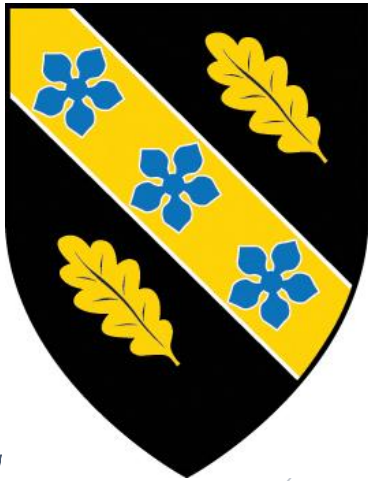


University of Wales Trinity Saint David
Wales Institute of Science and Art

January 2023

Vehicle Structures & EVs

Automotive Chassis Systems (ACHA5013)



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1 Introduction

Vehicle structures (not limited to automotive) are in constant evolution with consistent advancements in design, materials, production methods, longevity additives and costing. Motorsport wants an 'open cheque' attitude for ultimate track performance, meanwhile mass manufacturing is the opposite. Safety and driveability are important, but even more importance to the corporations is cost. Through the 20th century and beyond, huge advancements have been made throughout automotive vehicle construction, allowing companies to make millions of vehicles annually from one plant, or a handful of time-attack racing cars – or a blend in compromises from both.

This report will investigate how vehicle structures have historically developed into present day road cars, and a future consideration of EV powertrain conversion through the SSS method, highlighting implications. In doing so, future trends could be identified in a range of areas involved in vehicle production, and whether if the fitting of electric drive systems to older vehicles could be an effective solution with the upcoming sales ban of ICE-only cars.

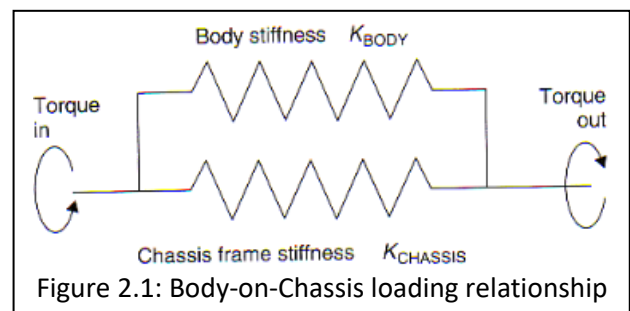


Figure 1.1: Industry Player influencing vehicle frame design

2 Literature Review

When tracing vehicle structures back through the 19th century, we begin with the horse and cart; a low-speed leaf-sprung wooden wheeled carriage, hand-made for the few. When propulsion became generated inside the car, frame design has evolved greatly and gradually.

The first major vehicle structure, only beginning to phase out in recent years, is the Ladder frame; consisting of two large lengthways Steel rails with beams connecting between them, that the body sits on. It's simple, inexpensive, and easy to mass produce, example being the Ford Crown Victoria. Another benefit is that the body can swap with another (of the same wheelbase), so to the consumer a new car is created, allowing flexibility in manufacturing. However, the ladder is heavy compared to other frames; this may not matter in most production vehicles, but safety certainly does, to which the rise of crash testing in the 1990s show they perform then satisfactorily, now poorly. Cruciform bracing adds triangles into the ladder 'slats' improving torsional rigidity, but the floor of the car is the only component bearing structural strength. The body isn't necessarily connected to the frame from a load path perspective, resulting in structural inefficiency. Therefore, a ladder-framed car functions like two parallel springs of different rates, often resulting



in mediocre or comedic vehicle handling. The suspension is usually leaf-sprung on solid/live axles, but coils appeared later with better ride comfort, but less load capability and are more expensive components to make.

A sportier vehicle structure can be made through triangulated tube welding, creating a Space Frame; this is a time-consuming process, so production is limited but the performance is excellent. These are seen in low-volume lightweight sports cars, like TVRs or the Caterham 7, as well as motorsport. The integration of roll cages makes the structure very efficient, pair with modern safety equipment to produce a very crash worthy vehicle. Repairing a space frame after an impact is not easy however, as cutting defect tubes out and welding more in is a delicate task. The material choice for the tubular frame is Steel alloys or high-grade Aluminium. Later in time when Carbon Reinforced Plastics slowly became feasible, filament winding of one tubular section is improving in effectiveness but still difficult and wasteful. Creating a Carbon Fibre space frame would therefore be seriously expensive and be near-unrepairable if damaged. Another issue with CRPs is recycling (Hernandez, 2022), sharing that con with Fibreglass, which was often, and today sometimes, used as vehicle bodywork.

To summarize motorsport-specific frame designs, for racecars that aren't based on a production chassis they can cost a lot more per unit and be designed for no other purpose. A pure Monocoque shell is the ultimate structure if minimum weight, maximum torsion resistance and strength is desired. Rarely seen outside of F1/Formula cars, the vehicle's packaging of components and the driver position is optimized to the limit, with open-wheels and the suspension arms connecting them to the body in open air. Material usage is the best available: CRPs, Titanium, polymeric fibers, cost is behind performance in material choice. Making a vehicle frame as small as physically possible has drawbacks like ingress and egress; getting into a Formula car is uneasy, having to climb over and lower themselves in (and fasten the harness, arm extinguisher, neck brace – unideal for school runs) as well as boot space or rearward visibility. These drawbacks are acceptable in motorsports where speed is the objective and the vehicles are high maintenance, but practicality is slashed.



Figure 2.2: World's first Integrated vehicle structure
Citroën 11CV: 1934 – 1956

The modern automotive structure for road vehicles takes properties from the above historical developments, as well as then new steel-press production methods; integration of body into frame became the standard throughout the rise of public car ownership, but surprisingly the first vehicle adopting this was introduced in 1934. Around this time

more people started driving, the roads were slowly improving; vehicles were travelling faster, and this uncovered issues with the body-on-chassis principle. Squeaks and rattles (NVH) affect occupant comfort and although these early cars had low tolerancing compared to today's production standards, on joining methods for example, efforts were being made to make them more comfortable. Softening the body-on-chassis with extra springs between the frame and cockpit smoothens the vehicle's ride and NVH but had adverse effects such as high body roll. Figure 2.3 compares two different frames/bodies in twisting resilience and its clear which structure is superior. Not only can the unitary frame-into-body design withstand over three times the twist torque per degree of deflection than the body-on-chassis, but the

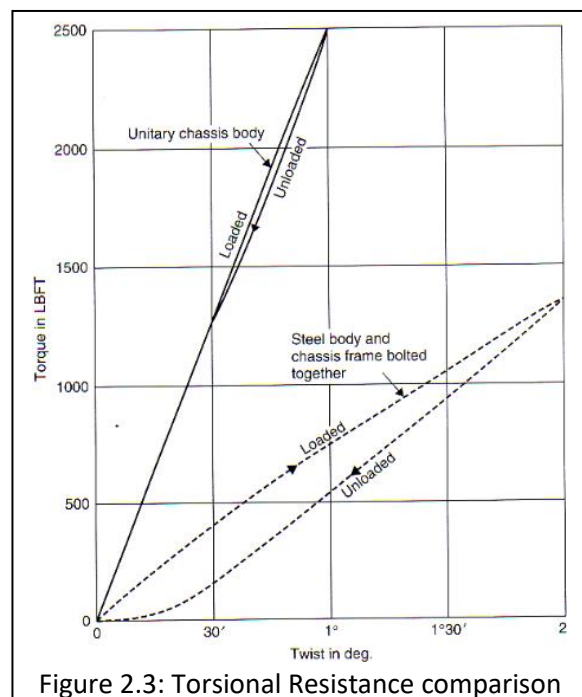


Figure 2.3: Torsional Resistance comparison

difference between the integral frame being loaded and unloaded is far narrower. A vehicle with the old-style ladder chassis may not behave the same in motion at Kerbweight, when at fully laden with 3+ passengers on board, due to the influence of weight on torsional resistance.

As automotive safety in the early days basically didn't exist, emergency scenarios were often fatal. However, in 1965 Larry Patrick rose to director of the Wayne State Biomechanics Research Center (Wayne State University, 2006) and his work became internationally recognized for his bravery of being a live vehicle crash test occupant. The human skeleton is well designed from a load-resilience perspective, but this was not understood at first until Patrick was giving valuable feedback, as well as voluntary rocket-sled testing at a similar time in the 1970s (NASA, 2012), learning the G-force resistance of humans. Before this, cadavers (deceased people) were used in vehicle crash testing, but inaccuracies and ethical concerns caught up to this method. These efforts helped General Motors create the Hybrid 3 crash test dummy (Foster, et al., 1977); a sophisticated replica of a 50th percentile adult male, with realistic vertebrae joints, mass/weight resemblance, and they are full of accelerometers. The Society of Automotive Engineers (SAE) recognized potential for a crash-test standard in controllable conditions with zero injury risk.

Some vehicle manufacturers were already big on safety, such as SAAB and Volvo; they had developed the three-point seatbelt in 1959 and patented it free for everyone (Volvo Cars, 2009), being a lifesaver instead of a profit generator. Consumers were beginning to consider automotive safety in vehicle choice at the later end of the 20th century, as cars became survivable but painful in crashes, improving from borderline lethal. National crash test standards were founded first by US governments, but most developed countries have a baseline of minimum expectation. However, these tests are basic compared to the private body Euro NCAP's tests (and IIHS in USA, ADAC etc.).

Founded in 1997, the European New Car Assessment Program is an organization that crash-test new vehicles in fully controlled conditions, at Thatcham Research in Berkshire, and award the car a safety rating up to 5 stars (as well as thorough breakdowns as to how good, or bad, they perform). They realized the most common road-traffic accident scenario is when a vehicle strays over the centre line and hits another oncoming car (EuroNCAP, n.d.). The Offset Deformable Barrier (ODB) replicates this with a 40:60 impact into an Aluminium-honeycomb structure, mimicking the other vehicle, at 40mph. The impact is concentrated to the driver side only which makes energy dissipation uneasy. The vehicle's objective in any crash is to absorb as much incoming compression/strain energy as possible without intrusion into the occupant area, testing structural resilience, as well as decelerate the occupants within known survivable limits, testing restraint and airbag systems. After the crash they'll need to get out, so being able to open the doors after an impact is a big win.

Honorable vehicle mentions include the first car to get a 5* rating: the Renault Laguna, and shortly after the Megane, which was highly impressive being a small car. Dishonorable mentions include the Chrysler Grand Voyager, a huge MPV that crushed itself with its own weight, and the Austin-Rover 100/Metro. The 80s design had so little strength, sales literally disappeared overnight in '97 and then new owners BMW had no choice but to withdraw the car from market, due to public interest in EuroNCAP twinned with the rise in internet users, making this information easily accessible.

In the early 2000s car firms realized they needed to make their vehicles indefinitely safer to keep them selling. As (Euro NCAP, n.d.) grew in popularity, more tests were introduced; a Full Width Rigid barrier test simulates hitting a solid concrete block like a bridge support, completely stopping the car. Side Impact tests are challenging as the crush space is far less than at the front, so the B-pillar is stressed with help from strengthening within the vehicle's doors. The IIHS toughened their test of this scenario recently as pick-ups and SUVs are especially popular in the US; by increasing the weight



Figure 2.4: Vehicle Crash Test (Mazda 6, 5* in 2009)

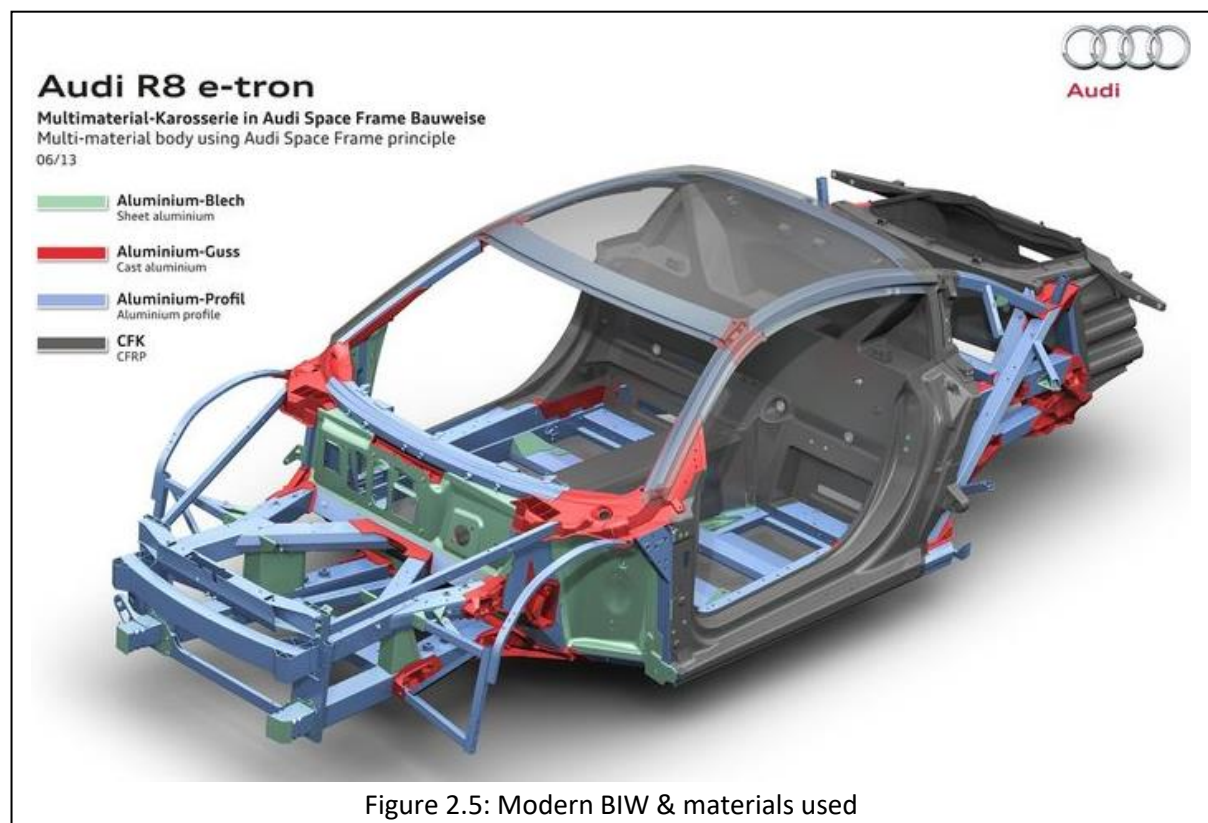
and raising the CofG of the impact cart, simulating a big vehicle T-bone at a junction/intersection (Insurance Institute for Highway Safety, 2022). At its debut only one vehicle passed: the Mazda CX-5, which uses advanced high-strength (AHS) Steel alloys in construction, but the other car's fails are anything but, because this drives development to improve this safety

aspect of vehicles. Another test, possibly the nastiest due to the small but tall impact area, is the side-on Pole test, simulating a loss of control into a telegraph pole or lamppost. Speed is reduced to 24mph, but danger is also from the punch throwing shrapnel like smashed glass or interior trim into the occupant area.

It's not only safety of the occupants in the vehicle that matter, but pedestrian contact is also damaging, leading to the phase-out of pop-up headlights. Head, upper and lower leg impacts are replicated with firing soft shaped projectiles at the car. Firing bonnets has been discussed among sports car manufacturers but feasibility is doubted, so focus into mounting radiators and similar ancillaries' lower helps cushion an impact to a pedestrian. Therefore, with the vehicle's frame able to withstand an impact without cockpit intrusion (to an acceptable extent), decelerating the occupants from the resultant G-forces is equally important. Volvo's 3-point belt is a major

improvement from the lap-belt; tough woven fibers or webbing makes the belt, anchored to the vehicle frame by the Retractor. This is the densely mechanical element that few people see (Autoliv, n.d.), rotating freely when in normal vehicle operation for ease of use, but when an impact is detected the spool locks in approximately a dozen milliseconds to support the occupant. It's a design headache as people aren't always 50th percentile adult males; the occupant could be a 17yo female, or a 21stone rugby player. Also, an adult male of US 50th percentile weighs more than an average UK adult man, causing differences in cars manufactured for different markets. Working with the seatbelt to decelerate occupants as gently as possible is the Airbag; an explosive charge filling a tough but soft cushion within 30 milliseconds of an impact detection. Located in the steering wheel and dashboard passenger-side at first, but several shape variants are later fitted in the A-pillar and under the steering column (curtain & knee airbags).

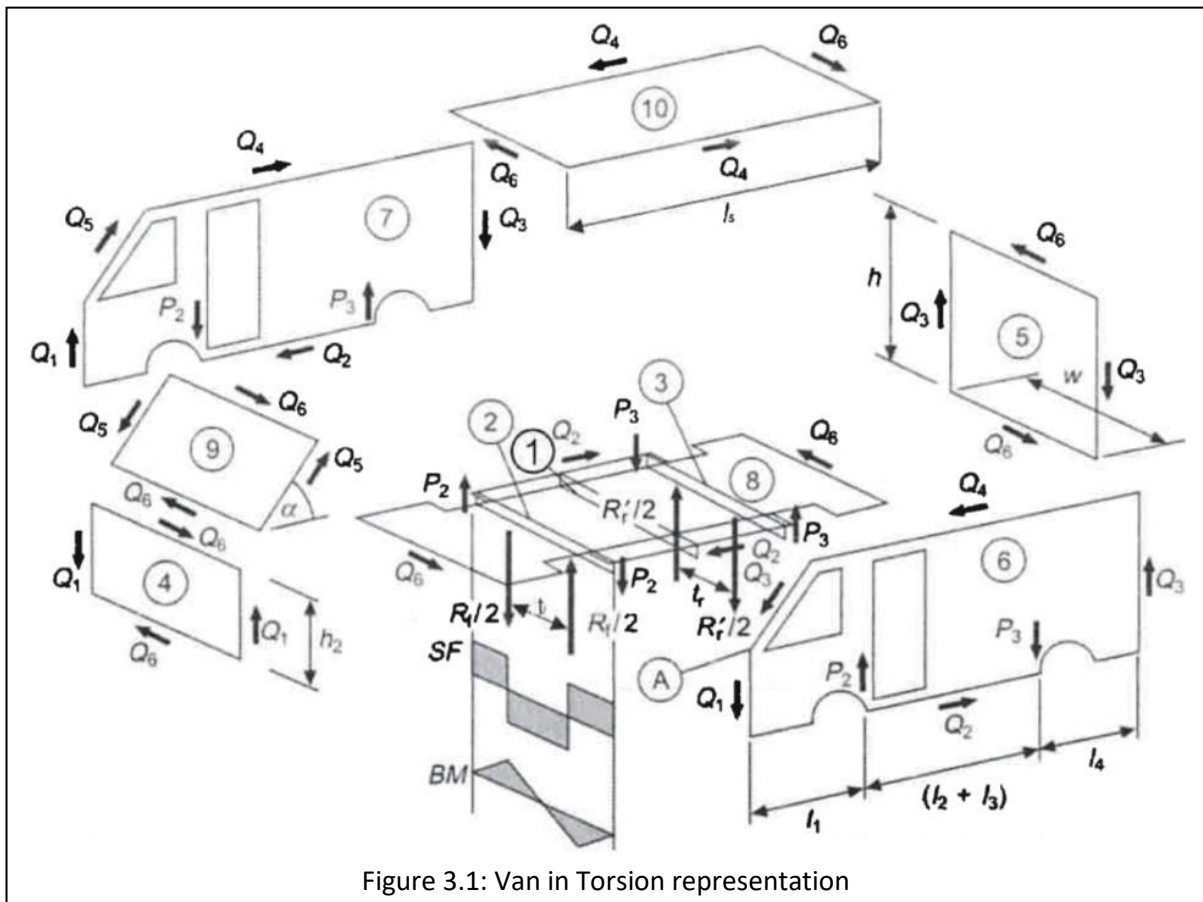
Incorporating these technologies into a modern vehicle structure makes the Body in White; a highly optimized (multi-material) space frame, designed using CAD to produce an impact resistant and mass-manufacturable frame with replaceable sections. Figure 2.5 shows the Carbon Fiber 'tub' of



the occupant area in grey, with a change of material for the front sub-frame and around the vehicle. A more typical car will use Steel alloys and or Aluminium, compared to an Audi R8's use of CFRPs for performance. The front and rear sub-frames can be replaced if an accident occurs for reasonable cost, but if the safety shell/occupant area is compromised, the vehicle would be written-off.

3 SSS Calculus

The Simple Structural Surfaces method, theorised in 1969, represents a vehicle or any structure as flat planes in equilibrium with each other. Cars of this time were particularly cubic and boxy so strain can be calculated with good accuracy. Although, modern vehicles with complicated crossmembers and sleek bodies, would make SSS equations highly difficult by hand. This paired with advances in mass-market computing hardware and software make Finite Element Analysis (FEA) preferable today. But for best understanding of advanced techniques, the SSS method shouldn't be forgotten.



Van in Torsion

$Q_1 > Q_6$ plane edges (10 planes total)

R_f reaction force at the front

R_r reaction at the rear

t_f track at front

t_r track at rear

$M_f = M_r$ vehicle in 50:50 balance

therefore $\frac{R_f}{2} \times t_f = \frac{R_r}{2} \times t_r$

Given values:

$$w = 2.1\text{m}$$

$$h = 2.5\text{m}$$

$$h_2 = 1\text{m}$$

$$l_1 = 2\text{m}$$

$$l_2 + l_3 = 3.5\text{m}$$

$$l_4 = 1\text{m}$$

Overall weight 3500kg

weight dist. 50:50

$$t_f = 1.5\text{m}$$

$$t_r = 1.5\text{m}$$

$$\alpha = 45^\circ$$

$$R_f = R_r = 5\text{kN}$$

P_2 front cross rail $\overline{M} = \overline{M}$

$$P_2 \frac{w}{2} + \frac{P_2 w}{2} = \frac{R_f t_f}{2} + \frac{R_r t_r}{2} \quad P_2(2.1) - \frac{(5000)(1.5)}{2} = 0$$

$$P_2 w = \frac{R_f t_f}{2} \quad \text{so} \quad P_2 w - \frac{R_f t_f}{2} = 0 \quad P_2(2.1) = 3750\text{N}$$

$$\frac{3750}{2.1} = P_2 = 1785.7\text{N}$$

P_3 rear cross rail is the same (van unloaded)

$$P_3 w - \frac{R_f t_f}{2} = 0 \quad \text{same inputs therefore} \quad P_3 = P_2$$

④ $\overline{M} = \overline{M}$ on front panel/grille

$$Q_6 \times h_2 = Q_1 \times w \quad Q_1 = \frac{Q_6 h_2}{w}$$

⑤ rear access door clockwise moments = anti.cl.w. moments

$$Q_3 w = Q_6 h \quad Q_3 = \frac{Q_6 h}{w}$$

Continued

Figure 3.2: SSS page 1

Continued

⑥ taking moments around van's side profile $\hat{M} = \bar{M}$

$$P_3(l_1 + l_{2+3} + l_4) = Q_4(h - h_2) + Q_3(l_1 + l_{2+3} + l_4) + Q_2 h_2 + P_2 h$$

$$P_3(l_1 + l_{2+3} + l_4) - Q_3(6.5) - Q_4(h - h_2) - Q_2 h_2 - P_2 h = 0$$

$$P_3(6.5) - Q_3(6.5) - Q_4(1.5) - Q_2(1) - P_2(2.5) = 0$$

⑦ is symmetrical to ⑥

⑧ floor panel $\hat{M} = \bar{M}$ $Q_2 W = Q_6(l_1 + l_{2+3} + l_4)$

$$Q_2 = \frac{Q_6(l_1 + l_{2+3} + l_4)}{W} \quad Q_2 = \frac{Q_6(6.5)}{2.1}$$

⑨ windscreen at 45° angle $\underline{S.A. C.A. T.A.}$

$$h - h_2 \quad \sin \alpha = \frac{h - h_2}{\Delta}$$

$$\Delta = \frac{h - h_2}{\sin \alpha}$$

$$\text{substitute into } \frac{Q_6(h - h_2)}{\sin \alpha} = Q_5 W$$

$$Q_5 = \frac{Q_6(h - h_2)}{W \sin \alpha}$$

⑩ the roof $\hat{M} = \bar{M}$ ~~Q₆~~ roof length undefined! Assume

$$l_5 = 5m. \quad Q_6 l_5 = Q_4 W \quad Q_4 = \frac{Q_6 l_5}{W}$$

equations arranged for $Q_1 > Q_6$ unknown shear loads.

find Q_6

$$P_3(l_1 + l_{2+3} + l_4) - \frac{Q_6 h}{W}(l_1 + l_{2+3} + l_4) - \frac{Q_6 l_5}{W}(h - h_2) - \frac{Q_6(6.5)}{W} h_2 - P_2 h = 0$$

$$P_3(6.5) - P_2 h = \frac{Q_6 h}{W}(6.5) + \frac{Q_6 l_5}{W}(h - h_2) + \frac{Q_6(6.5) h_2}{W}$$

$$P_3(6.5) - P_2(2.5) = \frac{Q_6}{W}(2.5(6.5) + 5(2.5 - 1) + 1(6.5))$$

$$\frac{(P_3 \times 6.5 - P_2 \times 2.5)}{2.5(6.5) + 5(1.5) + 1(6.5)} = Q_6 \quad Q_6 = 937.1 \text{ N.}$$

Finally, Continued

Figure 3.3: SSS page 2

Continued Find Q_1 & Q_5 when $Q_6 = 937.1 \text{ N}$.

$$Q_1 = \frac{Q_6 h_2}{w} \quad Q_1 = \frac{937.1 \times 1}{2.1} \quad Q_1 = 446.24 \text{ N}$$

$$Q_2 = \frac{Q_6 (6.5)}{w} \quad Q_2 = \frac{937.1 \times 6.5}{2.1} \quad Q_2 = 2,900.55 \text{ N}$$

$$Q_3 = \frac{Q_6 h}{w} \quad Q_3 = \frac{937.1 \times 2.5}{2.1} \quad Q_3 = 1,115.6 \text{ N}$$

$$Q_4 = \frac{Q_6 L_5}{w} \quad Q_4 = \frac{937.1 \times 5}{2.1} \quad Q_4 = 2,231.19 \text{ N}$$

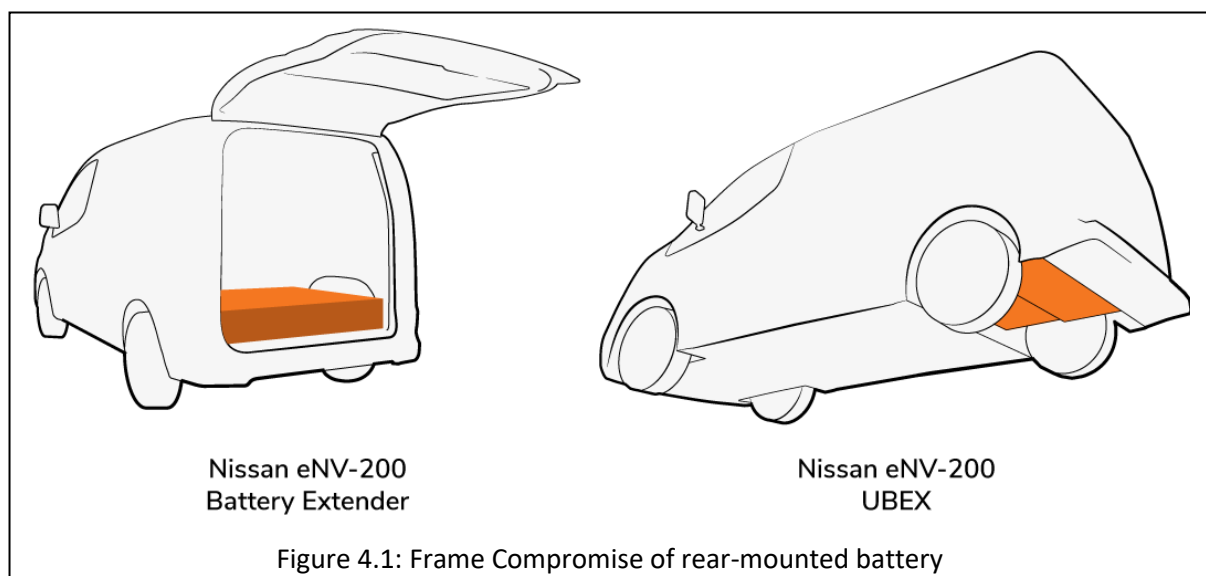
$$Q_5 = \frac{Q_6 (h - h_2)}{w \sin \alpha} \quad Q_5 = \frac{937.1 \times 1.5}{2.1 (\sin 45)} \quad Q_5 = \frac{1405.65}{1.485} \quad Q_5 = 946.56 \text{ N}$$

Figure 3.4: SSS page 3

4 EV Implications

Removing a load path from a vehicle or structure often has challenging affects, such as misalignment or sag. Usually, this is challenging when a manufacturer wants to make a convertible vehicle, as the roof is suddenly unable to transfer any structural loads whatsoever. Some exceptions have been engineered over time such as Triumph's (and others) T-bar roof arrangement to help in roll-over crash scenarios. But often, firms need to reinforce the floor plane to maintain adequate torsional resistance for the vehicle.

An EV powertrain and storage solution (batteries) has potential of retrofit into older vehicles, but component positioning is critical. Compromising Q_6 at the join between the rear and floor panels would create an opening for a battery hot swap at the rear but would send the load otherwise supported by this structural element throughout surrounding beams and affect the forces at the edges as well as in the planes. The vehicle's weight may increase in efforts to improve torsional rigidity while installing the EV powertrain, being a van it's no performance vehicle but affecting the loading characteristics, range, capacity, speed etc. of the van it is important to balance all aspects of the conversion according to vehicle intentions and use/lifespan.



Traditional vehicle building techniques and materials are becoming perceived as too heavy, where to get an electric car moving it ought to be lightweight and use CFRPs. Manufacturing carbon fibre has increased in popularity but is still very expensive and wasteful, but this has previously discussed issues such as recycling, repair and cost. Therefore, a balance of properties is desirable between vehicle operation and manufacturing preferences, and profit margins. Mixing materials is of galvanic corrosion risk so there will be no perfect design for all vehicles.

5 Conclusions

Throughout this report historical vehicle structures and how they have developed to current day has been discussed and analysed through thorough research and findings. The discussion of the impact that manufacturing and material developments have had over the course of the last century has been developed and displayed through the Simple Structural Surfaces (SSS) method, which has successfully shown scientific credibility within known parameters.

Vehicle structures have evolved through their 150+ years of development; rules, challenges and requirements, but the forthcoming bans and material choices/methods are now vast so there is no straightforward solution where each approach has its advantages and weaknesses. The incredible progress we have made should not be shadowed by the legal switch ahead, but if BIWs cannot be repurposed efficiently with an electric powertrain then suddenly, all the steel presses, tooling and many more assets used to manufacture ICE cars are suddenly valueless.

Vehicle frame development will not stop; it's come incredibly far from the days of horse carriages with wooden wheels, but as engineers the next hurdle is coming. It could see out the legacy car firms while new EV-specific firms enter the market, or a combination of technologies will see research to what's best in the 2040s after the ban.

6 References

Autoliv, n.d. *Safety Solutions | Autoliv*. [Online]

Available at: <https://www.autoliv.com/safety-solutions>

[Accessed 27th December 2022].

Euro NCAP, n.d. *The Official Site of the European New Car Assessment Programme*. [Online]

Available at: <https://www.euroncap.com/en>

[Accessed 4th January 2023].

EuroNCAP, n.d. *Offset-Deformable Barrier - ODB*. [Online]

Available at: <https://www.euroncap.com/en/vehicle-safety/the-ratings-explained/adult-occupant-protection/previous-tests/offset-deformable-barrier/>

[Accessed 2nd January 2023].

Foster, J. K., Kortge, J. O. & Wolanin, M. J., 1977. *Hybrid III—A Biomechanically-Based Crash Test Dummy*. Detroit: SAE International.

Hernandez, M., 2022. *Carbon Fiber Reinforced Polymers (CFRP): Material Properties & Tool Selection*. [Online]

Available at: <https://www.harveyperformance.com/in-the-loupe/carbon-fiber-reinforced-polymers-cfrp/#:~:text=CFRP%20Properties,must%20be%20considered%20when%20machining.>

[Accessed 3rd January 2023].

Insurance Institute for Highway Safety, 2022. *Side Impact Crashworthiness Evaluation 2.0*. [Online]

Available at: https://www.iihs.org/media/0027a26d-8dd2-4de4-affc-0eb98338c6ba/ZZFWDw/Ratings/Protocols/current/test_protocol_side-2.0.pdf

[Accessed 26th December 2022].

NASA, 2012. *Rocket Sled Tests Are Technology Pathway to Safely Land Humans, Habitats and Cargo on Mars*. [Online]

Available at: https://www.nasa.gov/mission_pages/tdm/ldsd/rocketsled2.html

[Accessed 26th December 2022].

Volvo Cars, 2009. *3-point safety belt from Volvo - the most effective lifesaver in traffic for fifty years*. [Online]

Available at: <https://www.media.volvocars.com/global/en-gb/media/pressreleases/18405>

[Accessed 26th December 2022].

Wayne State University, 2006. *Larry Patrick, pioneer auto safety researcher: 1920 - 2006*. [Online]

Available at: <https://engineering.wayne.edu/news/larry-patrick-pioneer-auto-safety-researcher-1920-2006-43071>

[Accessed 26th December 2022].

End of report, thank you for reading.