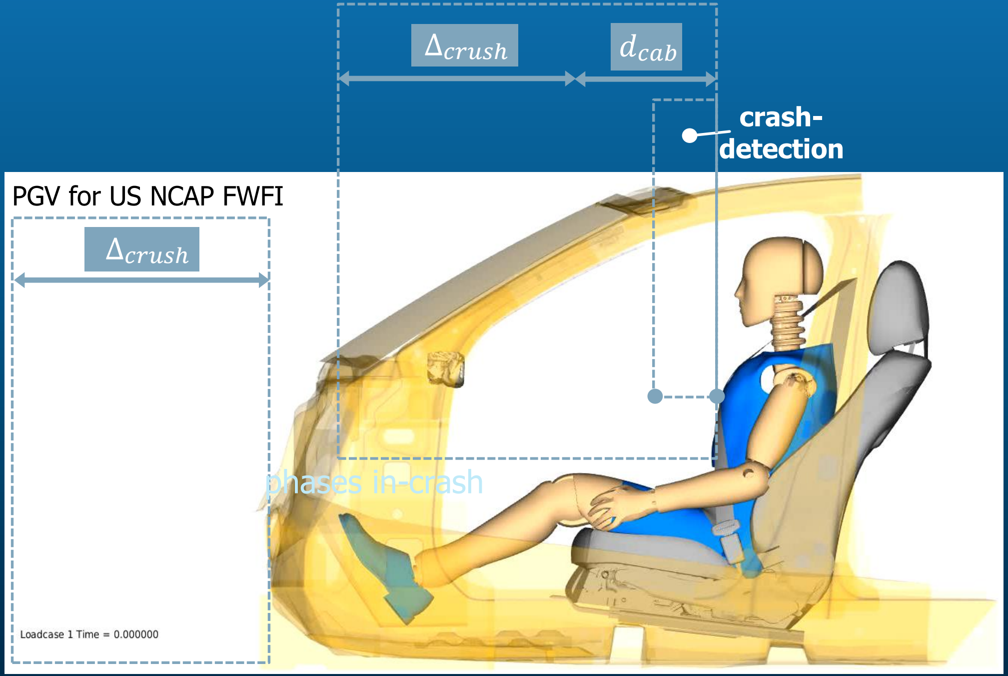
Reversible SBS activation → ***Irreversible*** SBS activation

Efficient coupling of occupant to vehicle major task of Seat Belt Systems & SBS pre-crash activation.
In **Integrated Safety** *pre-crash* and *in-crash* phase need to be evaluated together.

LL: Load Limiting
TTF: Time To Fire
SBS: Seat Belt System

In-Crash phases / SBS-Task

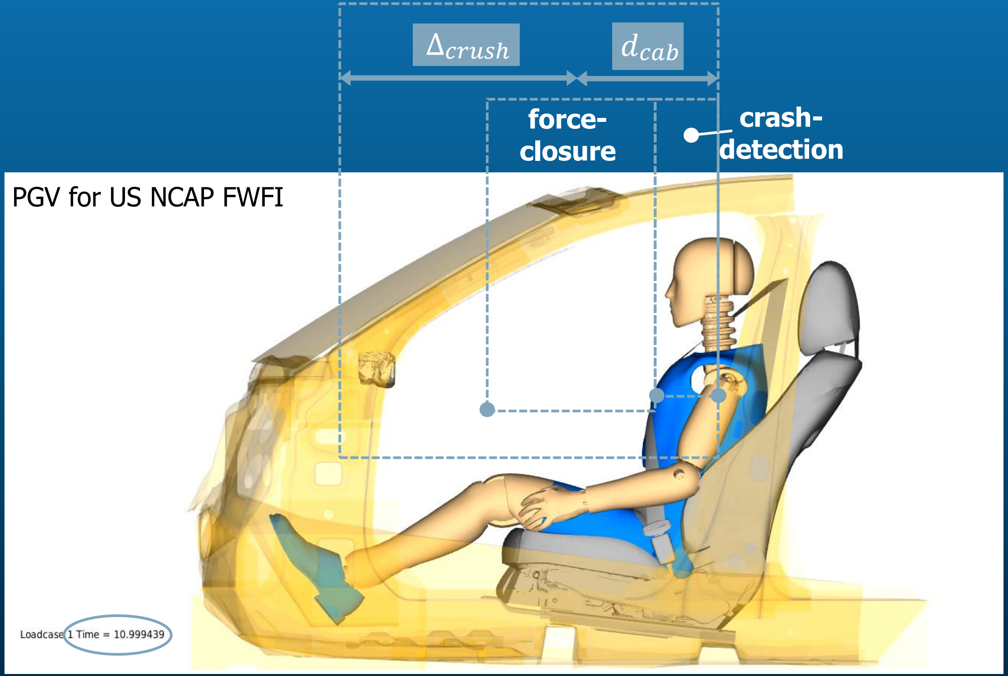
PGV: Front Passenger US NCAP FWFI (five star rated midsize sedan)



PGV: **P**retty **G**ood **V**ehicle
FWFI: **F**ull **W**idth **F**rontal **I**mpact
SBS: **S**eat **B**elt **S**ystem

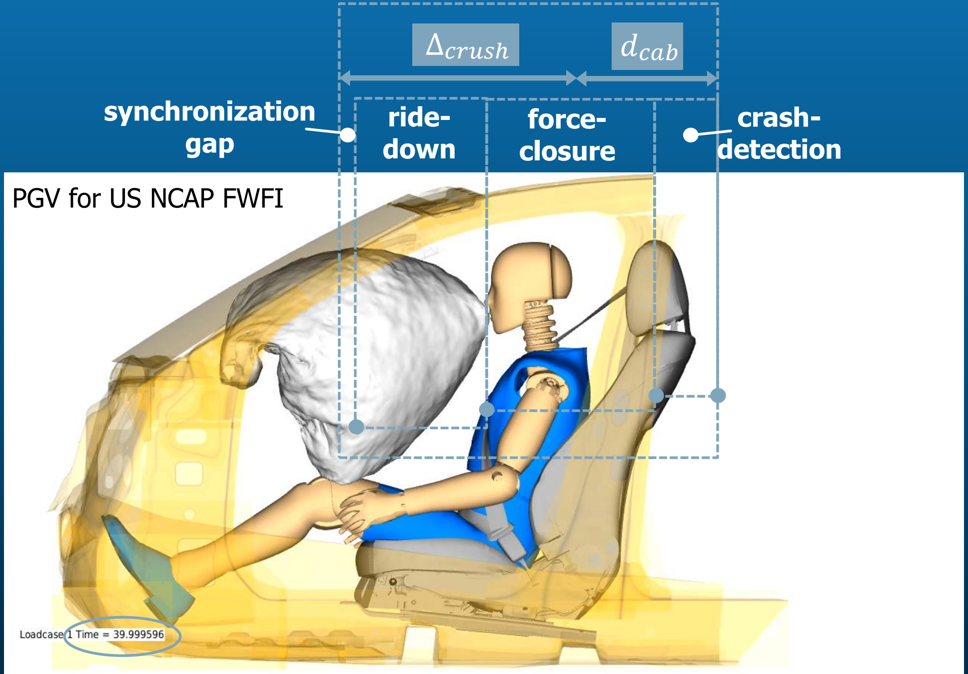
In-Crash phases / SBS-Task

PGV: Front Passenger US NCAP FWFI (five star rated midsize sedan)



In-Crash phases / SBS-Task

PGV: Front Passenger US NCAP FWFI (five star rated midsize sedan)



SBS subsystem contribution to mitigate occupant injury risk **depends upon integral scenario**

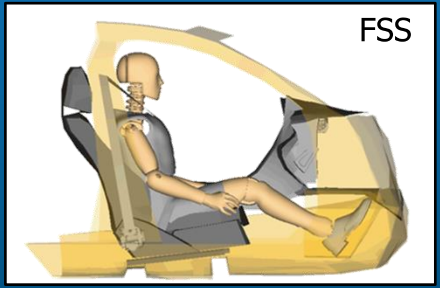
1. **Seat Belt System**
2. **Crash Scenario**
3. **Vehicle Sensory System**
4. **Occupant**
5. **Vehicle**
6. **Seat & Environment**
7. **Airbag System**

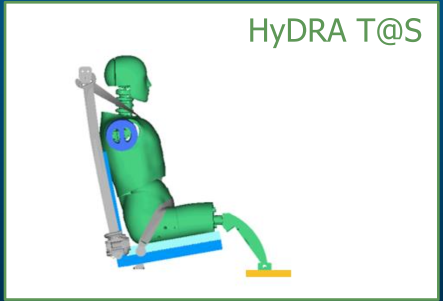
SBS performance can **not meaningfully be assessed from NCAP** vehicle crashworthiness point score.

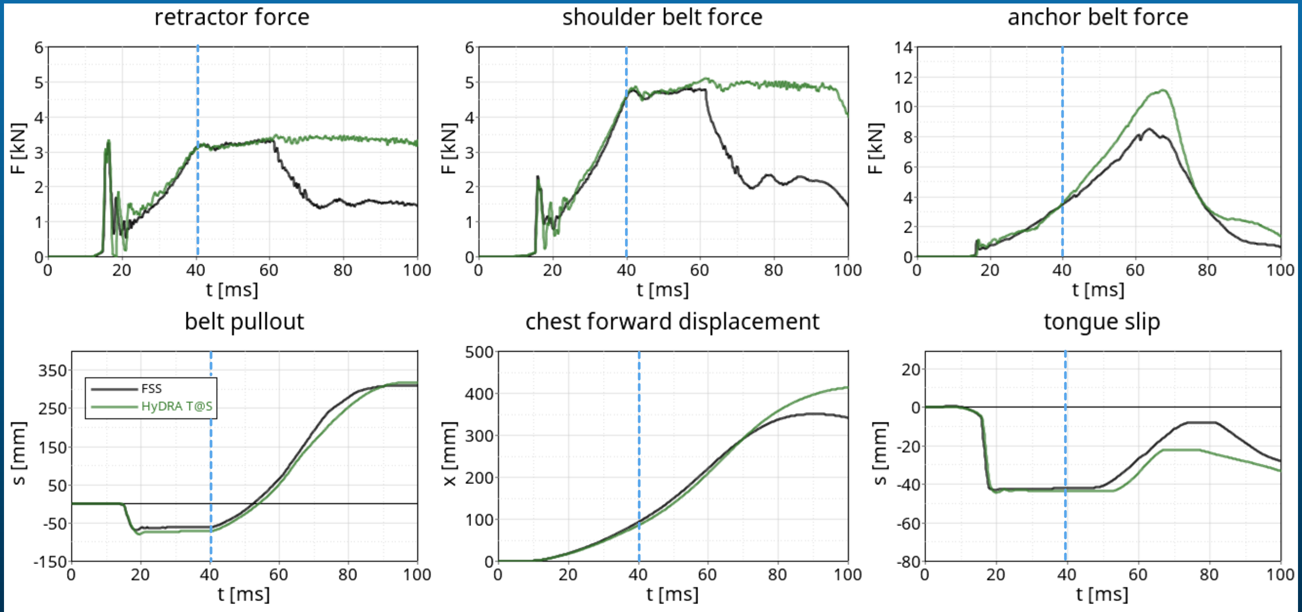
SBS: **S**eat **B**elt **S**ystem
NCAP: **N**ew **C**ar **A**ssessment **P**rogramme
PGV: **P**retty **G**ood **V**ehicle
FWFI: **F**ull **W**idth **F**rontal **I**mpact

How to rate SBS Performance?

by complexity reduction via simplified but equivalent setup







Up to **force-closure** the simplified **Torso@Seat corresponds** amazingly well to **Full Safety System** configuration in all six kinetic parameters. Simplified T@S improves **repeatability** (steal seat!) & **precision** in physical and virtual testing.

SBS Performance can be equivalently assessed at reduced HyDRA® T@S setup.

T@S: Torso@Seat
SBS: Seat Belt Systems