Development of a 2020 SUV vehicle FE model

Rudolf Reichert, Umashankar Mahadevaiah, Cing-Dao (Steve) Kan, Lukas Fuchs

Center for Collision Safety and Analysis, George Mason University, USA

1 Objective

Finite element (FE) vehicle models allow researchers to conduct diverse simulation studies. Members of the Center for Collision Safety and Analysis (CCSA) at the George Mason University (GMU), that also built the core team of the formerly known National Crash Analysis Center (NCAC), have been developing a fleet of publicly available FE vehicle models [1] over the past 25 years. This paper describes the latest model, representing a 2020 Nissan Rogue SUV vehicle, shown in Figure 1. Note that the vehicle has been named as the Nissan X-Trail in all countries it is sold, except for the United States and Canada, where it called Nissan Rogue.

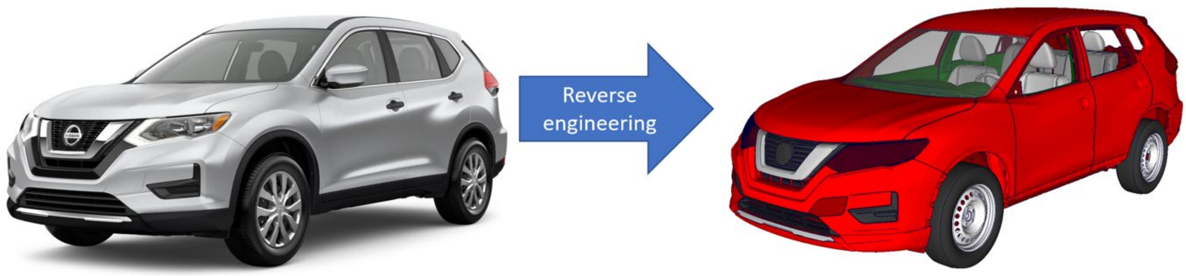

Fig.1: 2020 Nissan Rogue (a) physical vehicle and (b) developed FE model

2 Methods

State-of-the-art modeling techniques were used to develop a detailed SUV vehicle model. A reverse engineering process, which included geometry generation, vehicle tear down, meshing, connection modelling, and material characterization, was used. Data from available and conducted full-scale crash tests allowed to validate the FE model for multiple impact configurations. Side impact load cases included the Moving Deformable Barrier (MDB), pole, and static door crush configurations. The NCAP rigid barrier and NHTSA's frontal oblique impact scenarios were used for validating performance in frontal impact conditions. Furthermore, pedestrian safety characteristics were validated using the adult head form, child head form, upper leg, and lower leg impactors according to respective EuroNCAP test data [2].

3 Results

The developed detailed FE model of a crossover SUV consists of about 1300 parts and 3 million elements representing geometry, connections, and material characteristics of relevant structural and interior components. A uniform mesh with an average element size of 8 mm and a timestep of 0.9 microsecond was used. The developed FE model showed good correlation when compared to respective frontal and side impact test results. Kinematics, deformations, and time-history data compared overall well with respect to full-scale crash test data. Correlation and Analysis (CORA) [3] and ISO 18571 [4] were used for objective correlation metrics. While the initial validation focused on structural performance, the model includes interior components, such as front and rear seats, instrument panel, pedals, and steering wheel.

3.1 Full frontal impact

First, the FE model was validated using data from a full-frontal impact at 35 mph which equals to 56 km/h into a rigid wall. Deformations, kinematics, and structural performance were compared using pictures, videos, and animations, as shown in Figure 2 (a). The crash velocity pulse from the test and simulation, measured at the center of gravity, is shown in Figure 2 (b). The vehicle pulse from an existing full-scale test with the NHTSA number 8588 is shown in black and the respective pulse from the Nissan Rogue simulation is shown in blue. The test and simulation showed good correlation documented by a CORA score well above 0.9. While validation focused on structural performance, the model does include interior components, such as front and rear seats, instrument panel, pedals, and steering wheel.

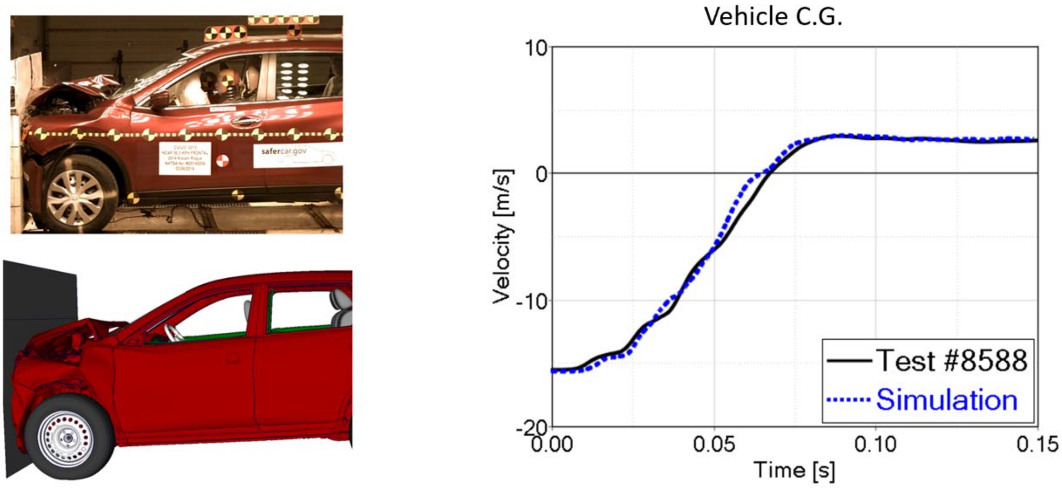

Fig.2: Full frontal impact test vs simulation (a) deformation; (b) crash pulse

3.2 Frontal oblique impact

The FE model was also evaluated in NHTSA’s frontal oblique impact configuration where an offset moving deformable barrier travelling at 90km/h impacts the stationary SUV at a 15-degree angle and a 35% overlap. Figure 3 (a) shows a top view of test and simulation with the characteristic significant vehicle deformation at the left corner due to the partial overlap and high impact energy. Figure 3 (b) shows the crash velocity pulse measured at the center of gravity of the vehicle. The crash pulse from an existing full-scale test with the NHTSA number 9574 is shown in black and the respective pulse from the Nissan Rogue simulation is shown in blue. Again, a good correlation was observed, documented by a CORA score above 0.9.

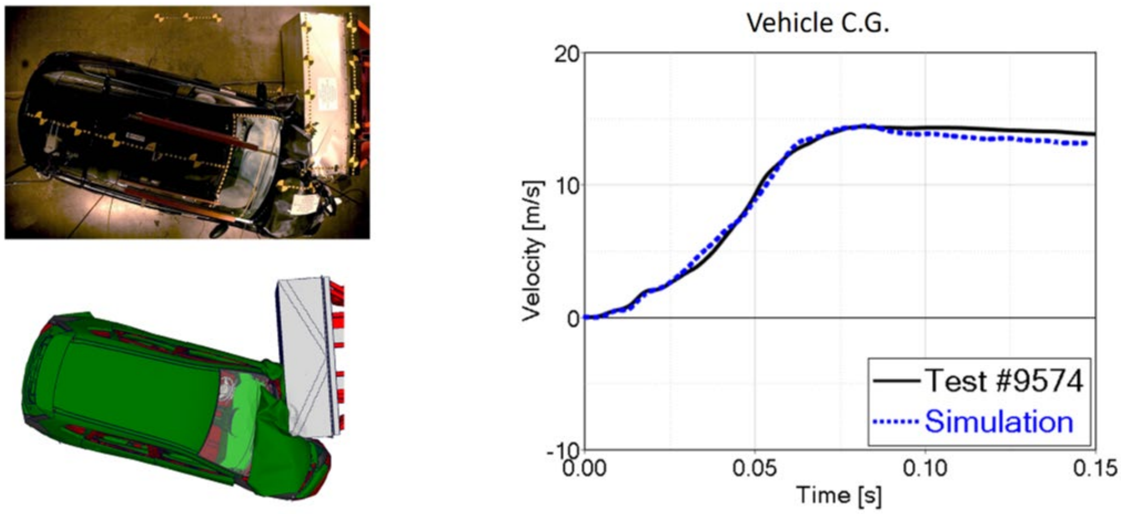

Fig.3: Frontal oblique impact test vs simulation (a) deformation; (b) crash pulse

3.3 Side impact – Moving Deformable Barrier (MDB)

The FE model was initially developed for a side impact study. First the moving deformable barrier configuration was simulated and compared against existing full-scale test data. The 27-degree crabbed MDB impacted the stationary SUV at 62km/h. In contrast to many sedan vehicles, the higher sill of the Nissan Rogue resulted in a clear overlap with the MDB face, as shown in Figure 4 (a). The resulting maximum external crush in the simulation was 185 mm, which is between the measurements from two existing full-scale tests of 168 mm and 220 mm, respectively. The time history data from the simulation, shown in blue showed good correlation with data from a full-scale test #8546, shown in black, as shown in Figure 4 (b). Maximum absolute velocity, measured at the middle of the B-Pillar was 6.8m/s and 7.1m/s in simulation and test (NHTSA #8546), respectively.

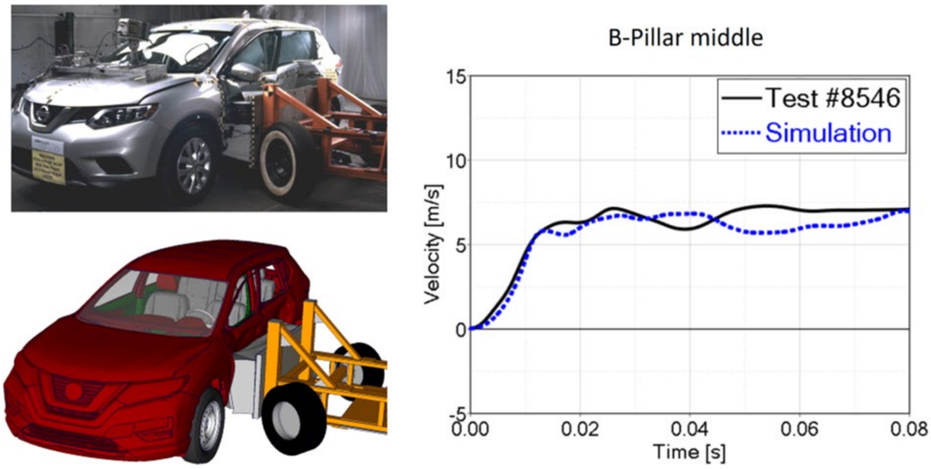

Fig.4: Side impact MDB test vs simulation (a) deformation; (b) B-Pillar pulse

3.4 Side impact – oblique pole

The FE model was also validated against the side oblique pole impact, where the vehicle hits the stationary pole at an angle of 75 degrees and at a speed of 32km/h. Higher intrusion compared to the MDB configuration with visible deformation of the sill, door and roof areas were observed in both the test and simulation, as shown in Figure 5. The maximum external crush of 398 mm in the simulation compared well with the maximum external crush of 390 mm documented for the full-scale test #9780.

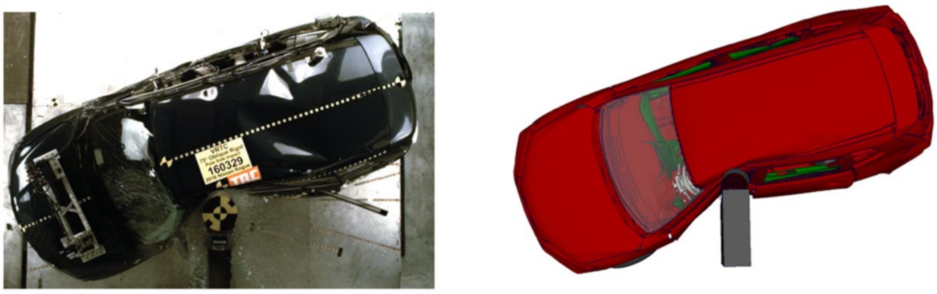

Fig.5: Side impact oblique pole test vs simulation

3.5 Side impact – quasi-static door crush

In addition to the dynamic side impact configurations MDB and pole, quasi-static door crush tests for the front and rear door were conducted in cooperation with the Technical Research Center in Ohio. In this configuration, a rigid cylinder is moved into the door up to 18 inches, which equals to 457mm according to FMVSS 214, as shown in Figure 6 (a). The resulting force versus displacement history, as shown in Figure 6 (b), is then used to verify that the door crush resistance meets the requirements for the first 6 inches, the intermediate crush between 6-12 inches, and the peak force. Force vs. displacement measured in the simulation, shown in blue, and documented for the conducted test, shown in red, compared reasonably well, documented by a CORA score of 0.87. The minimum initial, intermediate, and peak door crush resistance force criteria were clearly met in both the test and simulation.

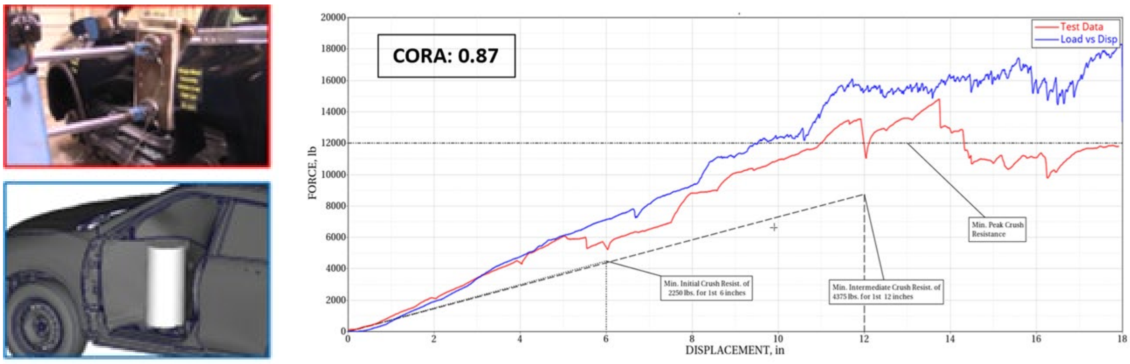

Fig.6: Quasi-static door crush test vs simulation (a) deformation; (b) Force vs intrusion

3.6 Vulnerable Road User (VRU) impact configurations

In addition to frontal and side impact evaluations, the 2020 Nissan Rogue FE model was validated against existing pedestrian impact test results. Validation was performed for impact configurations typically used to evaluate pedestrian safety. These included child and adult head forms, upper leg, and lower leg test devices according to EuroNCAPs test and evaluation protocols. Figure 7 (a) shows an example of a pedestrian impact using the global human body model, as well as the head form impactor, the upper leg impactor from LSTC, and the flexPLI lower leg impactor from “ATD models” company. Figure 7 (b) summarizes the results by color-coding the simulation data for the respective impact configurations and impact locations. Figure 7 (c) shows the respective test results. The Nissan Rogue simulation results correlated well at most impact points using the adult and child head forms, as well as for the upper and lower leg configurations. Simulation results for the windshield wiper and headlight areas were found to be conservative compared to the corresponding test results.

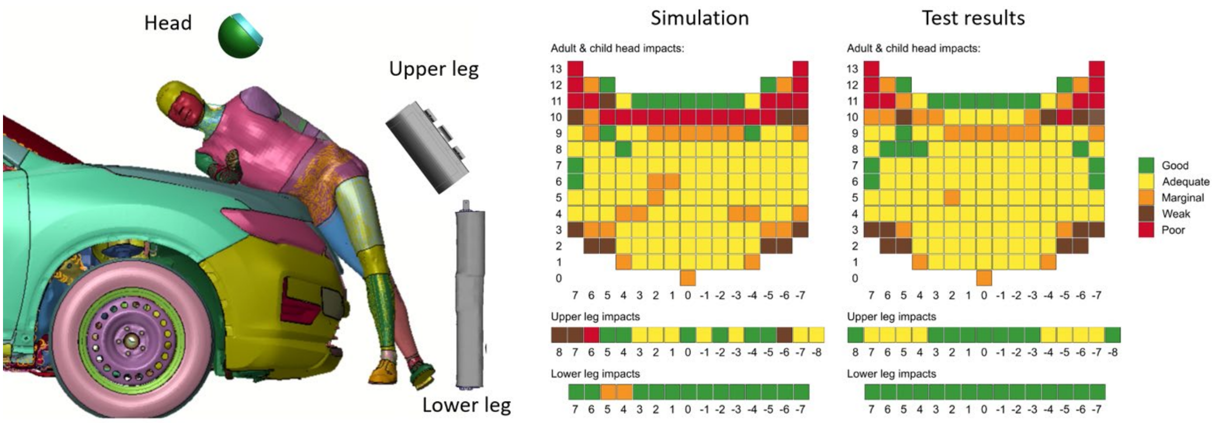

Fig.7: (a) Pedestrian safety impactors; (b)simulation results; (c) test results

Figure 8 compares simulations results using the adult headform with respective test results provided by EuroNCAP [7], NHTSA [8], and Nissan. Euro NCAP or NHTSA test results were available for 20 of 166 headform test points. These results were compared with the simulations results at these test impact locations. The ten results of the experimental Euro NCAP tests were used by Euro NCAP to calculate the correction factor for the assessment of the head impact score. This correction factor was 0.964, resulting in a score of 15.440, lower than Nissan predicted for the car. The ten results of the experimental NHTSA tests lead to a correction factor of 1.065. Hence, the head impact score of 17.045 calculated from NHTSA’s results was higher than predicted by Nissan. The simulation results resulted in a correction factor of 0.911 and head impact score of 14.582 by considering just the 20 headform test points. The improved model achieved a head impact score of 14.675 by considering all 166 test points and calculating the head impact score directly based on the achievable 166 points for all test points.

The overall head impact score of 14.582 for the simulation compared reasonably well with the head impact score of 15.440 for the EuroNCAP test results.

C/A	X	Y	Euro NCAP color	Euro NCAP HIC	NHTSA HIC	Nissan Predicted	Accepted Tolerance Range	Simul.
C	0	0			1199	1000-1350	909.09 ≤ HIC15 < 1500.00	1116
C	1	3		762		650-1000	590.91 ≤ HIC15 < 1111.11	863.8
C	1	-4			1574	1000-1350	909.09 ≤ HIC15 < 1500.00	1205
C	2	-2		807		650-1000	590.91 ≤ HIC15 < 1111.11	717.3
C	3	-7			1074	1350-1700	1227.27 ≤ HIC15 < 1888.89	1616
C	4	5			690	650-1000	590.91 ≤ HIC15 < 1111.11	1096
C	4	0			566	650-1000	590.91 ≤ HIC15 < 1111.11	845.3
C	4	-7		1019		650-1000	590.91 ≤ HIC15 < 1111.11	1120
C	5	2		704		1000-1350	909.09 ≤ HIC15 < 1500.00	1081
C	6	7			532	<650	HIC 15 < 722.22	712.4
C	6	0		758		650-1000	590.91 ≤ HIC15 < 1111.11	953.6
C	6	-2			423	650-1000	590.91 ≤ HIC15 < 1111.11	1075
C	7	4		647		650-1000	590.91 ≤ HIC15 < 1111.11	676
A	8	0		711	563	650-1000	590.91 ≤ HIC15 < 1111.11	764.7
A	8	-5			715	650-1000	590.91 ≤ HIC15 < 1111.11	728.4
C	8	-6		746		<650	HIC 15 < 722.22	952.8
A	9	7			1096	650-1000	590.91 ≤ HIC15 < 1111.11	1100
A	10	-1		1139		650-1000	590.91 ≤ HIC15 < 1111.11	2907
A	10	-7		1377		1350-1700	1227.27 ≤ HIC15 < 1888.89	1840
A	11	0			572	<650	HIC 15 < 722.22	543.7
Points			14	6.75	8.25			12.75
Correction factor				0.964	1.065			0.911
Head impact Scores				15.440	17.045			14.582
Head impact score including all test points of the improved model with a total score of 101.5 out of 166 possible points:								14.675

Fig.8: (a) Comparison of the results of the headform test points tested by EuroNCAP and NHTSA of NHTSA, Euro NCAP, baseline model, and improved model of the Nissan Rogue (Euro NCAP, 2014a; Suntay et al., 2019)

For seven out of fifteen lower legform test points experimental results of Euro NCAP or NHTSA were available. The experimental Euro NCAP and NHTSA results led to the full lower leg impact score of 6.0 points. The validated FE model achieved a lower leg impact score of 5.747 points.
Figure 9 highlights the quality of developed Nissan Rogue FE model by using an lower leg FlexPLI impact configuration example. The anterior cruciate ligament (ACL) elongation measured in the Flex PLI for the test at point L(3) [8] is shown in black. The initial simulation result before validation is represented by the blue curve, and the result for the validated Nissan Rogue vehicle (improved model) is shown in blue. Note that the maximum ACL elongation in the validated simulation model matches test result. The time history data in test and simulation correlate reasonably well.

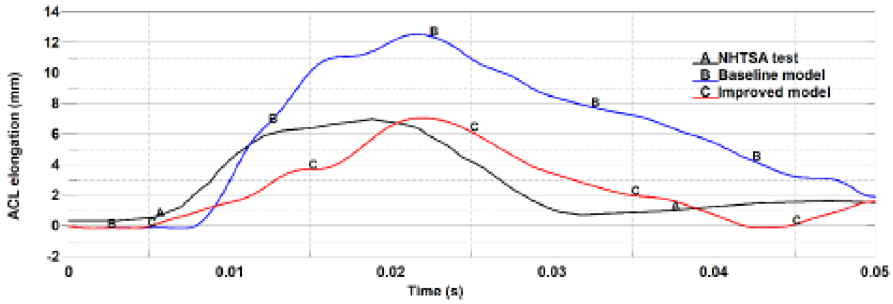

Fig.9: ACL elongation test vs simulation

3.7 Suspension validation

A total of eight (8) suspension tests were conducted by driving the 2020 Nissan Rogue over bumps. Tests were conducted at different vehicle speeds, bump heights and bump spacings. An example configuration is shown in Figure 10. Adequate suspension characteristics in the vehicle FE models are particularly relevant for roadside hardware impacts, such as a New Jersey barrier.

Fig.10: Suspension test configuration example (a) test; (b) simulation

The validation process is ongoing. Suspension components are depicted in Figure 11.

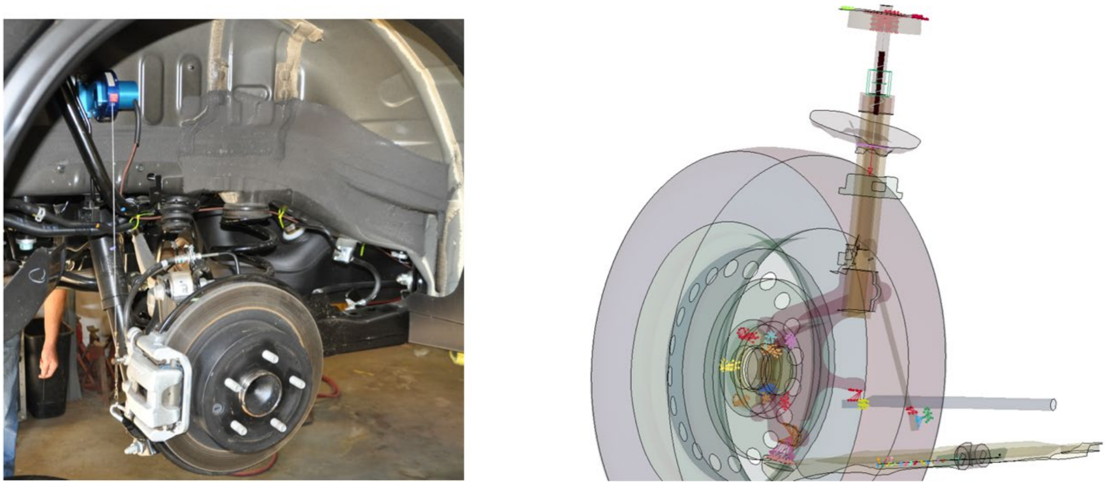

Fig.11: Suspension components (a) test; (b) simulation

In order to validate the characteristics of the suspension components, including the tyres, several physical tests were carried out on the entire vehicle. In these tests the suspension behaviour was observed as the car drove over one or more bumps at 16 km/hLinear and rotational movements of the vehicle at the centre of gravity were recorded using tri-axial accelerometers and compression of the suspensions using string-pots. The tests were also videotaped at high speed for motion analysis. Validation of suspension involves modifying material properties of tire, spring and damper to reasonably match the results from all the tests. Time history data collected from accelerometers and string-pots along with video analysis are used in validation. Detailed analysis and results of suspension validation will be published in a separate paper.

4 Discussion and Limitations

The FE model represents relevant exterior and interior parts, including body in white, wheels, axles, suspension, seats, door trims, pedals, steering wheel, and instrument panel. Correlation of structural deformation and kinematics for frontal and side impact configurations is considered good. The developed FE model was used for several studies funded by NTHSA. For example, the SUV FE model as used as a crash partner vehicle to study the effect when impacted by Unoccupied Automated Driving

Systems with different structural compatibility characteristic [5]. It was also used for research related to Federal Motor Vehicle Safety Standard No. 214. FMVSS in the US requires doors to meet minimum force requirements when the door is statically loaded. It also requires occupant protection during dynamic MDB and vehicle-to-pole tests. The FE model was used in addition to a Toyota Camry sedan to understand the effect of mutual non-compliance for each of the three FMVSS 214 requirements [6]. It is currently used for additional research, including the evaluation of various frontal barriers in comparison to the existing full-face Offset Moving Deformable Barrier (OMDB).
The increase in pedestrian fatalities over the past decade has made pedestrian protection in cars an important aspect in the US market and worldwide. An update of the United States New Car Assessment Program (US NCAP) is expected to include some pedestrian safety measures in the future. There are a limited number of publicly available vehicle models that have been validated for pedestrian safety. Therefore, the Nissan Rogue FE model developed by the Center for Collision Safety and Analysis (CCSA), may be of significant value for future related VRU safety research.
Adding non-structural components allowed to achieve overall good correlation with respect to pedestrian safety. Limitations exist with respect to detailed headlights and windshield wipers. They were not modeled in the latest FE model version, which explains the potential for improvement for respective pedestrian safety configurations in these areas.

5 Conclusion

A detailed FE model representing a 2020 Nissan Rogue SUV vehicle has been developed using a reverse engineering process. It showed good correlation with existing crash test data for frontal, side, and pedestrian safety impact configurations.

6 Acknowledgement

This research was mainly funded by the National Highway Safety Administration. We thank our colleagues, Daniel Brown, Kevin Arellano-Moya, Doug Wang, Dhafer Marzougui, and Christopher Story for their significant contributions. Pedestrian impactor FE models were obtained from Ansys LST and "ATD Models GmbH". The pedestrian GHBM FE model was obtained from Elemance.

7 Literature

[1] https://www.ccsa.gmu.edu/models
[2] Euro NCAP. Official Nissan X Trail 2014 safety rating results. Euro NCAP. 2014 https://www.euroncap.com/en/results/nissan/x-trail/7883
[3] Thunert, C: "CORAplus User's Manual, Version 4.0.4." Partnership for Dummy Technology and Biomechanics, 2017
[4] Barbat, S. et. al.: "Objective rating metric for dynamic systems (Paper Number 13-0448)", 23rd Enhanced Safety of Vehicles Conference, Seoul, Republic of Korea, 2013
[5] Reichert, Kan, Park (2022). Crash Compatibility for Unoccupied Automated Driving Systems (DOT HS 813 xxx). NHTSA
[6] Reichert, Kan, Park (2023). Crash Simulation of FMVSS No. 214 Safety Performance. 27th ESV conference, Yokohama, Japan.
[7] Euro NCAP (2014) Euro NCAP Crash Test Results Nissan X-Trail. https://cdn.euroncap.com/media/4758/euroncap_nissan_x-trail_2014_5stars.pdf
[8] Suntay, B., Stammen, J., & Martin, P. (2019). Pedestrian Protection–Assessment of the US Vehicle Fleet. United States. Department of Transportation. NHTSA.