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The Effectiveness of Synthesizing A-Pillar Structures in Passenger Cars

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***Abstract*—**The Toyota Camry is one of the best-selling cars in America. It is economical, reliable, and most importantly, safe. These attributes allowed the Camry to be the trustworthy choice when choosing dependable vehicle. However, a new finding brought question to the Camry's safety. Since 1997, the Camry received a "good" rating on its moderate overlap front crash test through the Insurance Institute of Highway Safety. In 2012, the Insurance Institute of Highway Safety introduced a frontal small overlap crash test into the overall evaluation of vehicle occupant safety test. The 2012 Camry received a "poor" rating on this new test, while the 2015 Camry redeemed itself with a "good" rating once again. This study aims to find a possible solution that Toyota implemented to reduce the severity of a frontal small overlap crash in the Camry during a mid-cycle update. The purpose of this study is to analyze and evaluate the performance of various A-pillar shapes as energy absorbing structures in improving passenger safety in a frontal crash. First, A-pillar structures of the 2012 and 2015 Camry were modeled using CAD software, namely SolidWorks. Then, a crash test simulation using ANSYS software, was applied to the A-pillars to analyze the behavior of the structures in similar conditions. Finally, the results were compared to safety values of cabin intrusion to determine the crashworthy behaviors of both A-pillar structures by measuring total deformation. This study highlights that it is possible that Toyota improved the shape of the A-pillar in the 2015 Camry in order to receive a "good" rating from the IIHS safety evaluation once again. These findings can possibly be used to increase safety performance in future vehicles to decrease passenger injury or fatality.

***Keywords*—**A-pillar, crashworthiness, design synthesis, finite element analysis.

I. INTRODUCTION

THE evolution of vehicle crash safety has increased exponentially over the past several decades. What was once considered to be the safest vehicle only 10 years ago would not be safe today. Although the goal of crash safety is to minimize injury and fatality to vehicle occupants, there is little incentive to increase safety if the standards are never changed. Vehicles that were deemed safe with good ratings were still involved in fatal crashes. It is clear that if the number of fatalities due to car crashes are not decreasing, safety standards must be updated.

Vehicle crashworthiness is the science of focusing on protecting occupants during an accident event through the utilization of various safety systems. These systems include: minimizing vehicle crush to maintain occupant survival space, providing proper restraint throughout the entire event, preventing ejection from the vehicle and maintain seating positions, distributing energy and dissipate crash forces, and prevent post-crash fires. These safety systems must work together to provide occupant protection throughout the entire accident. If one system fails, it is likely that injury will occur. The most important safety system is the body structure of the vehicle. It must be designed to dissipate crash forces and distribute energy away from the cabin to mitigate damage to the passenger cabin. A vehicle safety cage is a structure of various grades of high tensile steel that resists deformation in the event of a collision to protect the passengers from external injury. The area inside the safety cage is referred to as the survival space and maintaining this space is essential in preventing the life of the passengers. By studying various designs of these crash structures, possible improvements to vehicle crashworthiness may be found.

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II. IIHS FRONTAL CRASH TEST

The most common type of crash resulting in fatalities is the frontal crash. For this reason, major efforts have been made to improve front protection, mainly from the crash test program that the NHTSA began in the late 1970s and the crashworthiness evaluations that IIHS began in 1995. When IIHS began the moderate overlap frontal crash test, the majority of vehicles were rated poor or marginal. Today, all vehicles earn good ratings since vast improvements have been made to occupant compartments and standard passive safety restraints such as safety belts and airbags protect the passengers. In the moderate overlap frontal crash test, a vehicle travels at 40 mph into a 2 feet tall deformable barrier made of aluminum honeycomb. A Hybrid III dummy representing an average-size man is positioned in the driver seat. 40% of the total width of the vehicle strikes the barrier on the driver side. This test simulates a frontal offset crash between two vehicles of the same weight, each traveling at 40 mph [5].

Fig. 1 Moderate Overlap Frontal Test Configuration

To encourage further improvements in frontal crash protection, the IIHS introduced a driver-side small overlap frontal crash test in 2012 [8]. This test was designed to simulate a collision with the front left corner of the vehicle and another vehicle or object such as a tree. This crash test is a challenge for some safety belt and airbag designs because occupants move both forward and toward the side of the vehicle. In this test, the vehicle travels 40 mph into a 5-foot-tall rigid barrier [10]. Only 25% of the total width of the vehicle strikes the barrier on the driver side. The same Hybrid III dummy from the moderate overlap test is used here as well. Most modern cars have crush zones that help manage crash energy to reduce forces on the occupant compartment. Although these crush zones are built to withstand head-on collisions with little deformation, they are concentrated in the middle 50% of the front end. A moderate overlap crash involves these crush zones and the cabin is protected from intrusion and crash energy is mitigated with front airbags and safety belts. Small overlap frontal crashes primarily affect a vehicle's outer edges, which are not well protected by the crush structures. The crash forces can directly travel into the front wheel, through the suspension system and into the firewall, leading to cabin intrusion resulting in serious leg and foot injuries. To provide effective protection in small overlap crashes, the safety cage needs to resist crash forces that are not defended by the crush zone structures.

III. IIHS Small Overlap Test Protocol

Small overlap barrier crash tests are conducted at 40 ± 0.6 mi/h and 25 ± 1 percent overlap [4]. The test vehicle is aligned with the rigid barrier such that the right edge of the barrier face is offset to the left (driver side) of the vehicle centerline by 25 ± 1 of the vehicle width. The vehicle is accelerated by a propulsion system at 0.3 g until it reaches 40 mph, and then released about 25 cm before contacting the barrier. The vehicle's rear brakes are activated 1 second after release.

The rigid barrier is made of a vertical steel plate, with a radius on the right edge of 150 mm and continues to form a 115-degree arc. The front plate has a thickness of 38.1 mm and is 1000 mm wide. The barrier sits on the floor with a height of 1524 mm, and is attached to a base unit. The dimensions of the base unit are: 184 cm high, 366 cm wide, and 542 cm deep. It is composed of laminated steel and reinforced concrete with a total mass of 145,150 kg. The rigid barrier is mounted to the right side of the base unit, which allows the test vehicle to continue its motion after contact [9].

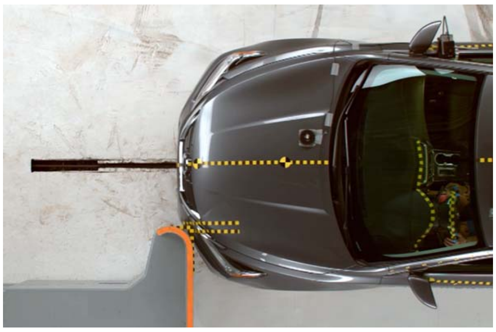

Fig. 2 Driver-side Small Overlap Frontal Test Configuration

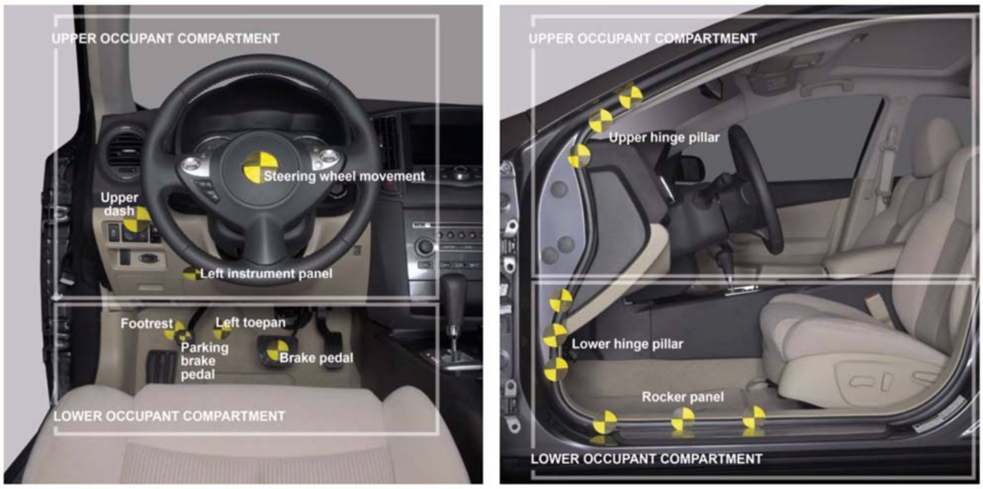

Fig. 3 Locations for Measuring Vehicle Intrusion

The lower and upper hinge pillars have three targets each. The hinge pillar is measured at the inner most surface of the door opening, usually on the pinch weld. The vertical coordinates for the three lower targets are obtained by adding 0 cm, 7.5 cm, and 15 cm, to the brake pedal reference point. The upper targets are obtained by adding 45 cm, 52.5 cm, and 60 cm from the pinch weld [10].

The exterior surfaces of the vehicle are trimmed with inch measurement tape and photographic targets are applied at specific points to enable analysis of the high-speed camera footage after the crash test. The targets are applied along the A-pillar, starting at the base, and every 10 cm in the longitudinal direction. By comparing the positions of these targets before and after the crash test, the amount of intrusion can be measured to determine the safety ratings. An intrusion plot is used to define the safety level thresholds for each target area, with ratings from poor, marginal, acceptable, and good. A car is deemed safe when most of its targets have a displacement that is in the green (good) region.

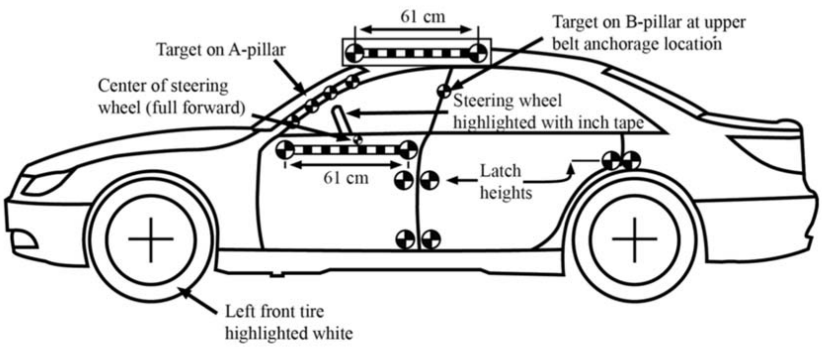

Fig. 4 Locations of Crash Test Targets

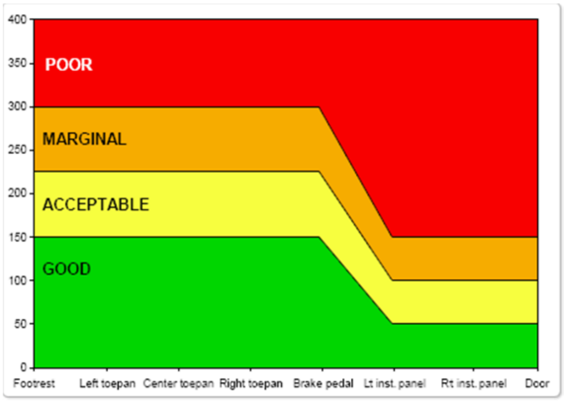

Fig. 5 Intrusion Plot

IV. A-Pillar Structure

The vertical structures on the front of an automobile that support the windshield and front windows are called A-pillars. These pillars provide rigidity and strength to the vehicle chassis and provide a layer of safety from frontal crashes and roof crushes during rollover accidents. Since the A-pillar is the strongest structure closest to the driver, it plays an important role in protecting the driver from injury. If the A-pillar is compromised during a crash, it is very likely that the occupant will be severely injured due to the proximity of the head and neck to the buckled A-pillar [7]. The A-pillar plays the most important role in the "safety cage" of cabin due to the fact that most fatal accidents are from frontal and rollover collisions.

V. Toyota Camry

The Toyota Camry is one of the best-selling vehicles in the United States, mainly due to its value, reliability, and most importantly, safety. Buying a Camry meant that you did not have to question its safety and this is an important factor to consider when purchasing a vehicle to transport your family. Although the Camry has always received good ratings in frontal crash tests from IIHS, it received a "poor" rating in the small overlap test that IIHS implemented in 2012 [1]. Toyota had to act quickly to make structural improvements to the Camry to increase their safety ratings.

Studying the data provided by IIHS for the Toyota Camry before and after the introduction of the frontal small overlap crash test showed that there was a likelihood that Toyota made changes to the A-pillar to increase their "poor" rating to "good" between 2012 and 2015 Camry [2]. By examining the cross-sectional shape of the A-pillar, the possibility of an enhanced structure can be confirmed.

Fig. 6 2012 Camry Small Overlap Frontal Crash Results

The post-crash image of the 2012 Camry shows that the A-pillar has buckled and there is major intrusion into the occupant cabin. There is definite contact between the dummy's legs and the dashboard from firewall intrusion. The dummy's position in relation to the door frame, steering wheel, and instrument panel after the crash test indicates that the driver's survival space was not well maintained.

Conversely, the post-crash image of the 2015 Camry shows that the A-pillar has low deformation and the occupant compartment has little intrusion. The dummy's position in relation to the door frame, steering wheel, and instrument panel after the crash test indicates that the driver's survival space was maintained reasonably well in the IIHS' test.

When comparing the two images of the 2012 and 2015

Camry post-crash images, it is apparent that the A-pillar deformed much less in the newer car. Thus, it is possible that Toyota upgraded the A-pillar structure in the 2015 Camry to earn a "good" rating in the frontal small overlap crash test.

Fig. 7 2015 Camry Small Overlap Frontal Crash Results

VI. Benchmarking

Due to limited resources, the exact cross-sectional shape of the Toyota Camry A-pillar was not available to be used in this study. These body structures and shapes are not readily available online through the manufacturer websites because they are considered intellectual property. Visiting a salvage yard to cut the correct vehicle's A-pillar to find the exact shape was not a feasible solution, consequently, a vehicle that exhibited high safety performance with an available A-pillar cross-section information was used.

Since the 2012 Toyota Camry did not fare well in updated frontal small overlap test by IIHS, a vehicle that did perform well throughout all the years had to be found as a benchmark. Many vehicles that previously earned a "good" rating in the IIHS moderate overlap test received a "poor" rating after the small overlap test was introduced. One vehicle that received the TOP SAFETY PICK+ award from IIHS was the Volvo XC60 [3]. To qualify for the TOP SAFETY PICK+, a vehicle must earn good ratings for occupant protection in at least 4 of 5 evaluations (moderate overlap front, driver-side small overlap front, side, roof strength, and head restraint tests) and no less than acceptable in the fifth test. The Volvo XC60 received this award from 2012 to 2019. As a result, the Volvo XC60's A-pillar cross-sectional shape was used as a benchmark to evaluate a possible upgrade in the 2015 Toyota Camry.

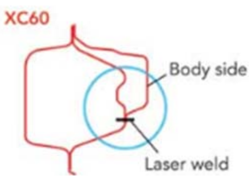

Fig. 8 2012 Volvo XC60 A-Pillar Cross-Section

The material typically used for modern A-pillar structures is high strength steel (HSS) which has a yield strength of 210-550 MPa and tensile strengths of 270 to 700 MPa. Many newer cars have adopted the use of advanced high strength steel (AHSS) while includes ultra-high strength steel (UHSS) which has a yield strength of 550 MPa or more and a tensile strength of 700 MPa or more [6]. Recent cars have been designed with smaller and thinner A-pillars made out of UHSS to increase visibility and stiffness to the safety cage. For the purpose of this study, the lower end of HSS steel will be used for both A-pillars to focus on A-pillar cross-section and not material.

VII. Concept Generation

The definition of design is to synthesize new or to arrange existing things in a new way to satisfy a recognized need of society. To confirm that Toyota improved the A-pillar structure of the 2015 Camry to receive good ratings in the small overlap test, the shape of the A-pillar had to be tested. Since the cross-sectional shape of the 2015 Camry A-pillar was unknown, a shape of an available, well performing A-pillar had to be used. The 2012 Volvo XC60 A-pillar cross section was available and the car not only received excellent ratings in the small overlap crash test, but won the IIHS TOP SAFETY PICK+ award for that year. By combining the side profile shape of the 2015 Camry A-pillar and the cross-section shape of the 2012 XC60 A-pillar, a new structure was synthesized to create a new design to be tested.

VIII. CAD Modeling with SolidWorks

Two A-Pillar CAD models were drawn in SolidWorks software to be analyzed. An image of the side profile of both the 2012 and 2015 Toyota Camrys were pasted into SolidWorks to accurately define the scale to find the actual size of the vehicle. Both vehicles had a wheelbase of 2772.2 mm and the scale was set accordingly. A spline was drawn to close follow the curvature of the A-pillar as a backbone. A generic A-pillar cross-section was drawn and extruded to follow the spline previously made to create the structure for the 2012 Camry. The wall thickness was set to 1.27 mm according to the 18-gauge steel commonly used in A-pillar sheet metal in most cars. The same process was executed for the 2015 Camry A-pillar, using the 2012 Volvo XC60 cross-section. These two A-pillars will have their performance tested in a simulation using ANSYS software.

Fig. 9 CAD Model of 2012 Camry A-Pillar

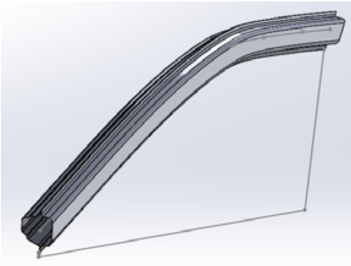

Fig. 10 CAD Model of 2015 Camry A-Pillar

Fig. 11 CAD Modeled A-Pillar Overlay of 2012 Camry

Fig. 12 CAD Modeled A-Pillar Overlay of 2015 Camry

IX. Simulation In Ansys Software

Using finite element analysis software, IIHS's small overlap crash test can be simulated to test the performance of the original and revised CAD models. The two 3D 2012 and 2015 Camry A-pillar models previously drawn were imported into ANSYS Workbench software for evaluation. Both models were imported into explicit dynamic loading analysis systems.

Both models were entered into Workbench as geometries and had meshes generated automatically with default settings. The material properties were entered as structural steel with a Young's Modulus of 200 GPa and Poisson's ratio of 0.3. The unit system was set to metric (m, kg, N, s). An explicit dynamic simulation was set up for each model. Initial conditions were set with an initial velocity of 17.9 m/s which is the equivalent of the 40 mph small overlap crash test speed in the Z-direction. The crash force was calculated using Newton's Second Law of Motion, F = ma. With an estimated weight of 1551 kg and acceleration of 17.9 m/s^2, the crash force was equal to 55.46 kN which was entered in the Z-direction. A solid wall was imported as a fixed geometry to acted as a rigid fixed barrier for the A-pillar to crash into. The simulation end time was set as 0.01 seconds. The solution outputs were set as total deformation, equivalent elastic (von Mises) strain, and equivalent (von Mises) stress. Total simulation time was 13.2 hours for the 2012 Camry and 14.3 hours for the 2015 Camry.

TABLE I
TABLE OF RESULTS OF SIMULATION

	2012 Toyota Camry	2015 Toyota Camry
Total Deformation	254.3 mm (9.843 in.)	29.3 mm (1.154 in.)
Maximum equivalent (von Mises) Strain	0.1407 m/m	0.16631 m/m
Maximum equivalent (von Mises) Stress	3.30 GPa	1.72 GPa

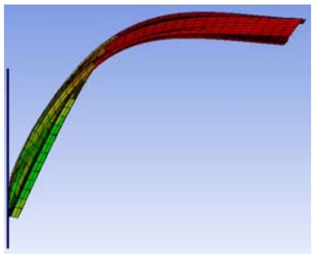

Fig. 13 ANSYS Simulation of 2012 Camry A-Pillar

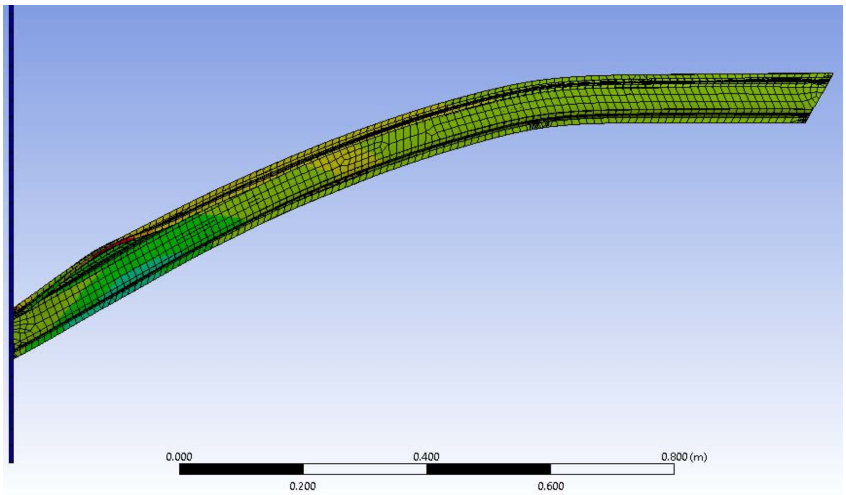

Fig. 14 ANSYS Simulation of 2015 Camry A-Pillar

X. Simulation Results

After simulating the A-pillar models to an applied dynamic load similar to a small overlap crash, the output data for total deformation, stress, and strain was obtained. The total deformation was 254.3 mm (9.843 in.) for the 2012 Camry and 29.3 mm (1.154 in.) on the 2015 Camry. The maximum equivalent (von Mises) elastin strain for the 2012 Camry was 0.1407 m/m and 0.16631 m/m on the 2015 Camry. The maximum equivalent (von Mises) stress on the 2012 Camry was 3.30 GPa and for the 2016 Camry, 1.72 GPa.

XI. Discussion

Comparing the results from the A-pillar simulations to the actual IIHS small overlap crash test photos containing the A-pillar structures, parallels can be seen. The total deformation of 9.843 in. in the longitudinal direction on the 2012 Camry appears to be consistent with the A-pillar buckling in the photo of the 2012 Camry in the IIHS crash test. Similarly, the lack of deformation of 1.154 in. from the 2015 Camry simulation matches the IIHS crash test photo for the 2015 Camry. Using the 61 cm. scale from the photo, the actual deformation is fairly close to total deformation from the simulation for both models. Examining the stress concentration denoted in red on the 2012 A-pillar in the simulation, it appears to be a match to the point of buckling on the actual 2012 Camry A-pillar. There is also a small stress concentration on the 2015 Camry pillar that matches the slight buckling on the actual pillar. Observing the data from NHTSA's NCAP test report for interior intrusion of the upper pillar, it appears to be a close match to the simulation results. The 2012 Camry reported an upper hinge pillar intrusion of 19 cm. whereas the simulation stated 25.4 cm. The 2015 Camry reported only 8 cm of upper hinge pillar intrusion and the simulation showed 2.93 cm. Comparing the values from the simulation, the data are a close match (within 6 cm) of the numbers from NHTSA's reports for both Camry models. Thus, the simulation performed validates the possibility of a cross-section shape upgrade between 2012 and 2015 in the Toyota Camry.

Fig. 15 Overlay of 2012 Camry A-Pillar Simulation on Actual Crash Photo

Fig. 16 Overlay of 2015 Camry A-Pillar Simulation on Actual Crash Photo

XII. Conclusion

In this experiment, two A-pillars from two different chassis of Toyota Camry were simulated and compared to their actual counterparts to validate the possibility of Toyota upgrading the A-pillar structure between 2012 and 2015 to obtain a good rating in the IIHS small overlap crash test. After an examination of the results of the simulation, similarities can be drawn from the reproduction and the real-world models. In conclusion, there is a high possibility that Toyota made structural improvements to the Camry A-pillar in terms of cross-sectional shape to strengthen the safety cage in order to earn high marks on the small overlap crash test.

By validating that a change in shape can greatly affect the deformability of a structure, ideas for new shapes can be formed. This study can potentially pave the way to develop new structures to improve crash safety in new vehicles. The study by IIHS mentioned earlier was performed because there was a need to decrease fatalities, thus safety standards were revised. Although vehicle safety has greatly increased in recent years, constant improvement in safety will always be a necessity as long as people drive cars. Through research and mechanical design, new structures will be developed to protect the lives of vehicle occupants.

XIII. Limitations

Although the results of the simulation closely matched the real-world counterparts, there is still a possibility that Toyota increased the tensile strength of the A-pillar structure. Since this study focused only on the cross-sectional shape of the A-pillar, further improvements in material choice and assembly techniques can be made. This study also does not take crush zones in front of the vehicle into account which may disperse most of the energy from the crash before it reaches the A-pillar and the rest of the safety cage. Since the actual cross-section of the Toyota A-pillar was unknown, there is no way to find the dimensions without having both cars present.

References

[1] "2012 Toyota Camry Crash Test." *IIHS*, Insurance Institute of Highway Safety, 2012, www.iihs.org/ratings/vehicle/Toyota/camry-4-door-sedan/2012.

[2] "2012 Volvo XC60 Crash Safety." *IIHS*, Insurance Institute of Highway Safety, 2012, https://www.iihs.org/ratings/vehicle/volvo/xc60-4-door-suv/2012.
[3] "2015 Toyota Camry Crash Safety." *IIHS*, Insurance Institute of Highway Safety, 2015, www.iihs.org/ratings/vehicle/Toyota/camry-4-door-sedan/2015.
[4] Aylor, David A.; et al. "How the 64.4 km/h (40 mi/h) Frontal Offset Deformable Crash Test Relates to Real-world Crash Severity." *Proceedings of the Second International Expert Symposium on Accident Research (CD-ROM)* September 2006.
[5] Farmer, Charles M. "Relationships of Frontal Offset Crash Test Results to Real-World Driver Fatality Rates." *Traffic Injury Prevention*, vol. 6, no. 1, 2005, pp. 31–37., doi:10.1080/15389580590928981.
[6] Larsson, Johnny K. "Laser Development at Volvo." *Industrial Laser Solutions*, 1 Mar. 2013, www.industrial-lasers.com/welding/article/16485578/laser-development-at-volvo.
[7] Mueller, Becky C., et al. "Structural Design Strategies for Improved Small Overlap Crashworthiness Performance." *SAE Technical Paper Series*, 2014, doi:10.4271/2014-22-0006.
[8] Sherwood, Christopher P., et al. "Development of a Frontal Small Overlap Crashworthiness Evaluation Test." *Traffic Injury Prevention*, vol. 14, no. sup1, 2013, doi:10.1080/15389588.2013.790539.
[9] Sherwood, Christopher P.; et al. "Characteristics of Small Overlap Crashes." *Proceedings of the 21st International Technical Conference on the Enhanced Safety of Vehicles (CD-ROM)* June 2009.
[10] "Small Overlap Test Protocol." *IIHS*, Insurance Institute of Highway Safety, 2017, www.iihs.org/ratings/about-our-tests/test-protocols-and-technical-information.