

FRONTAL CRASH

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Introduction

In this project, I will be researching how vehicle structures have historically developed through consideration of various needs of strength, packaging and comfortability. I will also be investigating the significance of consumer driven testing and how much that has influenced the design of automotive chassis.

As part of this report, I will also be choosing an automotive body in white and estimating the theoretical buckling load of a longitudinal. I will then pick a similar vehicle of my choice and compare the estimated data to the maximum forces seen in a typical frontal crash pulse. After comparing the two, I'll be discussing whether or not there's differences between the figures and why that might be.

Body on Frame Chassis

Up until the 1930's almost every automobile would have a body attached separately to its structural frame. The unibody construction appeared by the 1960's and became common among passenger cars. This trend continued over the future decades. However, most pickups, buses and trucks continue using separate structural frames from their bodies. The material used to construct vehicle chassis typically include carbon steel or aluminium alloys for the benefit of being a lightweight construction. For body on frame structures, rails or beams are manufactured by rolling, pressing or folding steel plates to create channel sections for the frame. The material can be folded twice to achieve an open ended "C" or "U" shaped frame rail. Alternatively, box frames include chassis beams that are closed either by welding them or using premanufactured metal tubing.

One of the older body on frame chassis is the ladder chassis which contains two long and heavy longitudinal beams supported by rails connecting them laterally, much like the shape of a ladder. "The main selling point of the ladder chassis was how easy it was to manufacture." Course (Solutions, 2022).^[1] The simplicity of the ladder chassis made it easier to mass produce in the early era of the automobile where technology wasn't as advanced. The ladder chassis is quite heavy and so it still finds use in vehicles that require transporting heavy payloads. Its advantage include being easier to assemble as components can be easily fit in. The construction of the frame makes it very tough. It's easier to repair as the parts aren't permanently attached. However, some disadvantages include the ladder chassis having weak torsional rigidity which doesn't help its cornering performance. Being heavyweight, it is not ideal for popular sports cars or hatchbacks, commonly used by the public for day to day commuting. Ladder chassis are usually made from steel, being outstandingly strong. The steel mix acts as a good shock absorber which provides a more comfortable ride over rough terrain. Being easier to fix is essential for long serving vehicles. Body twist is an important factor to consider as an off-road driver. When one or more wheels are airborne, the chassis will attempt to bend with the bodywork following. On a well manufactured ladder chassis such as the Land Rover Discovery 4^[1] there's little to no flex. This is significantly better than unibody monocoque chassis which can flex so much when two wheels are airborne to the point where you are unable to open or shut the doors. With the bodywork of the car and many other components simply bolted to the ladder chassis, many parts or sections of the car can be replaced with relative ease. Due to the simplicity of the ladder chassis, it makes them easier to design and mass produce. This is beneficial for car companies trying to make affordable cars or wanting to spend their money on developing other high quality components of their vehicle.

Backbone tube chassis is a type of chassis similar to the body on frame design. Instead of a ladder shaped construction, it consists of a strong tubular backbone with a rectangular cross section that connects the front and rear suspension. The body is then placed over this, much like the ladder frame chassis. The earliest use of the backbone chassis is said to have been the

Rover 8 hub of 1904 and sequentially in the French simplicit automobile in 1909. ^[1] The rectangular cross section tube connects to both the front and rear axle with the drive shaft placed safely underneath the backbone. Advantages of the backbone chassis include better connection from the axles to the ground which allows for better stability of the car. The drive shaft is kept safe when off-roading, even when the car bottoms out. The rigidity of the backbone chassis is also high and it can withstand high pressures. The backbone chassis does provide difficulty when trying to repair the drivetrain as the whole backbone needs to be opened up. Manufacturing the backbone chassis costs a lot which makes the vehicles using them expensive.

Unibody Chassis

The monocoque chassis is a structural system where loads are supported by the object's external skin, similar to an eggshell. A pure monocoque such as those used in aircrafts and boats will carry both tensile and compressive forces within its skin and lacks an internal frame to carry loads. In comparison, a semi monocoque chassis combines a tensile stressed skin and a compressive frame structure, seen commonly in vehicle unibodies or balloon tanks, both of which are pressure stabilized. A monocoque chassis is simple in the fact that the entire structure is made up of one single construction acting as the frame, foundation and body of the car. Other major components of the car including the suspension, engine and seats are attached to this construction. This makes the overall chassis is very compact and lightweight. Monocoque chassis are applied in several vehicles including small hatchbacks and modern SUVs which historically didn't feature the monocoque. Another advantage to the monocoque is that the handling of the vehicle is improved as the entire vehicle is a single, compact structure. Dynamic forces are easily transferred out to maintain stability within the corners. The cost of manufacturing them are quite low as they are being broadly used. The cage like construction enhances the safety aspect of the car and passengers within. Manufacturers can add a lot of crumple zone to the vehicle. Higher fuel efficiency is achievable with the lightweight construction. This makes their usage in smaller, budget cars more prominent. The monocoque does however have some drawbacks in that it doesn't have a lot of off-roading capabilities due to its stiff construction. There is no room for movement of components within the monocoque which restricts its agility, unlike the ladder chassis. They can only be affordable if produced in large quantities. The safety of race cars are heavily dependent on their chassis. The Lotus 25 F1 car of 1962 was the first to use an aluminium alloy monocoque. McLaren later became the first to use carbon fibre reinforced polymers to build the chassis of their 1981 MP4/1 F1 car. The relatively new usage of carbon fibre at the time made it largely safer and lighter within the monocoque structure. Following this, in 1990, the Jaguar XJR15 became the first production car with a carbon fibre monocoque. Road cars are almost never true monocoques and therefore use the semi-monocoque or unibody system which uses box sections, bulkheads and tubes to provide most of the strength of the vehicle. The skin adds relatively little strength and stiffness. Some armoured vehicles also use a monocoque structure with a bodyshell made up of armour plates, rather than attaching them to the structure. This does reduce weight for a given amount of armour.

Tubular Chassis

Tubular chassis are predominantly used in race cars due to the superior safety aspect of them. They were an upgrade from the ladder chassis as they were three dimensional and stronger. The strong structure below the doors is used to gain more overall strength. They have better rigidity compared to other chassis around the same weight which means they provide the best weight/rigidity ratio. This makes them the ideal option for a lot of race cars as they are lightweight and more rigid than other chassis. However, due to the complex structures involved in tubular structures, they cannot be manufactured using autonomous methods meaning they take a lot of time to build and cannot be mass produced. The structure of tubular chassis raises the doors which makes them difficult to enter the cockpit/cabin. This isn't ideal for most commercial road going vehicles.

Modern Developments

"Lightweighting" has become a trend recently, (Czerwinski, 2021) ^[2] which has taken over multiple industrial sectors but isn't entirely focused on reducing the weight of mechanical assemblies, but also looking to improve structural efficiency while being aware of the economic and environmental impact. A reduction of weight for vehicles would not only mean less resources and material used for its manufacturing process, but also less energy consumed for its transportation. "Lightweight steel", conventional aluminium and magnesium alloys are some types of materials being paid attention to by the metallic alloys sector in global research and development activities. Further research is being done into using more composites, fibre metal laminates, which takes advantage of both metals and composites, and sandwich structures which has high structural stiffness and energy absorption potential. The profound industries of aerospace and auto racing have been key drivers for this major modern trend, pushing it towards the automotive industry who are looking to maximize their fuel efficiency, especially with the increase in electric vehicles on the road.

Vehicle structures have also been developed to meet the passing requirements of standardized crash testing like EuroNCAP who upload their results onto their public website so anyone can view how well a vehicle has performed in it. With the public becoming more safety conscious, crash testing results like these have been a crucial factor in promoting a company's new automobile. Vehicles are now being designed with new high strength steel and advanced alloys, ^[3] OpenAI ChatGPT (2024) ChatGPT response to Ragulan Pulanthitan, 6 January. Crash testing and FEA have been part of the design process. Vehicles are designed with crumple zones which deform and absorb energy during a collision. This inherently reduces the impact forces that are transferred to the occupants inside. Interior occupant protection has also significantly improved with the addition of airbags surrounding the people inside. Structural reinforcements such as side-impact beams, roof reinforcements, and other reinforcement pillars help improve the structural rigidity of the passenger compartment. Energy absorbing structures and external airbags also reduce injury severity to pedestrians.

Estimating Buckling Load

For the second task of this project I will be estimating the theoretical fundamental buckling loads of a longitudinal member within a body in white of my choice. For this exercise I have chosen to use a 2002 Toyota Camry LE which is a typical sedan car used commonly in North America. After doing this, I will be able to compare my estimations with frontal crash pulse data from a similar vehicle and discuss the differences between them.

For the first part of this task, I will be investigating the rocker panel on the Toyota Camry's unibody. Rocker panels weren't needed as much to connect the front and rear wheel wells in the 1950s and '60s. They were instead added as extra support to the structure in order to prevent it from sagging, (Drummond, 2023).^[4] The rocker panel on the 2002 Toyota Camry is a rectangular shape with dimensions 1814mm in length x 191mm in width x 178mm in height weighing 1.86kg, (CARiD.com. 2024).^[5] The forces seen on a rocker panel tend to come from stress from the weight of the vehicle, road vibrations, and dynamic forces during acceleration, braking and turning. If subjected to a side impact collision, the panel plays a part in absorbing and distributing some of the impact forces and energy to protect the occupants inside, OpenAI ChatGPT (2024) ChatGPT response to Ragulan Pulanthitan, 3 January.^[6] The chassis of the 2002 Camry was largely comprised of steel which has a Young's Modulus of 210000 MPa, (team, 2024).^[7] The average Poisson's ratio for steel is 0.28 in accordance to (Britannica, 2023).^[8]

With the boundary conditions of my rocker panel having both rotation and translation fixed ends, I am able to use a K value of 0.5 as the effective length factor which I can plug into Euler's equation to find the critical buckling load of the longitudinal column in question.

Euler's Critical Buckling Load Equation:

$$P_{cr} = \frac{\pi^2 \cdot E \cdot I}{(K \cdot L)^2}$$

To calculate the moment of Inertia for the rectangular cross-section (I), the following equation is used: $I = \frac{1}{12} b \cdot h^3$, where the base is 191mm and the height is 178mm. This gives a moment of inertia of $8.977 \times 10^{-5} \text{m}^4$. With the rest of the information previously mentioned, we can use Euler's formula to find Pcr as 226170 kiloNewtons, which is the force at which it is expected to buckle.

Comparison to Crash Pulse Data

Figure 1: Comparison between Subaru Legacy crash pulse curve and Toyota Camry crash pulse curve

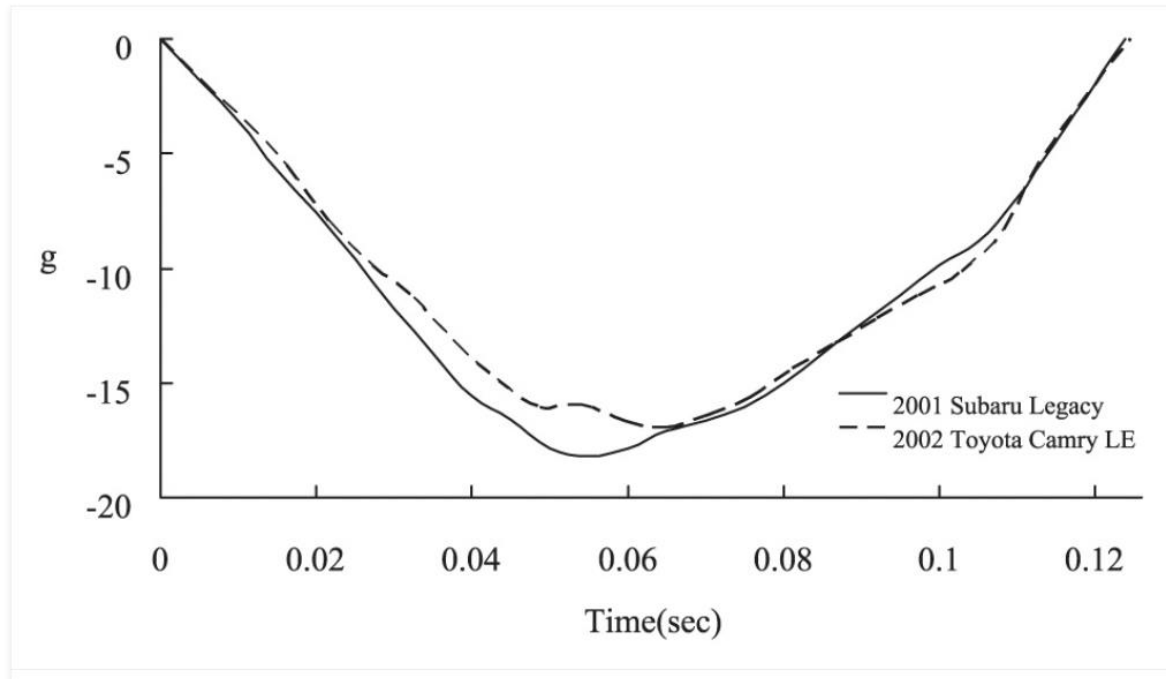


Figure 1 as seen above (Teng et al., 2017) ^[9] is a graph comparing the negative acceleration seen in a frontal crash pulse of the 2002 Toyota Camry LE I looked at earlier and a 2002 Subaru Legacy. The crash pulse curves show a similar area and time duration for both vehicles. However, the Subaru Legacy does appear to have a higher maximum acceleration. According to Autoblog, (2024) the gross weight of the 2002 Toyota Camry LE is 4123lbs, equivalent to 1870kg. ^[10] The 2001 Subaru Legacy weighs 4400lbs, or 1996kg. Taking “g” or the acceleration due to gravity as 9.81ms^{-1} we can calculate the approximate maximum forces in both of these crash tests using Newton’s second law of motion: $F = m \cdot a$ whereby we multiply the gross weight of the vehicles with “g”. The Toyota Camry exhibits a maximum “g” value of approximately -17 whereas the Subaru Legacy reaches about -18g. After calculating, the Camry’s crash pulse shows a maximum magnitude of force being 311.86 kN with the Legacy reaching 352.43 kN. That’s a difference in force of 40.57 kN. Both of these values are significantly smaller than the critical buckling load calculated previously for the steel rocker panel to reach failure. The steel rocker panels are made to withstand much greater forces than those recorded in the Figure 1 data and so the critical buckling load is reasonably a lot higher than the approximate maximum force calculated from the data above.

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