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Developments of Vehicle Structures

Automotive Chassis Systems ACHA5013

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1 Introduction

The chassis is the load-bearing structure of a vehicle that other components are fitted to. It is important for a chassis to be rigid and strong as it needs to withstand the loads that it will encounter through its use in the environment it is designed for. The strength of a structure deteriorates from repeated loading and unloading. It is necessary to plan for this and choose a material with a high fatigue resistance and implement a factor of safety in order to reduce the risk of the structure failing (Matthews, 1998). Torsion is caused by the twisting of a vehicle as it encounters loads which apply a moment to the chassis. Tubes and closed box structures are effective shapes for resisting torsion.

Simple structural surfaces (SSS), initially introduced by Pawlowski in 1969, allows for the analysis of a vehicle to approximate the type and magnitude of loads that are being applied to the vehicle's structural elements under static conditions by simplifying the body-in-white (BIW) into The surfaces of the chassis are assumed to be rigid planes where forces can only act within the plane and calculating loads these surfaces using just the geometry of the structure and known forces. (Brown, Robertson and Serpento, 2002).

2 Vehicle Structures

2.1 Body Design Progression

2.1.1 Body-on-chassis

Historically, cars had generally been constructed using a body-on-chassis method, a method passed along from horse-drawn carriages. A chassis fitted with a powertrain and beam axle suspension was created as a base with the vehicle's body manufactured separately and then later fitted onto the frame.

Using a body-on-chassis construction is beneficial as its versatility allowed for numerous types of vehicles to be assembled using only a single chassis design, allowing for reduced development costs. The ladder frame chassis is made from two longitudinal c-beams connected by several cross beams, it had a bending stiffness high enough for it to handle the type of loads that could be encountered. However, it had a low torsional resistance due to the chassis being planar (Brown, Robertson and Serpento, 2002).

With a body-on-chassis vehicle, the load paths can go through both the body and the chassis and act like parallel springs, with the portion of load acting through each component determined by the stiffness of that component in comparison to the other. In earlier vehicles, the body of the car was made from wood and textiles which were flexible and non-load bearing, resulting in most of the load passing through the chassis. Later, the bodies of cars were made from pressed steel as well as having steel roofs as this allowed for larger scale manufacturing. Using these materials increased the stiffness of the body and subsequently put the body under a greater load. This was detrimental as the torsional stresses on the body led to it rattling, which made the vehicle noisy to ride in and could also cause damage to the vehicle (Brown, Robertson and Serpento, 2002).

Body-on-chassis designs have been mostly phased out over time due to suspension improvements requiring stiffer chassis to function effectively; however, they are still used today in goods vehicles and SUVs (Hillier and Coombes, 2004).

2.1.2 Backbone Chassis

The backbone chassis structure has a high torsion stiffness despite the body being separate from the chassis. The body is typically made from a stiff composite, joined to the chassis at many points, which makes a very rigid vehicle when combined with the stiffness from the large, enclosed backbone running longitudinally through the vehicle (Brown, Robertson and Serpento, 2002).

2.1.3 Triangulated Tube Structure

A triangulated tube chassis is made from closed longitudinal tubes or closed beams joined together by smaller metal tubes, welded to the longitudinals in a triangular formation. The chassis is made in this way as the triangular structures are efficient at carrying shear loads. Triangulated tube structures are not suitable for mass production due to the amount of labour required in positioning and joining, compared to sheet metal stamping (Brown, Robertson and Serpento, 2002).

2.1.4 Pure Monocoque

Pure monocoque chassis are the closest to a tube structure, with the skin being load-bearing and usually made from a composite, the only gap in the shell is a hole for the driver to enter. This type of structure is mainly used for race cars due to the limited accessibility and impracticality of this structure in terms of ease of entry, storage, and visibility from the driver's seat. It requires reinforcement around the suspension mounting points to prevent the skin from buckling (Brown, Robertson and Serpento, 2002).

2.1.5 Punt Structure

The punt structure is a closed structure with the floor members usually carrying the majority of the torsional and bending loads. Some convertibles are made using a punt structure due to the design not depending on a roof for torsional rigidity (Brown, Robertson and Serpento, 2002).

2.1.6 Perimeter Space Frame

The space frame chassis is a load-bearing structure with the body panels added later being non-load bearing. The Audi A8 has a space frame chassis, its BIW is shown in Figure 1. It is manufactured from ultra-high strength steel, conventional steel, sheet and cast aluminium, carbon fibre reinforced polymer, and magnesium (Audi, 2017).

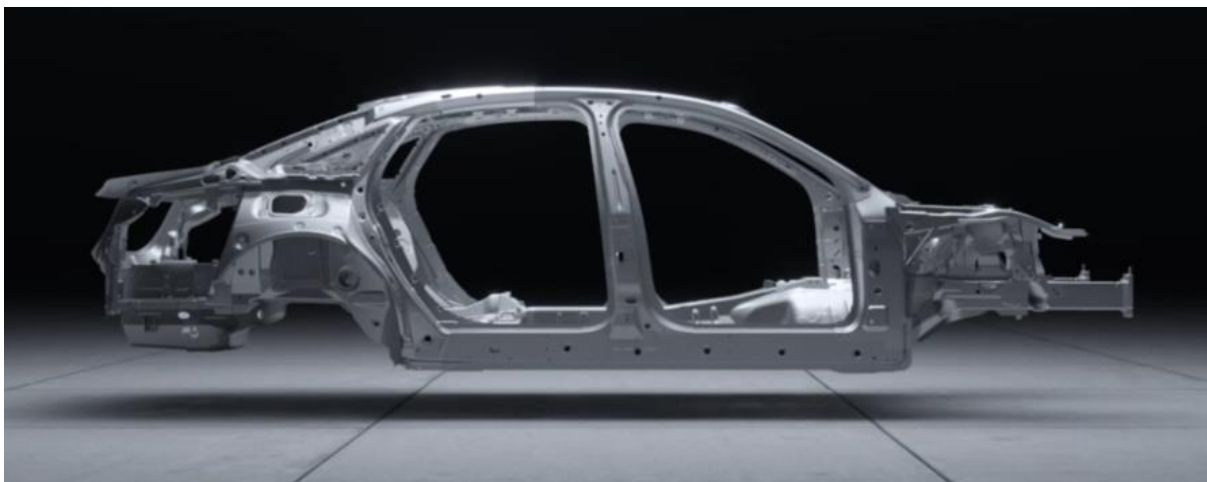


Figure 1 - Audi A8 BIW (Audi, 2017)

2.1.7 Integral Body

In an integral body, the body also acts as the chassis. Modern cars used a range of materials and joining techniques on different panels depending on the loads the panels are subjected to.

Traditionally, steel has been used for the manufacturing of parts of the body and chassis structures. Modern cars have an implementation of other materials such as aluminium, due to its low weight and high energy absorption making it useful for reducing the mass of a structure while maintaining rigidity, allowing for better fuel efficiency (Matthews, 1998).

If they aren't using a pre-existing platform's chassis, modern EVs typically use a skateboard platform to house the batteries with a body structure mounted on top, using many mounting points to prevent the issues with torsional rigidity found in older body-on-chassis vehicles, while maintaining the potential for modularity. The absence of an engine provides more crush space in front of the passenger cell, providing more energy absorption (*Safety | Tesla United Kingdom, 2022*).

2.2 Safety

Early automobiles did not have many, if any, safety features and occupants died frequently from collisions compared to today (Figure 2).

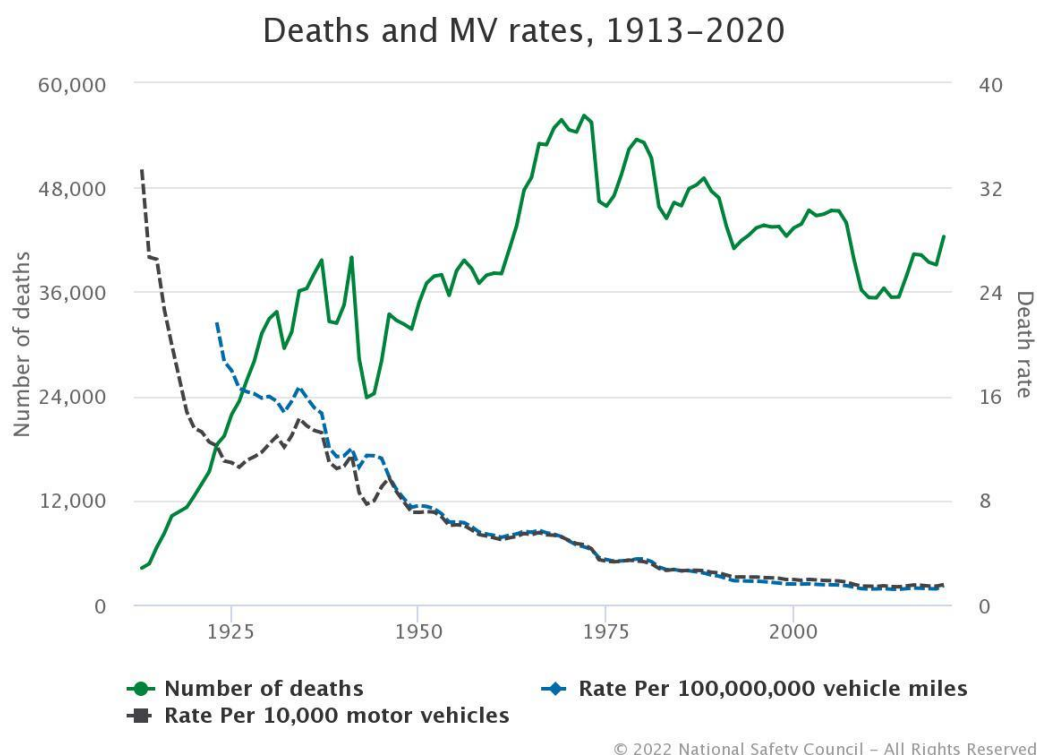


Figure 2 – Death rates as a result of motor vehicle accidents over time (National Safety Council, 2022).

2.2.1 Vehicle Safety Organisations

Organisations such as Euro NCAP, launched in 1996, and the IIHS, who were established in 1959 and began testing in 1995 (IIHS, 2022), perform a variety of crash tests and analyse other aspects of the vehicle, such as driver assists, to assess the safety of the vehicle for occupants and pedestrians (Euro NCAP, 2022). They then provide this information to the consumer in the form of a safety rating. As a customer is likely to prefer a safer car, this provides incentive for car manufacturers to improve on current safety features and implement more safety features into their vehicles. It also identifies issues that have been found with the vehicle, allowing the manufacturer to rectify issues.

Improving the construction of the unibody through improvements in geometry, materials and joining techniques has allowed for a stiffer chassis and passenger cell in modern vehicles. This makes it less likely that the passenger cell will encounter intrusion which reduces the chance of occupants sustaining injuries (Euro NCAP, 2015).

2.2.2 Chassis Adaptations

Crumple zones are designed to transfer kinetic energy into deformation energy during a crash. These parts of the chassis are designed to buckle in order to increase the duration of the crash and reduce the loads transferred into the passenger cell, reducing the deceleration forces experienced by the occupants and decreasing the likelihood of the passenger cell deforming due to loads. In a typical ICE passenger vehicle, the engine is mounted in the front of the vehicle, between the front bumper and the passenger cell. This creates issues as the engine is considered to be non-deformable, and its position reduces the length of the crush space. The structure of the car should be designed to maximise the transformation of kinetic energy to deformation energy with minimal or no deformation of the passenger cell.

By changing to an EV powertrain, the area the engine was occupying can be replaced with crumple zone structures to increase the duration of the crash and reduce the forces acting on the occupants. Impact bars can also be implemented in the front, side, and rear of the vehicle to better distribute the load of an impact through the chassis and decrease the likelihood of intrusion into the passenger cell.

Pedestrian safety is another topic that has an impact on the shape of modern cars, particularly the front as this is where most pedestrian-vehicle impacts occur. Pedestrian leg injuries are a more common injury and can be reduced through the use of compliant bumpers, and serious head injuries can be reduced through the use of bonnet and windscreen airbags. (Crandall, Bhalla and Madeley, 2002).

2.3 Aerodynamics

Aerodynamic drag reduces the fuel efficiency of a vehicle, increasing the running costs and decreasing the distance travelled between refuelling or recharging. The aerodynamics of a road vehicle in terms of drag coefficient are limited by the chassis due to the requirement for a passenger cell to be big enough to fit occupants into and allow them to have enough free space around them to reduce the risk of injuries through impacting internal surfaces during a crash, there also needs to be enough space in the passenger cell for fitment of safety devices such as side airbags.

The drag coefficient of EVs can be lower due to them having smooth undersides, unlike ICE vehicles which have components such as gearboxes and exhaust pipes interfering with the flow of air underneath the car, creating drag and turbulence. Reducing aerodynamic drag can also reduce wind noise, improving the experience of the occupants in the vehicle.

3 SSS Calculations

The focus of the SSS performed in this report was a van subjected to a static torsion load (Figure 3). The van is a closed body and the SSS is applicable so long as the doors and windows are adequately reinforced to maintain the assumption of rigid surfaces.

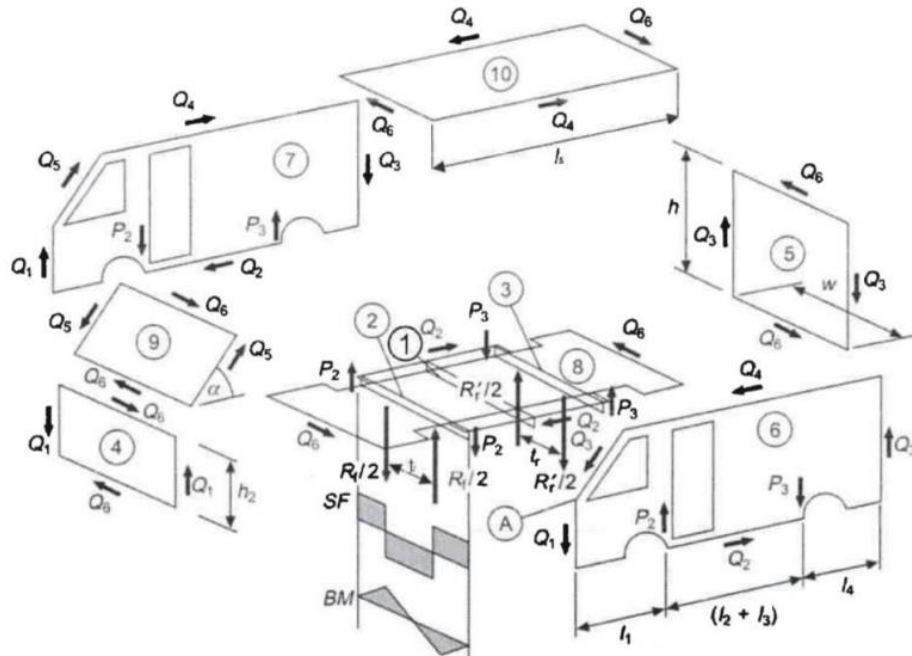


Figure 3 - Van subjected to torsion.

The SSS method was used to calculate edge forces acting on the van's body panels under static torsional loading by taking moments from points on each surface of the vehicle using the known information as well as calculated information (Table 1).

Table 1 - Torsion load & vehicle data

Item	Label	Value
Vehicle Width	w	2.1m
Body Height	h	2.5m
Front Panel Height	h2	1m
Length from Front Panel to Front Crossbeam	L1	2m
Length from Front Crossbeam to Rear Crossbeam	L2+L3	3.5m
Length from Rear Crossbeam to Rear Panel	L4	1m
Length of Roof Surface	L5	5m
Overall Weight	-	3500kg
Weight Distribution	-	50:50
Front Axle Width	t _f	1.5m
Rear Axle Width	t _r	1.5m
Windscreen Angle	α	45 degrees
Force Acting on Front Axle	R _f	5kN
Force Acting on Rear Axle	R _r	5kN

There are 10 panels with 6 unknown forces on them. First, the clockwise and anticlockwise moments on the axles where the torsional load is coming from must be in equilibrium:

$$M \curvearrowright = M \curvearrowleft$$

$$\frac{R_f}{2} * t_f = \frac{R_r}{2} * t_r$$

$$\frac{5000}{2} * 1.5 = \frac{5000}{2} * 1.5$$

$$3750 = 3750$$

$$3750 - 3750 = 0$$

SSS-2: Front Cross Beam

$$M \curvearrowright = M \curvearrowleft$$

$$\frac{P_2 w}{2} + \frac{P_2 w}{2} = \frac{R_f}{2} * \frac{t_f}{2} + \frac{R_f}{2} * \frac{t_f}{2}$$

$$P_2 w = \frac{R_f t_f}{2}$$

$$P_2 w - \frac{R_f t_f}{2} = 0$$

From this P_2 can be calculated

$$P_2 w = \frac{R_f t_f}{2}$$

$$P_2 = \frac{R_f t_f}{2w}$$

$$P_2 = \frac{5000 * 1.5}{2 * 2.1}$$

$$P_2 = 1785N$$

SSS-3: Rear Cross Beam

$$\text{Similarly: } P_3 w - \frac{R_r t_r}{2} = 0$$

Following this P_3 can be calculated

$$P_3 w = \frac{R_r t_r}{2}$$

$$P_2 = \frac{R_r t_r}{2w}$$

$$P_2 = \frac{5000 * 1.5}{2 * 2.1}$$

$$P_2 = 1785N$$

Following this, equations need to be made by taking moments around each panel to determine the 6 unknown forces:

SSS-4: Front Panel

$$M \curvearrowright = M \curvearrowleft$$

$$Q_6 h_2 = Q_1 w$$

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

SSS-5: Rear Panel

$$M \curvearrowright = M \curvearrowleft$$

$$Q_3 w = Q_6 h_1$$

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

SSS-6: At **A** on left side panel

$$M \curvearrowright = M \curvearrowleft$$

$$P_3(l_1 + l_2 + l_3) = P_2 l_1 + Q_3(l_1 + l_2 + l_3 + l_4) + Q_4(h - h_2) + Q_2 h_2$$

$$P_3(l_1 + l_2 + l_3) - P_2 l_1 - Q_3(l_1 + l_2 + l_3 + l_4) - Q_4(h - h_2) - Q_2 h_2 = 0$$

SSS-7: At equivalent of **A** on right side panel

Identical to SSS – 6

SSS-8: Floor Panel

$$M \curvearrowright = M \curvearrowleft$$

$$Q_2 w = Q_6(l_1 + l_2 + l_3 + l_4)$$

$$Q_2 = \frac{Q_6(l_1 + l_2 + l_3 + l_4)}{w}$$

SSS-9: Windscreen

$$M \curvearrowright = M \curvearrowleft$$

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

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

SSS-10: Roof Panel

$$M \curvearrowright = M \curvearrowleft$$

$$Q_6 l_5 = Q_4 w$$

$$Q_4 = \frac{Q_6 l_5}{w}$$

By substituting some of the equations into the one found for SSS-6, it is possible to solve the 6 unknown forces. The substituted equations are highlighted in yellow:

$$P_3(l_1 + l_2 + l_3) - P_2l_1 - Q_3(l_1 + l_2 + l_3 + l_4) - Q_4(h - h_2) - Q_2h_2 = 0$$

$$P_3(l_1 + l_2 + l_3) - P_2l_1 - \frac{Q_6h}{w}(l_1 + l_2 + l_3 + l_4) - \frac{Q_6l_5}{w}(h - h_2) - \frac{Q_6(l_1 + l_2 + l_3 + l_4)}{w}h_2 = 0$$

$$P_3(l_1 + l_2 + l_3) - P_2l_1 - \frac{Q_6h(l_1 + l_2 + l_3 + l_4)}{w} - \frac{Q_6l_5(h - h_2)}{w} - \frac{Q_6h_2(l_1 + l_2 + l_3 + l_4)}{w} = 0$$

$$P_3(l_1 + l_2 + l_3) - P_2l_1 - \frac{Q_6}{w}[h(l_1 + l_2 + l_3 + l_4) + l_5(h - h_2) + h_2(l_1 + l_2 + l_3 + l_4)] = 0$$

$$P_3(l_1 + l_2 + l_3) - P_2l_1 = \frac{Q_6}{w}[h(l_1 + l_2 + l_3 + l_4) + l_5(h - h_2) + h_2(l_1 + l_2 + l_3 + l_4)]$$

$$\frac{w[P_3(l_1 + l_2 + l_3) - P_2l_1]}{h(l_1 + l_2 + l_3 + l_4) + l_5(h - h_2) + h_2(l_1 + l_2 + l_3 + l_4)} = Q_6$$

$$Q_6 = \frac{2.1 * [1785 * (2 + 3.5) - (1785 * 2)]}{2.5 * (2 + 3.5 + 1) + 5 * (2.5 - 1) + 1 * (2 + 3.5 + 1)}$$

$$Q_6 = \frac{13119.75}{30.25}$$

$$Q_6 = 433.71$$

This value for Q_6 can then be used to find the values of all the other edge forces through their respective equations. The results are shown in Table 2.

Table 2 - Calculated Edge Forces

Edge Force	Magnitude (N)
Q1	206
Q2	1342
Q3	516
Q4	1032
Q5	384
Q6	433

4 Analysis of SSS

From the results of the SSS it was possible to determine which panels would be transferring the largest forces hence which joins between the panels would require the most reinforcement.

The shear load was calculated from the sum of the edge forces acting within the plane.

Table 3 - Shear load on each surface.

Simple Surface	Edge Forces	Shear Load (N)
Floor	Q2, Q6	3552
L/R Sidewalls	Q1, Q2, Q3, Q4, Q5	3482
Roof	Q4, Q6	2932
Rear Panel	Q3, Q6	1900
Windscreen	Q5, Q6	1636
Front Panel	Q1, Q6	1280
F/R Crossbeams	-	1785
Mid Crossbeam	-	-

Table 3 shows the shear loads calculated to be carried through each surface. The crossbeams transfer the torsion moment to the sidewalls, which will be brought back into equilibrium through edge forces from the panels joined to the sidewalls.

The sidewalls and crossbeams would encounter bending loads from the weight of the vehicle. The mid crossbeam does not appear to carry shear load.

5 Impact of Frame Adaptation

One caveat of EV usage compared to ICE is the time required to recharge the battery compared to refuelling, as it takes longer this could be considered an inconvenience for a potential customer. This is especially important as recharging the battery at a high rate can lead to a reduction in energy capacity of a battery. One way to circumvent this issue is to have a battery that can be quickly replaced with another fully charged battery, an example of this is Toyota researching the potential for cartridge batteries for commercial vehicles (Matt Burt, 2022). In order to implement this on the van examined previously, it was determined that the connection between the rear panel and the floor panel would have to be altered to create a space to remove and insert the battery.

Removing the join between the floor and rear panel would lead to Q6 not existing as the load would not be able to be transferred from the floor to the rear panel. Therefore Q3 is also not existent as it is not needed for equilibrium. If Q3 doesn't exist, the shear loads acting through the side panels are decreased due to there being no force from Q3. As Q6 is needed for equilibrium with Q2, Q2 can not exist. Q1 also requires Q6 for equilibrium therefore Q1 can not exist. In the windscreen, Q6 is required for equilibrium with Q5 so Q5 can not exist. In the roof, Q4 can not exist as it counters the force of Q6. This means the remaining structure to carry the torsional load is the grillage connected to the floor. The SSS of this structure is voided as the forces R_f and R_r are acting normal to the floor.

6 References

- Audi (2017) *Animation: Looking ahead to the new Audi A8 Space Frame with a unique mix of materials*. Available at: <https://www.audi-mediacenter.com/en/audimediavideo/video/animation-looking-ahead-to-the-new-audi-a8-space-frame-with-a-unique-mix-of-materials-3583> (Accessed: 3 January 2023).
- Brown, J.C., Robertson, A.J. and Serpento, S.T. (2002) *Motor vehicle structures: concepts and fundamentals*. Oxford: Butterworth-Heinemann.
- Crandall, J.R., Bhalla, K.S. and Madeley, N.J. (2002) 'Designing road vehicles for pedestrian protection', *BMJ : British Medical Journal*, 324(7346), p. 1145. Available at: <https://doi.org/10.1136/BMJ.324.7346.1145>.
- Euro NCAP (2015) *Euro NCAP Introduces a New Full Width Frontal Test*. Available at: <https://www.euroncap.com/en/about-euro-ncap/timeline/> (Accessed: 7 December 2022).
- Euro NCAP (2022) *Euro NCAP | The European New Car Assessment Programme*. Available at: <https://www.euroncap.com/en> (Accessed: 10 December 2022).
- Hillier, V.A.W. and Coombes, P. (2004) *Hillier's fundamentals of motor vehicle technology*. 5. ed. Cheltenham: Nelson Thornes.
- IIHS (2022) *IIHS-HLDI*. Available at: <https://www.iihs.org/> (Accessed: 19 December 2022).
- Matt Burt (2022) *EV battery swap - Toyota joins cartridge batteries research - Toyota UK Magazine, Toyota UK Magazine*. Available at: <https://mag.toyota.co.uk/ev-battery-swap-toyota-joins-cartridge-batteries-research/> (Accessed: 27 December 2022).
- Matthews, C. (1998) *Case Studies in Engineering Design*. Oxford, England: Butterworth-Heinemann. Available at: <https://doi.org/10.1016/b978-0-340-69135-9.x5000-0>.
- National Safety Council (2022) *Historical Car Crash Deaths and Rates - Injury Facts*. Available at: <https://injuryfacts.nsc.org/motor-vehicle/historical-fatality-trends/deaths-and-rates/> (Accessed: 27 December 2022).
- Safety | Tesla United Kingdom* (2022) *Tesla*. Available at: https://www.tesla.com/en_gb/safety (Accessed: 30 December 2022).