Institute of Transport Economics
Norwegian Centre for Transport Research

Frontal Crash Protection for Bus Drivers

Simulation-Based Assessment of Test Methods and Structural Countermeasures

Manuel Laso, Tor-Olav Nævestad

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Summary

Current bus front structures and applicable regulatory tests do not provide adequate protection for drivers in frontal collisions. This study investigates structural countermeasures and representative test methods for improving bus driver protection using finite element simulations. Bus-to-bus collisions with varying overlap ratios and impact angles were analysed alongside alternative impact configurations using narrow rigid barriers and pole impactors. These test methods were found to better reproduce localized intrusion patterns and energy concentration observed in real-world accidents than existing regulatory tests. Based on these findings, a reinforced driver crash-box was developed and virtually integrated into a low-floor city bus model. The simulations show that the crash-box reduces steering column intrusion in the driver area with about 50-60% in the simulated frontal impact collisions. This reduction may be large enough to potentially transform many of the simulated scenarios from non-survivable to potentially survivable. While the reinforced structure redirects deformation away from the driver zone, increased stiffness brings the motion to a more abrupt stop, subjecting the driver to higher G-forces. Reinforcing the front structure improves the survival space but may lead to higher loads if energy is not sufficiently absorbed through deformation and restraint systems (e.g. seatbelt, airbag).

Kort sammendrag

Dagens frontstrukturer på busser og gjeldende regelverk gir ikke tilstrekkelig beskyttelse for bussjåfører ved frontkollisjoner. Denne studien undersøker strukturelle løsning og representative testmetoder for å forbedre førerbeskyttelsen ved hjelp av numeriske simuleringer. Buss-mot-buss-kollisjoner med varierende overlapp og kollisjonsvinkler er analysert, sammen med alternative kollisjonsoppsett basert på smale, stive barrierer og stolper. Disse testmetodene viser seg å gjenskape lokal inntrengning og energikonsentrasjon fra reelle ulykker bedre enn eksisterende regulatoriske tester. På bakgrunn av dette ble en forsterket «førerkollisjonsboks» utviklet og virtuelt integrert i en lavgulvs bybussmodell. Simuleringene viser at en kollisjonsboks for føreren reduserer rattstammens inntrengning i førerplassen med omtrent 50–60% i de simulerte frontkollisjonene. Dette kan være nok til å potensielt omgjøre mange av de simulerte scenarioene fra dødelige til potensielt overlevbare. Når fronten på bussen gjøres stivere for å hindre at den presses inn mot sjåføren, stopper den også kollisjonsbevegelsen bråere. Det betyr at sjåføren utsettes for høyere G-krefter under sammenstøtet. Forsterkning av frontstrukturen forbedrer dermed overlevelsesrommet, men kan føre til høyere belastninger på føreren dersom energien ikke absorberes tilstrekkelig gjennom deformasjon og fastholdelsessystemer (bilbelte, airbag).

Preface

This report is financed by Ruter, the largest public transport authority in Norway. Ruter's contact for this study has been Jon Stenslet. We are very grateful for good cooperation and interesting discussions.

The report aims to assess new structural solutions for improving bus driver protection in frontal collisions and to investigate alternative test methods for evaluating structural integrity and driver safety. The report builds on previous studies conducted by the Institute of Transport Economics (TØI) and IDIADA, commissioned by the Norwegian Public Roads Administration (Nævestad et al., 2025; Laso et al., 2025). These earlier studies provide quantitative overviews of the extent of bus accidents in Europe, as well as qualitative analyses of shortcomings in current bus front designs. Based on these analyses, new solution trends for improved bus front designs were proposed. However, it was concluded that further in-depth studies based on simulations and/or testing were necessary to refine and validate models for improved bus driver collision safety.

The present report provides such simulations. Its purpose is to contribute to the international debate on enhanced collision protection for bus drivers. In September 2025, the European Transport Workers' Federation (ETF) published a manifesto calling for stronger crash and collision protection for bus drivers in Europe, addressing governments, employers, and vehicle manufacturers. In the same year, the Norwegian government raised the issue of bus driver collision safety within the United Nations Economic Commission for Europe (UNECE) Working Party on Passive Safety (GRSP).

GRSP is an international regulatory working group under UNECE's World Forum for Harmonization of Vehicle Regulations (WP.29), responsible for developing and updating global vehicle safety regulations related to passive safety. As such, GRSP represents a key arena for potential future international standards aimed at improving collision safety for bus drivers. Developing such standards is, however, a long-term process, and current efforts remain at an early stage.

By indicating the potential effects of new solution trends for improved frontal protection in bus frontal collisions, this report may help identify or inspire solutions that can be implemented on a voluntary basis, or that may serve as a foundation for future international requirements.

To ensure that the findings address the current industry needs and have global relevance, a panel of industry experts has been assembled to discuss the proposed solutions and contribute their insights into this international safety issue. We thank the many individuals and organizations in the Norwegian and the international public transport environment for insightful discussions and valuable feedback.

Project manager at TØI has been Tor-Olav Nævestad. Manuel Laso from IDIADA has been responsible for conducting and presenting the simulations, while Nævestad has provided the context and the background text. ChatGPT was used as a support tool for language editing, translation, text shortening, and summarising key points. All content was reviewed and approved by the authors. Head of research, Trine Dale, has quality assured the report.

Oslo, February 2026
Institute of Transport Economics

Bjørne Grimsrud	Trine Dale
Managing Director	Head of Research

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ENGLISH **Summary**

Frontal Crash Protection for Bus Drivers

Simulation-Based Assessment of Test Methods and Structural Countermeasures

TØI Report 2139/2026 • Authors: Manuel Laso, Tor-Olav Nævestad• Oslo 2026 • 83 pages

- Current bus front structures and regulatory tests do not provide adequate driver protection in frontal collisions.
- This study investigates structural countermeasures and representative test methods to improve driver protection, using finite element simulations.
- We develop new test methods that better reproduce real-world intrusion patterns and energy concentration than current regulatory tests.
- Based on the results, we design a reinforced driver crash box to enhance protection in frontal collisions.
- Simulations show that the crash box reduces steering column intrusion in the driver area with about 50-60% in the simulated frontal impact collisions.

Due to the absence of crumple zones in bus fronts, the lack of mandatory EU crashworthiness standards focusing on bus drivers, and the low seating position of drivers in many buses, bus drivers are more exposed in frontal collisions than drivers of passenger cars and trucks. This has been demonstrated in several serious bus accidents in Norway over the past decade, where drivers have been killed or severely injured despite relatively low impact speeds. In one head-on collision investigated by the Accident Investigation Board, one driver was killed and the other critically injured at an impact speed of just over 30 km/h. Comparable collisions between modern passenger cars at similar speeds would be unlikely to result in fatal injuries due to advanced crashworthiness systems.

While vehicle safety has improved significantly for passenger cars and trucks through stricter regulations, safety requirements for buses have developed more slowly. Truck cabs are subject to crashworthiness standards under UN Regulation R29.03, and passenger cars must meet comprehensive frontal impact requirements, whereas no EU-wide crashworthiness standards specifically address frontal protection for bus drivers. Norway’s adoption of UN R29.03 for buses in 2023 represents an important step, but the regulation was developed for trucks and may not fully account for bus-specific design characteristics. This underscores the need to study bus driver crash protection and to develop targeted solutions for frontal collisions.

The overall aim of this study is therefore to establish a technical basis for improved design solutions that can enhance the protection of bus drivers in frontal collisions, as well as for the development of test procedures for assessing the passive safety of bus drivers, with relevance for future regulatory development.

Our evaluation of existing international passive safety regulations demonstrates that current (UNECE) requirements do not adequately represent frontal collision conditions for buses. Regulations addressing rollover protection do not load the front structure, while cab strength tests developed for trucks (e.g. UN R29.03) apply impact energies that are far below those observed in real bus accidents.

To address these limitations, our report develops and investigates alternative frontal impact test configurations, including narrow rigid barrier and pole impact tests. The results show that such localized impact tests better reproduce the energy concentration, deformation patterns, and intrusion levels observed in real bus accidents than current regulatory tests, such as UN R29.03, which is mandatory for buses in Norway. As a result, these test configurations emerge as more suitable candidates for future bus-specific frontal impact assessment. The development and demonstration of these new tests is a key contribution of the report, which can inform future work in this area, including efforts to develop new voluntary or mandatory standards for collision safety in buses.

Another key contribution of the report is new simulation-based evidence on how bus drivers can be better protected in frontal collisions. The study develops and evaluates a reinforced driver crash-box as a targeted structural countermeasure for increased bus driver safety in frontal collisions. The simulations show that the implementation of a driver crash box reduces steering column intrusion in the driver area from approximately 600–730 mm in the baseline configuration to about 260–330 mm, corresponding to a reduction on the order of 50–60%, in the simulated 30 km/h frontal impact collisions. This reduction may be large enough to potentially transform many of the simulated scenarios from non-survivable to potentially survivable, provided that adequate restraint systems (seatbelt, airbag) are used. Authorities, companies and stakeholders can use the crash box as an inspiration for future efforts to increase the safety of bus drivers in collisions.

At the same time, the results highlight the need to balance increased structural stiffness with effective energy absorption and the performance of restraint systems. We propose that the crash box should be combined with measures such as airbags and seat belts. This is an important area for future research. Future research should also examine the effect of a small deformable zone in front of the crash box, as well as the effects of combinations of passive and active safety measures.

Transportøkonomisk institutt
Stiftelsen Norsk senter for samferdselsforskning

NORSK **Sammendrag**

Frontkollisjonsbeskyttelse for bussjåfører

Simuleringsbasert vurdering av testmetoder og strukturelle tiltak

TØI rapport 2139/2026 • Forfattere: Manuel Laso, Tor-Olav Nævestad• Oslo 2026 • 83 sider

- Dagens frontstrukturer i busser og gjeldende regelverkstester gir ikke tilstrekkelig beskyttelse for føreren ved frontkollisjoner.
- Studien undersøker strukturelle mottiltak og representative testmetoder for å forbedre førerbeskyttelsen ved bruk av simuleringer.
- Vi utvikler nye testmetoder som bedre gjengir inntrengningsmønstre og energikonsentrasjon observert i reelle ulykker enn dagens regelverkstester.
- Basert på resultatene utvikler vi en forsterket førerkollisjonsboks for å styrke beskyttelsen ved frontkollisjoner.
- Simuleringene viser at kollisjonsboksen reduserer rattstammeinntrengning i førerområdet med om lag 50–60 % i de simulerte frontkollisjonene.

Bussjåfører er mer utsatt enn bil- og lastebilsjåfører ved frontkollisjoner. Dette skyldes manglende deformasjonssoner i fronten av busser, mangelen på obligatoriske EU-standarder for kollisjonssikkerhet som fokuserer på bussjåfører, og lav førerposisjon i mange busser (for eksempel bybusser). Dette har blitt påpekt i analyser av bussulykker i Norge de siste ti årene. I noen av disse ulykkene har bussjåfører blitt drept eller alvorlig skadet, selv om kollisjonshastigheten har vært relativt lav. I én av disse ulykkene ble én sjåfør drept og den andre kritisk skadet i en frontkollisjon, selv om bussene bare hadde en hastighet på litt over 30 km/t ved sammenstøtet. Hadde to personbiler med moderne kollisjonssikkerhetsstandard kollidert front mot front ved en tilsvarende hastighet, er det lite sannsynlig at ulykken ville vært dødelig. Hvis alle sikkerhetssystemer (deformasjonssoner, sammenleggbar rattstamme, setebelter og kollisjonsputer) hadde fungert som de skulle, ville det trolig bare ha resultert i materielle skader.

Selv om kjøretøysikkerheten har blitt betydelig forbedret for personbiler og lastebiler gjennom strengere regelverk, har utviklingen av sikkerhetskrav for busser gått langsommere. Førerhus i lastebiler er underlagt krav til kollisjonssikkerhet gjennom FN-regulativ R29.03, og personbiler må oppfylle omfattende krav til frontkollisjonssikkerhet. Det finnes imidlertid ingen EU- krav som spesifikt fokuserer på beskyttelsen av bussjåfører i frontkollisjoner. Norges innføring av UN R29.03 for busser i 2023 representerer et viktig steg på vegen, men denne standarden er opprinnelig utviklet for lastebiler og tar ikke nødvendigvis fullt hensyn til bussers særskilte konstruksjon og driftsforhold. Dette viser behovet for å undersøke kollisjonsbeskyttelse for bussjåfører nærmere og utvikle målrettede løsninger for frontkollisjonsbeskyttelse i buss.

Det overordnede målet med denne studien er derfor å etablere et teknisk grunnlag for forbedrede konstruksjonsløsninger som kan styrke beskyttelsen av bussjåfører ved frontkollisjoner, samt for utvikling av testprosedyrer for vurdering av bussjåførers passive sikkerhet, med relevans for fremtidig regelverksutvikling.

Vår gjennomgang av eksisterende internasjonalt regelverk for passiv sikkerhet, viser at dagens krav ikke i tilstrekkelig grad representerer frontkollisjonsforhold for busser. Regelverk som omhandler veltebeskyttelse, spesifiserer ikke tester som påfører belastning på frontstrukturen, mens tester for førerhusstyrke utviklet for lastebiler (for eksempel UN R29.03), anvender kollisjonsenergier som ligger langt under nivåene observert i reelle bussulykker.

For å adressere disse begrensningene, undersøker rapporten alternative måter å teste bussenes frontkollisjonssikkerhet. Vi foreslår og tester effekter av smale, stive barrierer og stolper i kollisjonstester. Testene vi gjennomfører likner i større grad enn de eksisterende testene på de reelle ulykkene vi kjenner til, med alvorlig utfall. Resultatene våre viser at våre kollisjonstester i større grad gjenskaper energikonsentrasjon, deformasjonsmønstre og inntrengning observert i reelle bussulykker enn det dagens regulatoriske tester gjør, for eksempel UN R29.03, som er obligatorisk for busser i Norge. Utviklingen og demonstrasjonen av disse nye testene er et sentralt bidrag i rapporten, og kan gi viktige innspill til videre arbeid på dette området, inkludert utvikling av nye frivillige eller obligatoriske standarder for kollisjonssikkerhet i busser.

Et annet viktig bidrag i rapporten er ny, simuleringsbasert dokumentasjon av hvordan bussjåfører kan beskyttes bedre ved frontkollisjoner. Studien utvikler og evaluerer en forsterket førerkollisjonsboks som et målrettet strukturelt tiltak for økt bussikkerhet. Simuleringene viser at implementeringen av en kollisjonsboks for føreren reduserer rattstammens inntrengning i førerplassen fra omtrent 600–730 mm i grunnkonfigurasjonen til rundt 260–330 mm. Dette tilsvarer en reduksjon på rundt 50–60 % i de simulerte frontkollisjonene ved 30 km/t. Denne reduksjonen kan være stor nok til å potensielt omgjøre mange av de simulerte scenarioene fra dødelige til potensielt overlevbare, forutsatt at tilstrekkelige sikringssystemer (dvs. bilbelte, airbag) benyttes. Myndigheter, virksomheter og andre aktører kan bruke kollisjonsboksen som inspirasjon i fremtidig arbeid for å forbedre sikkerheten for bussjåfører ved kollisjoner.

Samtidig viser resultatene våre behovet for å balansere økt strukturell stivhet med effektiv energiabsorpsjon og ytelsen til fastholdelsessystemer. Vi foreslår at kollisjonsboksen kombineres med tiltak som kollisjonsputer og sikkerhetsbelter. Dette er et viktig område for fremtidig forskning. Fremtidig forskning bør også undersøke effekten av en mindre deformasjonssone foran kollisjonsboksen, og effekten av kombinasjoner mellom passive og aktive sikkerhetstiltak.

1 Introduction

1.1 Background

As a result of the lack of crumple zones in bus fronts, absence of mandatory EU crashworthiness standards focusing on bus drivers, and a low driver seating position in many buses (e.g. city buses), bus drivers are more exposed in crashes with frontal impact than e.g. car and truck drivers (Afripin et al., 2019; Holenko et al., 2024). This has been indicated in bus accidents in Norway in the last ten years. In some of these crashes, bus drivers have been killed or seriously injured despite the fact that impact speeds were quite low.

In one of these crashes (Norwegian Safety Investigation Authority (NSIA), 2019), one driver was killed and the other critically injured in a head-on crash, even though the speed of the buses was just over 30 km/h at the time of impact. The buses struck each other with an overlap of about 40-50%. This means that the first point of impact for both buses was the driver's compartment. In both buses, this compartment was crushed completely, leaving little or no space for survival.

If two passenger cars with state-of-the-art crashworthiness had crashed head-on at a similar speed, the crash would probably not have been fatal. If all protective systems (crumple zone, collapsible steering wheel column, seat belts, air bags) had worked properly, such a crash might very well have resulted in property damage only.

The NSIA compared buses to other motor vehicles with respect to crashworthiness standards. This comparison is shown in Figure 1.1.

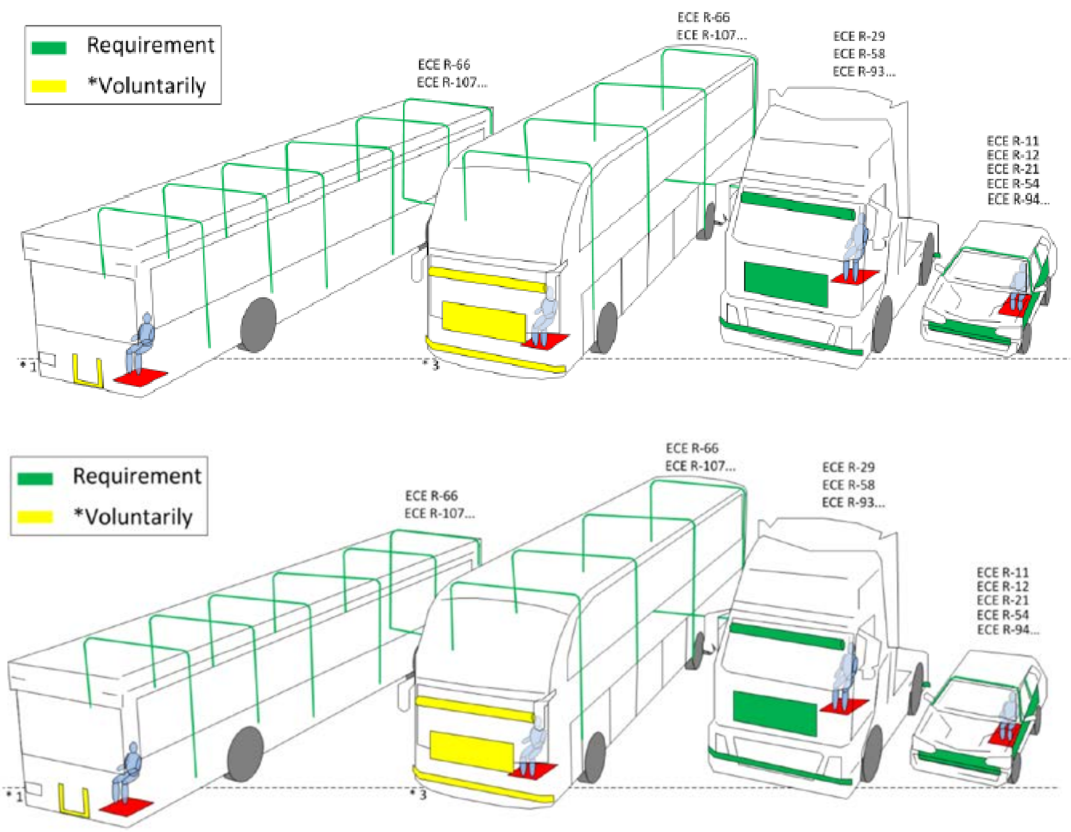


Figure 1.1: Illustration of the most relevant UNECE[1] regulations for collision protection on urban buses (bus categories 1 and 2), express coaches (bus category 3), tractors, and passenger cars. Source: Illustration by AIBN (now: NSIA) report Road 2019-04, figure 26 on p. 20.

For coaches used in long distance traffic, safety bars can be installed but are not mandatory (shown in yellow on the second bus from the left in Figure 1.1). For trucks, safety bars are mandatory (shown in green). The buses that crashed in the head-on collision mentioned above were of the type shown to the left in Figure 1.1. In these buses, the seat belt is the only protection of the driver. There are no safety bars, no extra bumper functioning as a buffer, no airbag, and no system for retracting and/or reclining the seat in case of an impact. There are, in other words, many measures that can improve crashworthiness, but that are not required by current safety standards for city buses or buses operating regional routes.

Truck cabins are subject to strict crashworthiness standards under UN R29.03, which mandates tests for structural integrity and occupant safety in head-on and rollover crashes. Passenger cars must meet crash-test standards that ensure survival space for drivers and passengers during collisions. There are, however, no mandatory crashworthiness standards targeting the situation of bus drivers. The exception is Norway, which in 01.10.2023 adopted UN R29.03 for buses. This standard applies, however, to trucks, and it may not fully address the unique design and operational characteristics of buses compared to trucks. Thus, there is a need to study the crash protection of bus drivers and to develop targeted solutions which can provide bus drivers with sufficient protection in case of accidents with frontal impacts. As indicated by Figure 1.1, the main crashworthiness issue in buses has been the protection of the passengers in case of rollover accidents (cf. UN R66.02), and passenger evacuation (cf. UN R107.10).

[1] United Nations Economic Commission for Europe

A recent study commissioned by the Norwegian Public Roads Administration indicates that current structural designs of bus fronts provide insufficient collision protection for drivers, that UN R29.03 type A crash test design requirements are insufficient, and that there is a need for an improved bus front structure (Nævestad et al 2025). The study conducted by Nævestad et al (2025) use the three fatal Norwegian low speed (e.g. 30 km/h) bus collisions as point of departure and shows that the energy level in these collisions was 10 times higher than the energy tolerance level required by type A test from UN R29.03. Based on a critical review of current bus front designs, Nævestad et al (2025) and Laso et al (2025) suggest new bus front solution trends to provide bus drivers with sufficient structural protection in case of collisions with frontal impact. Laso et al (2025) and Nævestad et al (2025) conclude, however, that it is necessary to implement a deeper study based on simulations and/or testing to refine and validate models for improved bus driver collision safety. The present report provides such simulations.

1.2 Aims

The overall aim of this study is to establish a technical basis for improved design solutions that can enhance the protection of bus drivers in frontal collisions, as well as for the development of test procedures for assessing the passive safety of bus drivers, with relevance for future regulatory development.

More specifically, the study aims to:

1. **Evaluate the crashworthiness of current bus front structures,** through finite element simulations of head-on collisions with varying overlap ratios and impact angles, to identify critical weaknesses affecting driver survival space. Critical weaknesses are identified by analysing intrusion levels, driver-relevant displacements, and recurring structural failures across a systematic set of collision configurations.
2. **Assess the relevance and limitations of existing passive safety regulations,** (notably UN R29.03 and UN R66.02) when applied to buses, by comparing regulatory test energies and loading conditions with those observed in real-world bus collisions.
3. **Examine alternative test configurations for assessing bus driver protection,** including bus-to-bus simulations, rigid barrier impacts, and pole/impactor tests, with the aim of identifying test methods capable of reproducing realistic impact energies and deformation patterns.
4. **Evaluate the effectiveness of structural countermeasures for improved driver protection,** by virtually testing reinforced front-end concepts (e.g. driver crash-box solutions) and quantifying their effects on intrusion levels, steering column displacement, and acceleration pulses. The effectiveness is evaluated through crash simulations using a 12-meter city low floor bus as the reference vehicle.

To ensure the findings address the current industry needs and have global relevance, a panel of industry experts has been assembled to assess the proposed solutions and contribute their insights on this international safety issue.

2 Method

2.1 Overview of the study approach

This chapter describes the methodological framework used to investigate frontal collision protection for bus drivers. The approach follows a coherent, stepwise structure that links real-world accident data, numerical modelling, and systematic simulation analyses to ensure that the results are grounded in realistic crash conditions.

The method starts with an analysis of documented real-world bus-to-bus frontal collisions to identify representative impact speeds, overlap ratios, impact angles, energy levels, and recurring structural failure mechanisms affecting the driver compartment. These accident-derived parameters are then used to define realistic boundary conditions for the simulation work. A generic low-floor city bus model is subsequently developed and converted into a finite element model with representative geometry, mass distribution, material properties, and structural layout. Material behaviour is defined using experimentally derived stress–strain curves to capture realistic plastic deformation and energy absorption during impact.

Based on this modelling framework, explicit dynamic finite element simulations are performed for a structured matrix of bus-to-bus collision scenarios with varying overlap and impact angle. The results from this simulation matrix establish a quantitative reference baseline for assessing structural response, intrusion, and energy absorption. This baseline is later used to evaluate alternative frontal impact test methods and targeted structural countermeasures. Through this integrated approach, the methodology ensures consistency between accident reality, simulation design, and subsequent result interpretation.

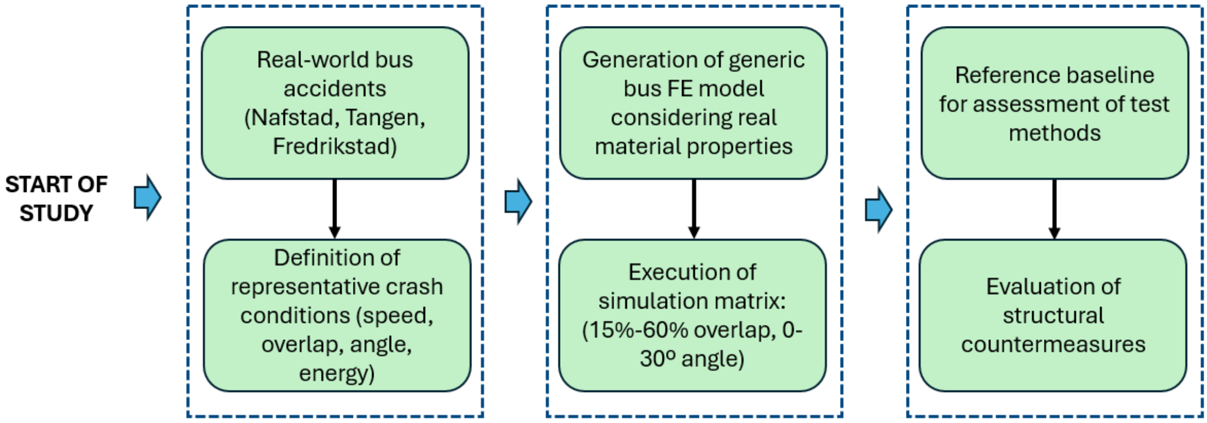


Figure 2.1: Overview of the methodological approach used in the study.

Real-world bus-to-bus accident analyses are used to define representative crash conditions, which form the basis for finite element modelling and a structured simulation matrix. The resulting reference baseline is subsequently used to assess alternative frontal impact test methods and structural countermeasures.

2.2 Accident data and scenario definition

This section analyses selected real-world bus-to-bus frontal collision cases that serve as the empirical foundation for the simulation work in the report. The purpose is to identify realistic impact conditions, including collision speeds, overlap ratios, impact angles, energy levels, and typical structural failure mechanisms affecting the driver compartment.

The three crash accident cases occurred in Norway; Nafstad (2017), Tangen (2021), and Fredrikstad (2022), involving two buses colliding frontally.[2] The impact in all cases occurred at a speed of approximately 30-35 km/h. The structural damage was severe, with significant deformations and, above all, large detachments and ruptures of the tubular structure. One common aspect was the tearing of structural tubes in the welded joint area, where the steel material is harder but has less capacity for plastic deformation. Another aspect was the inconsistency of a welding strategy in manufacturing, between these structural tubes, which demonstrates a lack of reinforcement plates that act as stress distributor and load transfer elements, thereby avoiding stress concentration over welds.

The evaluation of the three accidents B (Naftad), D (Tangen), and F (Fredrikstad) (see table below) performed by numerical calculation concluded a level of energy absorption of approximately 550kJ (cf. Laso et al 2025).

- Accident 1 (Nafstad): This frontal crash occurred with an approximate overlap of 1 meter. The image shows with a dashed line the exact impact area, which is located in the driver's zone. In the image below on the right, you can observe the direction of the impact and how the deformation was caused by sharp elements detached from the opposing vehicle's structure.

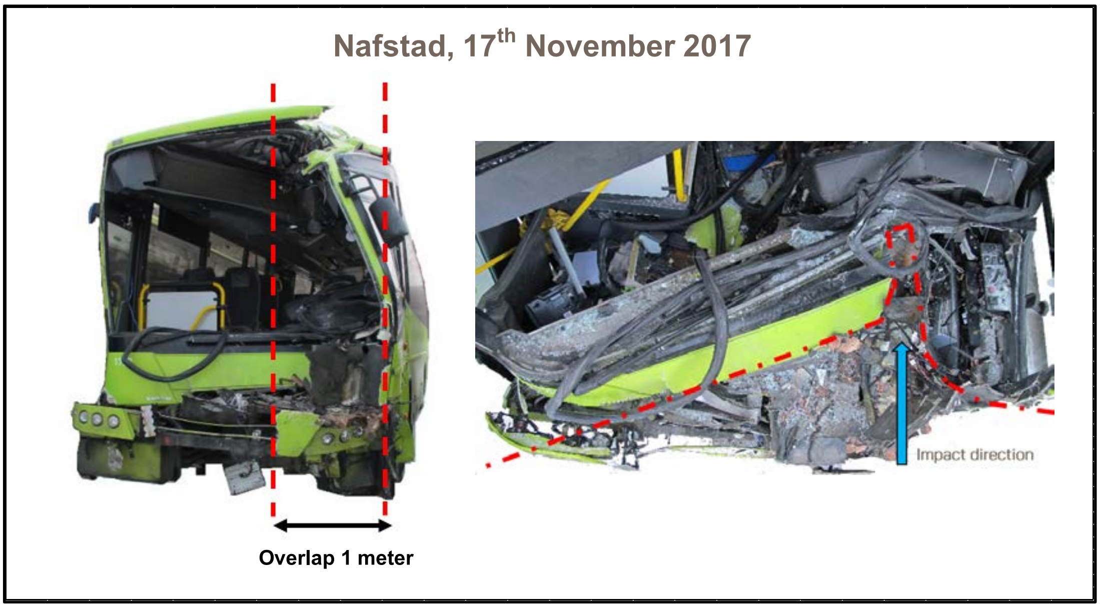


Figure 2.2: Source: Accident Investigation Board Norway (AIBN 2019).

[2] In recent years, the Norwegian Safety Investigation Authority (now NSIA, previously AIBN) has issued three reports on accidents with head-on collisions between buses, i.e. in Nafstad 2017, Tangen 2021 and Fredrikstad 2022 (AIBN 2019; 2022; 2023). All three accidents resulted in fatalities, and the accidents all raised questions about weaknesses in the collision safety of current bus designs, and insufficiencies in regulatory requirements for the crashworthiness of buses. As a result, the NSIA issued several safety recommendations and is currently working on a theme report on the topic.

- Accident 2 (Tangen): In this accident, the collision overlap between both buses was only 300-400mm. This overlap was very small compared with the previous accident, but the severity of the structural damage was high. Again, the large amount of energy and the lack of structural compatibility caused the entire side of the bus to be completely detached with almost no deformation in the front, and consequently, it was literally driven into the opposing bus.

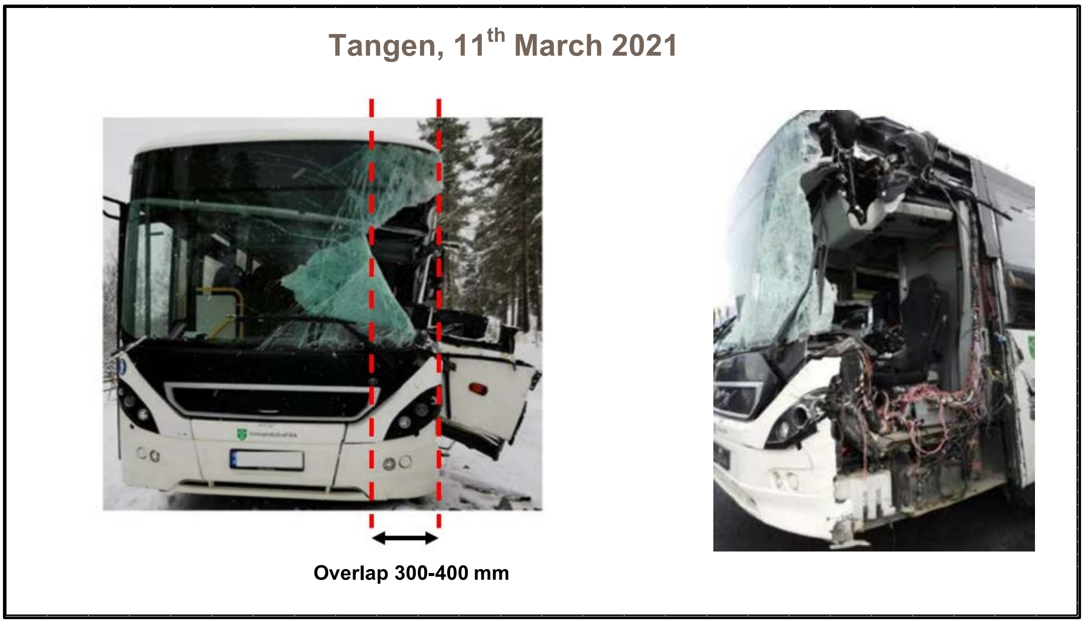


Figure 2.3: Source: Accident Investigation Board Norway (AIBN 2022).

- Accident 3 (Tangen): In this accident, the overlap collision between both buses was 700-800mm. The right picture shows how the entire side completely detached and acted as a battering ram, or lance against the opposing vehicle. Again, you can observe that the front structure of the bus is not designed or prepared for a frontal impact, and the structural compatibility during the collision was extremely poor.

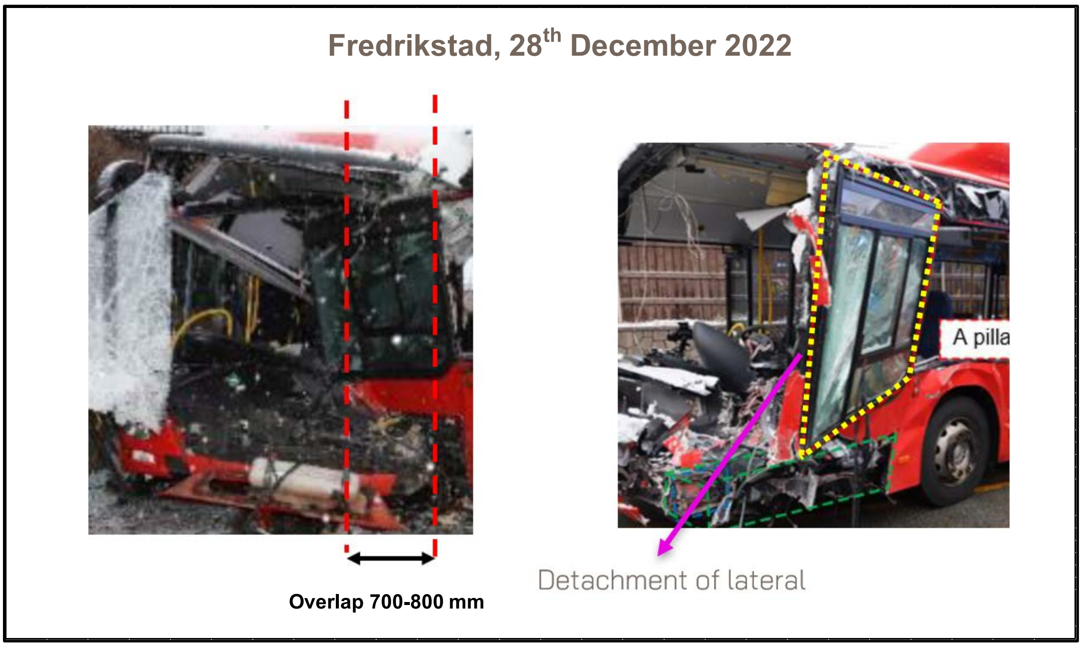


Figure 2.4: Source: Accident Investigation Board Norway (AIBN 2023).

By reconstructing and reviewing documented Norwegian accidents, this section had demonstrated that severe driver compartment intrusion can occur even at relatively low speeds, particularly when impacts involve small overlap or angled configurations. The analysis highlights recurring structural issues, such as tube tearing at welded joints and poor structural compatibility between vehicles. In the report, these findings are used to quantify the energy absorption demands placed on the bus front structure and to define realistic boundary conditions for subsequent simulations. Overall, the analyses of the three accidents have provided a real-world reference against which both test methods and structural countermeasures can be evaluated, ensuring that the study remains grounded in accident-relevant conditions rather than purely theoretical scenarios.

2.3 Vehicle model and assumptions

This section describes the generic low-floor city bus model used as the basis for all simulations in the study. The objective is to ensure transparency and credibility in the vehicle representation and to demonstrate that the model reflects realistic bus design, mass distribution, and structural layout.

The study uses a generic low-floor bus model developed by IDIADA. The vehicle represents a typical urban bus with a monocoque structure and a low floor configuration, without a ladder-frame chassis. The structural design consists primarily of welded hollow sections and plates, which are characteristic of many modern city buses.

The geometric model was converted into a finite element (FE) model that represents realistic assembly conditions of key components, including steered and driven axles, steering column, driver seat, and pedal system. Component masses were assigned based on a generic bus configuration to achieve a realistic overall mass distribution.

Figure 2.5 shows the bus model used in the simulations.

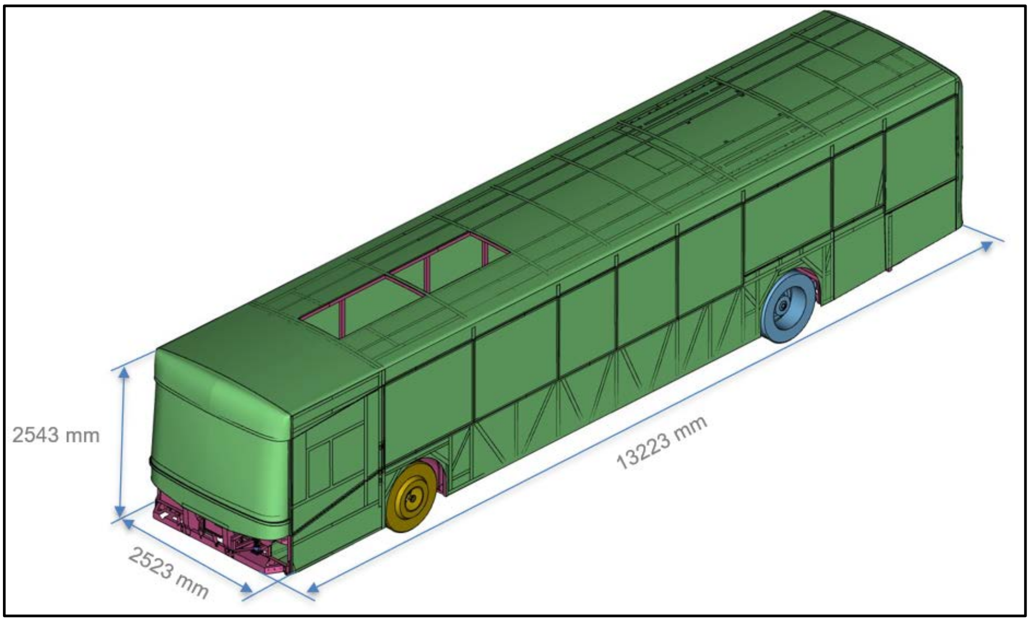


Figure 2.5: Bus model used in the simulations.

Table 2.1 presents the mass distribution of the main assemblies included in the model.

Table 2.1: Description of the bus model used in the simulations.

General bus distribution	Mass - Kg
Structure	13044
Exterior trims	1441
FR Suspension	502
RR Suspension	1440
Others	568
Total	16995

This section has outlined the geometric configuration of the bus, its monocoque structure, and the absence of a ladder-frame chassis, which is characteristic of many urban buses. It has explained how the physical vehicle was converted into a virtual finite element model, including the representation of major subsystems such as axles, steering components, driver seat, and structural members. Material selection and mass properties are also introduced to show how the model corresponds to typical production buses. By documenting the vehicle model in detail, the chapter has provided a necessary foundation for interpreting the simulation results and for assessing the transferability of the findings to real buses operating in European urban and regional traffic.

2.4 Material selection

In this study, two different stainless-steel grades commonly used in bus superstructures were considered for the numerical simulations. These materials were selected to represent typical structural solutions in modern city buses and to capture differences in strength and ductility relevant for frontal collision behaviour.

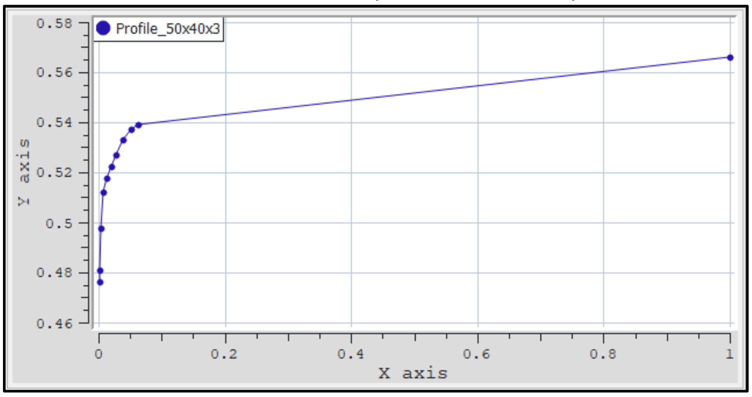
For both materials, the following elastic properties were assumed:

- Young’s modulus: 210 GPa
- Density: 7,850 kg/m^3
- Poisson’s ratio: 0.30

The plastic material behaviour was defined using stress–strain curves obtained from physical material tests. These curves were implemented in the finite element model with strain dependency to provide a more realistic representation of material response under dynamic loading conditions. This approach allows the simulations to capture plastic deformation, strain hardening, and energy absorption more accurately during impact.

The first material considered was STALA 400F (EN 1.4003), a ferritic stainless-steel grade characterised by moderate strength and good ductility, which is widely used in bus structures. The second material was STALA 630D (EN 1.4162), a dual-phase stainless steel with higher strength and enhanced energy absorption capability. For comparison purposes, properties of STALA 800 (EN 1.4678), an austenitic stainless steel were also included in the material summary.

Steel 1: STALA 400F EN 1.4003 (Ferritic material):



Steel 2: STALA630D EN 1.4162 (Dual phase material):

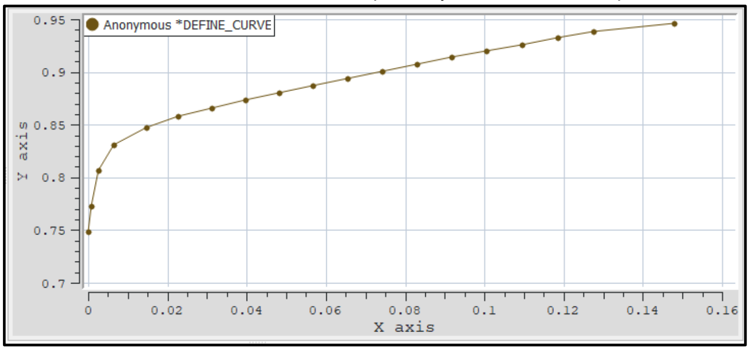


Figure 2.6: Properties of the tube materials used in the simulations.

Table 2.2 summarises the key mechanical properties of the tube materials used in the study. The combination of material grades allows assessment of how different strength and ductility levels influence structural deformation, intrusion, and energy absorption in frontal collision scenarios.

Table 2.2: Summary of key mechanical properties of the tube materials used in the study.

Mechanical properties of tubes				
Strength class	**EN**	**Rp0.2 min.(Mpa)**	**Rm min. (Mpa)**	**A5 min. (%)**
STALA400F	1.4003	400	450	10
STALA630D	1.4162	630	750	20
STALA800	1.4678	800	1000	25

2.5 Finite element calculation

This section explains how computer simulations were used to recreate bus crashes to study how the vehicle structure behaves and how well the driver is protected during a collision. More specifically, the section presents the numerical methodology used to simulate frontal collisions and impact tests throughout the study. Its purpose is to explain how the simulations were conducted and to justify the modelling choices and assumptions that influence the results.

The mathematical model employed in this study aims to represent the real physical behavior of frontal collision between two buses and the impact tests represented. The parameters of mass distribution, center of gravity, and moments of inertia correspond identically with the generic model created by IDIADA, which corresponds to values similar to market vehicles. The model hypotheses and assumptions have been carefully defined to ensure that calculations yield conservative and reliable results.

The geometry was modeled using a combination of shell elements (2D) throughout the superstructure and beam elements (1D) in all non-structural components that are assembled.

Possible contacts between all vehicle parts were modeled and a generic friction coefficient was considered, based on the experience of simulation technicians.

In summary, the entire modeling, calculation, and analysis process followed a methodology established in IDIADA Automotive Technology's internal procedures.

Dynamic simulations of explicit calculation were performed on the FEM model of the bus, including both bus-to-bus collisions and additional impactor tests. This simulation approach is well suited for capturing large deformations, complex contact interactions, and energy absorption processes that occur during high-severity collision events.

The following software tools were used to execute simulation activities:

- ANSA v23.1.1 For mesh model generation and vehicle modelling, boundary conditions, contacts, etc.
- META v23.1.1 For results analysis.
- LS-DYNA, version R12: Used for finite element model computation and results obtainment. For these simulations, computing power with 96 processors was utilized.

2.6 Calculation matrix bus to bus

This section presents a systematic simulation matrix of bus-to-bus frontal collisions designed to explore how impact overlap and collision angle influence driver compartment intrusion and overall structural response. The objective is to simulate collision conditions comparable to documented real-world bus accidents to reproduce representative structural deformation and energy absorption levels and establish a reference baseline for further analysis.

A set of collision scenarios with varying overlap ratios and impact angles was analysed, using representative impact speeds derived from real accident cases (cf. Section 2.1). The simulations compare deformation patterns, steering column displacement, seat movement, and structural failure modes across the different configurations. Particular attention was given to small overlap and angled impacts, which are expected to impose especially high demands on the driver area.

The results from this section provide a quantitative reference against which alternative frontal impact test methods and structural countermeasures are assessed in later chapters. They also support identification of worst-case collision scenarios relevant for the development of future bus-specific frontal impact tests.

Ferritic stainless steel was used as the material basis for the simulation matrix, as it is one of the most used stainless-steel grades in bus manufacturing and provides a representative baseline for structural response. A total of nine crash scenarios were simulated, covering overlap ratios from 15% to 60% of the total bus width and impact angles from 0° to 30°, allowing systematic assessment of how these parameters influence the severity of structural intrusion.

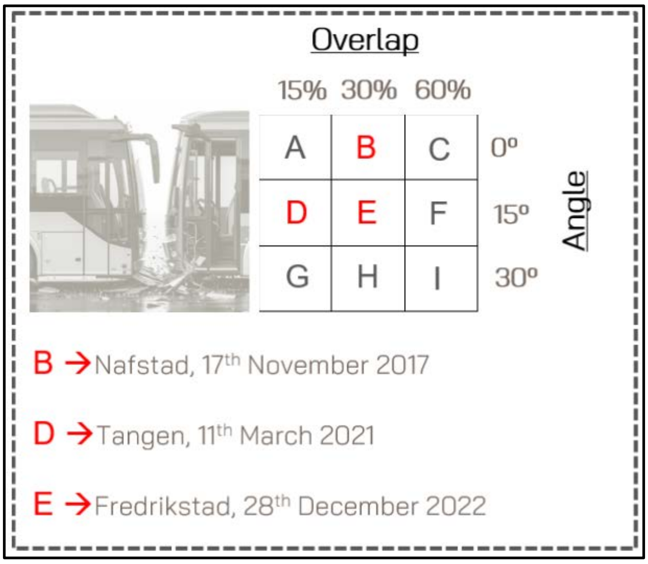


Figure 2.7: Schematic overview of the bus-to-bus collision simulation matrix,

Figure 2.7 provides A Schematic overview of the bus-to-bus collision simulation matrix, illustrating the range of overlap ratios (15–60%) and impact angles (0–30°) analysed in the study. The highlighted matrix positions indicate configurations corresponding to documented real-world bus accidents in Nafstad (2017), Tangen (2021), and Fredrikstad (2022), which were used as reference cases for defining representative and critical collision scenarios.

2.7 Reference group meetings

To assess the realism and relevance of the simulations in the study, a reference group was established in the project. Two main reference group meetings were held, in addition to several small-scale consultations with individual reference groups members during the course of the project. The purpose of the reference group meetings was to present and discuss preliminary results from the simulation study on frontal collision safety for bus drivers, with particular focus on structural behaviour, test method representativeness, and potential countermeasures. The meeting provided an opportunity to obtain expert feedback on the realism of the accident scenarios, the validity of the modelling approach, and the relevance of the proposed test concepts and structural solutions. In addition, the meetings aimed to ensure that the work addresses current industry and regulatory challenges and to identify priorities and directions for further research and development in the area of bus collision safety. More information about the reference group meeting is presented in Appendix 2.

3 Bus-to-bus collisions

The chapter relates to the first aim of the study, which is to evaluate the crashworthiness of current bus front structures, through finite element simulations of head-on collisions with varying overlap ratios and impact angles, to identify critical weaknesses affecting driver survival space. The chapter presents the results from the bus-to-bus collision simulations defined in the simulation matrix. Each subsection describes the structural response, intrusion levels, and driver-relevant displacements for a specific impact configuration. We have conducted simulations of nine different crash scenarios. The results of all the scenarios are described in detail in appendix A. In this chapter, we provide a description of Crash A as an example, before we sum up the results of all the simulations.

3.1 Crash A (30km/h, 15% overlap, 0º angle orientation)

The image below shows a frontal impact between 2 buses, with a 15% contact overlap, 0º angle orientation (straight), at 30 km/h.

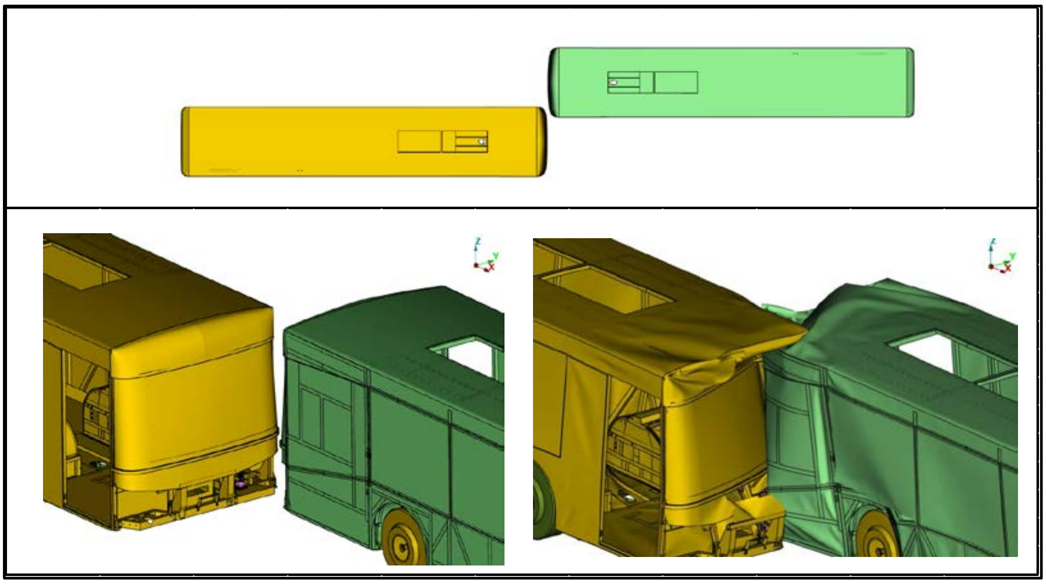


Figure 3.1: Frontal impact between 2 buses, with a 15% contact overlap, 0º angle orientation (straight), at 30 km/h.

Figure 3.1 illustrates the simulated bus-to-bus frontal collision with 15% overlap and zero impact angle at an impact speed of 30 km/h. Despite the relatively low speed, the limited overlap results in highly concentrated loading of the front structure in the driver area. This configuration represents a demanding collision scenario, as only a small portion of the front structure is available to absorb the impact energy.

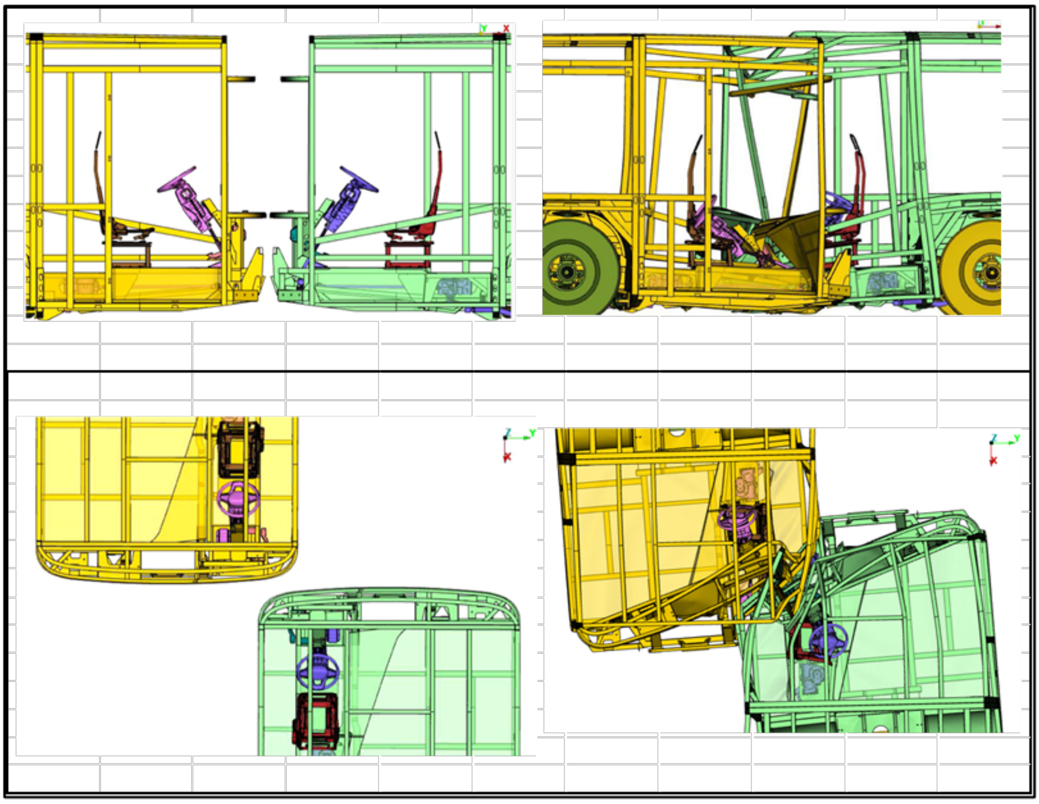


Figure 3.2: Maximum deformation of the cockpit area, including how the steering column and seat suffered displacement.

Figure 3.2 shows the maximum deformation of the cockpit area during the collision. The results demonstrate extensive intrusion into the driver compartment, with significant displacement of both the steering column and the driver seat. This loss of survival space indicates a high risk of serious or fatal injury to the driver, even at moderate impact speeds.

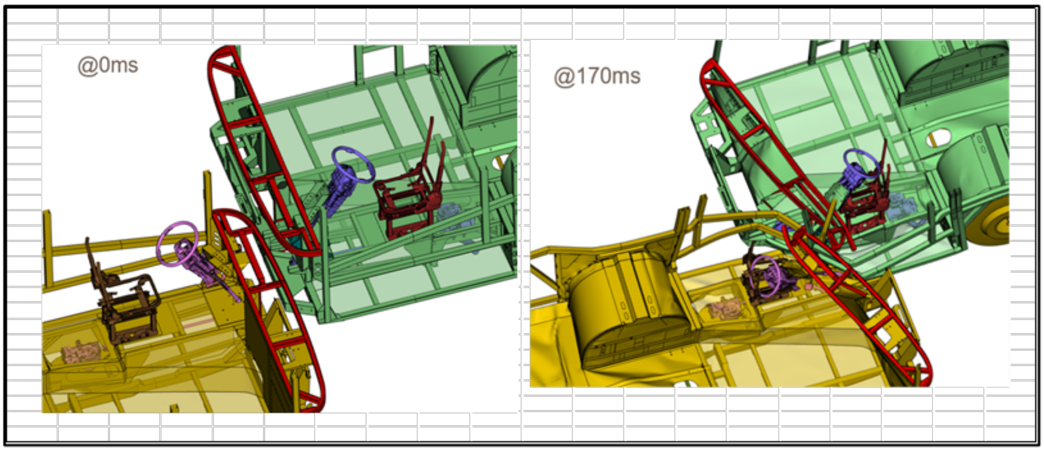


Figure 3.3: The intrusion in the front of each bus.

Figure 3.3 illustrates the intrusion of the front structures of both buses. The deformation patterns show limited progressive collapse and a lack of effective energy absorption in the front structure, resulting in direct intrusion into the driver zone rather than controlled deformation ahead of the cockpit.

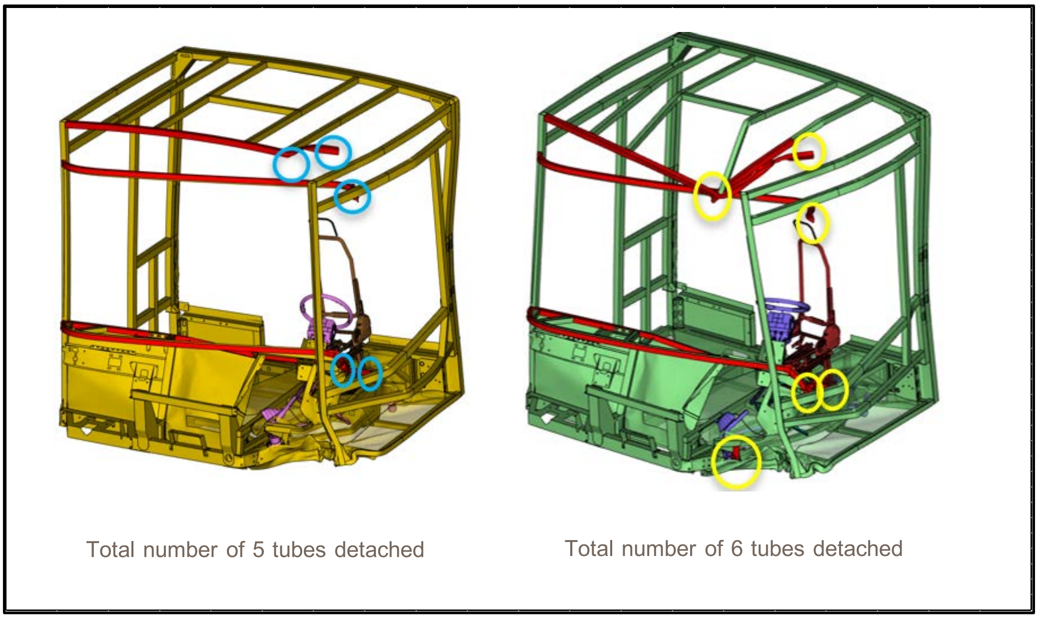


Figure 3.4: Detachment of tubes in the bus fronts.

Figure 3.4 highlights multiple structural tube detachments occurring at welded joints in the front structure. These failures indicate a critical weakness in the load transfer paths of the bus front, where brittle failure at welded connections limits the structure's ability to absorb energy.

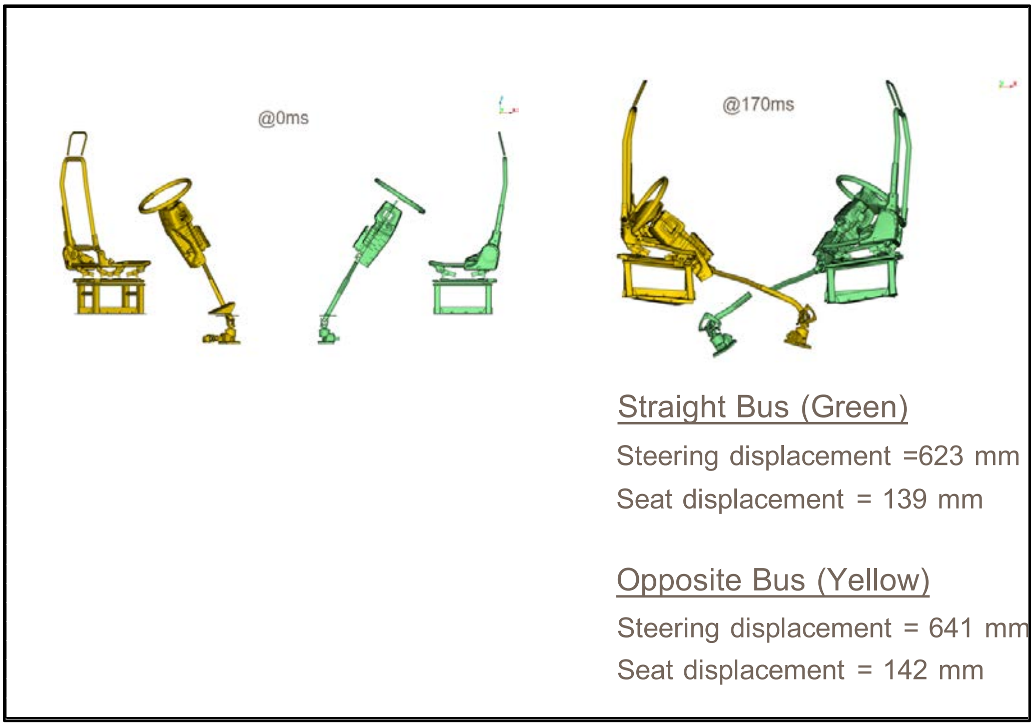


Figure 3.5: Representation of the steering columns and seats in both buses.

Figure 3.5 shows the position of the steering column and driver seats in both buses at maximum deformation. In both cases, the steering column is displaced rearwards into the seating area, significantly increasing the risk of severe chest and head injuries. This result underlines the vulnerability of the driver compartment in small-overlap frontal impacts.

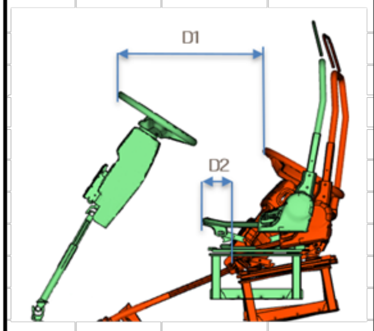
3.2 Summary of the results

The purpose of the results presented in this chapter is to identify critical weaknesses in current bus front structures under realistic frontal collision conditions. By systematically varying overlap ratio and impact angle, the simulations provide a quantitative basis for assessing how different collision configurations influence driver compartment intrusion, structural failure modes, and loss of survival space. These results establish a reference baseline that is used in later chapters to evaluate alternative test methods and structural countermeasures

The simulations were conducted at an impact speed of 30 km/h, based on documented real-world bus-to-bus accidents in Norway that resulted in fatal and serious driver injuries. While higher-speed collisions can occur, the selected speed is representative of urban and peri-urban traffic environments across Europe. The focus on small overlap and angled impacts reflects accident scenarios that are particularly demanding for the driver area and are not adequately addressed by existing regulatory tests. As such, the selected scenarios are considered relevant for a European context, while recognising that they do not represent the full spectrum of possible bus collisions.

The summary of results from the calculation matrix for these 9 different scenarios is as follows:

Table 3.1: Summary of results from the calculation matrix for 9 different crash scenarios.



CRASH CASE	TYPE OF CRASH		BUS 1 (STRAIGHT)		BUS 2 (OPPOSITE WITH ANGLE)	
	ANGLE (º)	OVERLAP (%)	D1 (mm)	D2 (mm)	D1 (mm)	D2 (mm)
A	0	15	623	139	641	142
B	0	30	631	136	642	147
C	0	60	436	151	423	154
D	15	15	729	62	472	131
E	15	30	302	9	631	209
F	15	60	325	53	616	177
G	30	15	540	3	492	173
H	30	30	255	1	617	200
I	30	60	36	13	801	166

Table 3.1 summarises the key results from the full simulation matrix, covering nine different bus-to-bus frontal collision scenarios. The table compares intrusion levels, steering column displacement, and other driver-relevant response parameters across varying overlap ratios and impact angles. The results show that small overlap and angled impacts consistently produce the most severe driver compartment intrusion and therefore represent worst-case scenarios for driver protection.

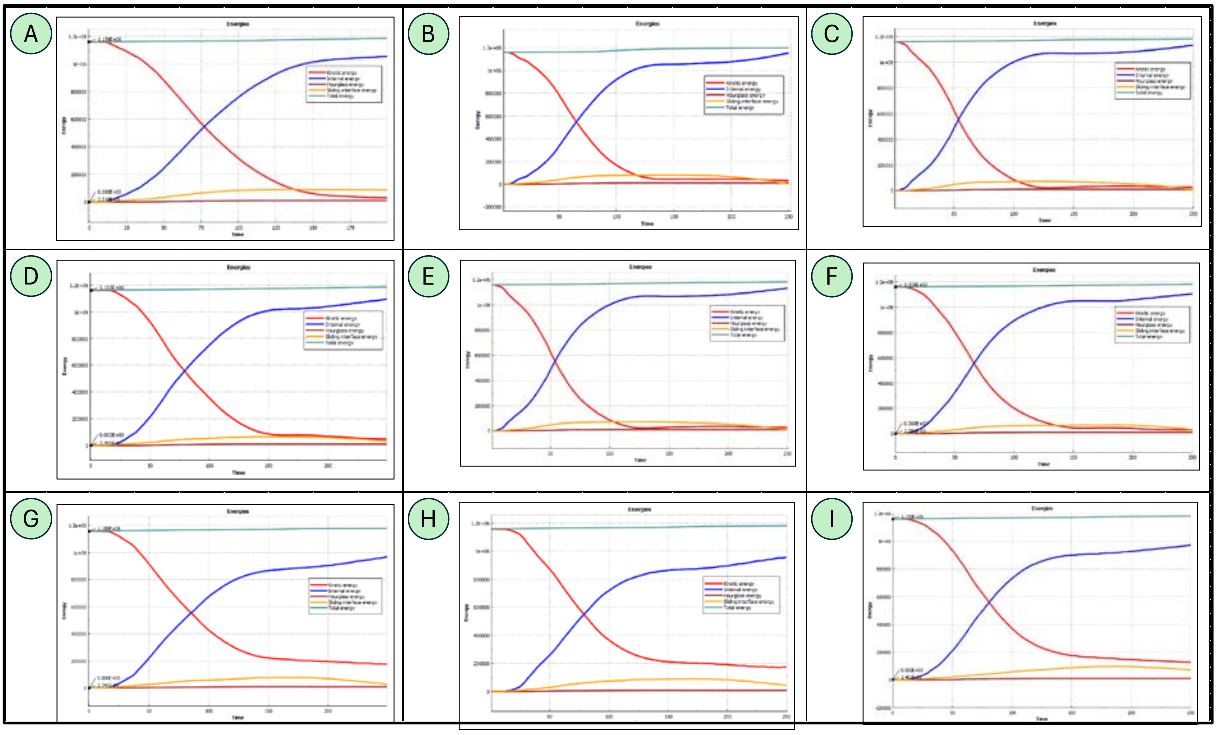


Figure 3.6: Energy absorbed by the impact of the buses in the accident scenarios.

Figure 3.6 shows the total energy absorbed during the simulated bus-to-bus collisions. The results indicate that approximately 1,159 kJ of energy is absorbed in the impact, corresponding to about 579 kJ per bus. These energy levels are substantially higher than those represented in existing regulatory frontal impact tests, highlighting a significant gap between real-world bus collision severity and current test requirements. The specific type A test from regulation UN R29.03 requires for instance an energy level of 55kj.

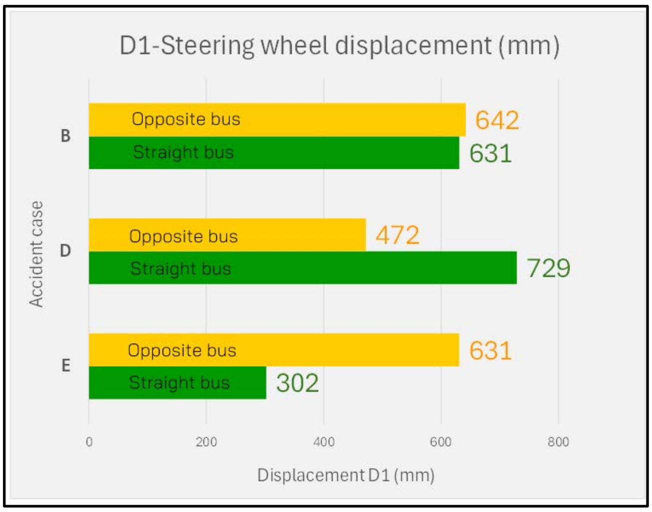


Figure 3.7: Comparison between the three real accident scenarios B, D and E.

Figure 3.7 compares steering column displacement for the three real-world accident scenarios B (Nafstad), D (Tangen), and E (Fredrikstad). Scenario D represents the most critical case, with a maximum steering column displacement of 729 mm. This illustrates how small overlap configurations can lead to extreme intrusion and severe loss of driver survival space, even at similar impact speeds.

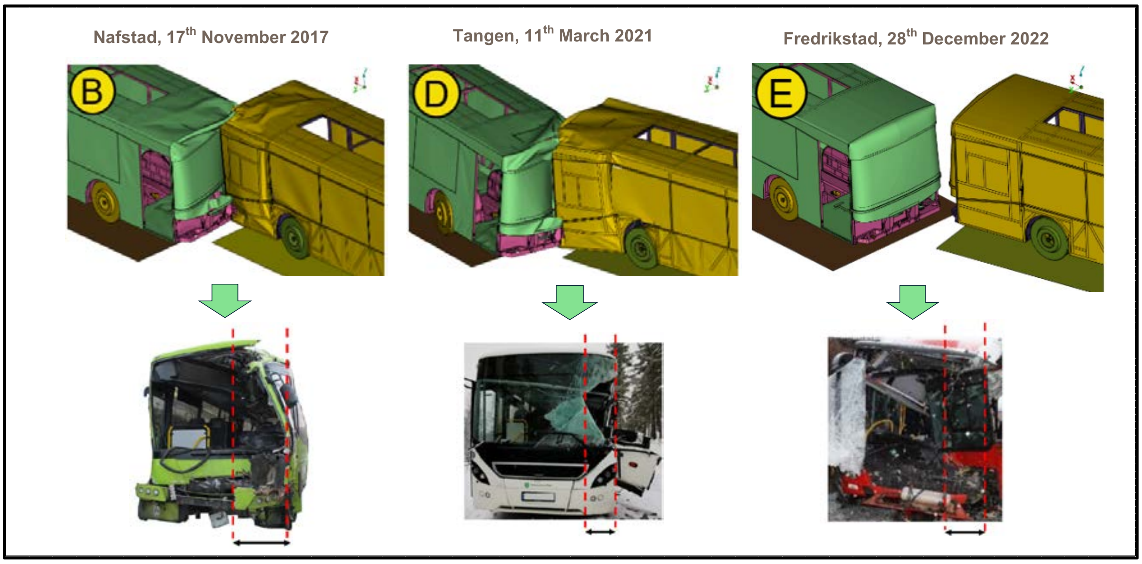


Figure 3.8: Comparison of the impact points in the three real accident scenarios B, D and E.

Figure 3.8 compares the impact locations for the three real-world accident scenarios. The figure illustrates how variations in impact point and overlap significantly influence load paths and deformation patterns in the bus front structure. Impacts occurring close to the driver area result in more direct intrusion and less effective energy absorption, reinforcing the importance of impact location in frontal collision severity.

Overall, the results demonstrate that current bus front structures perform poorly in small-overlap and angled frontal collisions, providing limited protection of the driver compartment and motivating the investigation of alternative test methods and structural countermeasures in subsequent chapters.

4 Evaluation of existing passive safety regulations

4.1 Introduction

The focus of this chapter is the second aim of the study, which is to assess the relevance and limitations of existing passive safety regulations, (notably UN R29.03 and UN R66.02) when applied to buses, by comparing regulatory test energies and loading conditions with those observed in real-world bus collisions.

This chapter examines how current UNECE passive safety regulations apply to buses and evaluates their relevance for driver frontal crash protection. The purpose is to assess whether existing regulatory tests can represent the conditions identified in real bus accidents and simulations.

The chapter reviews regulations such as UN R66.02 (rollover protection) and UN R29.03 (cab strength), explaining their original scope, test configurations, and energy levels. It then compares these regulatory requirements with the energy absorption and intrusion observed in real bus-to-bus collisions. The analysis shows that existing tests either focus on different accident types or apply energy levels that are far below those encountered in real frontal crashes involving buses.

By highlighting these discrepancies, the chapter provides a technical rationale for exploring alternative test methods better suited to assessing bus driver protection in frontal impacts.

4.2 Current passive safety regulations

4.2.1 UN R66.02 and UN R29.03

Currently, the only passive safety regulation that is mandatory for buses is UN R66.02, which establishes superstructure strength requirements in the event of a rollover.

The rollover test is designed to protect passengers and the driver in the event of a lateral rollover. Therefore, it focuses on how the pillars, which are part of the superstructure, absorb the necessary energy to maintain the survival space. The regulation requires the creation of a survival space volume within the bus cab, considering 600mm ahead of the R-point of the first seat, including the driver, and 200mm behind the last seat. For this reason, the front part of the vehicle does not protect against frontal impact and only protects the driver in the event of a lateral rollover, with the first structural pillar located just behind the driver's seat.

However, trucks are required to fulfill regulation UN R29.03, which addresses the protection of occupants in the cab. This regulation specifies three different crash tests: Type A, Type B, and Type C, which shall be applicable depending on the truck category and configuration.

Type A test is a frontal crash test in which a pendulum impactor is used. This pendulum impactor shall strike the cab at the front in the direction toward the rear of the cab. The direction of impact shall be horizontal and parallel to the median longitudinal plane of the vehicle. The impact energy for Type A test shall be 55kJ for vehicles of category N3 and vehicles of category N2 with a gross vehicle mass exceeding 7.5t. The scope of UN Regulation is not considering buses, so in practice, buses are not required to pass this test.

After the fatal low-speed bus accidents in Norway, the authorities decided to request this specific Type A pendulum test in buses, with the intention of improving the safety of drivers in case of an impact. This test was legally required as of October 1., 2023. The inconvenience of applying this type

A test is mainly related to the level of energy applied to the structure and the type of crash. The real accident scenarios, even at low speed, demonstrate a level of energy which is 10 times greater than the regulatory test (Laso et al 2025; Nævestad et al 2025).

In Figure 4.1, the Type A test applied to trucks is shown (left in picture). The picture also shows the description of the pendulum impactor (middle). On the right, it shows how the test would be adapted for a bus.

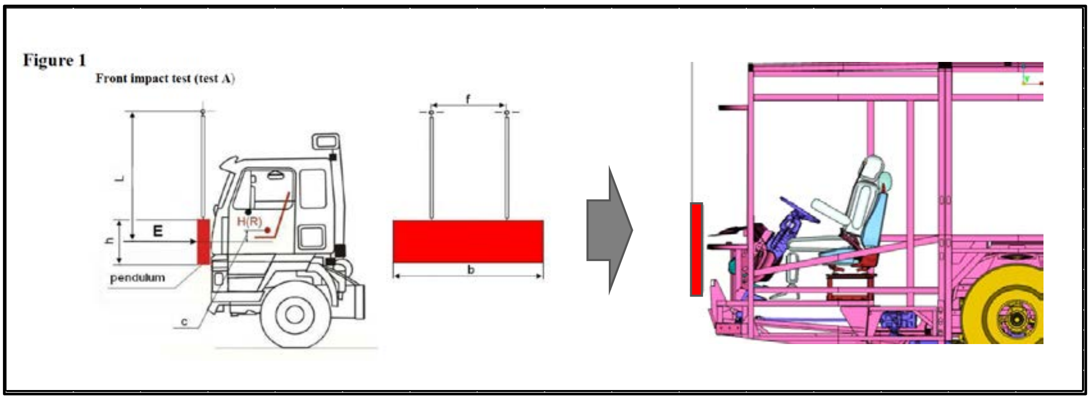


Figure 4.1: Illustration of the test required by UNECE R29 Type A test.

4.2.2 Analysis of energies by regulation

In Figure 4.2, we can see a comparison of all the tests that are applied for each passive safety regulation applicable to vehicles. The X-axis represents the total mass of the vehicle, and the Y-axis represents the energy level. The vertical dotted line indicates the maximum gross vehicle weight in 3,5Tn for passenger cars. The right side of this dotted line is applicable to commercial vehicles. The horizontal dotted line represents the energy level occurred in the representative accident scenarios. Each of the energy levels has been calculated for each of these regulations and represented in the image. In the case of regulation UN R29.03 the energy level is much lower than the actual energy level in the three Norwegian low-speed accidents, which is 550kJ. This demonstrates how far the test requirements are from the real-world accident scenario.

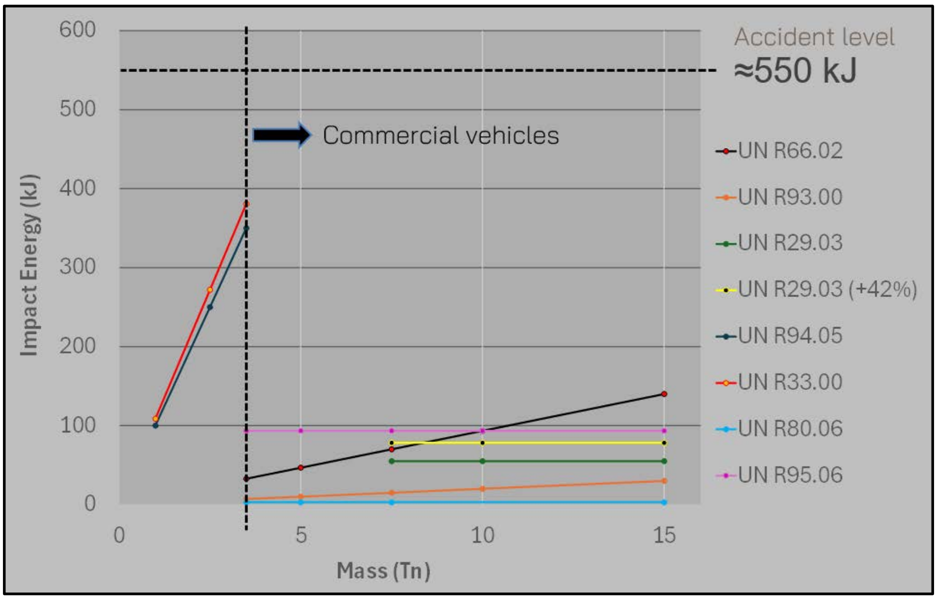


Figure 4.2: Comparison of impact energy levels required in all the tests that are applied for each passive safety regulation applicable to vehicles.

Figure 4.2 compares the impact energy levels required by different UNECE passive safety regulations as a function of vehicle mass, together with estimated energy levels from real bus-to-bus frontal accidents. The comparison shows that the energy applied in UN R29.03 is substantially lower than the approximately 550 kJ observed in real accidents, indicating a large gap between regulatory test severity and real-world bus collision conditions.

Table 4.1: Applicability of each passive safety regulation depending on the vehicle category.

		M1 	N1 N2 N3 	M2 M3 
UN R94.05	Occupant protection in front impact	✓	✓ Only (N1*)	
UN R95.06	Occupant protection in lateral impact	✓	✓ Only (N1*)	
UN R33.00	Behaviour in front impact	✓		
UN R93.00	Front underrun protective devices		✓	
UN R29.03	Occupant protection in cabs		✓	
UN R66.02	Occupant protection in rollover			✓
UN R80.04	Strength of seats and anchorages			✓

(N1*): Read scope details on the specific regulation to confirm the applicability.

Table 4.1 summarizes the applicability of existing UNECE passive safety regulations across different vehicle categories. The table highlights that no EU-wide regulation explicitly targets frontal crash protection for bus drivers, underlining a regulatory gap that this study seeks to address. As noted, Norway represents an exception to the results in Table 4.1, as Norway implemented UN R29.03 for buses from October 2023.

4.2.3 UN R29.03 -Type A: 55kJ (extended pendulum 2.500mm)

In Figure 4.3, we can see the general dimensions of the pendulum, which correspond to those established in the current UN R29.03 regulation for Type A tests. You can observe that the pendulum is as wide as the bus itself, the joints are located at the red points, and the bars that support the impactor are rigid. The impact energy applied was 55kJ. The impact energy is applied at a rate of 27.5kJ per square meter of impactor surface.

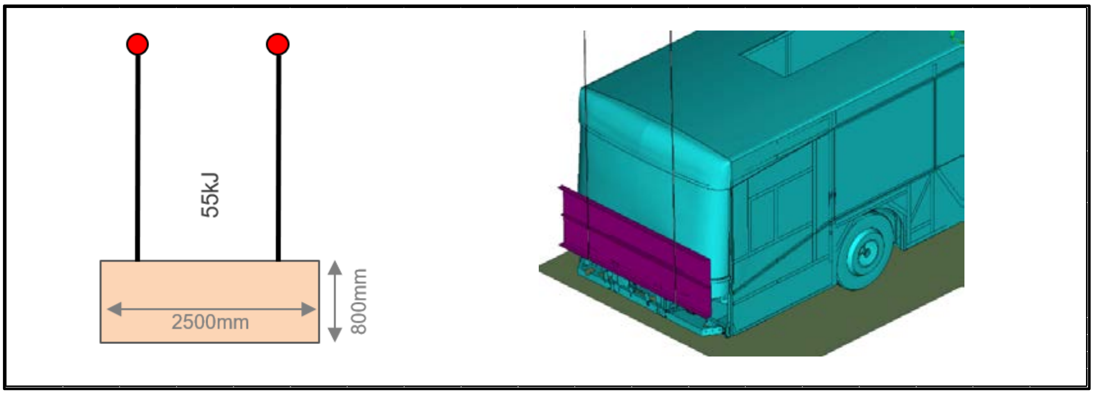


Figure 4.3: Dimensions of the pendulum used in the current UN R29.03 regulation for Type A tests.

Figure 4.3 shows the geometry and dimensions of the pendulum impactor used in the current UN R29.03 Type A test, with a width comparable to the full bus front. The large impact width results in low energy density and distributed loading, limiting the test's ability to load the driver zone in a representative manner.

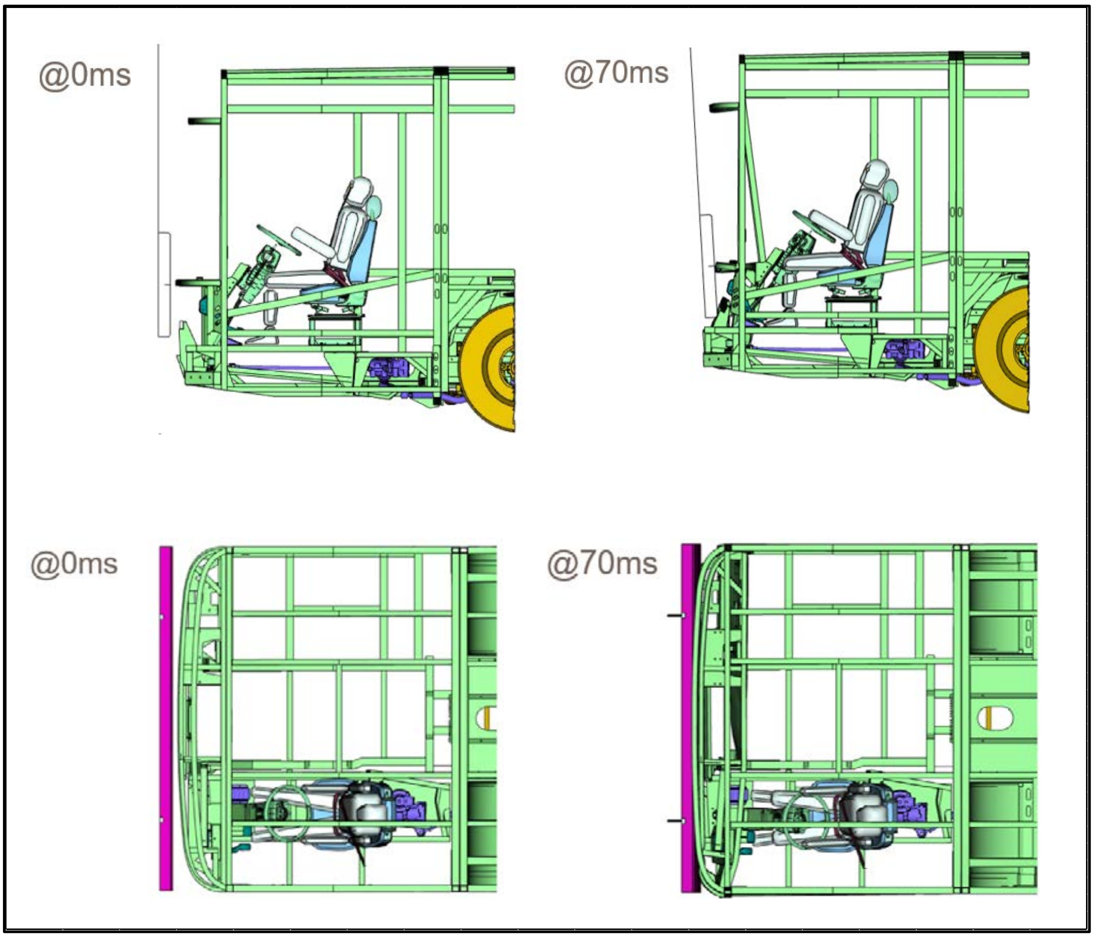


Figure 4.4: Illustration of the pendulum used in the current UN R29.03 regulation for Type A tests.

Figure 4.4 presents lateral and top views of structural deformation and dummy intrusion resulting from the standard UN R29.03 Type A pendulum test. The deformation is spread across the entire front width, demonstrating that the test does not produce concentrated intrusion in the driver compartment.

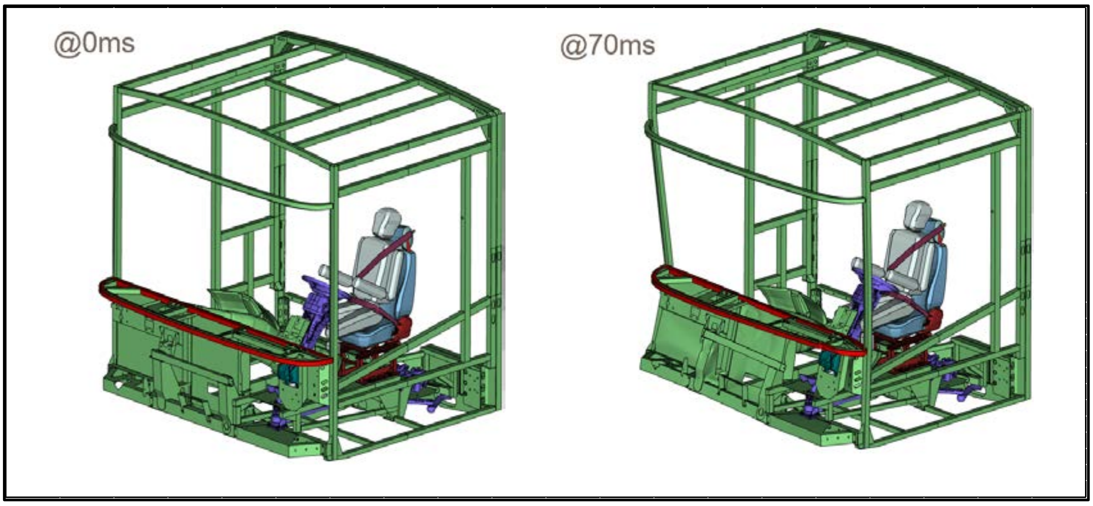


Figure 4.5: Illustration of deformation by the pendulum used in the current UN R29.03 regulation for Type A tests

Figure 4.5 shows an isometric view of the bus front structure after impact with the standard UN R29.03 pendulum. The uniform deformation across the front structure confirms that the test does not replicate the localized structural failures observed in real bus-to-bus collisions.

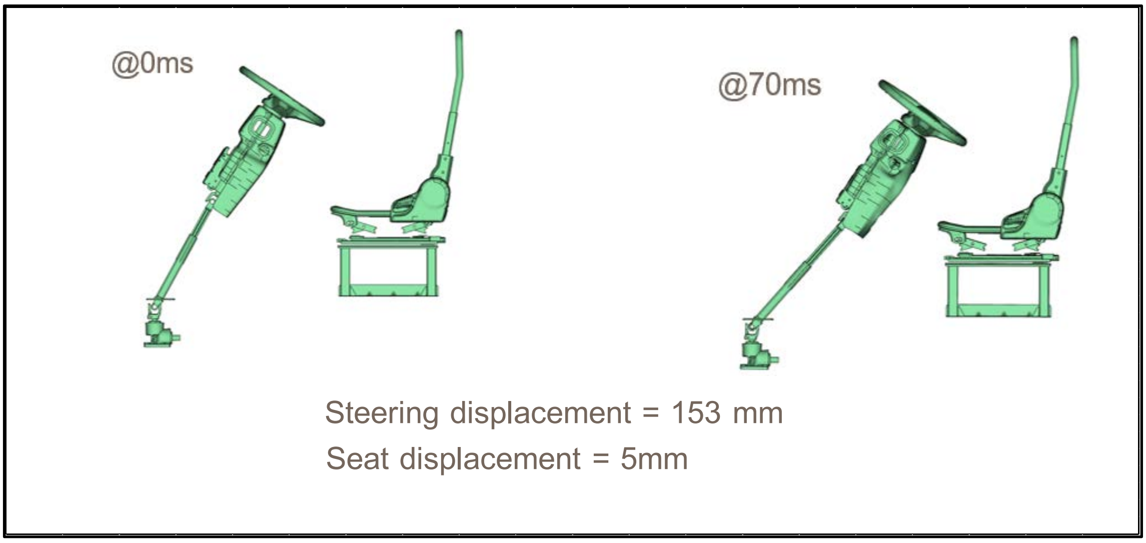


Figure 4.6: Illustration of steering column and seat displacement related to the pendulum used in the current UN R29.03 regulation for Type A tests

Figure 4.6 illustrates steering column and seat displacement resulting from the standard UN R29.03 Type A test. The relatively limited displacements indicate low loading of the driver area, consistent with the low energy density of the test configuration.

4.3 Alternative ways to test for UN R29.03

This section evaluates alternative impact configurations to assess how changes in impactor width and energy influence driver compartment loading. We provide alternative ways to test for UN R29.03, which may provide results that are more representative to the real-world accident scenarios that we are familiar with from Norway (cf. section 2.2). The tests involve different types of impactors; smaller to make them more realistic as compared to real accidents, and higher energy levels, also to make the tests more comparable to real accidents.

4.3.1 UN R29.03 -Type A: 55kJ (short pendulum 800mm)

In Figure 4.7, we can see the general dimensions of the pendulum, which has a different configuration from what is established in the Type A test of regulation UN R29.03. The idea is to determine what results can be obtained when the impact is applied directly in the driver's zone. You can observe that the pendulum is only 800mm wide, and the bars that support the impactor are rigid. The red points represent the articulation points. The impact energy applied remains at 55kJ. The impact energy is applied at a rate of 85.9kJ per square meter of impactor surface, which represents more than 3 times the energy density compared with the official Type A test from UN R29.03.

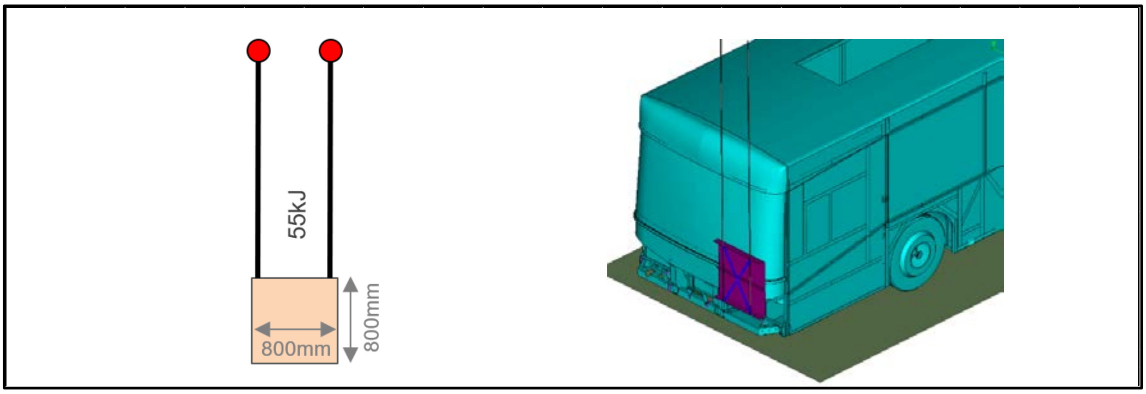


Figure 4.7: General dimensions of a smaller pendulum than what is normally used for the Type A test of regulation UN R29.03

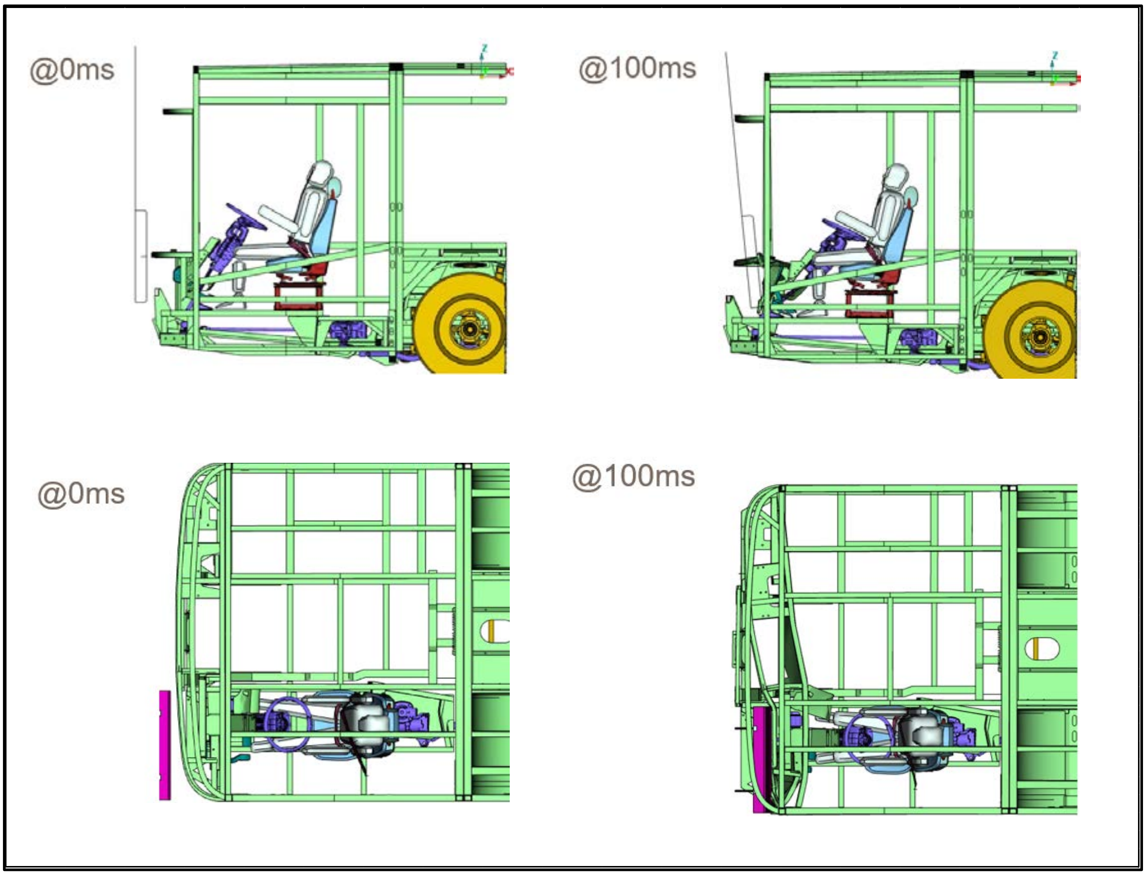


Figure 4.8: Lateral and top view of the deformation produced in the steering column and the intrusion on the dummy with a smaller pendulum to test for R29.3 Type A test.

Figure 4.8 presents lateral and top views of deformation and dummy intrusion produced by the narrow pendulum impact. The localized deformation and increased intrusion demonstrate that concentrated loading produces driver-area damages closer to those observed in real accidents.

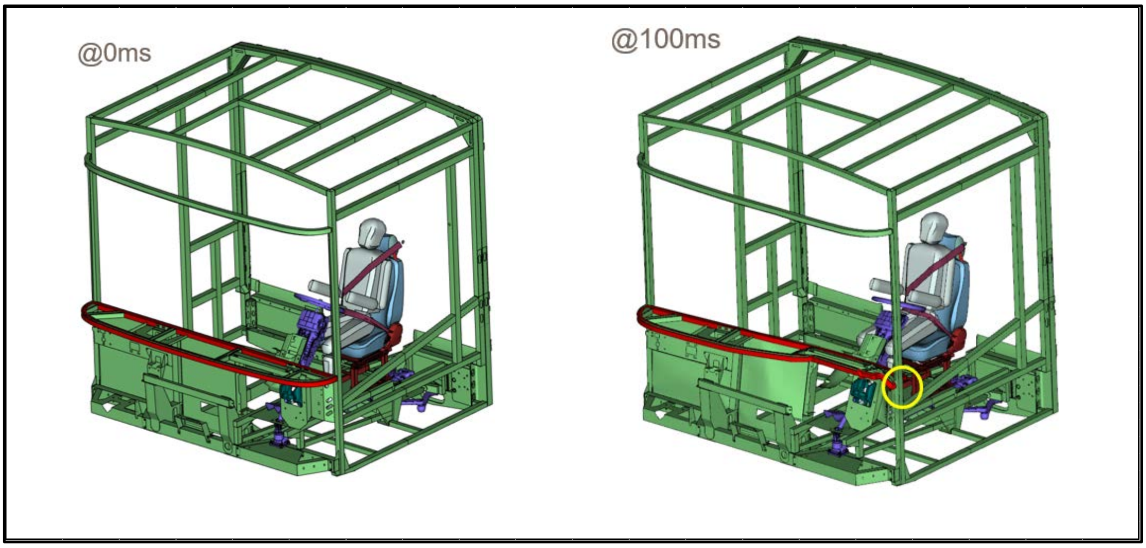


Figure 4.9: Isometric view of the deformation produced with a smaller pendulum to test for R29.3 Type A test.

Figure 4.9 shows an isometric view of the bus structure following impact with the narrow pendulum. Localized deformation and tube fracture at welded joints highlight structural failure modes consistent with those identified in accident investigations.

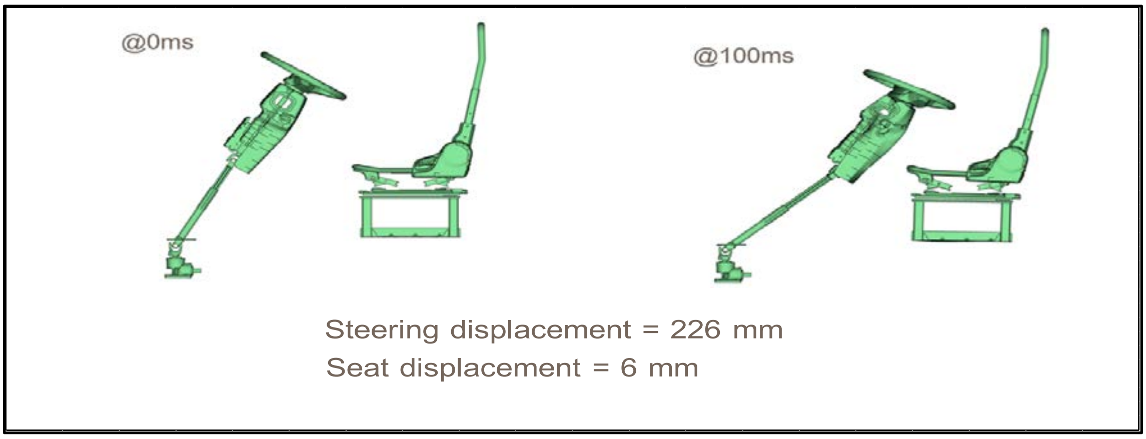


Figure 4.10: Illustration of steering column and seat displacement related to the smaller pendulum used in UN R29.03 regulation for Type A test.

Figure 4.10 illustrates steering column and seat displacement resulting from the narrow pendulum test at 55 kJ. The increased steering displacement compared with the standard test indicates higher driver-relevant loading despite unchanged total impact energy.

4.3.2 UN R29.03 -Type A: 78,4kJ (pendulum 800mm, with chain)

In the next simulated test we used the same pendulum as in the previous test, with a couple of alterations. In Figure 4.11, we can see the general dimensions of the pendulum, which remain the same as in the previous test. The difference is in the braces, which, as you can see, in addition to the red points that represent the articulation points, now have additional articulations at the orange points to allow rotation of the pendulum mass during impact.For this test the energy was increased by 40%, with the impact energy now being 78.4kJ. The impact energy is applied at a rate of 122.5kJ per square meter of impactor surface, which represents more than 4.5 times the energy density compared with the official Type A test from UN R29.03. This specific test has been considered to follow and verify the GRSP meeting proposal presented in Paris, in September 2008 (see UNECE, second meeting: GRSP/INF/CS/14).

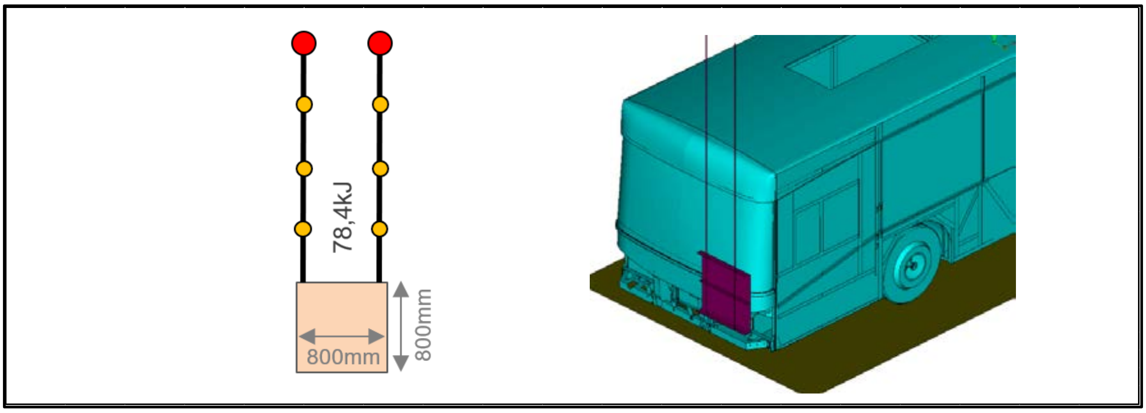


Figure 4.11: General dimensions of a smaller pendulum than what is normally used for the Type A test of regulation UN R29.03, attached with braces and applied with a higher energy level (78.4 kJ).

Figure 4.11 shows the geometry of the narrow pendulum equipped with articulated braces and applied with an increased impact energy of 78.4 kJ. The higher energy and increased energy density significantly raise the severity of driver-area loading relative to the standard regulatory test.

In this case, the impact is centered in the driver's zone, but unlike the previous case, the braces behave like a cable, so the impactor mass is free to rotate. In Figure 4.12, the impactor rotates during the collision toward the area with less rigidity.

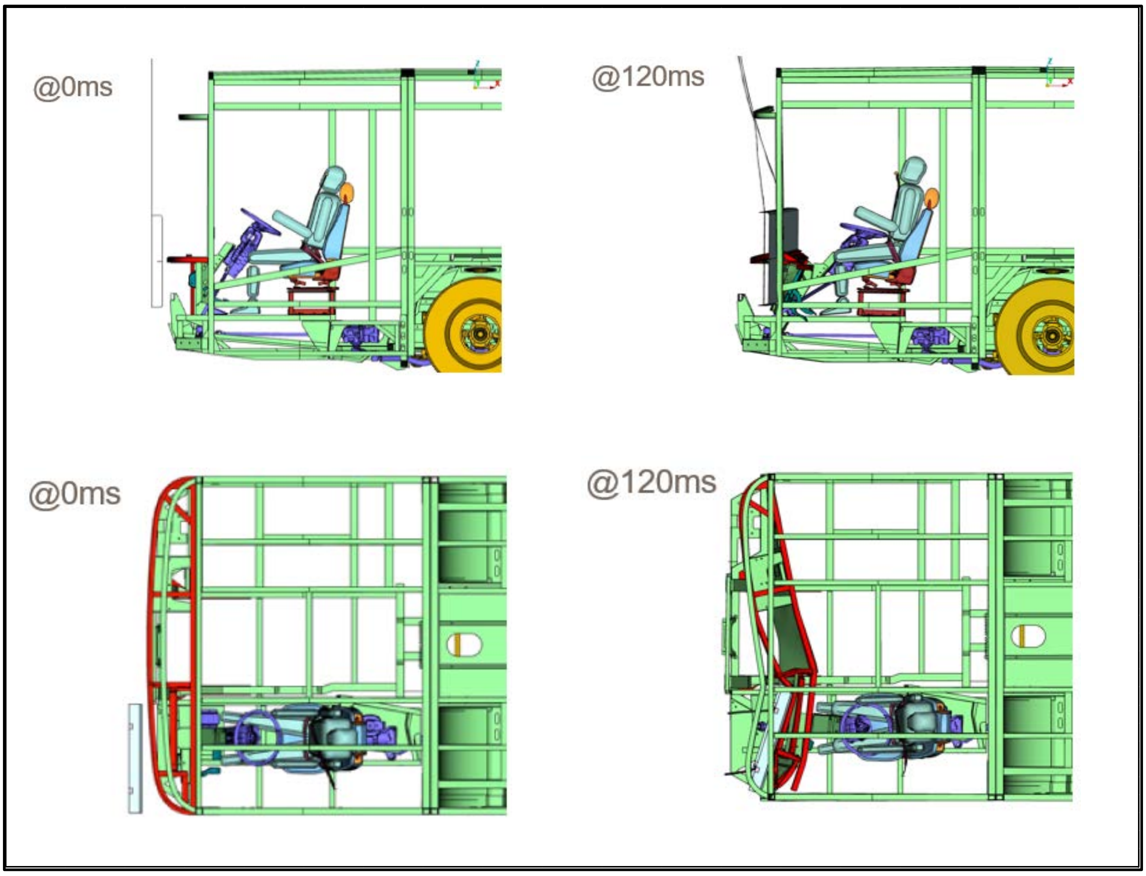


Figure 4.12: Lateral and top view of the deformation produced in the steering column and the intrusion on the dummy with a smaller pendulum to test for R29.3 Type A test, attached with braces and applied with a higher energy level (78.4 kJ).

Figure 4.12 presents lateral and top views of deformation and dummy intrusion for the articulated narrow pendulum impact. The rotating impactor and localized deformation illustrate how impactor kinematics influence load paths and intrusion severity in the driver compartment.

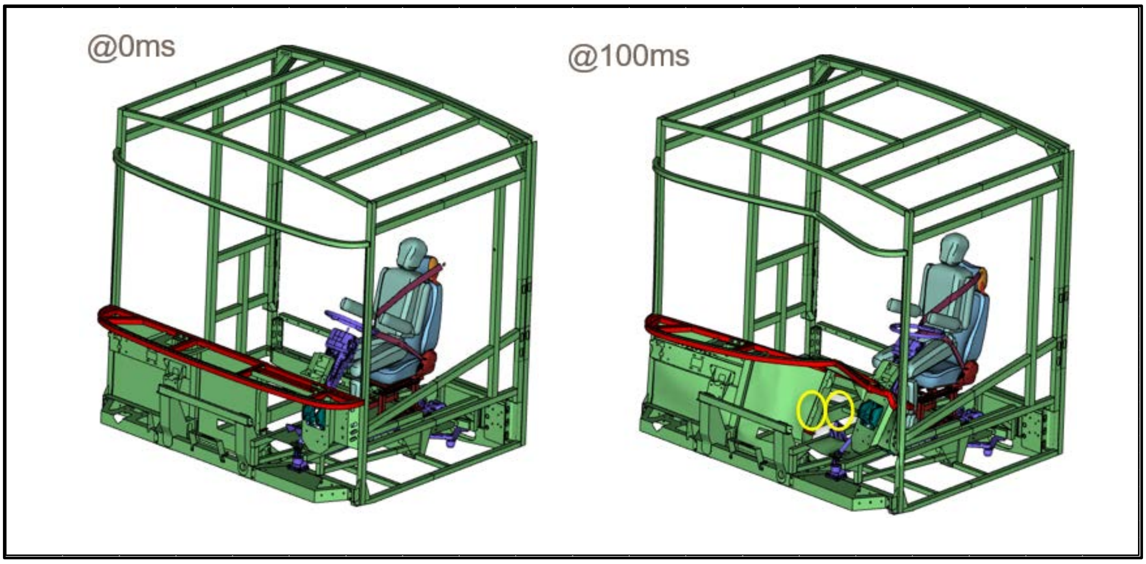


Figure 4.13: Isometric view of the deformation produced with a smaller pendulum to test for R29.3 Type A test, attached with braces and applied with a higher energy level (78.4 kJ).

Figure 4.13 shows an isometric view of the bus structure after impact with the articulated narrow pendulum at 78.4 kJ. Multiple tube fractures and localized collapse demonstrate a severity level comparable to real bus-to-bus frontal collision damage.

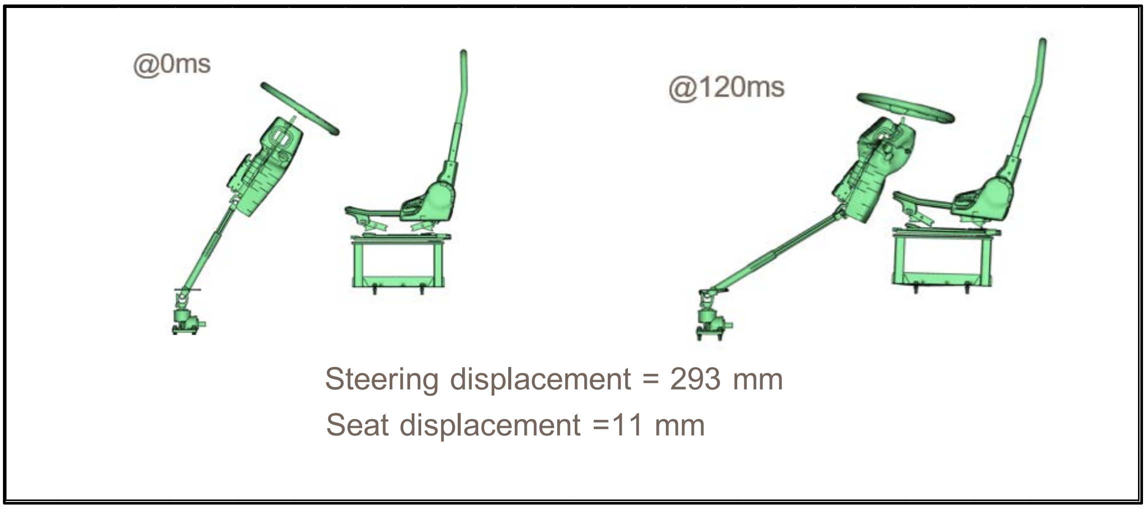


Figure 4.14: Illustration of steering column and seat displacement related to the pendulum used in the current UN R29.03 regulation for Type A tests, with a smaller pendulum to test for R29.3 Type A test, attached with braces and applied with a higher energy level (78.4 kJ).

Figure 4.14 illustrates steering column and seat displacement for the articulated narrow pendulum test at increased energy. The large steering displacement confirms that higher energy density and localized loading substantially increase driver injury risk compared with the current UN R29.03 test.

4.4 Summary of regulatory evaluation

The analysis demonstrates that existing UNECE passive safety regulations do not represent frontal collision conditions relevant for bus driver protection. Current tests apply substantially lower energy levels and distribute loads across wide structural areas, resulting in limited intrusion and low steering column displacement. In contrast, localized impacts with higher energy density produce deformation patterns that are more consistent with real bus accidents. These findings highlight the need for test principles that concentrate energy in the driver zone when assessing frontal protection for buses.

5 Evaluation of alternative frontal impact test methods

5.1 Introduction

This chapter investigates alternative frontal impact test configurations aimed at reproducing realistic accident conditions for bus drivers, which is the third aim of the study. The focus is on rigid barrier and pole impact tests that concentrate energy in the driver zone and better reflect small overlap and localized impacts.

The objective is to find a representative test capable of reproducing an impact energy level, similar to what occurred in the three accidents in Norway (cf. section 2.2.). This test could be proposed as a possible application in new passive safety regulations applicable to buses.

Different impactor geometries and boundary conditions are evaluated through simulations, and their resulting deformation patterns and intrusion levels are compared with those observed in real accidents and bus-to-bus simulations. The chapter assesses the practicality, representativeness, and severity of each test configuration.

Together, the results presented in this chapter show that localized frontal impact tests, such as flat rigid barrier and pole impacts, are capable of reproducing driver-relevant deformation and intrusion patterns observed in real bus-to-bus collisions.

5.2 Crash study flat barrier

Below, we show results for a test setting which considered a flat fixed rigid barrier.

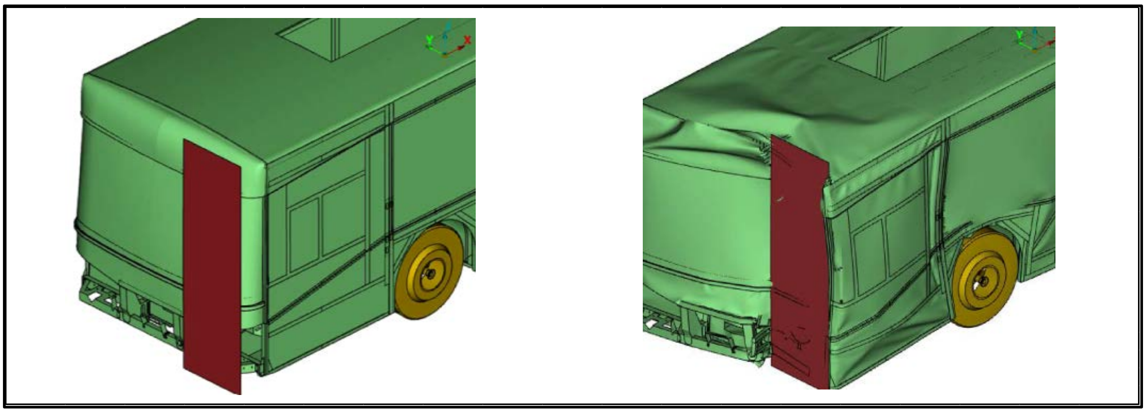


Figure 5.1: Illustration of test setting with a flat fixed rigid barrier with a width of 800mm and a height of 3,500mm. In this case, the bus is launched against the barrier at a speed of 30km/h.

Figure 5.1 shows the flat rigid barrier impact configuration applied to the front of the bus at an energy level representative of real bus-to-bus frontal collisions. This configuration is intended to concentrate impact energy in the driver zone and provides a controlled reference for evaluating localized structural response.

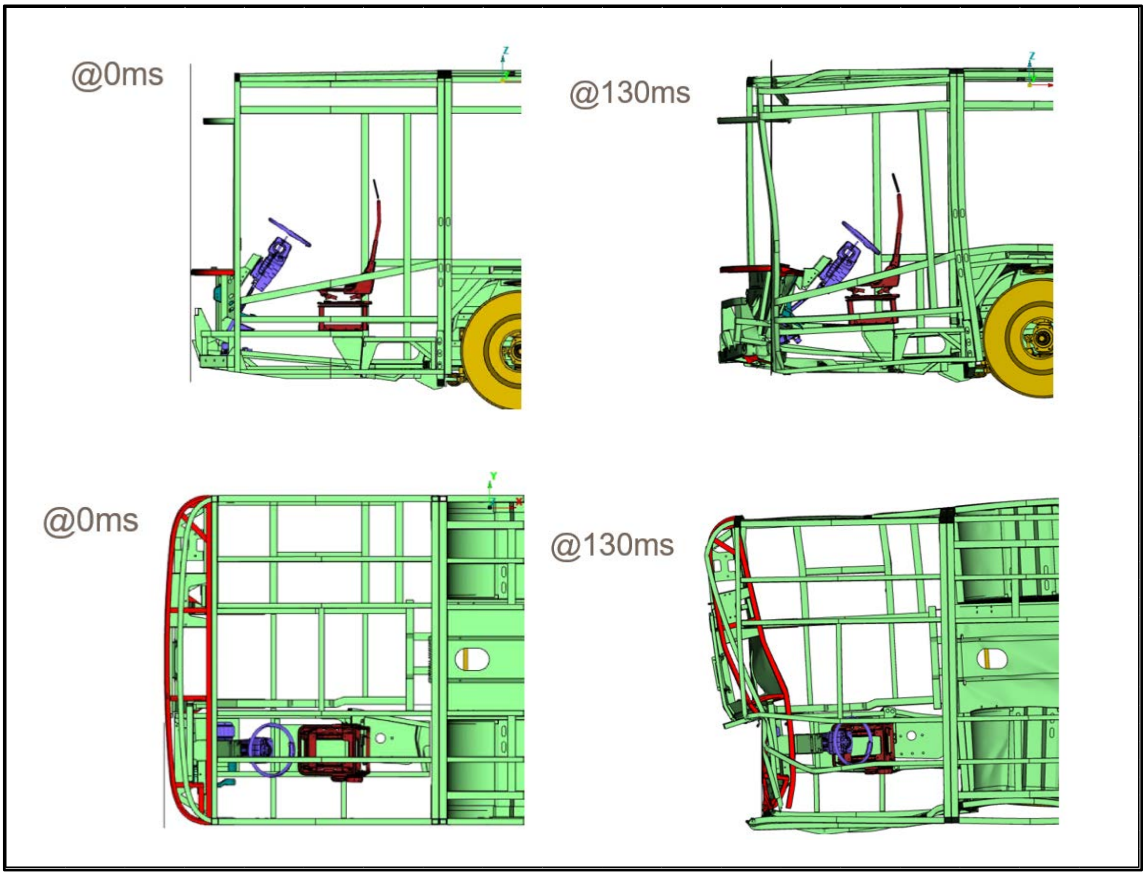


Figure 5.2: Lateral and top view of the deformation produced in the steering column and the intrusion on the dummy, in a test setting with a flat fixed rigid barrier with a width of 800mm and a height of 3,500mm. In this case, the bus is launched against the barrier at a speed of 30km/h.

Figure 5.2 presents lateral and top views of the structural deformation resulting from the flat rigid barrier impact. The localized collapse of the front structure and intrusion into the driver compartment demonstrate that the barrier produces deformation patterns comparable to those observed in real accident scenarios.

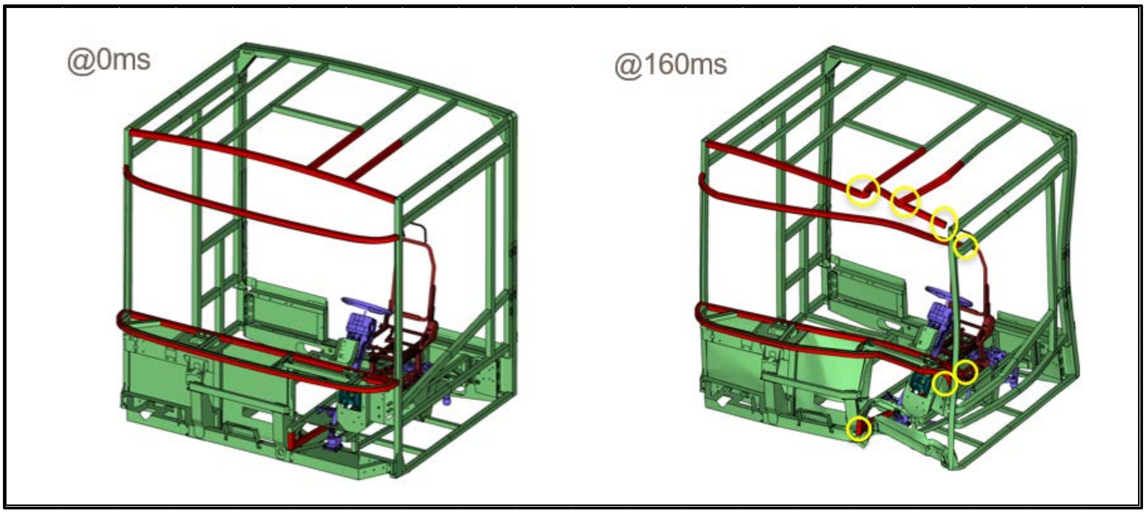


Figure 5.3: Isometric view of the deformation produced in a test setting with a flat fixed rigid barrier with a width of 800mm and a height of 3,500mm. In this case, the bus is launched against the barrier at a speed of 30km/h.

Figure 5.3 shows an isometric view of the bus front structure following impact with the flat rigid barrier. Multiple tube fractures and localized structural collapse indicate effective energy concentration in the driver area, consistent with small-overlap bus collisions.

The deformation levels of the steering column are quite considerable and correspond to values like those obtained in the accident cases.

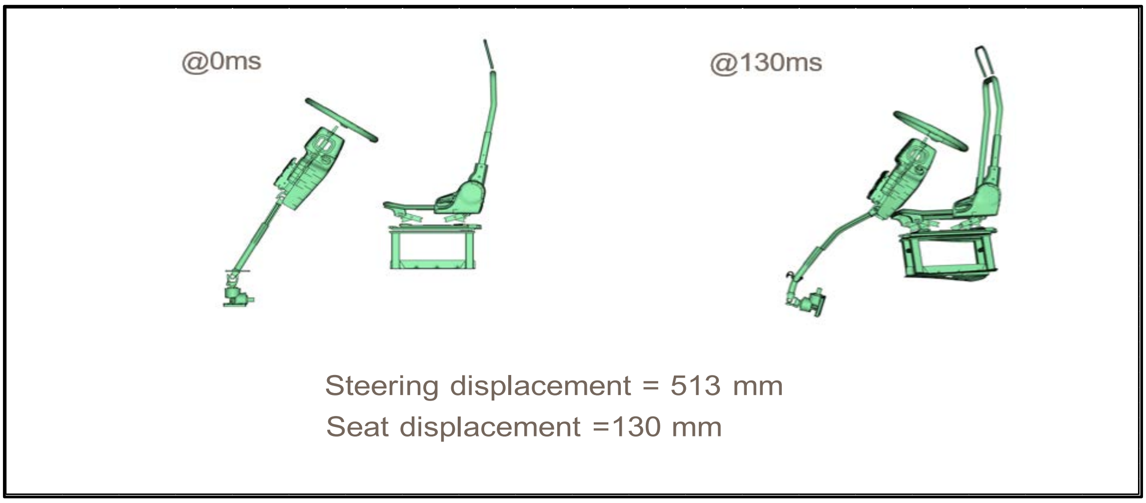


Figure 5.4: Illustration of steering column and seat displacement in a test setting with a flat fixed rigid barrier with a width of 800mm and a height of 3,500mm. In this case, the bus is launched against the barrier at a speed of 30km/h.

Figure 5.4 illustrates steering column and driver seat displacement resulting from the flat rigid barrier impact. The large rearward displacement of the steering column confirms that this test configuration generates driver-relevant loading levels similar to those seen in real bus-to-bus accidents.

5.3 Crash study with pole impactor

In Figure 5.5, the option of a fixed pole impactor is shown, where the bus is the one that moves and impacts. Another valid option would be to use a trolley with this pole impactor that moves against the stationary bus.

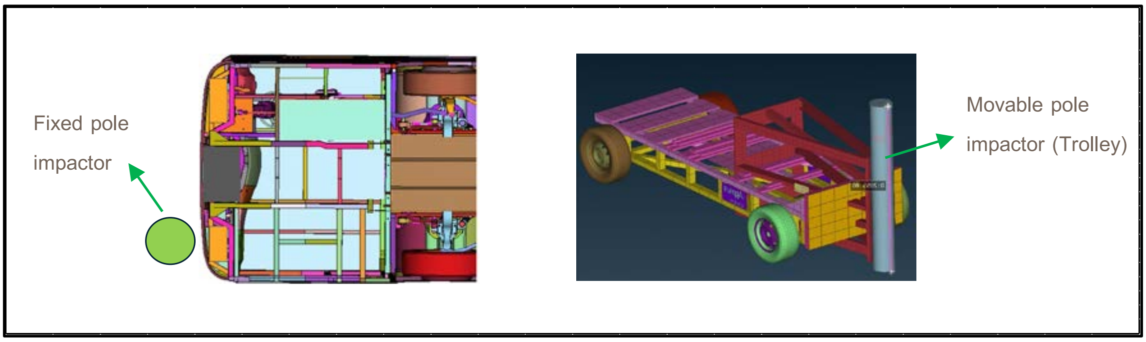


Figure 5.5: Illustration of test setting with a fixed pole impactor.

The narrow contact area represents a highly localized impact condition, intended to reproduce severe small-overlap collision scenarios.

This test setting selected considered a fixed rigid pole barrier with a diameter of 350mm and a height of 3,500mm. In this case, the bus is launched against the pole barrier at a speed of 30km/h.

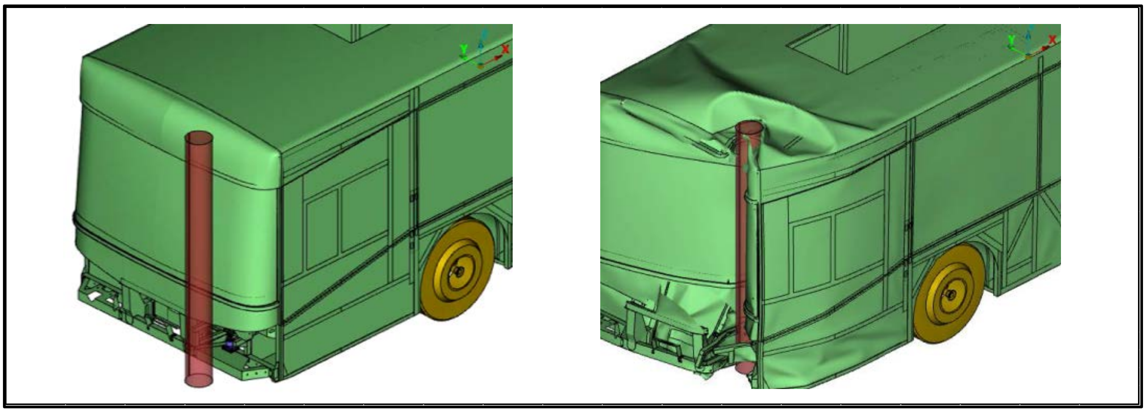


Figure 5.6: Test setting with a fixed rigid pole barrier with a diameter of 350mm and a height of 3,500mm. In this case, the bus is launched against the pole barrier at a speed of 30km/h.

Figure 5.6 presents the deformation of the bus front structure following impact with the pole impactor. The concentrated intrusion and limited load distribution demonstrate that the pole impact produces extreme driver-area loading comparable to the most critical real-world accident cases.

Figure 5.7 shows that significant deformation in the driver's area occurred. The main difference with the flat barrier is that the deformation is concentrated in a smaller area, so the impactor intrudes a greater distance but breaks less hollow sections in the frontal structure.

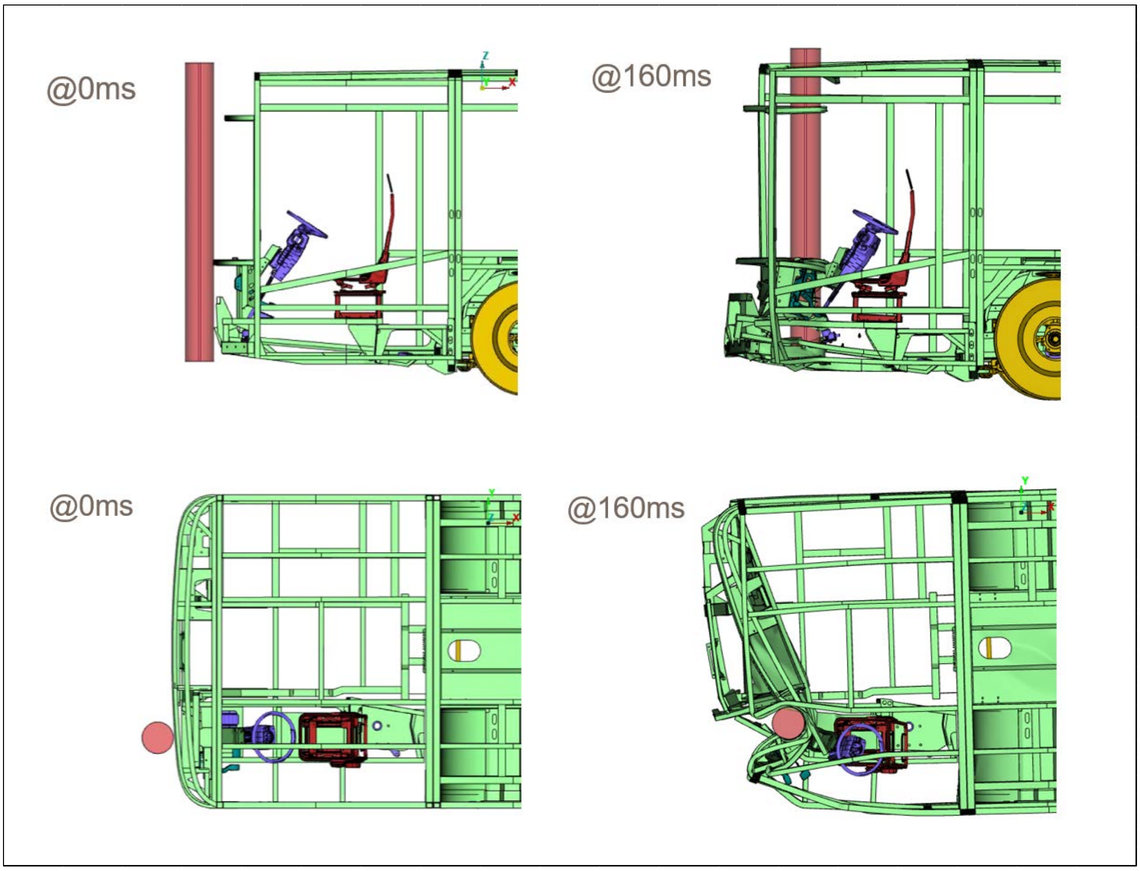


Figure 5.7: Lateral and top view of the deformation produced in the steering column and the intrusion on the dummy, in a test setting with a fixed rigid pole barrier with a diameter of 350mm and a height of 3,500mm. In this case, the bus is launched against the pole barrier at a speed of 30km/h.

Figure 5.7 shows an isometric view of the structural damage caused by the pole impact. Severe local collapse and tube rupture at welded joints highlight structural failure mechanisms consistent with those identified in accident investigations.

Figure 5.8 shows that, after the impact, the deformation occurs locally in the driver's area. There are 5 tubes broken from welded connection.

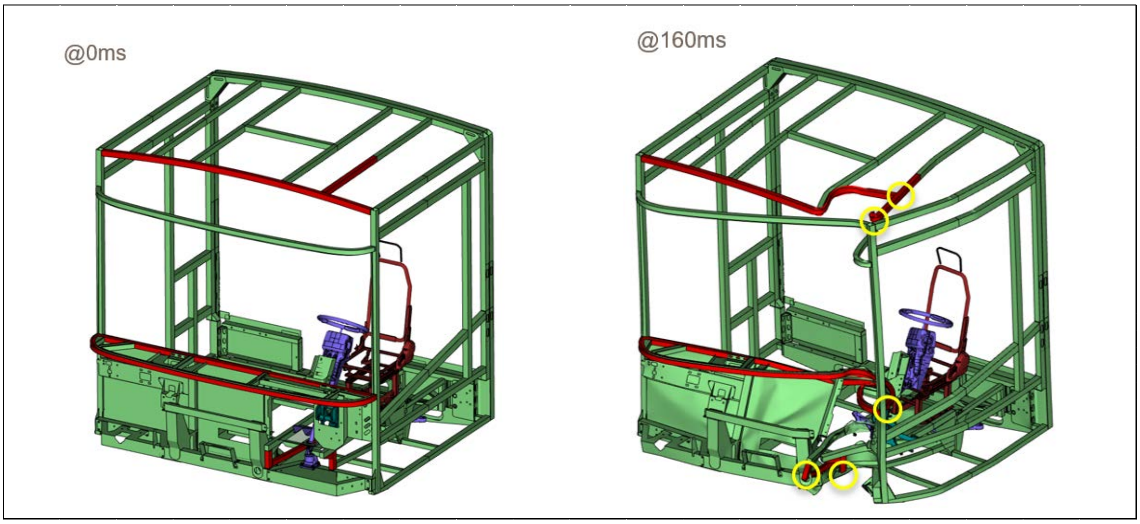


Figure 5.8: Isometric view of the deformation produced in a test setting with a fixed rigid pole barrier with a diameter of 350mm and a height of 3,500mm. In this case, the bus is launched against the pole barrier at a speed of 30km/h.

Figure 5.8 illustrates that the steering column is displaced as a result of the pole impact test. The extreme rearward displacement confirms that the pole impactor generates very high driver-relevant loads, representing a worst-case frontal collision scenario.

Figure 5.9 shows that the deformation levels of the steering column are quite considerable and correspond to values obtained in the accident cases.

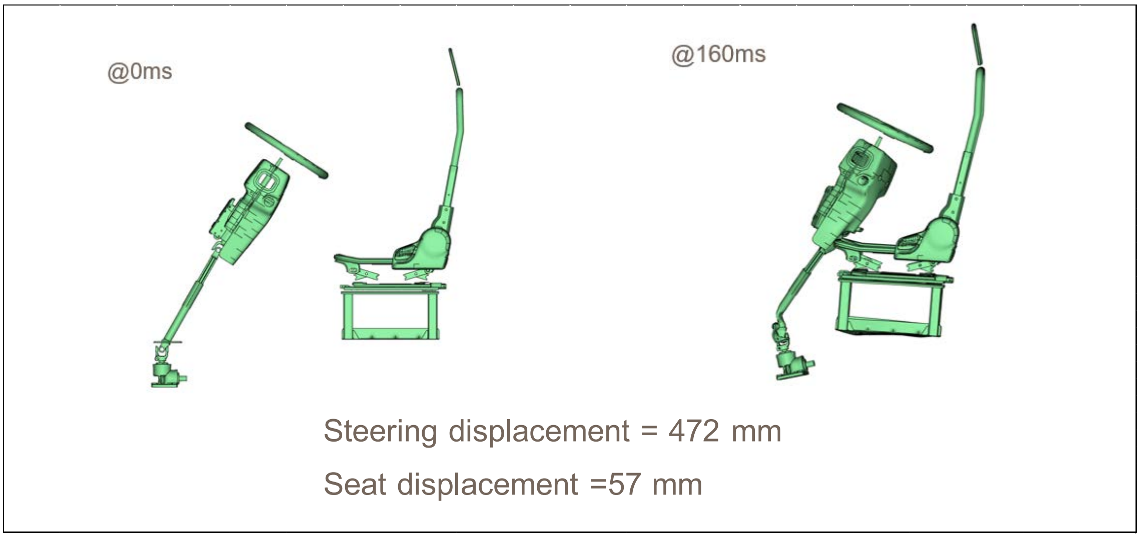


Figure 5.9: Illustration of steering column and seat displacement in a test setting with a fixed rigid pole barrier with a diameter of 350mm and a height of 3,500mm. In this case, the bus is launched against the pole barrier at a speed of 30km/h.

5.4 Summary

The results demonstrate that representative frontal impact tests for buses must account for the high energy levels observed in real accident cases. Tests based on impactors similar to those used in UN R29.03 are not suitable, as achieving comparable energy levels would require impractically large masses.

Flat rigid barrier and pole impact tests provide a more feasible and representative alternative by concentrating energy in the driver area and reproducing deformation and intrusion patterns consistent with real bus-to-bus collisions. These findings confirm that localized impact tests can reproduce relevant energy densities and structural responses more effectively than existing regulatory tests, thereby forming a key link between accident analysis and the development of feasible, bus-specific frontal impact assessment methods.

6 Effects of structural countermeasures on driver protection

6.1 Introduction

The focus of this chapter is the fourth aim of the study, where we evaluate a reinforced driver crash-box concept as a targeted structural countermeasure for improving driver protection in frontal collisions. The objective is to assess how such a reinforcement affects intrusion, structural load paths, and acceleration levels.

We describe the design principles of the crash-box, its integration into the bus structure, and the materials used. Simulation results are then presented for selected critical collision scenarios, comparing the reinforced configuration with the baseline bus design. The analysis shows that the crash-box substantially reduces driver compartment intrusion and steering column displacement.

We also highlight trade-offs associated with increased structural stiffness, particularly higher acceleration pulses, underscoring the need for balanced energy absorption and coordination with restraint systems. These findings inform future optimization and design considerations.

6.2 Proposal for reinforcement

The driver's position is in the front overhang of the bus, just in front of the front axle. This means that almost no structural components can be placed in front of the driver. For this reason, it is important to increase stiffness to minimize deformations and prevent intrusion into the survival space. For this purpose, an additional protective structure will be implemented to protect the driver.

The strategy followed in this study is to reinforce the driver's cockpit with a structural barrier. This structure has been designed considering the integration requirements of the main components, such as the steering column, steering box, and the transmission from the bevel box to the steering box.

The general measures considered the current space available behind the driver and the height of the step that the driver has for access to the driver's seat.

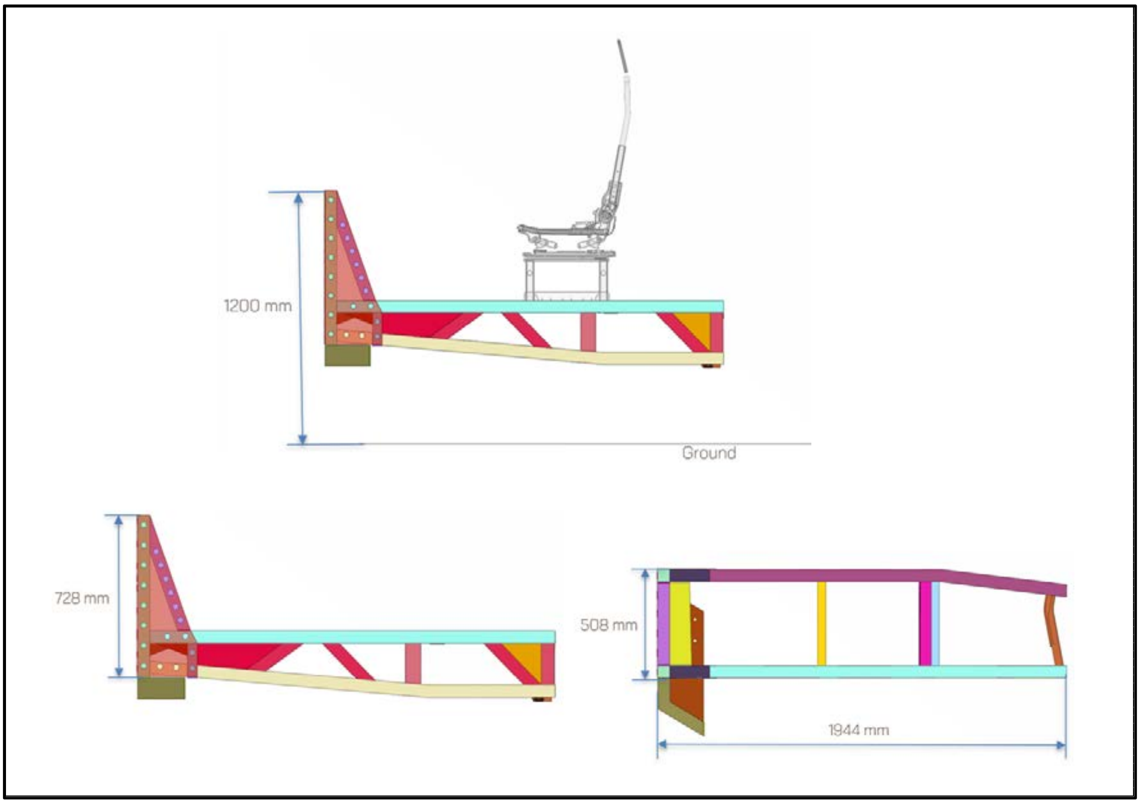


Figure 6.1: Illustration of the additional protective structure to protect the driver; the "Crash box".

Figure 6.1 illustrates the proposed driver crash-box concept, showing its geometry, dimensions, and integration below the driver's seating position. The figure demonstrates how the crash-box can be integrated within the limited space of the front overhang to provide additional stiffness and protection of the driver survival space.

This image shows how the structure integrates just below the driver's zone. This driver crashbox would have the following characteristics:

- Modular design with easy body integration.
- Protection against low and high impacts.
- Uncoupled from steering column.
- Sub-assembly weight of 100-120kg.
- Made of high strength and high plasticity steel grade.

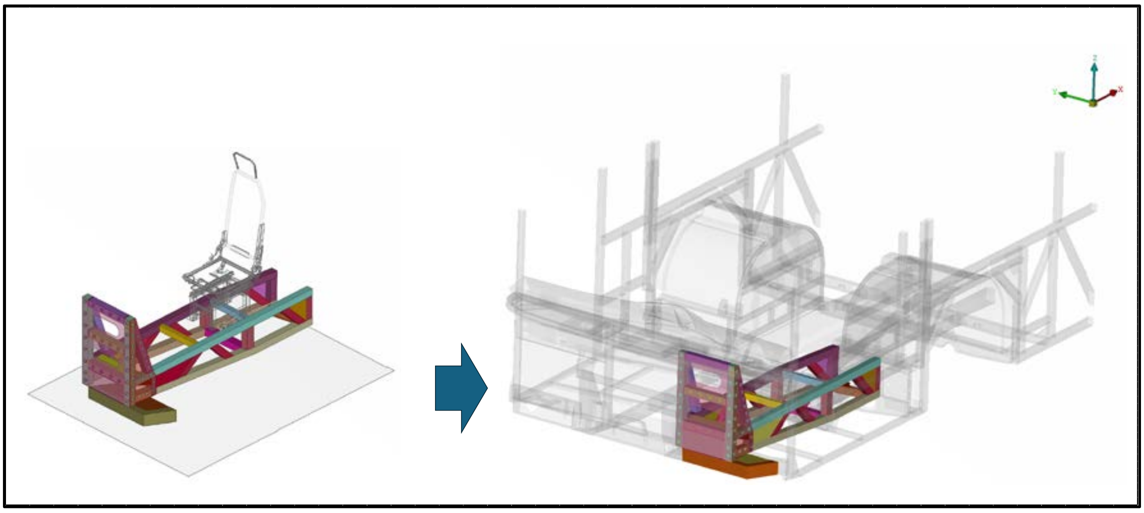


Figure 6.2: Illustration of the additional protective structure to protect the driver; the Crash box placement in the bus structure.

Figure 6.2 shows the placement of the crash-box within the bus front structure relative to the driver position and front axle. The configuration illustrates how the crash-box restrains deformation in the driver area while allowing controlled collapse to be transferred rearwards in the structure.

During the crash, the front overhang remains with low deformation, but the collapse is transferred to the rear part of the structure.

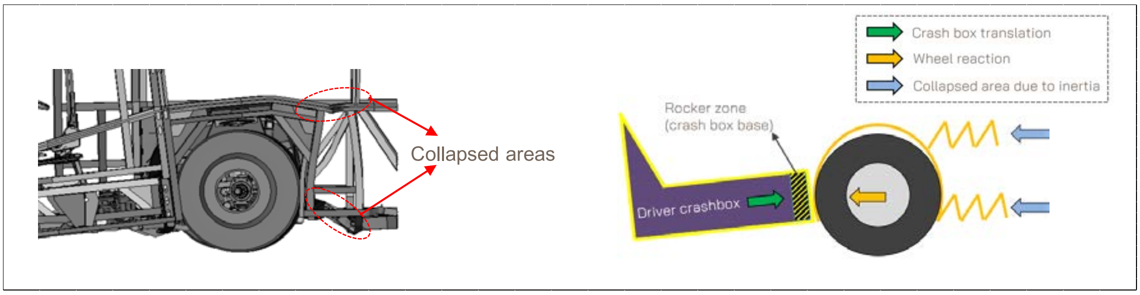


Figure 6.3: Illustration of how the Crash box transfers energy to the rear part of the structure in a bus crash.

Figure 6.3 illustrates the mechanism by which the crash-box transfers impact energy from the front overhang to the rear part of the structure during a frontal collision. This load-path redirection reduces localized intrusion in the driver compartment and improves preservation of the survival space.

The manufacturing cost breakdown for the driver Crash box is related to:

- Steel material
- Cut/ scrap operation
- Weld operation
- Coating / painting operation

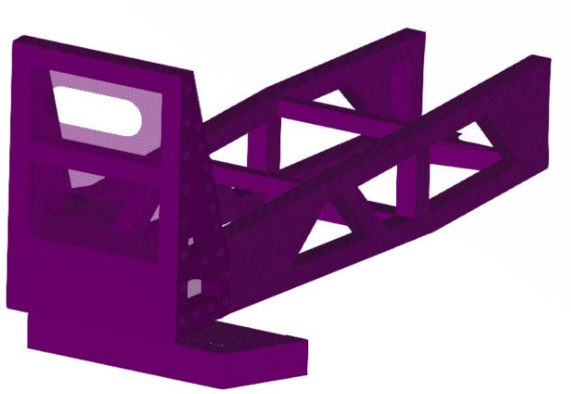


Figure 6.4: Illustration of the Crash box.

Figure 6.4 shows the detailed structural design of the driver crash-box as a standalone sub-assembly. The figure highlights the modular and manufacturable nature of the design, supporting feasibility for integration into existing bus structures. The estimated manufacturing cost for this subframe is between 900€ and 1,200€. This considers only the operational costs in Europe, and investment in equipment, tools, etc., are not included.

In addition, the manufacturing and integration of this crash box into the bus structure will require design and engineering project activity with a complete analysis to validate the following points:

- Crashworthiness
- Noise, Vibration and Harshness
- Strength and fatigue analysis
- Review of regulation requirements, such as regulation UN R107.10 (general construction of a bus)

An estimated average cost for a full development project to integrate the solution could be around 100k€ to 120k€, with an estimated timeframe of 5 months.

6.3 Results from simulation

Below, we show results from different simulations.

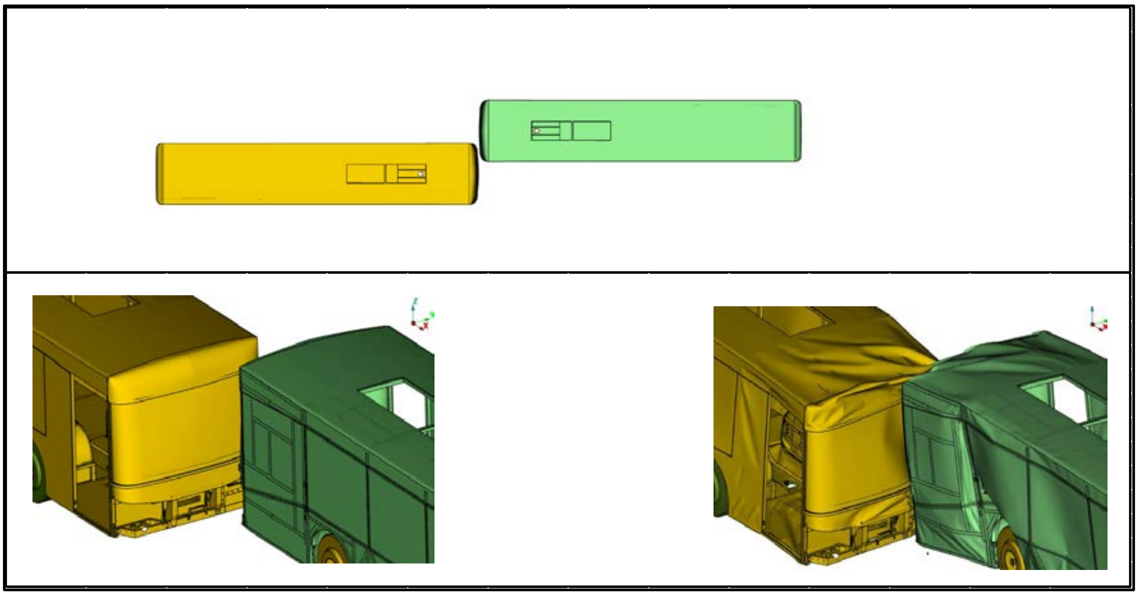


Figure 6.5: Illustration of frontal impact between 2 buses, with a 15% contact overlap, 0º angle orientation (straight), at 30 km/h, with Crash box.

Figure 6.5 illustrates a simulated frontal bus-to-bus collision with 15% overlap and zero impact angle at 30 km/h, with the crash-box installed. The limited deformation visible in the driver area demonstrates the effectiveness of the crash-box in reducing direct intrusion under a critical collision scenario.

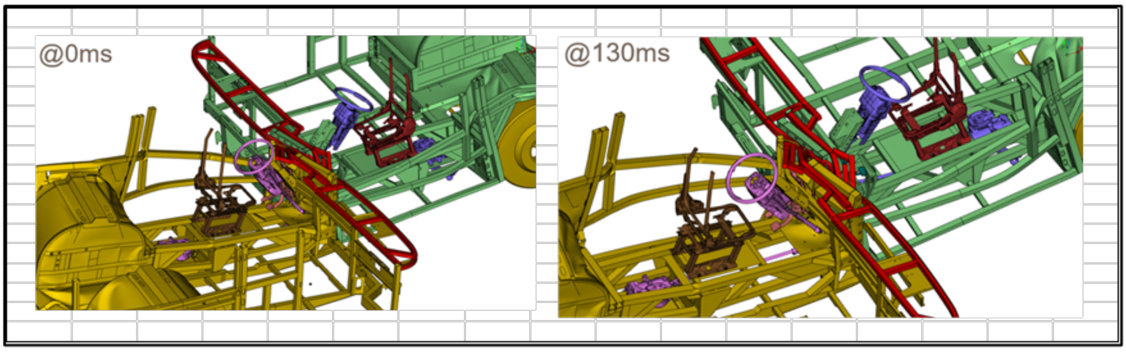


Figure 6.6: Illustration of deformation in the frontal area in an accident with frontal impact between 2 buses, with a 15% contact overlap, 0º angle orientation (straight), at 30 km/h, with Crash box.

Figure 6.6 shows deformation of the front structure during the same collision scenario, highlighting the structural response around the driver area. The results indicate that deformation is largely constrained by the crash-box, with collapse shifted away from the driver compartment.

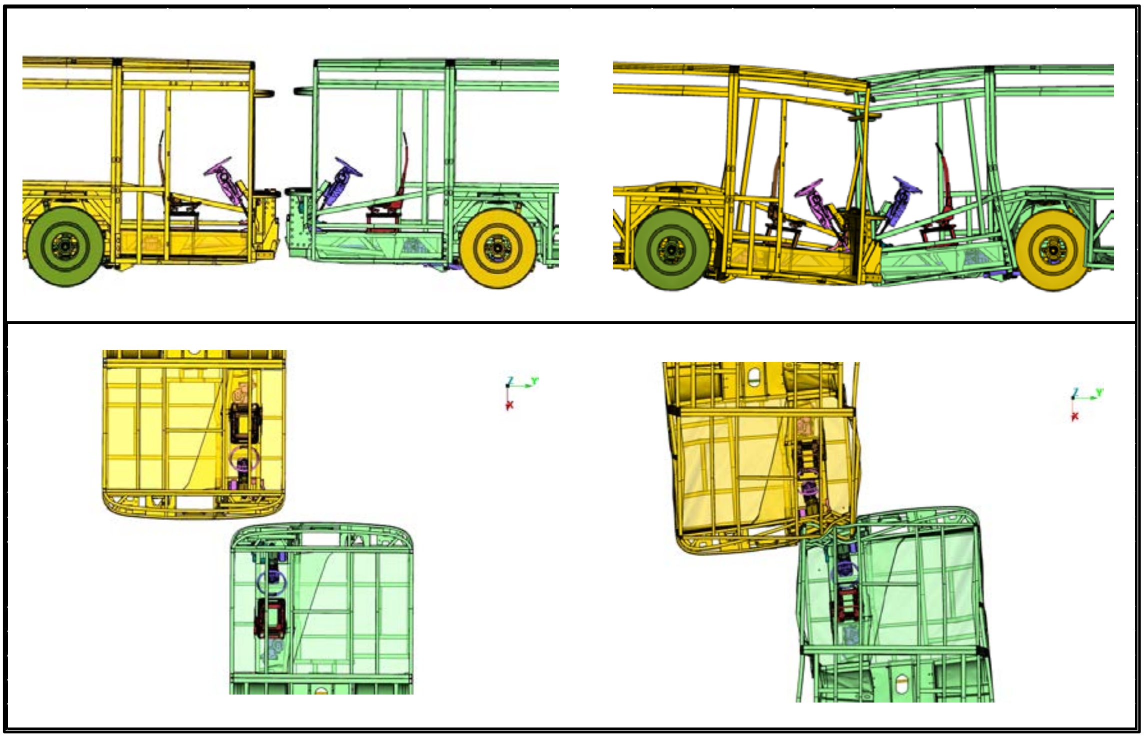


Figure 6.7: Lateral and top view of the deformation produced in the steering column and the intrusion on the dummy, in an accident with frontal impact between 2 buses, with a 15% contact overlap, 0º angle orientation (straight), at 30 km/h, with Crash box.

Figure 6.7 presents lateral and top views of steering column deformation and dummy intrusion during the frontal collision with the crash-box installed. The views show that driver compartment deformation is limited, while rotation and collapse occur primarily behind the driver due to increased local stiffness. In the lateral view of the collision in Figure 6.7, you can see that there is little deformation in the driver's zone. However, you can observe how the entire front overhang rotates downward. This is due to the high rigidity of this area, which causes the collapse to occur just behind the driver.

The isometric view in Figure 6.8 shows that after the impact, the structure deformation occurs partially over the front part of the crash-box.

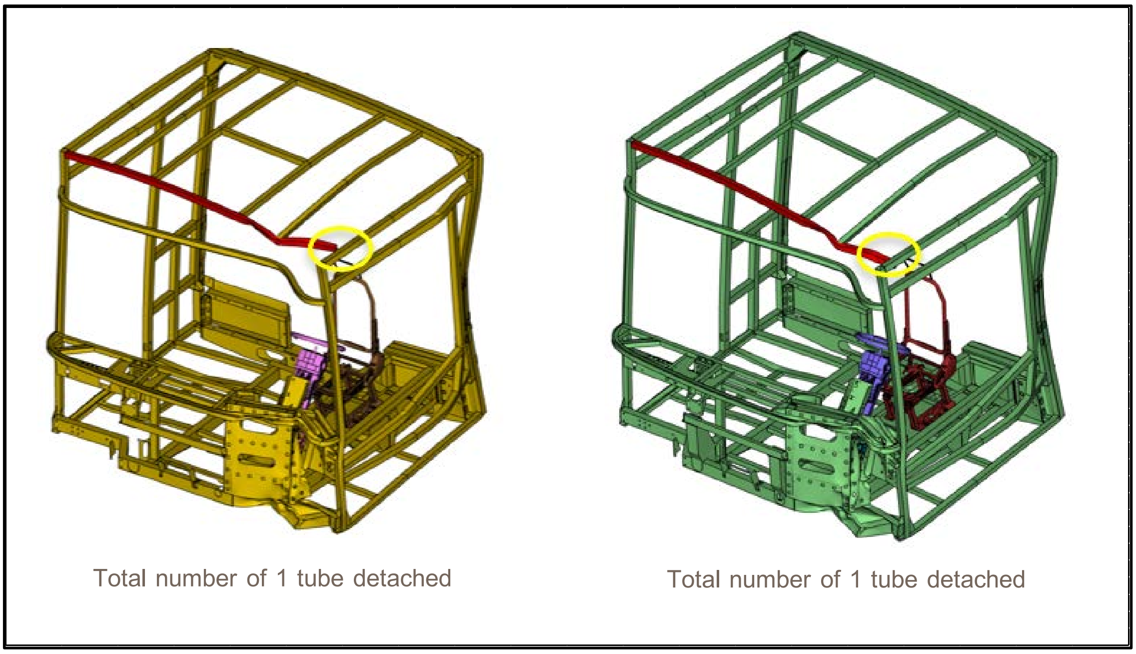


Figure 6.8: Isometric view of the deformation produced in an accident with frontal impact between 2 buses, with a 15% contact overlap, 0º angle orientation (straight), at 30 km/h, with Crash box.

The isometric view in Figure 6.8 illustrates the overall deformation pattern of the bus structure following impact with the crash-box installed. Deformation occurring mainly in front of and around the crash-box confirms its role in restraining collapse and preserving driver survival space.

The image in Figure 6.9 identifies the structure of the crash-box, showing how it restrains the deformation. The level of deformation achieved makes the driver retention system effective. At this point, one could continue with studies to adjust the retention system and evaluate whether it is convenient to integrate the airbag.

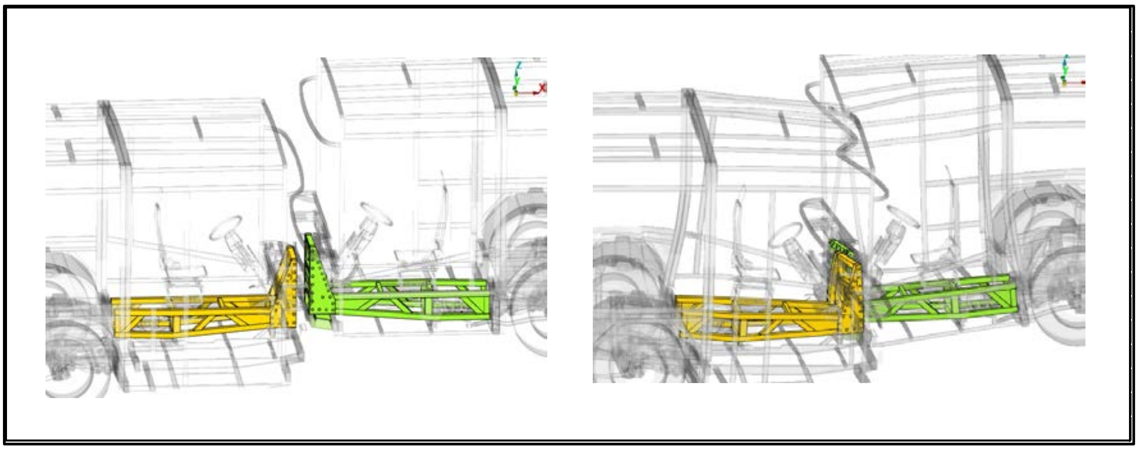


Figure 6.9: Illustration of accident with frontal impact between 2 buses, with a 15% contact overlap, 0º angle orientation (straight), at 30 km/h, with Crash box.

The results demonstrate that the crash-box effectively restrains deformation in the driver area and limits intrusion into the driver compartment, thereby preserving the driver's survival space. This level of intrusion reduction indicates that the structural solution provides a favourable basis for further optimisation of the driver restraint system, including potential integration and tuning of seat belts and airbags to manage the resulting deceleration loads.

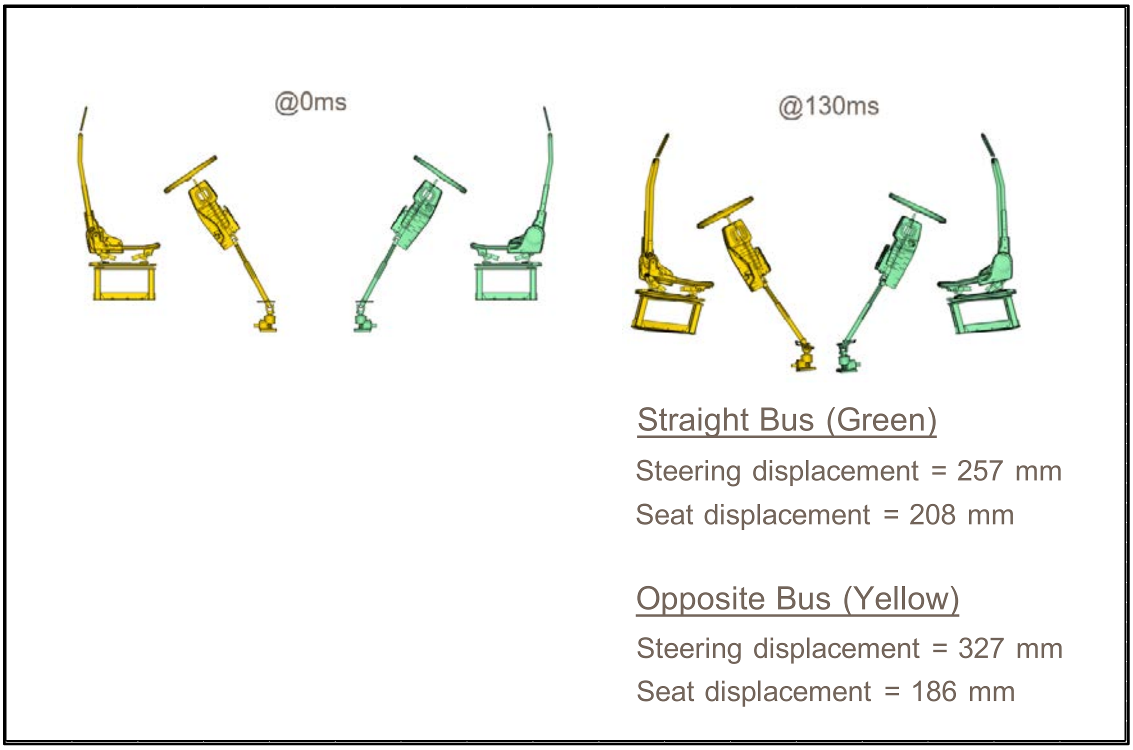


Figure 6.10: Illustration of steering column and seat displacement in an accident with frontal impact between 2 buses, with a 15% contact overlap, 0º angle orientation (straight), at 30 km/h, with Crash box.

Figure 6.10 shows steering column and driver seat displacement for both buses in the collision scenario with the crash-box installed. The reduced steering displacement confirms that the crash-box significantly limits rearward movement of driver-relevant components.

6.3.1 Acceleration pulses

In addition to the structural intrusion analysis, preliminary acceleration pulses were obtained after implementing the driver crash-box in the bus model. An acceleration pulse describes how rapidly the vehicle structure decelerates during a collision, typically expressed as acceleration versus time. It reflects the severity and duration of the forces transmitted through the vehicle structure and, ultimately, to the occupant.

Acceleration pulses are a key indicator of crash severity because higher peak accelerations and shorter pulse durations generally correspond to higher loads on the occupant. In frontal collisions, increased structural stiffness can reduce intrusion into the driver compartment but may also result in more abrupt deceleration, leading to higher acceleration peaks. Conversely, controlled structural deformation can extend the deceleration time and reduce peak accelerations by absorbing energy progressively.

In this study, the acceleration pulses are used to qualitatively assess how the introduction of the driver crash-box influences the overall crash dynamics and the trade-off between reduced intrusion and increased structural stiffness. The presented pulses are therefore indicative and intended for comparative assessment between configurations and impact scenarios rather than for direct quantification of injury risk. A detailed injury assessment would require occupant models, restraint systems, and validated injury criteria, which are beyond the scope of the present work.

Figure 6.11 describes pulse values after crash (BUS to BUS): In this case, a maximum value of 30G was obtained.

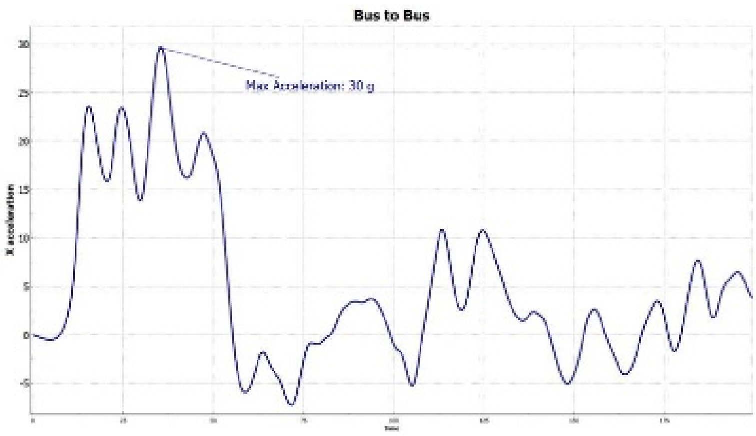


Figure 6.11: Pulse values after crash (BUS to BUS): In this case, a maximum value of 30G was obtained.

Figure 6.11 presents the acceleration pulse measured during the bus-to-bus collision with the crash-box installed, showing a peak value of approximately 30G. The pulse indicates moderate acceleration levels relative to intrusion reduction, highlighting the trade-off between increased stiffness and occupant loading.

Figure 6.12 shows pulse values after crash (Rigid barrier): In this case, a maximum of 43G was obtained.

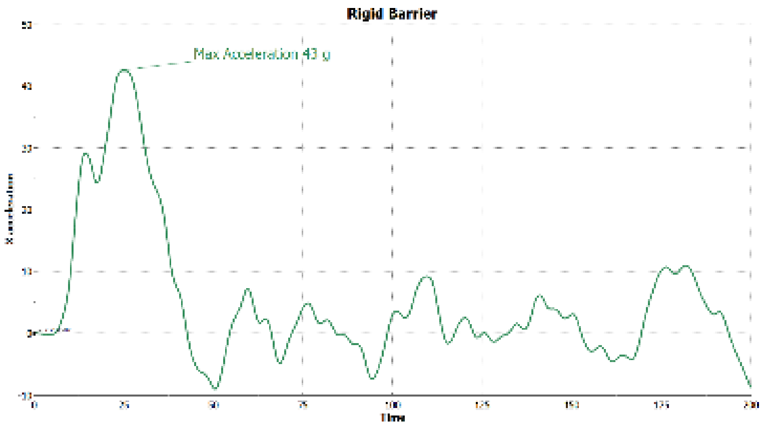


Figure 6.12: Pulse values after crash (Rigid barrier): In this case, a maximum of 43G was obtained.

Figure 6.12 shows acceleration pulses measured for rigid barrier and pole impact configurations, with peak values of approximately 43G and 23G respectively. The differences illustrate how impact configuration and energy concentration influence acceleration severity, underscoring the need for balanced energy absorption.

Figure 6.13 shows pulse values after crash (Pole barrier): In this case, a maximum of 23G was obtained.

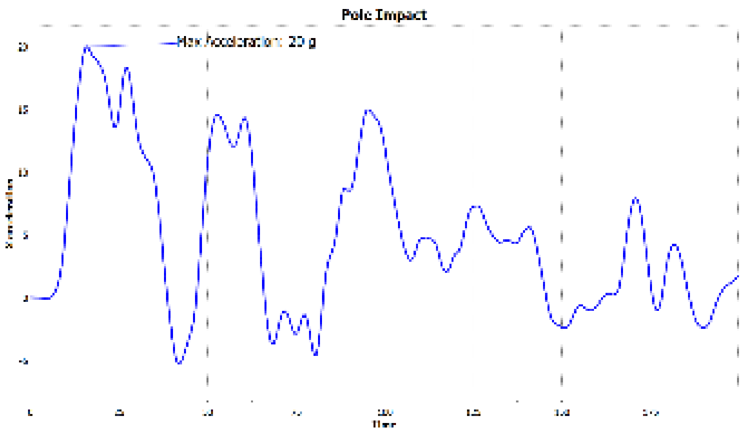


Figure 6.13: Pulse values after crash (Pole barrier): In this case, a maximum of 23G was obtained.

Figure 6.13 identifies a proposed local deforming zone within the crash-box intended for future optimisation of impact pulse characteristics. This concept suggests that introducing controlled deformation in the crash-box could reduce acceleration peaks while maintaining intrusion protection.

In Figure 6.14, the driver crash-box. The volume indicated in yellow, the area where it would be possible to study the possibility of integrating a collapsible zone to help reduce the acceleration pulse is indicated.

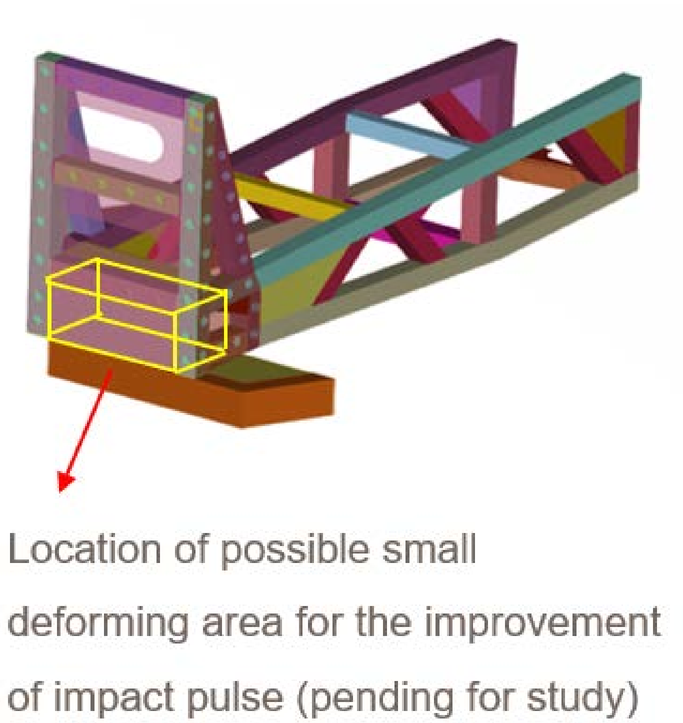


Figure 6.14: Location of possible small deforming area for improvement of impact pulse in the crash box.

The figure identifies a proposed local deforming zone within the crash-box intended for future optimisation of impact pulse characteristics. This concept suggests that introducing controlled deformation in the crash-box could reduce acceleration peaks while maintaining intrusion protection.

6.4 Conclusions

In this chapter we evaluate a reinforced driver crash-box as a targeted structural countermeasure for improving bus driver protection in frontal collisions. Using finite element simulations, the crash-box concept was integrated into a generic low-floor city bus model and assessed under critical frontal collision scenarios identified in earlier chapters.

The results show that the crash-box substantially reduces intrusion into the driver compartment and limits rearward displacement of the steering column and driver seat across the evaluated scenarios. By increasing local stiffness in the driver zone and redirecting load paths away from the cockpit, the crash-box helps preserve the driver's survival space in small-overlap and angled frontal impacts that are particularly demanding for current bus front structures.

At the same time, the simulations indicate that the increased stiffness introduced by the crash-box leads to higher acceleration pulses, reflecting a more abrupt deceleration of the vehicle structure. This highlights an important trade-off between intrusion reduction and occupant loading and underlines the need for further optimization of energy absorption characteristics and coordination with restraint systems.

Overall, the findings demonstrate that targeted structural reinforcement can significantly improve frontal crash protection for bus drivers, while also emphasizing the importance of balanced design solutions that combine structural strength with effective energy management.

7 Expert and stakeholder feedback

7.1 Introduction

The technical findings presented in the preceding chapters are based on structured finite element simulations and comparative evaluations of test configurations and structural countermeasures. However, improving bus driver collision safety is not solely a technical matter; it is also shaped by regulatory frameworks, procurement practices, manufacturing constraints, and international policy processes. For this reason, the project included structured consultations with a multidisciplinary reference group composed of representatives from transport authorities, research institutions, vehicle manufacturers, public transport operators, safety organisations, and actors involved in international regulatory work.

The purpose of involving the reference group was threefold. First, it provided an opportunity to assess the realism and relevance of the simulated accident scenarios, modelling assumptions, and identified structural weaknesses. Second, it allowed critical evaluation of the proposed alternative test methods and the crash-box concept from both engineering and operational perspectives. Third, it enabled discussion of how the technical findings may inform future regulatory development, voluntary standards, and procurement-based safety requirements at national and international levels.

This chapter synthesises the main feedback and discussion points emerging from the reference group meetings and related consultations. Rather than functioning as a meeting record, the chapter identifies key themes, areas of consensus, and strategic considerations that are relevant for interpreting the study's findings and for situating them within the broader policy landscape for bus driver collision safety.

7.2 The composition of the reference group

In order to assess the realism and relevance of the simulations in the study, a reference group was established in the project. Two main reference group meetings were held, in addition to several small-scale consultations with individual reference groups members during the course of the project. The main reference group meeting was attended by about 50 representatives from transport authorities, research institutions, vehicle manufacturers, safety organisations, and public transport operators with expertise in bus safety, accident investigation, regulation, and vehicle design. Participants included members of the project reference group as well as invited experts with experience in real-world accident analysis, vehicle crashworthiness, and urban bus operations. This multidisciplinary composition ensured a broad perspective on both technical feasibility and practical relevance, and facilitated constructive discussion on how the study's findings could inform future safety improvements and regulatory considerations.

Participants came primarily from Europe, including representatives from Norway, Sweden, Germany, Belgium, Spain, and the United Kingdom, reflecting strong involvement from Nordic countries, EU institutions, research organisations, and public transport stakeholders. In addition, participants with experience and roles linked to international regulatory work at the UNECE level contributed perspectives with relevance beyond Europe, giving the discussion a global regulatory context. The mix of national authorities, European NGOs, research institutes, vehicle manufacturers, and international safety experts ensured that the feedback reflected both regional operational realities and wider international policy and standardisation considerations.

7.3 The realism and relevance of the simulations

Participants expressed strong appreciation for the realism, technical depth, and relevance of the simulation work. Several key themes emerged in the feedback and discussion:

1) Overall relevance and realism of the simulations. The simulation approach was widely regarded as credible and well aligned with real-world bus accidents, particularly the focus on low-speed but high-severity bus-to-bus frontal collisions. Participants agreed that the energy levels and deformation patterns presented were consistent with accident investigation findings and highlighted the inadequacy of existing regulatory test energies (e.g. UN R29) for buses.

2) Structural compatibility as a central problem. A recurring point was that the main safety issue is not only energy magnitude, but poor structural compatibility between buses and between buses and other heavy vehicles. Several participants supported the emphasis on tube detachment, welded joint failures, and lateral structural intrusion, noting that these mechanisms cannot be mitigated by restraint systems alone.

3) Small overlap and angled impacts seen as critical scenarios. The focus on small overlap and angled collisions was strongly endorsed. These configurations were considered particularly representative of severe real-world outcomes and appropriate for identifying worst-case scenarios that future test methods should address.

4) Limitations of current regulatory tests. There was broad agreement that existing tests (including UN R29 and pendulum-type impactors) do not reproduce the intrusion and deformation observed in real bus-to-bus crashes. The discussion supported the project's conclusion that alternative test concepts—such as sled-based pole tests, or mass-impact tests with higher energies—should be explored.

5) Need to integrate restraint systems, but not as a standalone solution. Several participants asked whether seatbelts and airbags were included in the solutions that we suggested. We answered that the current study prioritises structural integrity and intrusion prevention. This was generally supported. It was emphasized that restraint systems (seatbelts, airbags, seat anchorage strength) are important, but only effective if structural intrusion is first controlled.

6) Seat and anchorage strength highlighted as critical. Based on real accident experience (notably from Transport for London), participants stressed that seat failure and anchorage rupture can negate the benefits of seatbelts and airbags. This reinforced the need to consider the driver seat, its mountings, and load paths as part of any safety concept.

7) City buses identified as a worst-case vehicle type. There was agreement that low-floor city buses represent a particularly vulnerable configuration due to low driver position, lack of a chassis frame, and limited space for energy management. Participants accepted our view that solutions developed for city buses would likely be transferable to coaches, but not vice versa.

8) Active safety systems (ADAS) seen as complementary, not sufficient. While some participants highlighted ADAS, emergency braking, and other active systems, there was consensus that these cannot replace passive structural measures. Even with advanced ADAS, crashes will still occur, making improved structural crashworthiness essential.

9) Strong support for continuing and expanding the work. Several participants encouraged further development of the simulations, including refinement of impactor concepts, investigation of alternative materials, and future inclusion of acceleration pulses and occupant loading.

7.4 Current and future policy situation

Reference group participants said that the current policy landscape for bus driver collision safety is characterised by growing recognition of the problem, but fragmented regulatory responses and uneven progress across regions in the world. While passenger cars and, to some extent, trucks have benefited from decades of progressively strengthened safety regulations, buses remain comparatively underregulated in terms of frontal collision protection for drivers. Several initiatives and perspectives presented at the reference group meeting illustrate both the limitations of today's policy framework and possible pathways forward.

From an industry and procurement perspective, Jofri Lunde (NHO Transport, Norway / Bus Nordic) highlighted the absence of EU-wide mandatory requirements specifically addressing bus frontal collision safety. She argued that this gap undermines occupational safety for bus drivers and is inconsistent with broader transport policy goals, including Vision Zero and increased reliance on public transport. As an interim measure, Lunde pointed to the Bus Nordic standards as a potential first step, using Nordic public procurement to raise minimum safety requirements ahead of harmonised EU regulation.

At the international level, Hamza Guirrou (International Road Union, IRU) described the existing mix of active and passive safety measures relevant to bus driver safety and outlined the policy context within UNECE and EU processes. He emphasised that while advanced driver assistance systems (ADAS) and other active measures are important, they cannot fully compensate for structural weaknesses in vehicle design. From a policy standpoint, he mentioned a need to strengthen the evidence base and build broader international support before new mandatory standards for bus driver collision safety can be introduced at UN or EU level.

Rikard Fredriksson (Swedish Transport Administration / Euro NCAP) presented Euro NCAP's evolving roadmap for heavy vehicle safety ratings. While current efforts focus on trucks, initially prioritising active safety, buses are envisaged as the next step in the programme. Fredriksson stressed that future policy and rating schemes should combine active and passive safety measures, but also cautioned that local structural strengthening, if poorly designed, could reduce crash compatibility with other vehicles. This highlights an emerging policy tension between improving driver protection and maintaining system-wide safety for all road users.

A contrasting and more interventionist approach was presented by Kerri Cheek (Transport for London, TfL). In the absence of sufficiently ambitious national regulation, TfL has used its procurement power to impose the London Bus Safety Standard, requiring features such as improved frontal crash protection for pedestrians, intelligent speed assistance, ADAS, and cab design improvements. This approach has enabled faster implementation than traditional regulation. TfL's forthcoming policy phase will further extend requirements to include seatbelts, airbags, and stronger driver cabs, illustrating how large public transport authorities can act as de facto regulators and policy innovators.

Evidence from outside Europe, presented by Angelo D'Elia (Monash University, Australia), reinforced concerns about stagnation in bus safety performance. Using real-world crash data and "used heavy vehicle safety ratings", D'Elia showed that bus crashworthiness has not improved significantly in recent decades. Moreover, buses and trucks remain substantially more aggressive to other road users than passenger cars. These findings suggest that, without targeted policy intervention, market forces alone are unlikely to deliver meaningful safety gains.

Finally, Graziella Jost (European Transport Safety Council, ETSC) placed these developments within a broader European policy context. She highlighted ongoing efforts to inform public debate, influence EU institutions, and prepare the ground for future revisions of vehicle safety legislation, including potential updates to the General Safety Regulation. ETSC's experience underscores the importance of coordinated advocacy, research-based evidence, and alignment between EU and UNECE processes to achieve lasting regulatory change.

7.5 Summary

This chapter summarises and analyses expert and stakeholder feedback on the study’s simulation results, proposed test methods, and structural countermeasures, assessing their realism, relevance, and implications for future policy and regulatory development in bus driver collision safety. The chapter highlights broad consensus on the need for improved structural frontal protection for bus drivers, while identifying regulatory gaps, practical implementation challenges, and strategic pathways for advancing both voluntary and mandatory safety standards.

8 Concluding discussion

8.1 How much does the crash box reduce intrusion in the driver area?

It is very relevant to ask how much the crash box reduces intrusion in the driver area in collisions, as this may indicate whether the crash box may transform the simulated scenarios from non-survivable to potentially survivable for bus drivers, if adequate restraint systems (e.g. seat belts, air bag) are used.

Based on the simulation results in the report, the driver crash box reduces intrusion substantially, roughly by about half compared with the baseline bus structure. We can derive this by comparing the reported steering column displacement in the driver area from in the simulations with and without crash box.

Without crash box (baseline bus-to-bus impacts, 30 km/h), maximum steering column displacement in the driver area is typically 600–730 mm (Crash case D is the worst case reported, with 729 mm displacement). Seat displacement is generally lower but still significant (often around 100–200 mm).

With driver crash box installed, and the same impact conditions, steering column displacement is reduced to approximately 250–330 mm (reported values are e.g. 257 mm (straight bus) and 327 mm (opposite bus). Seat displacement is of similar magnitude or slightly reduced, but the key improvement is preservation of driver survival space

To sum up, this shows that the overall effect involves about 300–450 mm less steering wheel intrusion with the crash box solution. When it comes to relative reduction of steering wheel intrusion, this involves approximately 50–60% reduction in intrusion into the driver compartment. We also see that the crash box solution involves that structural collapse is redirected behind the driver, instead of crushing the cockpit.

Thus, the crash box does not mainly work by absorbing all energy in front of the driver (there is little space for that), but by:

- Increasing local stiffness around the driver,
- Preventing tube detachment in the cockpit,
- Forcing deformation to occur further rearward,
- Making restraint systems (seat belt, potential airbag) much more effective.

This reduction is large enough to transform many of the simulated scenarios from non-survivable to potentially survivable, provided adequate restraint systems are used.

8.2 Why were the simulations of bus-to-bus-scenarios conducted?

Using finite element simulations, a matrix of bus-to-bus collision scenarios was analysed, covering varying overlap ratios and impact angles. The results show that small overlap and angled impacts are particularly critical, leading to severe intrusion into the driver compartment, large steering column displacements, and frequent structural failures in welded tubular connections. The energy levels involved in these collisions were found to be substantially higher than those represented in current regulatory test procedures.

However, why were the simulations of bus-to-bus-scenarios conducted? We knew from real world collisions that they would be very critical. Although real-world accident investigations had already shown that certain bus-to-bus frontal collisions are highly critical, these previous accidents did not provide:

- Controlled variation of overlap and impact angle,
- Quantitative and comparable measures of intrusion, displacement, and energy absorption,
- The ability to systematically link accident severity to test configurations, or
- A reproducible basis for evaluating alternative test methods and structural solutions.

The simulations were therefore necessary to systematically map crash severity as a function of overlap and impact angle, quantify energy levels and structural response under controlled conditions, and create a reference set of results against which regulatory tests and new countermeasures could be evaluated.

8.3 How the report provides technical input to the international regulatory discussion

The report contributes technical input to ongoing international regulatory discussions (e.g. UNECE / GRSP) in four concrete ways:

1) By defining realistic reference conditions for bus frontal collisions. Through reconstruction and simulation of real-world bus-to-bus accidents, the report quantifies, e.g. representative impact speeds, overlap ratios and impact angles, energy levels and intrusion patterns. These parameters provide a technical reference baseline that can be used to judge whether proposed or existing test procedures are representative of real bus accidents.

2) By demonstrating limitations of existing regulatory tests. The report systematically compares, e.g. impact energies and load distribution in UN R29.03 tests, with those observed in realistic bus collision scenarios. This comparison provides evidence-based justification for why current tests do not adequately address frontal driver protection in buses, which is a necessary first step in regulatory development.

3) By identifying test principles suitable for buses. Rather than proposing a finished regulation, the report identifies general test principles, such as localized frontal loading of the driver area, narrow overlap or concentrated impact configurations, and energy levels aligned with real bus-to-bus collisions. These principles are directly transferable to regulatory discussions without prescribing a specific test setup prematurely.

4) By linking performance criteria to driver protection outcomes. The report consistently uses driver-relevant metrics, including intrusion into the driver compartment, steering column displacement, preservation of survival space, and acceleration pulse trends. These metrics function as candidate performance criteria that regulators can discuss, refine, or adopt when considering future voluntary or mandatory requirements.

8.4 What did the reference group meetings teach us?

A broad, multidisciplinary reference group confirmed that the simulation approach is realistic, technically credible, and well aligned with real-world severe bus accidents, particularly low-speed but high-severity frontal collisions that are not adequately addressed by existing regulations such as UN R29. Feedback consistently highlighted poor structural compatibility, small overlap and angled impacts, and structural intrusion as the core safety challenges, with strong agreement that restraint systems and ADAS are necessary but insufficient without improved structural integrity, especially for low-floor city buses. Overall, participants strongly supported further development of the work, noting its clear relevance for future safety concepts, test methods, and regulatory discussions at both European and international levels.

In summary, the current policy situation is marked by increasing awareness, pilot initiatives, and local leadership, but also by regulatory gaps and slow harmonisation. Reference group members seemed to agree that, looking ahead, future progress is likely to depend on a combination of strengthened international standards, proactive public procurement, improved safety rating schemes, and continued integration of both passive and active safety measures; ensuring that bus driver safety is addressed as an integral part of a safe-system approach to road transport.

8.5 Policy implications

The report aims to assess new structural solutions for improving bus driver protection in frontal collisions and to investigate alternative test methods for evaluating structural integrity and driver safety. The report builds on previous studies conducted by the Institute of Transport Economics (TØI) and IDIADA, commissioned by the Norwegian Public Roads Administration (Nævestad et al., 2025; Laso et al., 2025). These earlier studies provide quantitative overviews of the extent of bus accidents in Europe, as well as qualitative analyses of shortcomings in current bus front designs. Based on these analyses, new solution trends for improved bus front designs were proposed. However, it was concluded that further in-depth studies based on simulations and/or testing were necessary to refine and validate models for improved bus driver collision safety.

The present report provides such simulations. Its purpose is to contribute to the international debate on enhanced collision protection for bus drivers. In September 2025, the European Transport Workers' Federation (ETF) published a manifesto calling for stronger crash and collision protection for bus drivers in Europe, addressing governments, employers, and vehicle manufacturers. In the same year, the Norwegian government raised the issue of bus driver collision safety within the United Nations Economic Commission for Europe (UNECE) Working Party on Passive Safety (GRSP).

GRSP is an international regulatory working group under UNECE's World Forum for Harmonization of Vehicle Regulations (WP.29), responsible for developing and updating global vehicle safety regulations related to passive safety. As such, GRSP represents a key arena for potential future international standards aimed at improving collision safety for bus drivers. Developing such standards is, however, a long-term process, and current efforts remain at an early stage.

By indicating the potential effects of new solution trends for improved frontal protection in bus frontal collisions, this report may help identify or inspire solutions that can be implemented on a voluntary basis, or that may serve as a foundation for future international requirements.

To ensure that the findings address the current industry needs and have global relevance, a panel of industry experts has been assembled to discuss the proposed solutions and contribute their insights into this international safety issue. We thank the many individuals and organizations in the Norwegian and the international public transport environment for insightful discussions and valuable feedback.

The findings of this report have several important implications for transport safety policy and vehicle regulation at national and international levels.

First, the results indicate that existing passive safety regulations applicable to buses do not adequately address frontal collision protection for drivers. Current regulatory frameworks focus primarily on rollover protection or apply test conditions that do not represent the energy levels, impact configurations, or localized loading observed in real bus frontal collisions. From a policy perspective, this suggests that compliance with existing regulations cannot be assumed to provide sufficient driver protection in frontal impacts.

Second, the report demonstrates that more representative frontal impact test principles are technically feasible. Localized test configurations, such as narrow rigid barrier and pole impacts, better reproduce real accident conditions and could serve as a foundation for future voluntary or regulatory test procedures. Policymakers may therefore consider supporting the development of bus-specific frontal impact assessments rather than adapting tests originally developed for other vehicle categories.

Third, the study shows that targeted structural countermeasures, such as a reinforced driver crash-box, can substantially improve driver survival space in frontal collisions. This indicates that meaningful safety improvements are achievable through vehicle design, even in the absence of immediate regulatory changes. Policy instruments such as voluntary guidelines, procurement requirements, or incentive schemes could therefore play a role in accelerating the adoption of improved designs.

Finally, the report provides technical evidence that can support informed discussions within international regulatory forums, such as UNECE, by linking real-world accident conditions, test methodology, and driver-relevant performance indicators. Rather than prescribing specific regulations, the findings contribute a technical basis for future policy development aimed at improving bus driver safety.

8.6 Methodological strengths and weaknesses

8.6.1 Methodological strengths

1) Use of real-world accident cases as a starting point. A key strength of the study is its grounding in documented real-world bus-to-bus frontal collisions. These cases provide realistic impact speeds, overlap ratios, and structural failure patterns, ensuring that the simulations are anchored in accident-relevant conditions rather than hypothetical scenarios.

2) Systematic and controlled simulation design. The use of a structured simulation matrix with varying overlap ratios and impact angles allows for systematic exploration of crash severity and structural response. This approach makes it possible to isolate the influence of key parameters and to identify recurring failure mechanisms and critical loading conditions affecting driver survival space.

3) Consistent use of driver-relevant performance metrics. The study focuses on intrusion, steering column displacement, survival space, and acceleration pulses—metrics that are directly relevant to driver safety and suitable for comparing scenarios, test methods, and structural countermeasures.

4) Comparative evaluation of test methods and countermeasures. By applying the same modelling framework to bus-to-bus collisions, alternative impactor tests, and a reinforced crash-box concept, the study enables meaningful comparisons across different assessment approaches and design solutions.

5) Relevance for regulatory discussion. Rather than proposing a single prescriptive test, the study identifies general test principles and performance indicators, which is methodologically appropriate for supporting early-stage regulatory development.

8.6.2 Methodological weaknesses and limitations

1) Limited range of impact speeds and accident scenarios. The simulations are primarily conducted at impact speeds around 30 km/h, reflecting documented Norwegian accident cases. While highly relevant, this limits the generalisability of the findings to higher-speed collisions or different traffic environments.

2) Reliance on numerical simulations without physical validation. All analyses are based on finite element simulations. Although the modelling approach follows established industry practice, the absence of corresponding physical crash tests means that the results should be interpreted as indicative rather than fully validated.

3) Generic vehicle model and simplified variability. The use of a generic low-floor city bus model improves transparency and comparability but does not capture the full variability in bus designs, materials, and manufacturing quality across manufacturers and vehicle categories.

4) Simplified representation of occupant injury risk. Acceleration pulses are reported as indicators of crash severity, but no biomechanical injury criteria or human body models are applied. As a result, injury risk is inferred indirectly rather than quantified.

5) Focus on frontal structural response only. The study concentrates on structural crashworthiness and does not fully address interactions with restraint systems, interior components, or post-impact dynamics, which would be relevant for a comprehensive injury assessment.

8.7 Future research

1) Use of protected and reinforced welding zones. Another important area for future research concerns the design and performance of structural tube connections in bus front structures. The simulations and accident analyses indicate that welded joints are often critical failure points, with tube detachment occurring early in frontal impacts and limiting the structure’s ability to absorb energy through controlled plastic deformation. Further work is therefore needed to investigate improved connection designs, alternative welding and assembly techniques, and the use of protected or reinforced welding zones that can maintain structural integrity under high localized loads. In addition, research should address measures to improve structural compatibility between colliding buses, such as aligned load paths and controlled deformation interfaces, to reduce asymmetric intrusion and severe localized damage. Advances in these areas could significantly enhance energy absorption capability and contribute to more predictable and crash-compatible structural behaviour in frontal bus collisions.

2) Acceleration pulse and deformation zone. Future research should also focus on a more detailed analysis of the acceleration pulses generated during frontal collision events. The acceleration pulse provides important information on the severity and duration of the deceleration experienced by the vehicle structure and is a key input for assessing potential injury risk to the driver. While the present study uses acceleration pulses for comparative assessment, further work is needed to optimise their magnitude and shape. In particular, the introduction of a dedicated deforming zone at the front of the crash-box could enable more progressive energy absorption and reduce peak accelerations.

3) Seat belts and airbag. The structural optimisation mentioned above should be investigated in combination with restraint system tuning, as the effectiveness of intrusion reduction depends on how the resulting deceleration loads are managed by the occupant restraint systems. While a reinforced front structure or crash-box can preserve the driver’s survival space, increased structural stiffness may lead to higher acceleration pulses and greater loads acting on the driver. Seat belt systems play a critical role in controlling driver kinematics by limiting forward motion and distributing forces across the torso, while airbags can further reduce injury risk by cushioning the head and chest and extending the deceleration time. Future research should therefore consider the coordinated design and tuning of structural deformation characteristics, seat belt performance, and airbag deployment to achieve an optimal balance between intrusion prevention and acceptable occupant loading in frontal bus collisions.

4) Integration of ADAS and passive safety measures
Future research should examine how advanced driver assistance systems (ADAS) can be effectively combined with passive safety measures to further reduce injury risk for bus drivers in frontal collisions. Systems such as autonomous emergency braking (AEB) have the potential to reduce impact speed or modify collision configuration before contact occurs, thereby lowering the energy that passive safety systems must manage. Even modest speed reductions can significantly decrease collision energy and structural intrusion, particularly in bus-to-bus impacts where energy levels are high.

An integrated assessment should therefore consider how ADAS-triggered braking influences the loading conditions applied to the bus front structure and how passive measures such as reinforced crash-boxes, deformable zones, and restraint systems respond under these modified conditions. Coordinated design of ADAS intervention thresholds, structural deformation characteristics, and occupant restraint performance could enable a more robust safety concept in which active systems reduce crash severity and passive systems manage the remaining energy in a controlled manner. Simulation-based studies combining vehicle dynamics, braking performance, and structural crash response would be a logical next step toward evaluating the combined safety benefit of active and passive systems for bus driver protection.

9 Conclusion

The severity of accidents is attributed to excessive intrusion and structural component detachment. The front structure of buses is clearly not safe in terms of passive safety to protect the driver. The impact energy in real-world bus-to-bus-collisions in 30 km/h is approximately ten times higher than the test A energy threshold prescribed in UN R29.03.

The level of intrusion obtained in the frontal pole and rigid wall impact tests are close to real accident scenarios; therefore, we could consider these as the main guidelines for implementing specific tests in the new safety regulations applicable to buses.

The floor rigidity in the driver area maintains the survival space and redirects structural collapse towards the rear section of the front axle. The suggested crash box design will consider steering column decoupling and extending to provide higher protection. Another aspect to investigate is finding improved solutions for tube connections, welding assembly techniques, protected welding areas, and all necessary measures to improve vehicle compatibility.

The next steps will involve conducting a more in-depth study of the acceleration pulse measured during the crash event. Acceleration pulse is important data for evaluating the severity of driver injuries. The implementation of a separate deforming area placed at the front of the crash-box could help to reduce the acceleration pulse, and in combination with the adjustment of the retention system.

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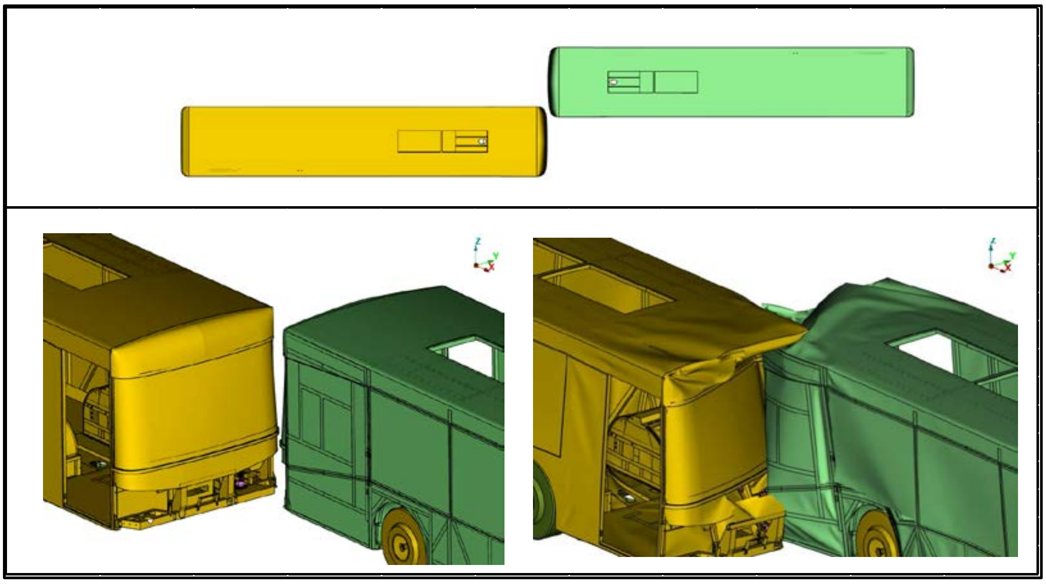
Exhibit 1. Appendix 1 Results – bus-to-bus collisions

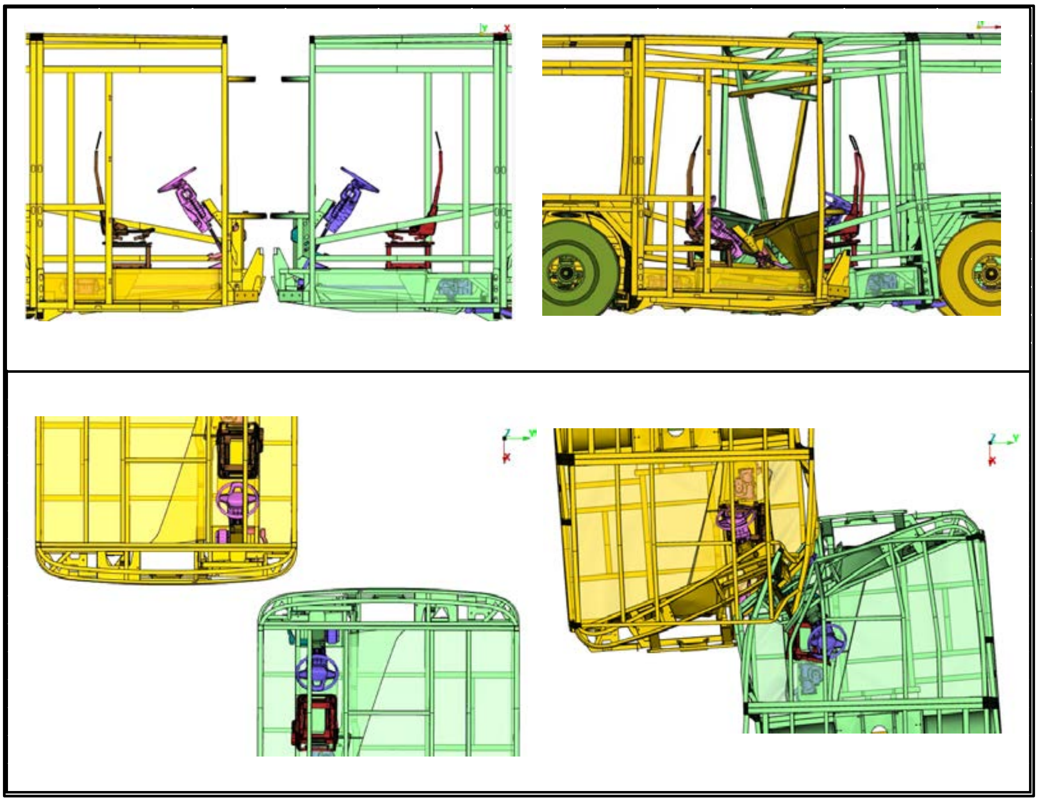
The chapter presents the results from the bus-to-bus collision simulations defined in the simulation matrix. Each subsection describes the structural response, intrusion levels, and driver-relevant displacements for a specific impact configuration.

Crash A (30km/h, 15% overlap, 0º angle orientation)

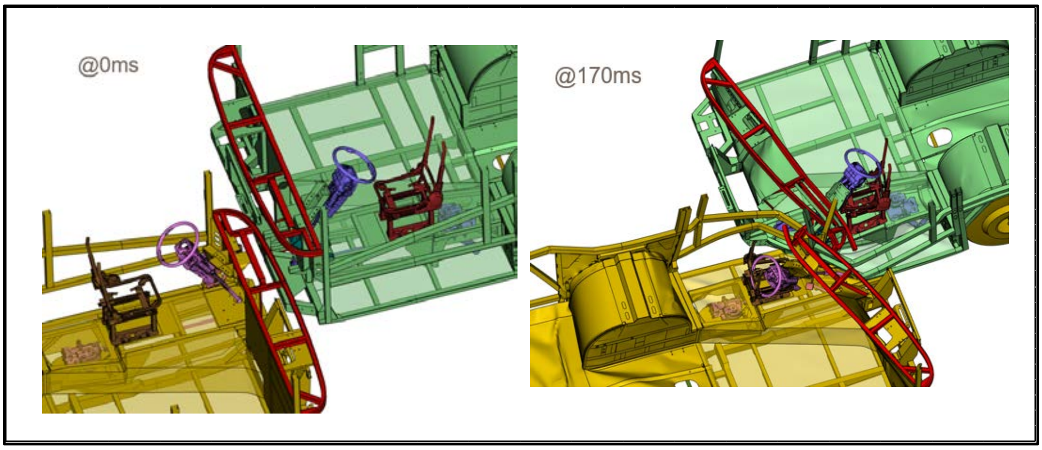
The image below shows a frontal impact between 2 buses, with a 15% contact overlap, 0º angle orientation (straight), at 30 km/h. During the crash, a big deformation of structural tubes provoked a big intrusion in the driver area.



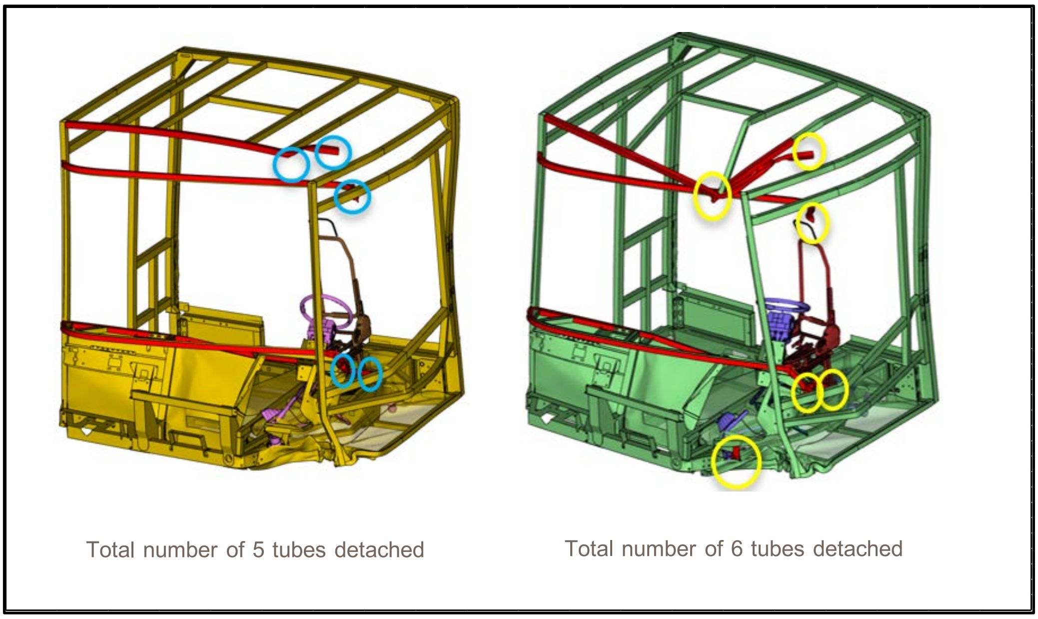
The image below shows the maximum deformation of the cockpit area, including how the steering column and seat suffered displacement.



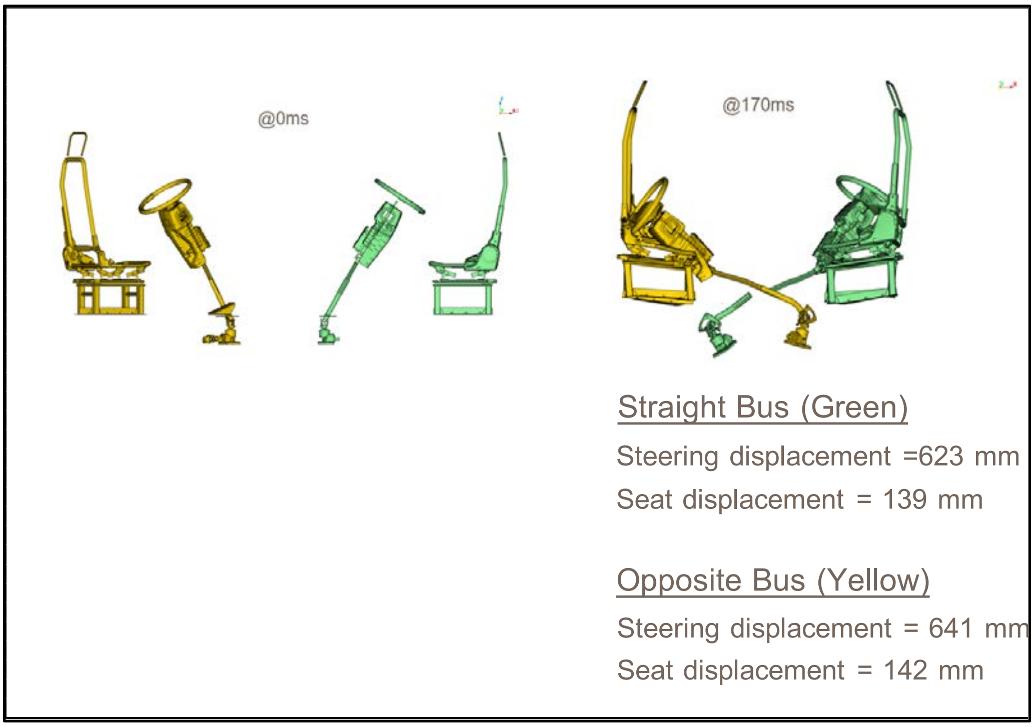
In addition, the intrusion of each of bus frontal faces can be seen.



Many detached tubes were detected, located in the welded area.



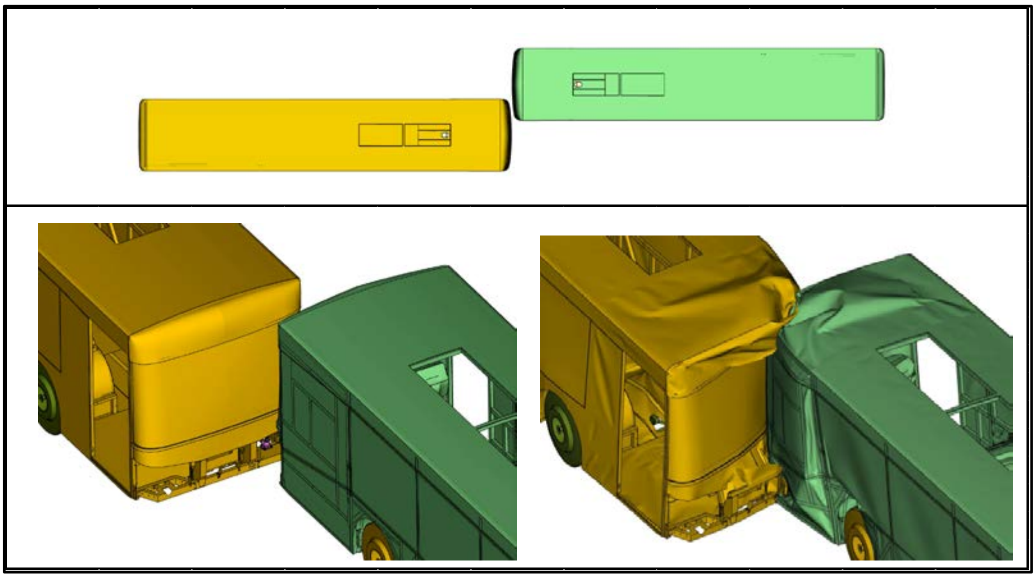
In the next image, the steering column and seat are represented in both buses.



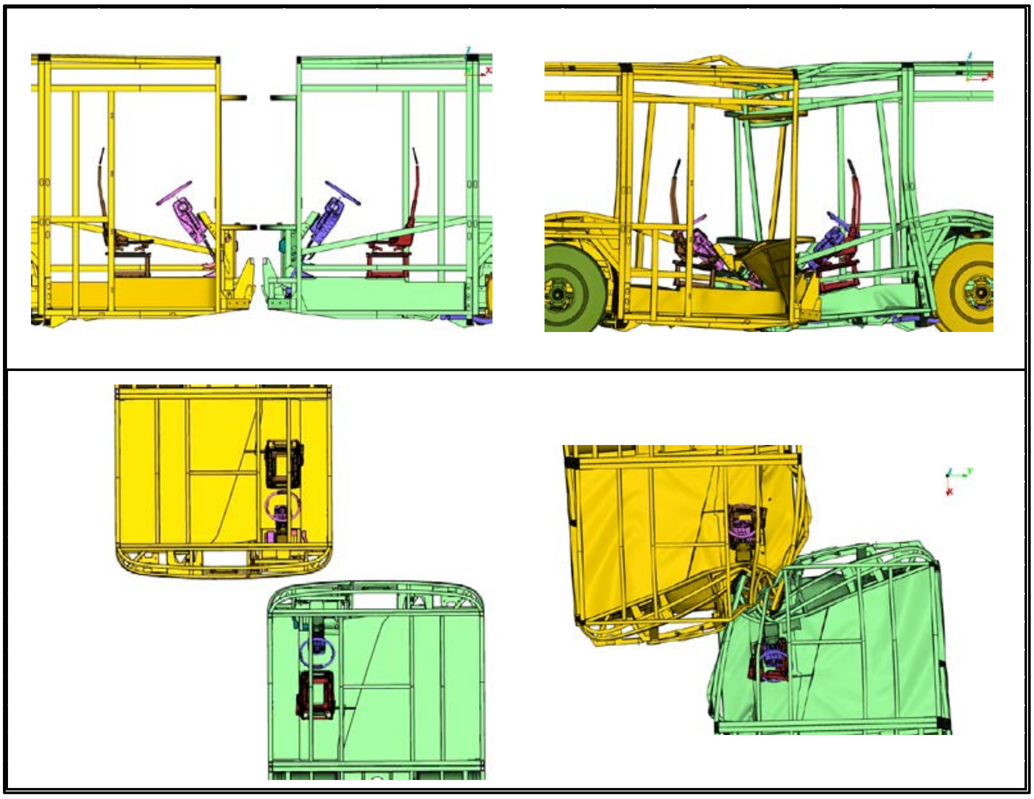
As shown in the image, the steering columns displaced into the seating area, creating a high risk of severe injury to the bus drivers.

Crash B (30km/h, 30% overlap, 0º angle orientation)

The image below shows a frontal impact between 2 buses, with a 30% contact overlap, 0º angle orientation (straight), at 30 km/h. During the crash, a big deformation of structural tubes provoked a big intrusion in the driver area.

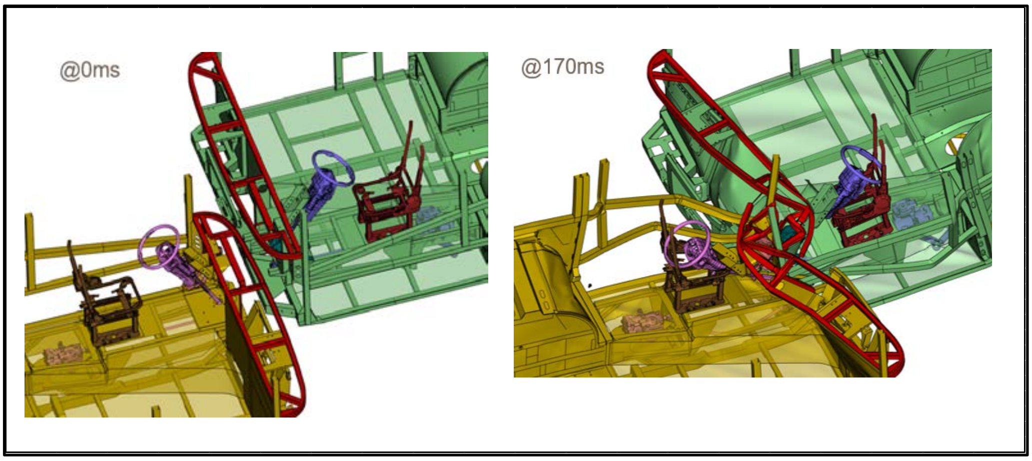


The image below shows the maximum deformation of the cockpit area, including how the steering column and seat suffered displacement.

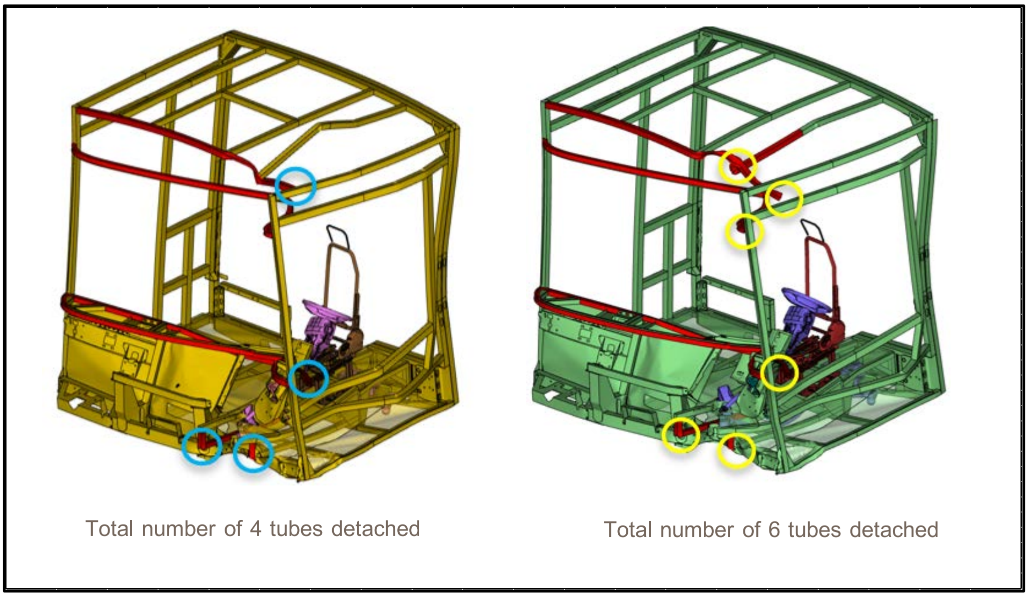


As shown in the image, the steering columns displaced into the seating area, creating a high risk of severe injury to the bus drivers.

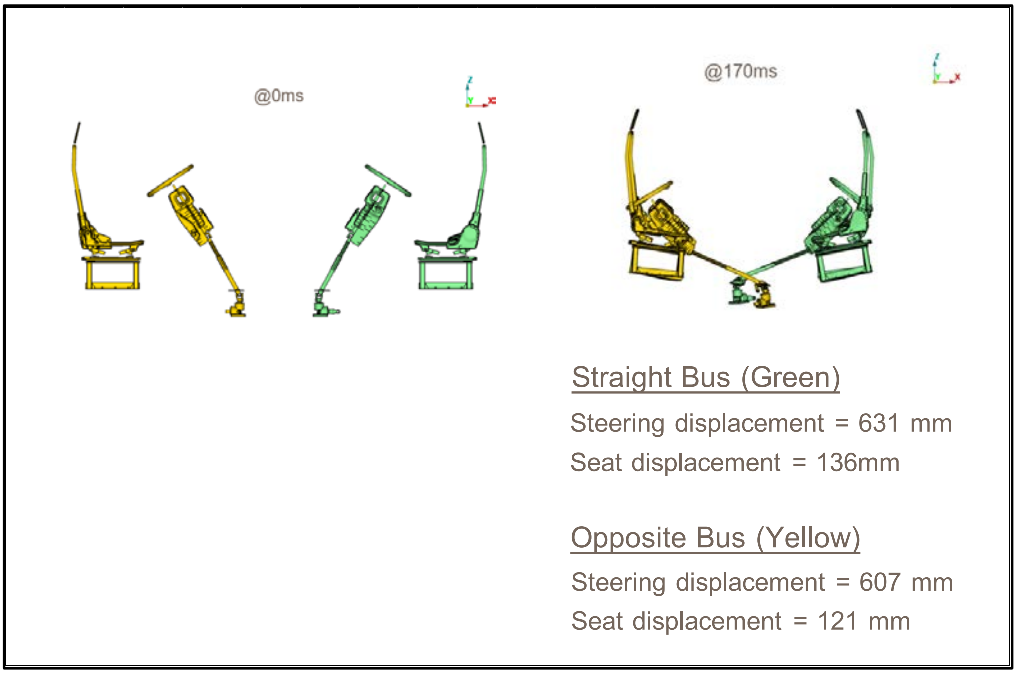
In addition, the intrusion of each of bus frontal faces can be seen.



Many detached tubes were detected, located in welded area.



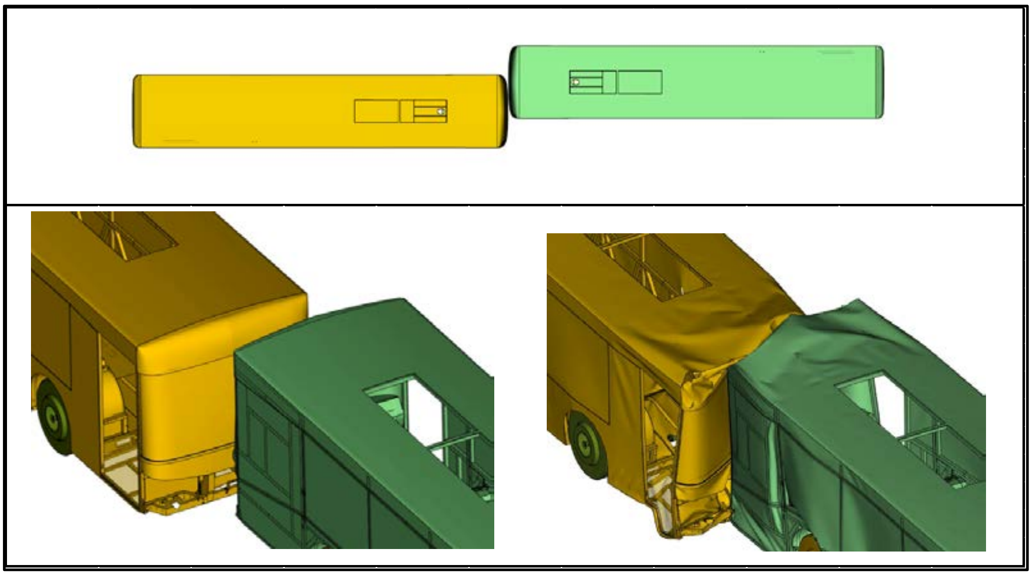
In the next image, the steering column and seat are represented in both buses.



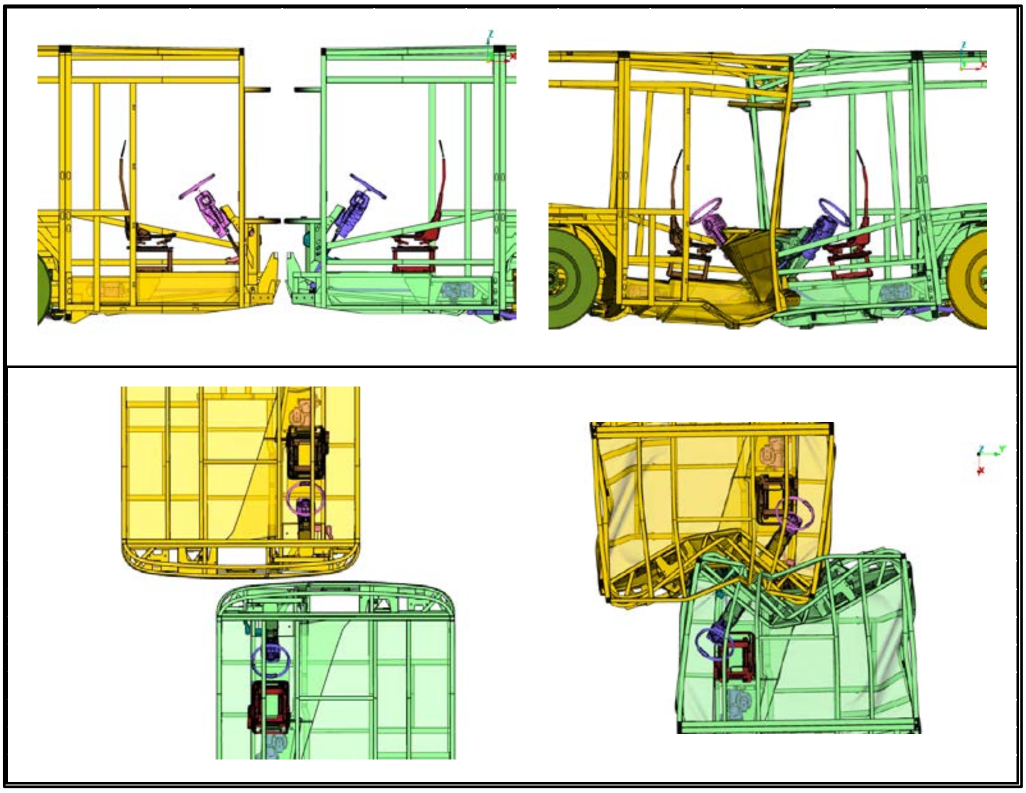
As shown in the image, the steering columns displaced into the seating area, creating a high risk of severe injury to the bus drivers.

Crash C (30km/h, 60% overlap, 0º angle orientation)

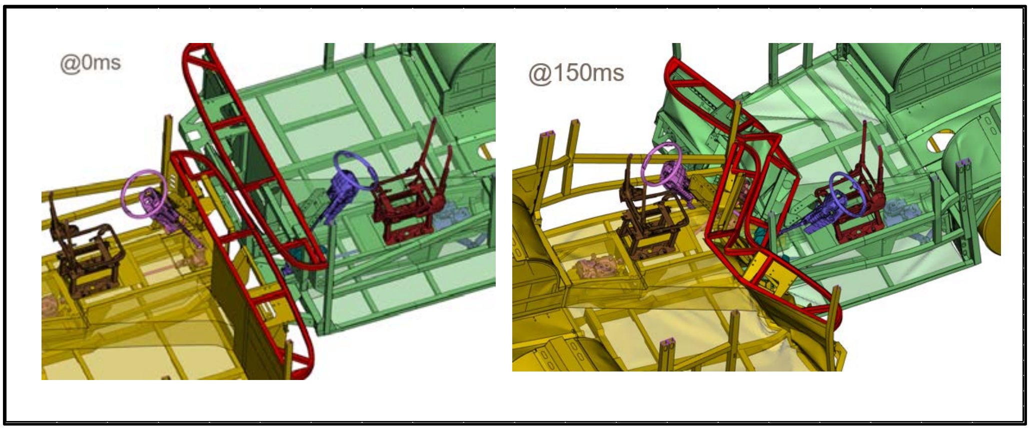
The image below shows a frontal impact between 2 buses, with a 60% contact overlap, 0º angle orientation (straight), at 30 km/h. During the crash, a big deformation of structural tubes provoked a big intrusion in the driver area.



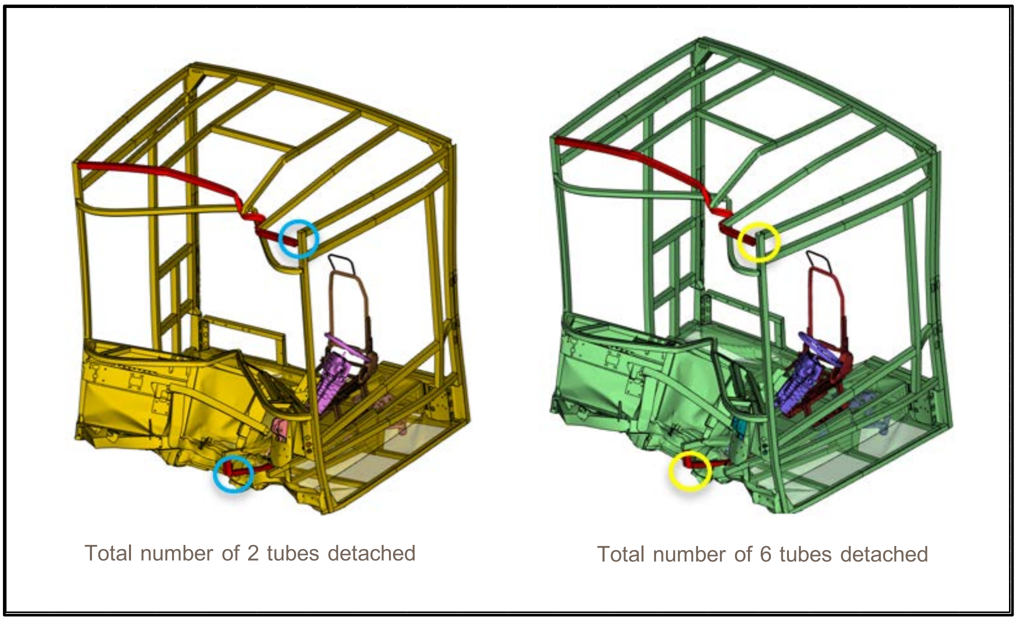
The image below shows the maximum deformation of the cockpit area, including how the steering column and seat suffer displacement.



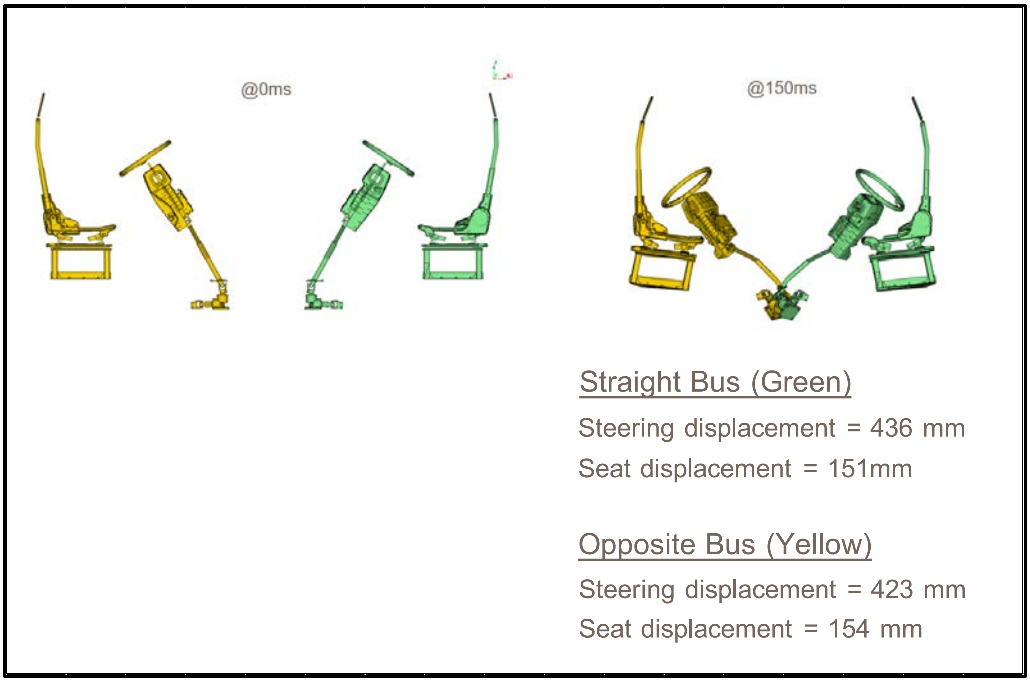
In addition, the intrusion of each of bus frontal faces can be seen.



Many detached tubes were detected, located in welded area.



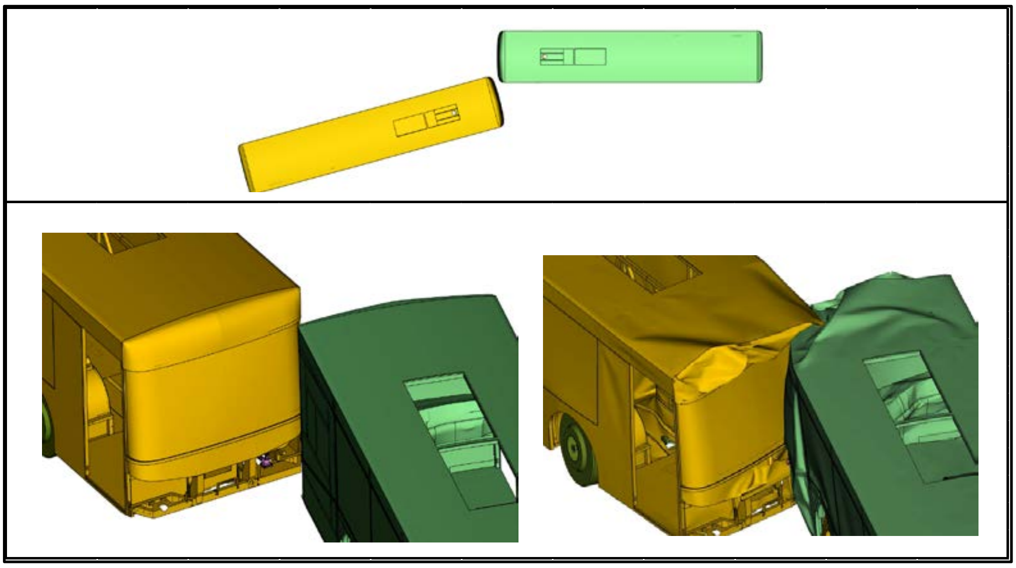
In the next image, the steering column and seat are represented in both buses.



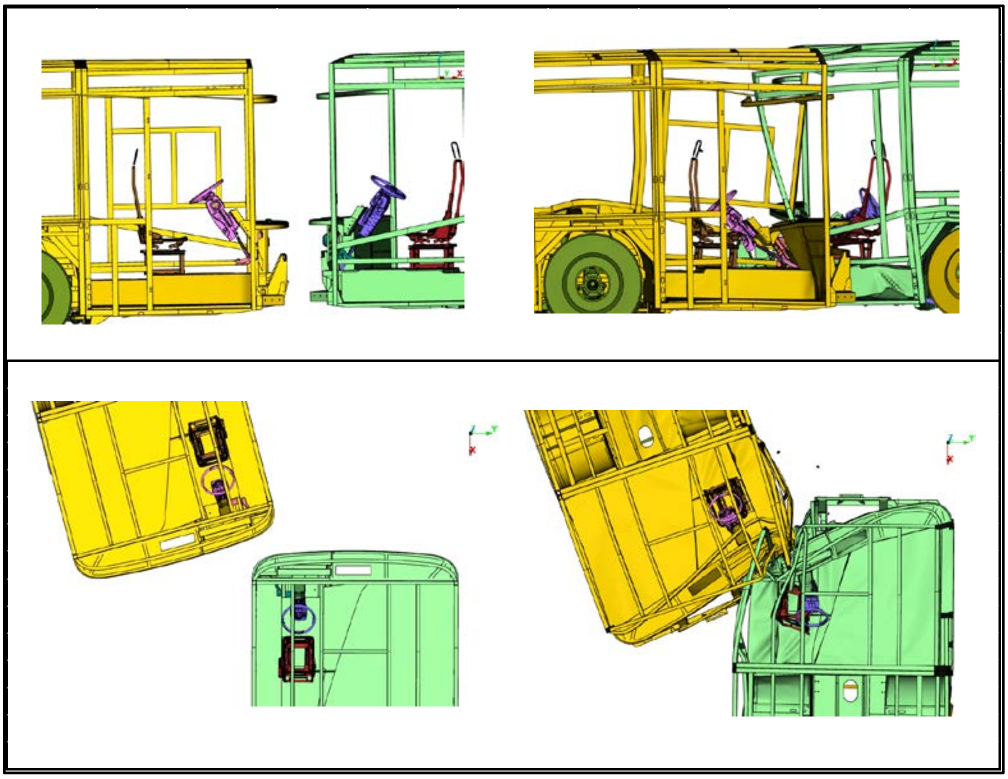
As shown in the image, the steering columns displaced into the seating area, creating a high risk of severe injury to the bus drivers.

Crash D (30km/h, 15% overlap, 15º angle orientation)

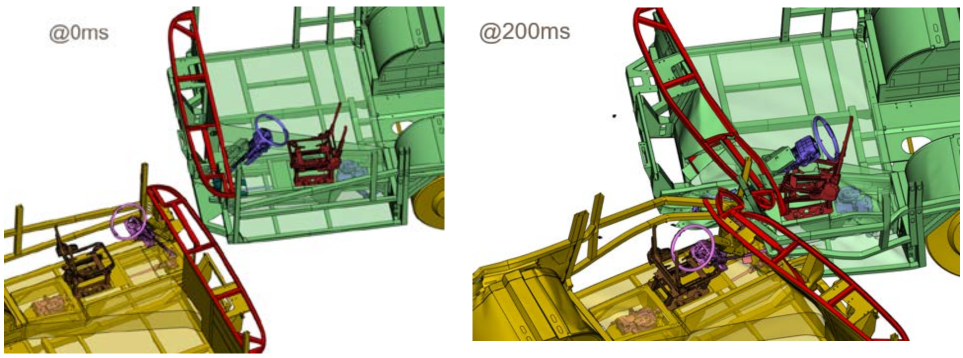
The image below shows a frontal impact between 2 buses, with a 15% contact overlap, 15º angle orientation, at 30 km/h. During the crash, a big deformation of structural tubes provoked a big intrusion in the driver area.



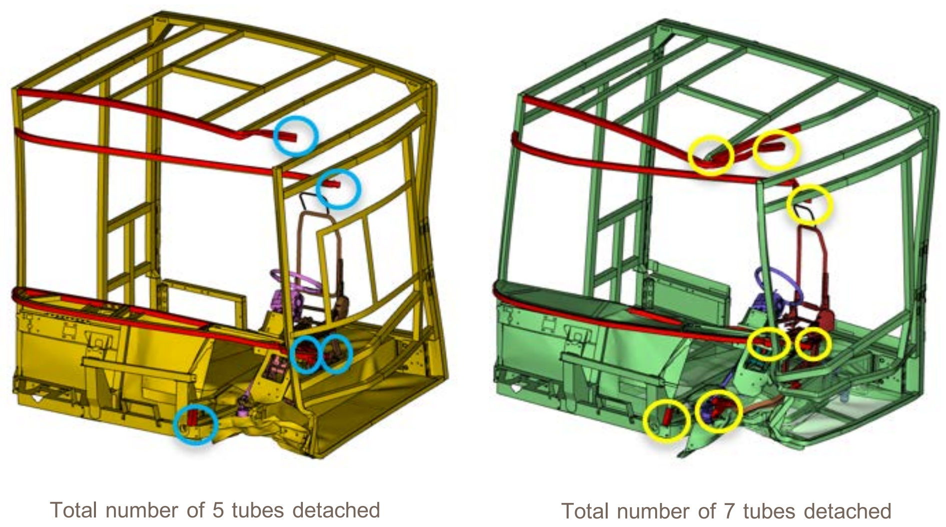
The image below shows the maximum deformation of the cockpit area, including how the steering column and seat suffered displacement.



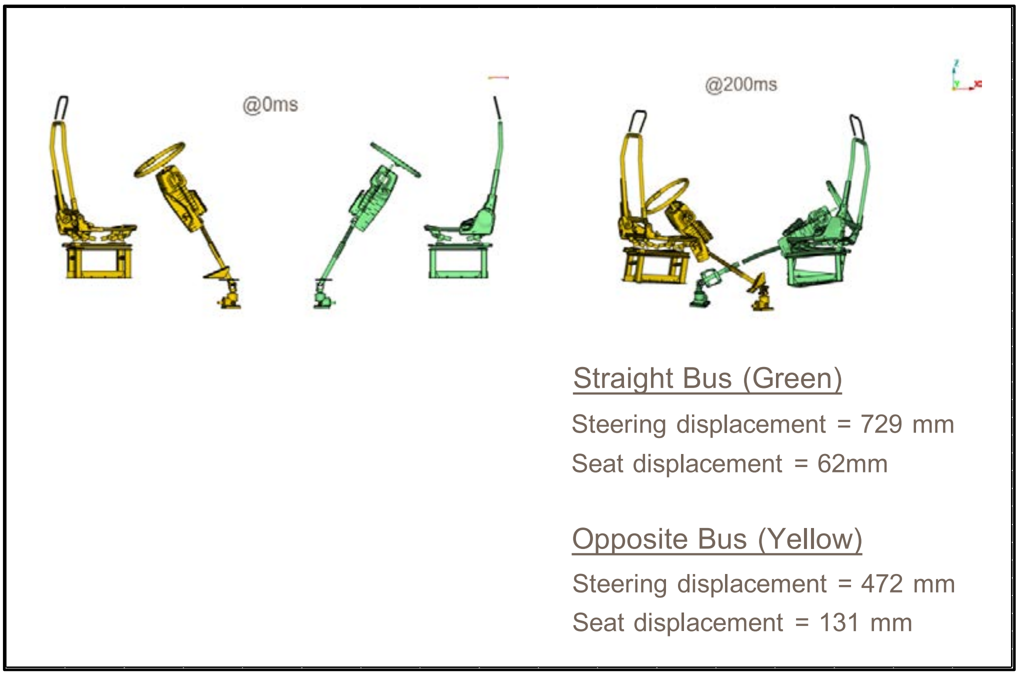
In addition, the intrusion of each of bus frontal faces can be seen.



Many detached tubes were detected, located in welded area.



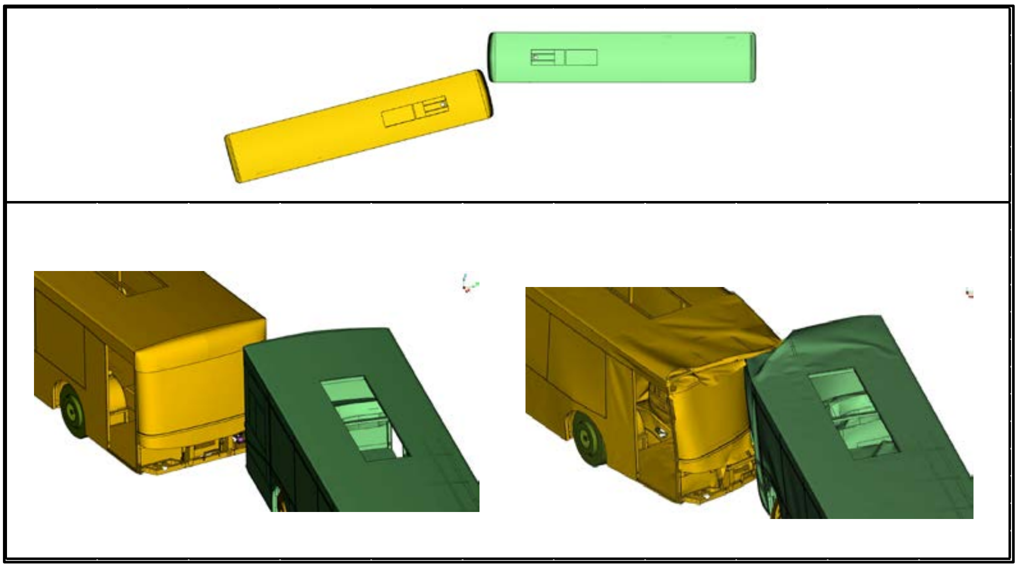
In the next image, the steering column and seat are represented in both buses.



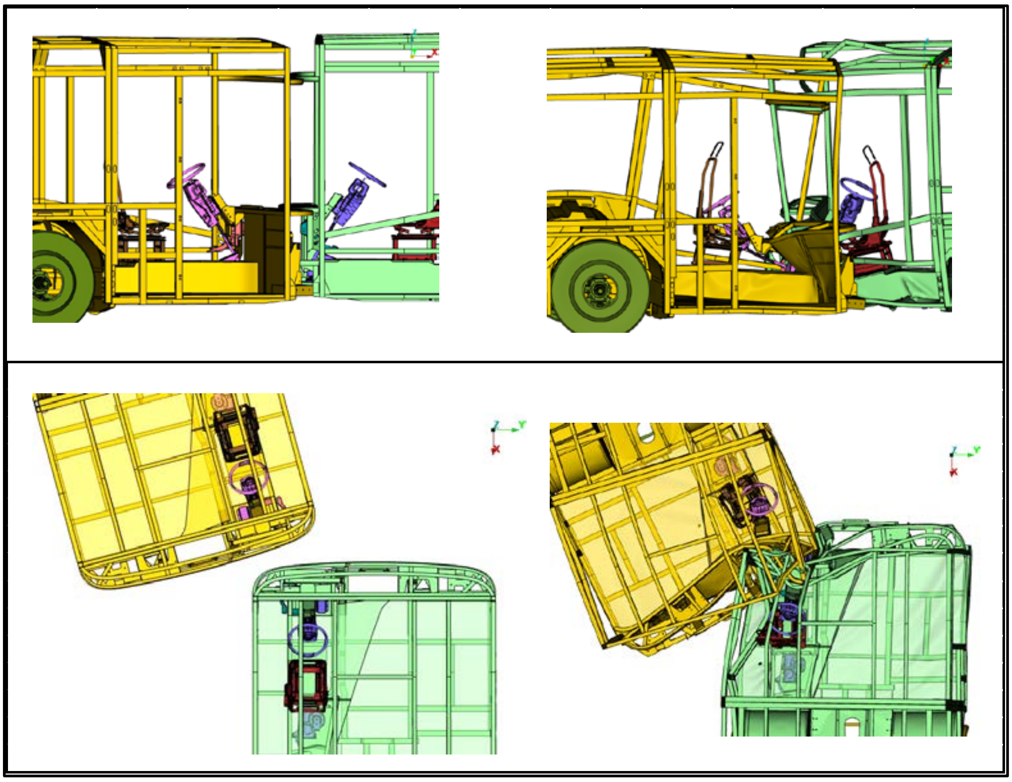
As shown in the image, the steering columns displaced into the seating area, creating a high risk of severe injury to the bus drivers.

Crash E (30km/h, 30% overlap, 15º angle orientation)

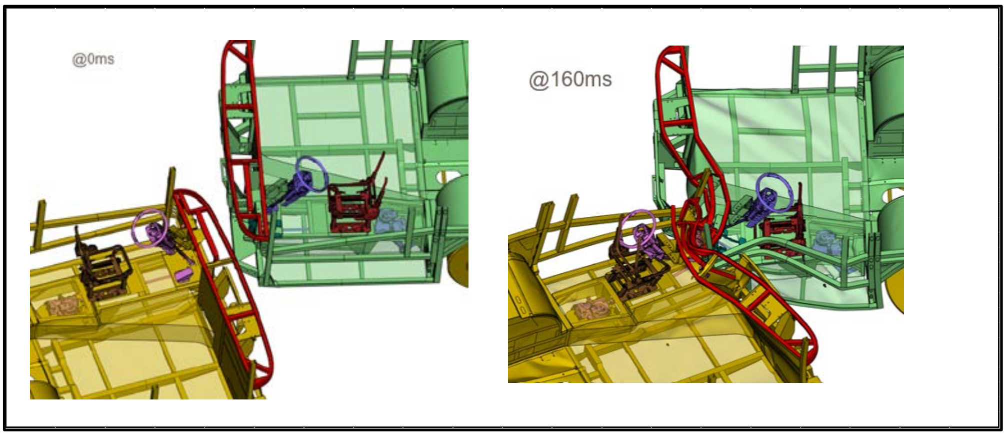
The image below shows a frontal impact between 2 buses, with a 30% contact overlap, 15º angle orientation, at 30 km/h. During the crash, a big deformation of structural tubes provoked a big intrusion in the driver area.



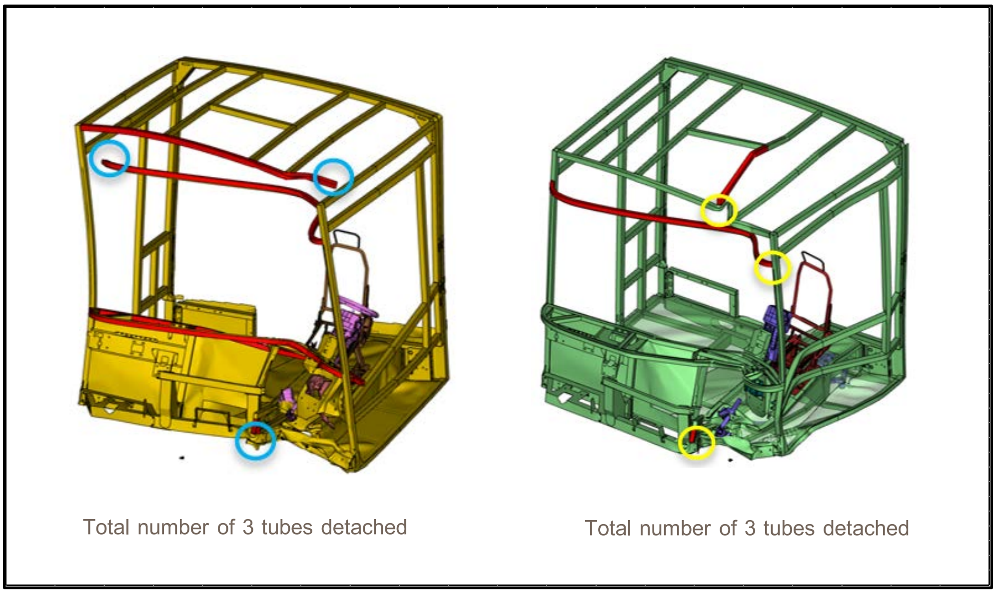
The image below shows the maximum deformation of the cockpit area, including how the steering column and seat suffer displacement.



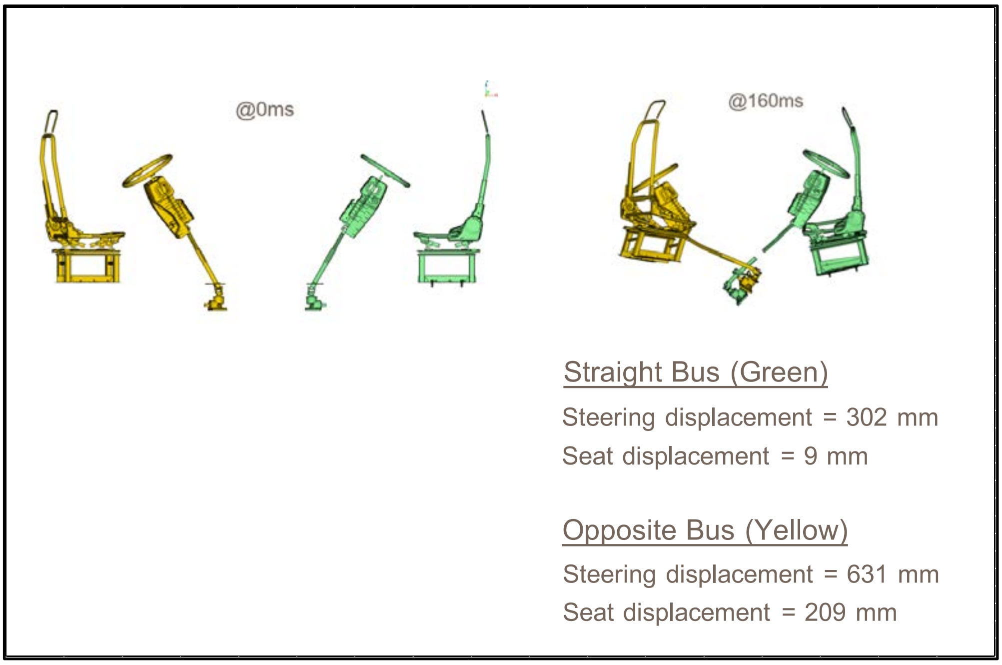
In addition, the intrusion of each of bus frontal faces can be seen.



Many detached tubes were detected, located in welded area.



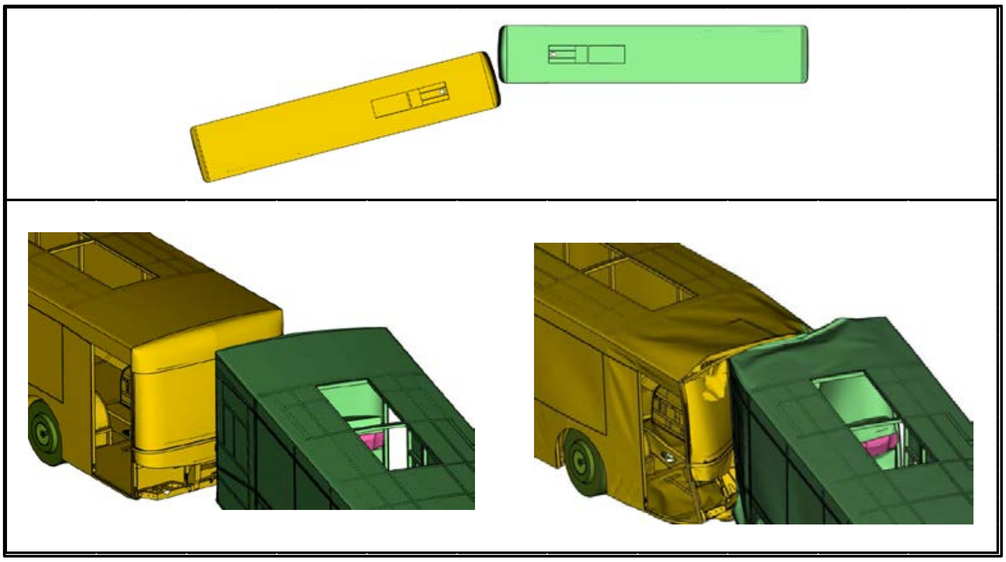
In the next image, the steering column and seat are represented in both buses.



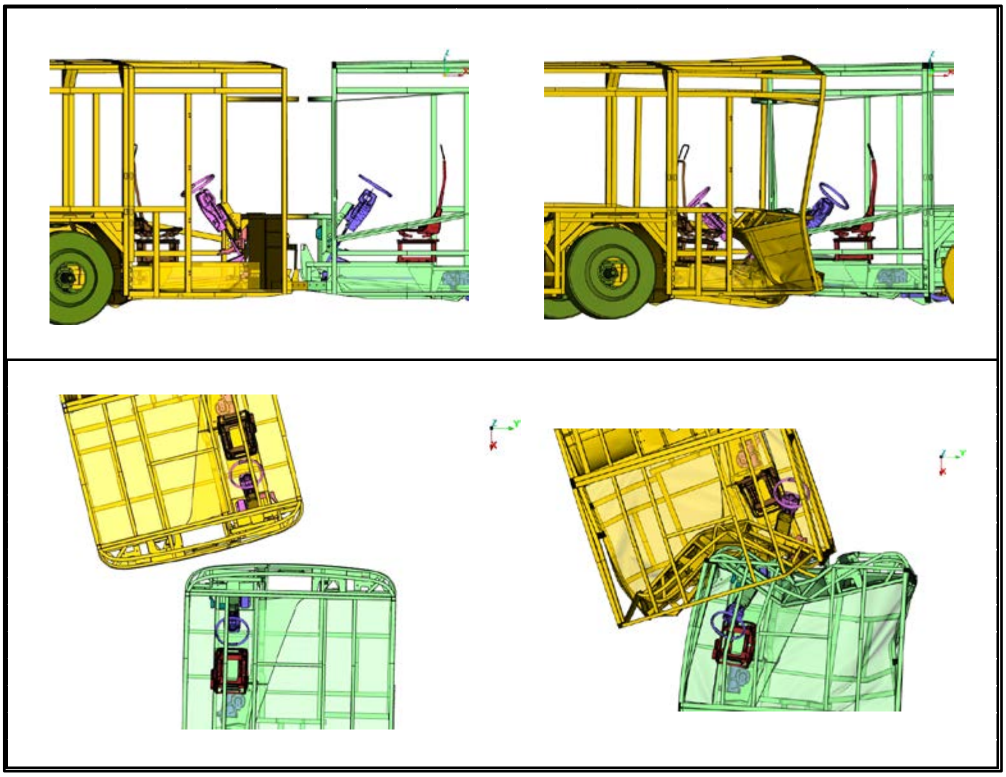
As shown in the image, the steering columns displaced into the seating area, creating a high risk of severe injury to the bus drivers.

Crash F (30km/h, 60% overlap, 15º angle orientation)

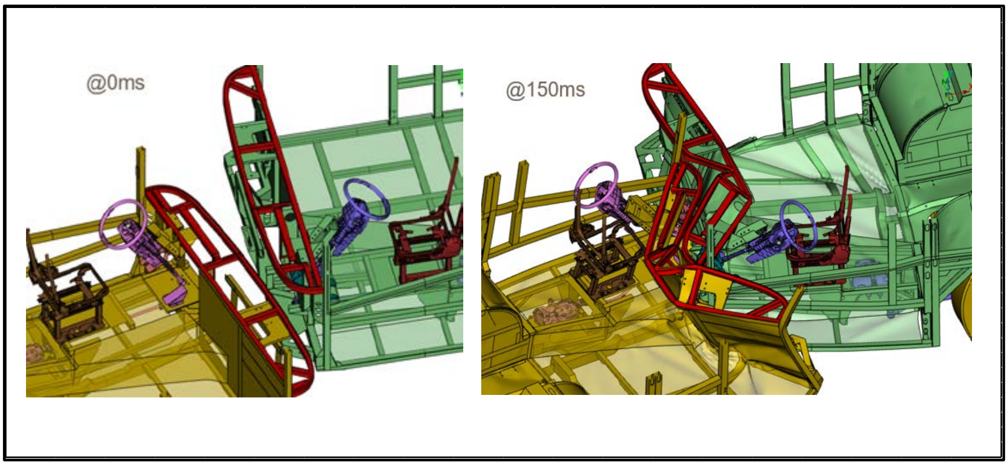
The image below shows a frontal impact between 2 buses, with a 60% contact overlap, 15º angle orientation, at 30 km/h. During the crash, a big deformation of structural tubes provokes a big intrusion in the driver area.



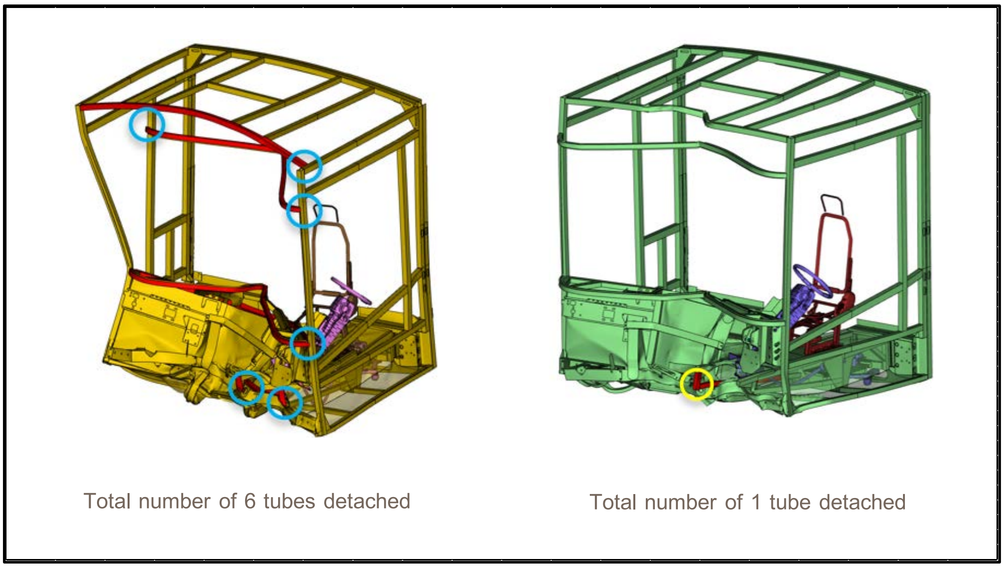
The image below shows the maximum deformation of the cockpit area, including how the steering column and seat suffer displacement.



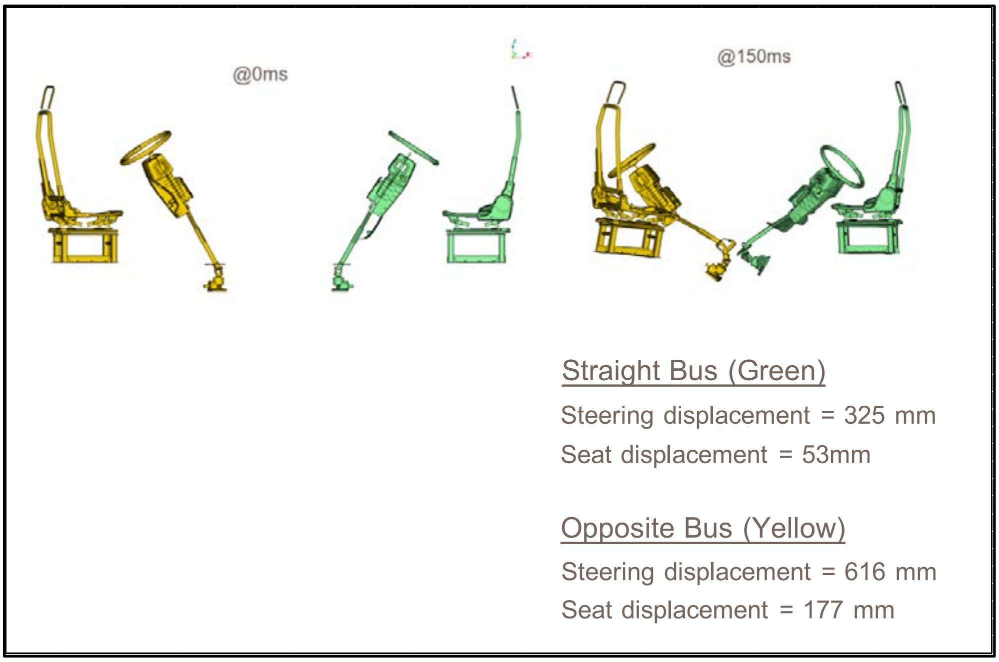
In addition, the intrusion of each of bus frontal faces can be seen.



Many detached tubes were detected, located in welded area.



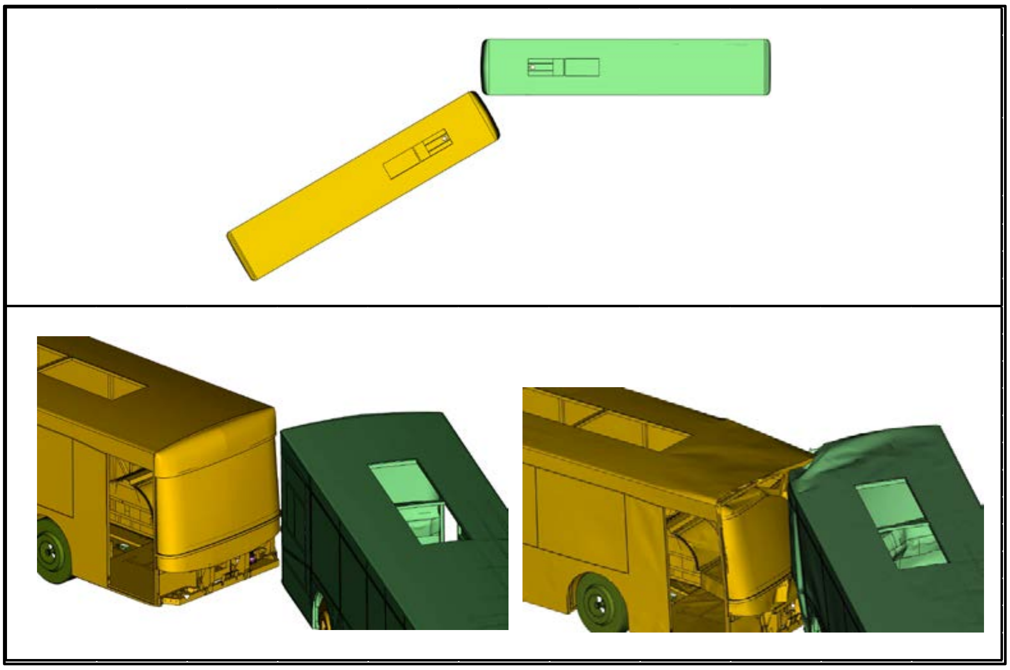
In the next image, the steering column and seat are represented in both buses.



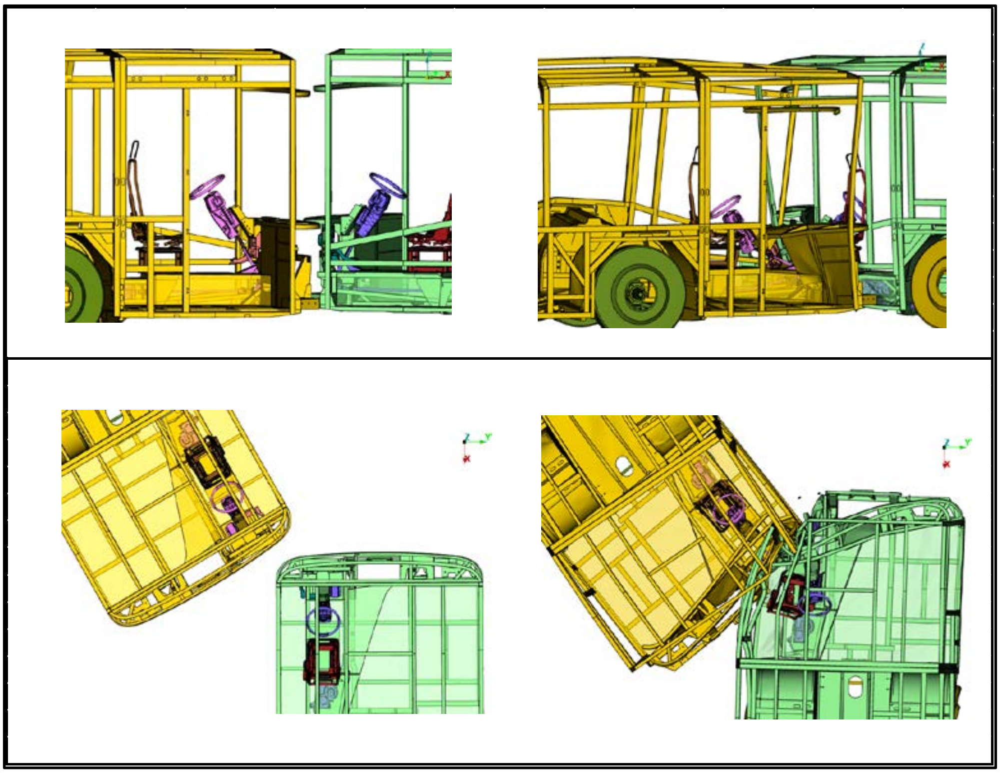
As shown in the image, the steering columns displaced into the seating area, creating a high risk of severe injury to the bus drivers.

Crash G (30km/h, 15% overlap, 30º angle orientation)

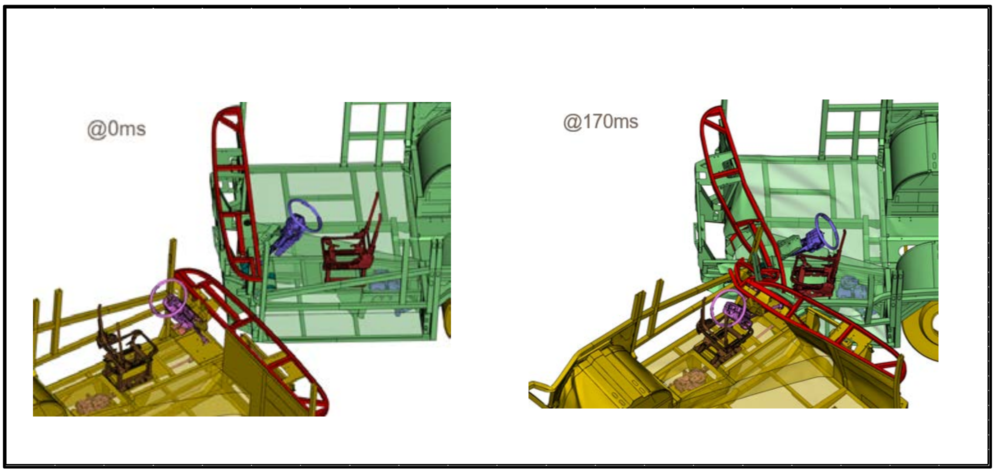
The image below shows a frontal impact between 2 buses, with a 15% contact overlap, 30º angle orientation, at 30 km/h. During the crash, a big deformation of structural tubes provokes a big intrusion in the driver area.



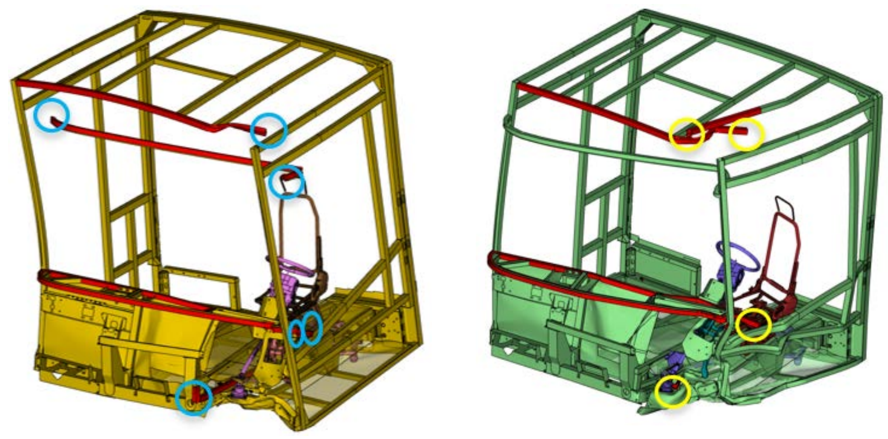
The image below shows the maximum deformation of the cockpit area, including how the steering column and seat suffered displacement.



In addition, the intrusion of each of bus frontal faces can be seen.

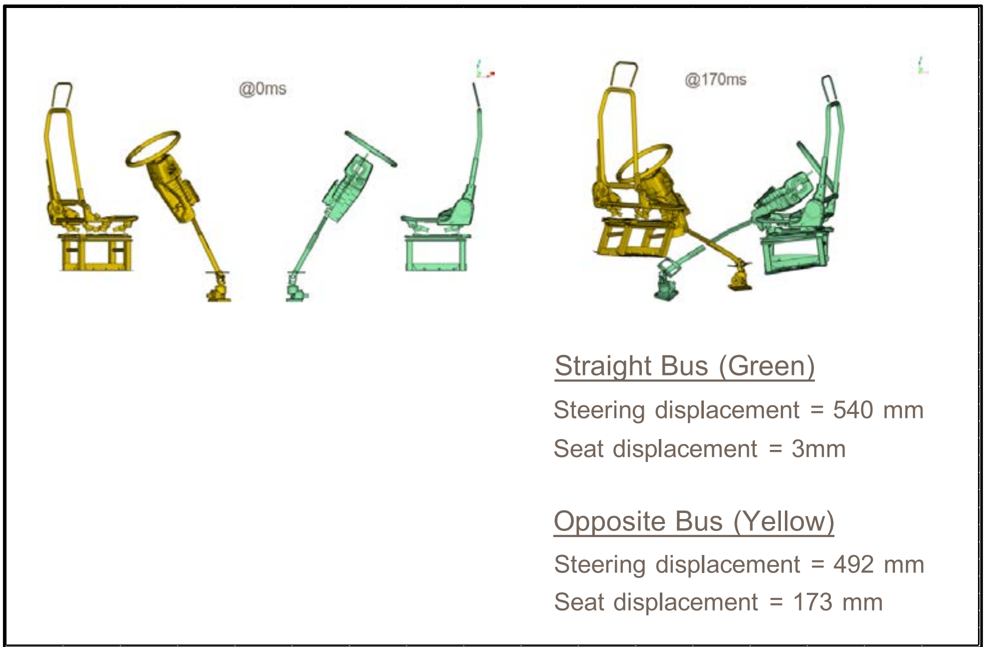


Many detached tubes were detected, located in welded area.



Total number of 6 tubes detached   Total number of 4 tubes detached

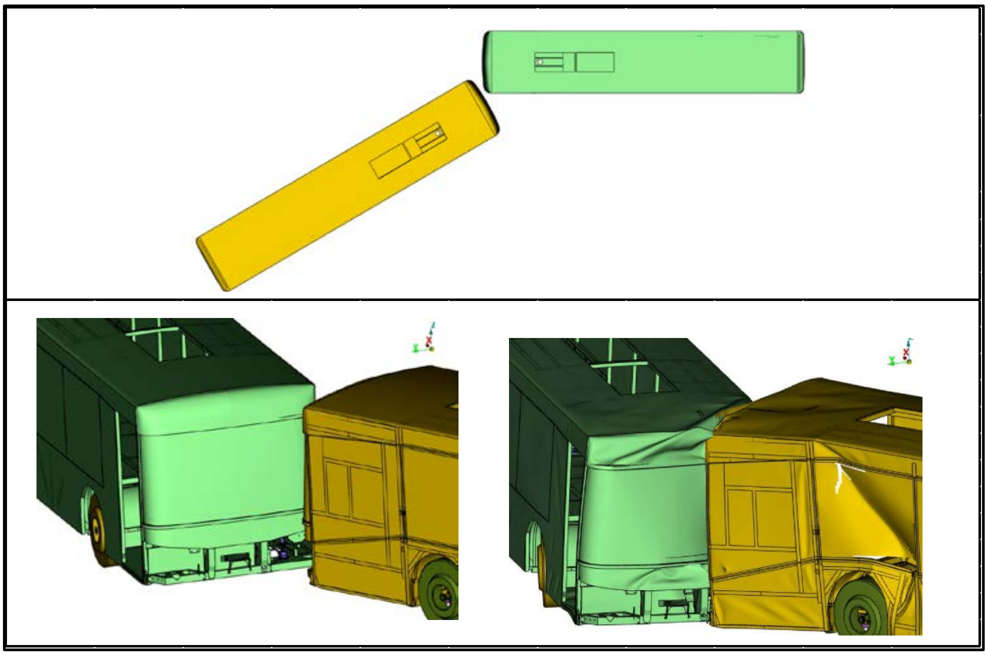
In the next image, the steering column and seat are represented in both buses.



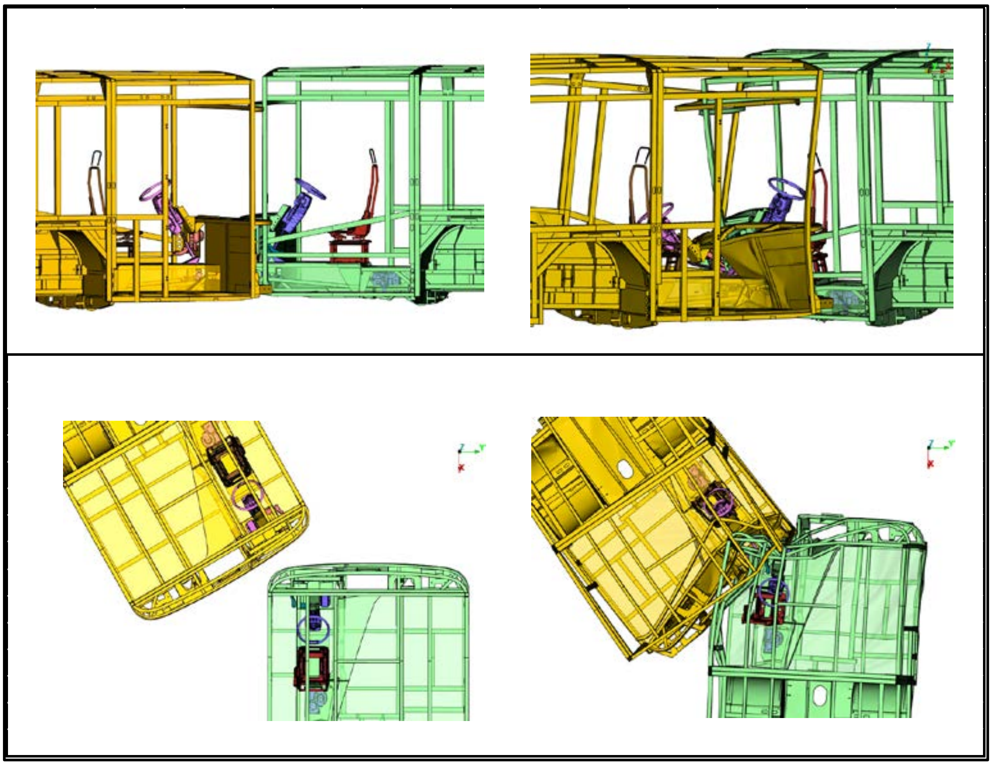
As shown in the image, the steering columns displaced into the seating area, creating a high risk of severe injury to the bus drivers.

Crash H (30km/h, 30% overlap, 30º angle orientation)

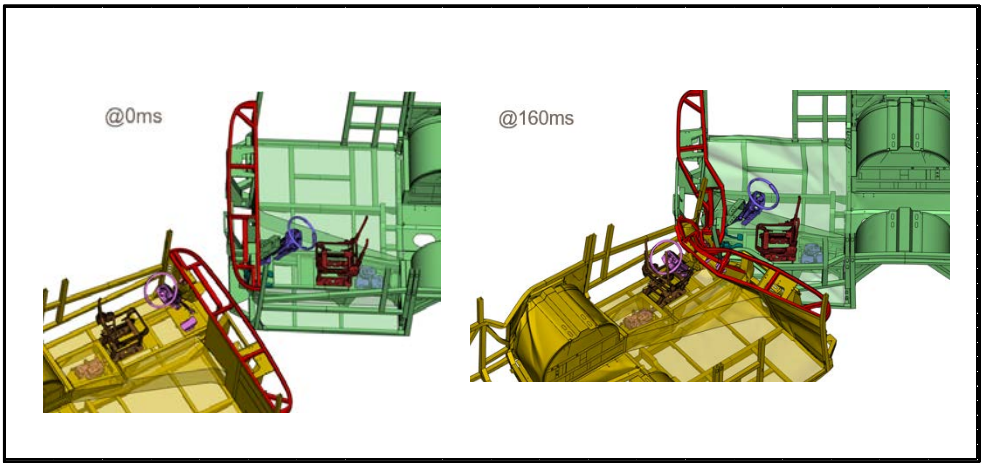
The image below shows a frontal impact between 2 buses, with a 30% contact overlap, 30º angle orientation, at 30 km/h. During the crash, a big deformation of structural tubes provokes a big intrusion in the driver area.



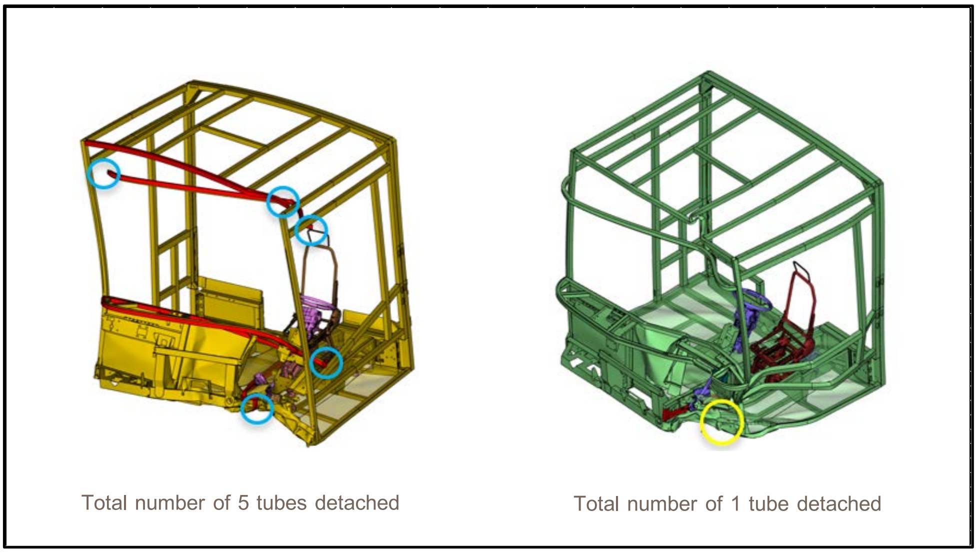
The image below shows the maximum deformation of the cockpit area, including how the steering column and seat suffer displacement.



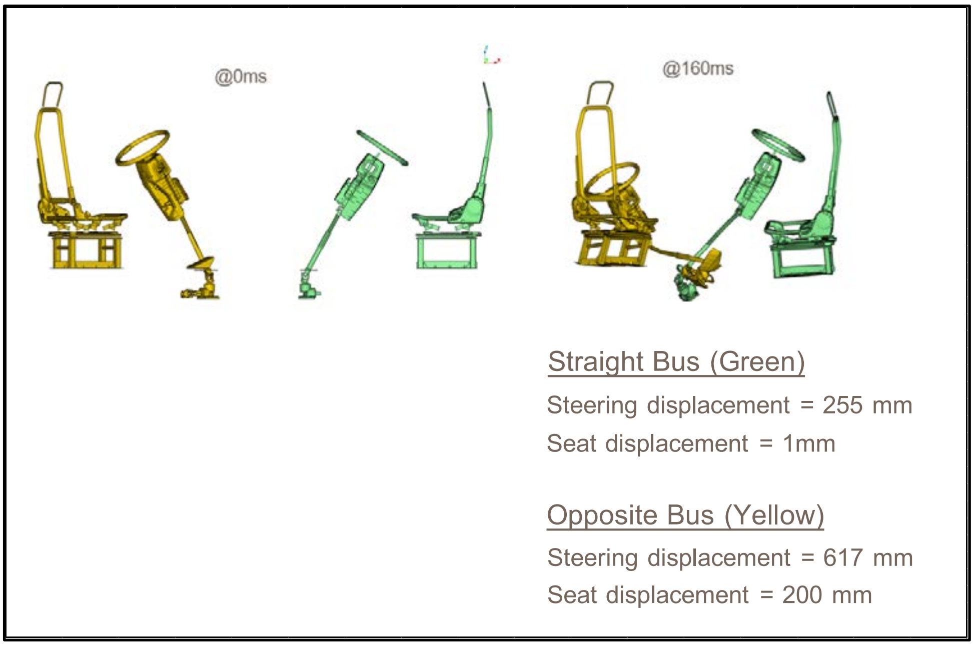
In addition, the intrusion of each of bus frontal faces can be seen.



Many detached tubes were detected, located in welded area.



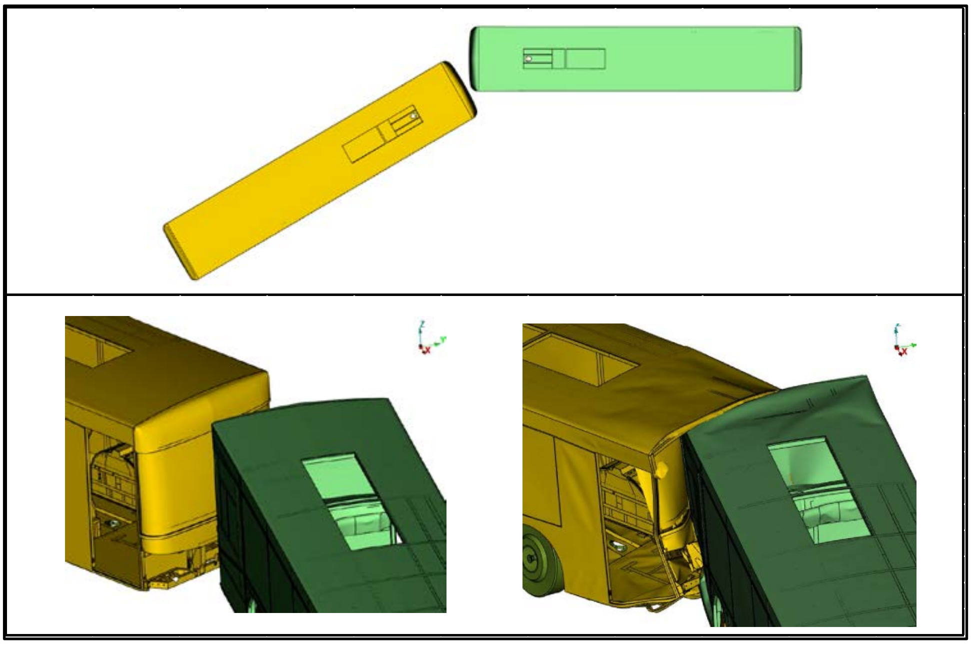
In the next image, the steering column and seat are represented in both buses.



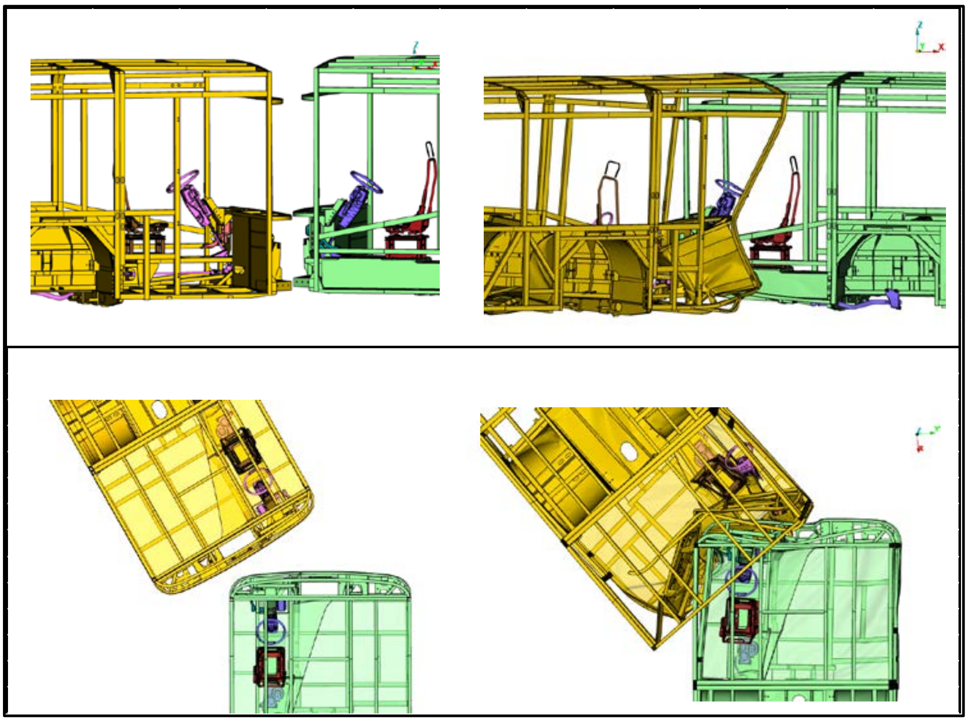
As shown in the image, the steering columns displaced into the seating area for the opposite bus (yellow), creating a high risk of severe injury to the bus drivers.

Crash I (30km/h, 60% overlap, 30º angle orientation)

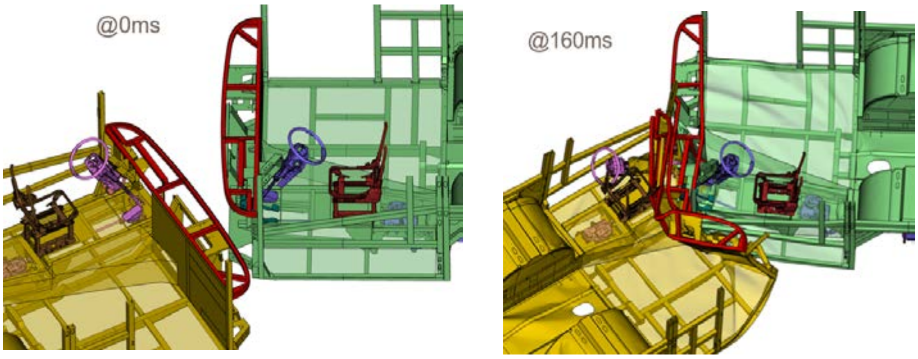
The image below shows a frontal impact between 2 buses, with a 60% contact overlap, 30º angle orientation, at 30 km/h. During the crash, a big deformation of structural tubes provoked a big intrusion in the driver area.



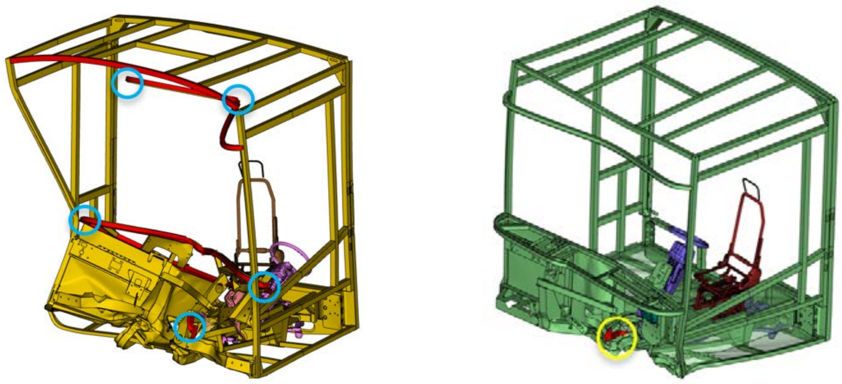
The image below shows the maximum deformation of the cockpit area, including how the steering column and seat suffer displacement.



In addition, the intrusion of each of bus frontal faces can be seen.



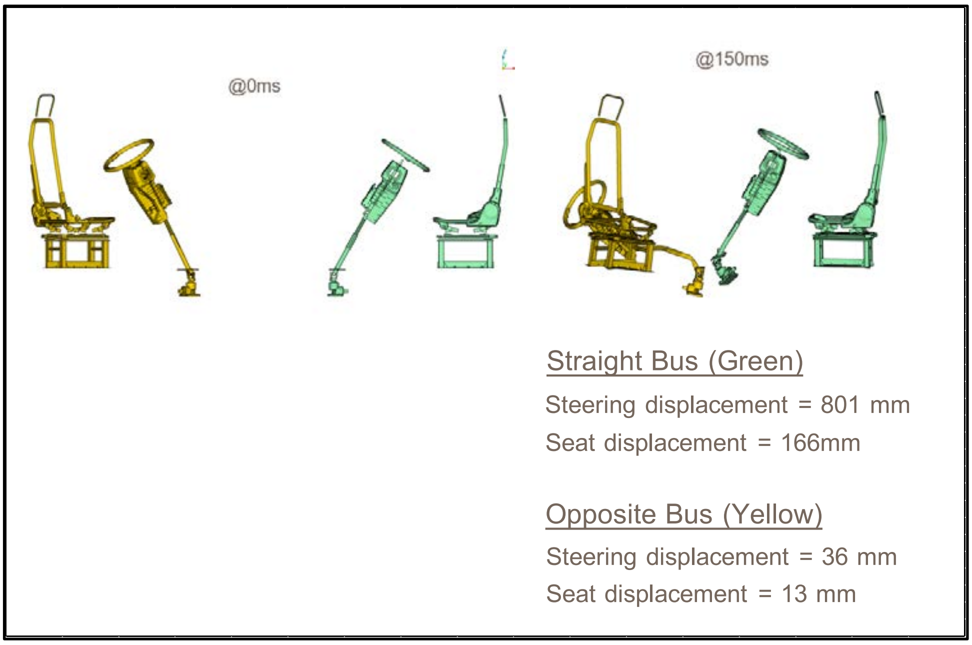
Many detached tubes were detected, located in welded area.



Total number of 5 tubes detached

Total number of 1 tube detached

In the next image, the steering column and seat are represented in both buses.



As shown in the image, the steering columns displaced into the seating area for the opposite bus (yellow), creating a high risk of severe injury to the bus drivers.

Exhibit 2. More info from the main reference group meeting

Summary of reference group meeting bus driver collision safety 01.09.2025, TEAMS

Part 1 – Presentations and Feedback

1. Study on Collision Safety for Bus Drivers in Europe (Tor-Olav Nævestad, TØI)

- Presented results from a major research project commissioned by the Norwegian Public Roads Administration.
- Key finding: bus drivers are disproportionately vulnerable in low-speed head-on crashes due to weak frontal structures and low seating position.
- Norway has already adopted UN R29.03 for buses (from October 2023), but this standard was designed for trucks and is inadequate for buses.

2. Simulation Study of Bus Collisions (Manuel Laso, IDIADA)

- Ongoing simulation program commissioned by Ruter.
- Early results show:
  - Real-world bus crash energy (~500 kJ per bus) far exceeds UN R29 requirements (55 kJ).
  - Structural failures (tube detachment, weak frontal arch) explain fatalities in relatively low-speed crashes.
  - Reinforcement of the lower frontal area and tube connections are essential.
- **Feedback Manuel received:**
  - Need to include more crash scenarios (multi-vehicle crashes, lateral intrusions, differences between city buses and coaches).
  - Seat anchorage and integration of seatbelts/airbags must be addressed.
  - Compatibility with trucks and other heavy vehicles needs deeper analysis.
  - Participants confirmed that without stronger structures, restraint systems alone won’t protect drivers.

Part 2 – Invited Speakers and Initiatives

Each initiative presented its perspective on improving bus driver safety:

- **Jofri Lunde (NHO, Norway / Bus Nordic):**
  - Suggested EU-wide mandatory requirements for bus frontal collision safety.
  - Suggested Bus Nordic standards could be a first step for Nordic procurement.

- **Hamza Guirrou (International Road Union, IRU):**
    - Provided a description of passive and active safety measures to increase bus driver safety, and the policy situation related to bus driver safety.
- **Rikard Fredriksson (Swedish Transport Administration / Euro NCAP):**
    - Shared roadmap for truck safety ratings, with buses next in line.
    - Warned that strengthening local areas could reduce compatibility with other vehicles.
    - Advocated combining active and passive safety measures.
- **Kerri Cheek (Transport for London):**
    - Presented **London's Bus Safety Standard** (frontal crash protection for pedestrians, ISA, ADAS, cab improvements).
    - London has required these through procurement power, bypassing slow regulation.
    - Future phase will include seatbelts, airbags, and stronger cabs.
- **Angelo D'Elia (Monash University, Australia):**
    - Showed *used heavy vehicle crash ratings* based on real-world data.
    - Found no significant improvement in bus crashworthiness in recent decades.
    - Buses and trucks remain more aggressive to other road users compared to cars.
- **Graziella Jost (European Transport Safety Council, ETSC):**
    - Provided a description of the policy context and examples of other efforts to inform the public debate and call for new safety standards in road safety.

Part 3 – Discussion and Next Steps

- **Themes:**
    - Importance of **passive vs active safety**: active systems (e.g. AEB) are valuable but not sufficient. Intrusion prevention must come first.
    - PTAs (e.g. Ruter, TfL) have strong market leverage to set safety requirements through procurement.
    - Manufacturers confirmed simulations exist internally, but without regulation or market demand improvements won't be prioritized.
- **Next steps agreed and follow up meetings**

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