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Evaluation of SSF, Roof Crush Test as an Alternative to Dynamic Rollover Test using Numerical Approach

Khairul Amri Tofrowaih[1,2,*], Mohd Hafizi Abdul Rahman[1,2], Mohd Syazwan Abdul Samad[4], Mohd Suffian Ab Razak[1,2], Saiful Naim Sulaiman[1,2], Khairul Azri Azlan[1,2], Muhammad Zulkarnain[1,2], Ahmad Lukman Achmad Joehary[5], Abdul Munir Hidayat Syah Lubis[3]

[1] Faculty of Technology and Mechanical Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[2] Centre for Advanced Research on Energy, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[3] Department of Mechanical Engineering, Faculty of Engineering, Universitas Muhammadiyah Surakarta, Indonesia
[4] Perusahaan Otomobil Nasional Sdn. Bhd., 47600 Shah Alam, Selangor, Malaysia
[5] DreamEdge (M) Sdn. Bhd., 63000 Cyberjaya, Selangor, Malaysia

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ABSTRACT

Rollover accidents are classified into various scenarios, and with the increasing prevalence of high-centre-of-gravity (CG) vehicles in Southeast Asia (SEA) particularly in Malaysia, such as SUVs, MPVs and pickup trucks; assessing vehicle rollover risk has become critical. Even though rollover incident recorded low number of cases compared to other crash types in Malaysia, it had the highest casualty index for killed or seriously injured (KSI) and the situation induces worries because majority of the fatalities in rollover crashes among passenger vehicle occupants goes to high CG vehicle type. There are several limitations from the SEA nations to enforce costly dynamic rollover test as safety specification for SEA market requirement. Therefore, this study aims to evaluate Static Stability Factor (SSF), and roof resistance test (FMVSS 216), as an alternative to the dolly rollover test (FMVSS 208) using Finite Element Analysis (FEA). A correlated Chevrolet Silverado MY 2014 model is employed, with different SSF values representing varying levels of vehicle stability. The study evaluates peak force, peak energy absorption, and maximum intrusion during rollover simulations according to FMVSS 208 for vehicle models with different SSF values. Results indicated that vehicles with lower SSF values lead to higher energy absorption and intrusion, signifying increased rollover impact. Additionally, the article suggests that FMVSS 216 Roof Resistance Test is more severe than FMVSS 208 and vehicle rating system based on SSF value is vital for market awareness. Understanding the vehicle structural integration in rollover scenarios is essential for improving safety measures and vehicle design, especially for high-centre-of-gravity vehicles prevalent in the market.

1. Introduction

* *Corresponding author.*
E-mail address: khairul.amri@utem.edu.my

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Rollover accidents can occur in two ways, tripped or untripped. Tripped rollover happens when tires run over any mechanical obstacles whereby untripped rollover occur without any mechanical obstacles involved. Rollovers have been further classified into eight categories in the US according to the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) based on typical rollover crash initiation scenarios namely trip-over, flip-over, bounce-over, turn-over, fall-over, climb-over, collision with another vehicle, end-over-end. Considering the complex dynamics involved in rollover incidents, various experimental tests have been developed to closely replicate real-world scenarios. Examples of such tests include the FMVSS 208 (dolly rollover test), Jordan Rollover System (JRS), Controlled Rollover Impact System (CRIS) test, Ramped Rollover Test (flat and corkscrew), inverted drop test, curb trip rollover test, FMVSS 216 quasi-static roof resistance test by Young *et al.,* [1] 2006 compiled all legal requirements and design considerations for rollover safety of different vehicle types. It is observed that only FMVSS 216, FMVSS 208, and NCAP rollover rating are applicable to passenger vehicle class.

Recently, number of vehicles with high center of gravity (CG) on road has increased considerably especially in Southeast Asian region. High CG vehicles include Four Wheel Drive (4x4) vehicles, Sports Utility Vehicle (SUV), Multi-Purpose Vehicle (MPV) as well as Pick-ups. Trend shows that consumers tend to buy vehicles with more passenger capacity for their vehicle of choice. According to study by Santosa *et al.,* [2], between 2015 and 2016, Indonesia experienced specific trends in its new and second-hand car markets. In the new cars market, the distribution of vehicle types was as follows: SUVs accounted for 31%, MPVs for 28%, and hatchbacks for 22%. On the other hand, the second-hand cars market displayed a slightly different pattern, with SUVs still in the lead at 28%, followed by sedans at 28% (the second most popular type), and MPVs at 19%. The popularity of SUVs and MPVs among Indonesian consumers can be attributed to their ability to accommodate more passengers, making them preferred choices. Meanwhile, statistics of total industry volume sales for passenger vehicle and commercial vehicle from 2010 to 2022 extracted from Malaysian Automotive Association (MAA) data are as depicted in Figure 1 and Figure 2 below.

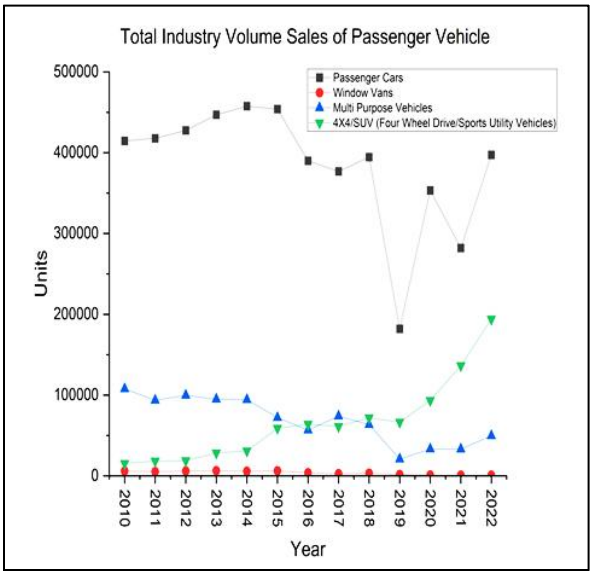

Fig. 1. Total industry volume sales of passenger vehicle

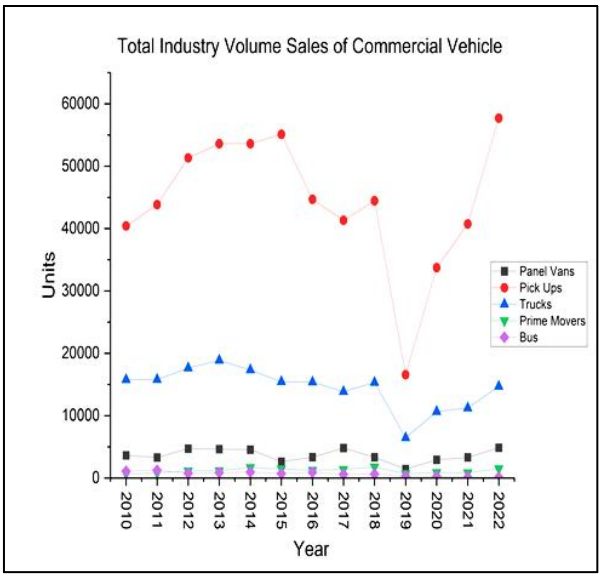

Fig. 2. Total industry volume sales of commercial vehicle

For the passenger vehicles category, 4x4 and SUV segments have shown consistent overall uptrend for the last 11 years, except for 2019 due to nation's lockdown because of COVID-19 pandemic. The pandemic significantly causes a drop in vehicle production and sales in Malaysia and the recovery is also affected by global shortage of semiconductor chips despite incentives put by Malaysian government by [3]. It seems like most of Malaysian drivers have started shifting towards the SUV segment rather than passenger cars in 2015, as the passenger cars yearly sales have showed downtrend compared to 4x4 and SUV segments counterparts. On the other hand, Pickups has visibly the highest yearly sales of commercial vehicles category which consistently sold more than 30,000 units every year excluding year 2019 as compared to other segments. To sum up, 4x4, SUV and Pickups vehicle segment dominate Malaysian Market recently regardless of the pandemic effect. One of the key indicators to assess the rollover risk is by calculating the vehicle Static Stability Factor (SSF). SSF measures the ratio of track width to the CG height of a vehicle. 4x4, SUV and Pickups segments by trends would have lower SSF value compared to sedan vehicle and higher SSF value unstable and tends to rollover in single vehicle collision [4]. The National Highway Traffic Safety Administration (NHTSA) also has established a rollover resistance rating system based on statistical correlation between SSF and rollover probability back in year 2002. For instance, Santosa *et al.,* [2] in their work projected a graph of rollover risk probability versus SSF of ASEAN SUV and MPV based on CG height predicted from published data, as shown in Figure 3 below. Vehicles with lower rollover probability number will be marked with excellent stars rating indicating the vehicle is less susceptible to rollover.

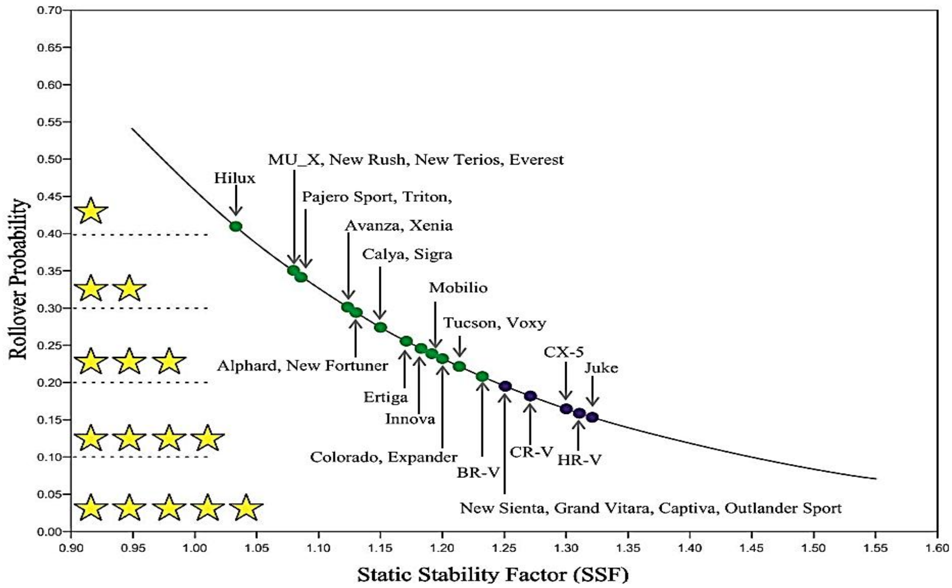

Fig. 3. The result of rollover risk probability versus of ASEAN SUV and MPV [2]

According to Traffic Safety Facts published by National Highway Traffic Safety Administration (NHTSA) for year 2017 to 2021, rollover accidents were responsible for more than a quarter (range of 28% to 29%) of all fatalities involving occupants of passenger vehicles. The highest percentage of fatalities in rollover crashes among passenger vehicles occupants killed in during 2017 to 2020 is SUV, except for the year 2021 pickups become the highest, refer to [5-16]. The summary is as shown in Table 1 below.

Malaysian Institute of Road Safety Research (MIROS) Crash Investigation and Reconstruction Annual Statistical Report for the year of 2007-2010 and 2011-2013 indicated that although rollover incident recorded low number of cases compared to other crash types, it had the highest casualty index for killed or seriously injured (KSI) of 6.06 and 10.07 respectively [17, 18]. The situation induces worries because majority of the fatalities in rollover crashes among passenger vehicle occupants goes to SUVs and pickups vehicle type as shown in Table 1 above since high CG vehicles (low SSF value) tend to roll more than lower CG vehicles (high SSF value).

Table 1
Summary of traffic safety statistics involving rollover crashes

Year	Percentage of fatalities due to rollover crashes involving occupants of passenger vehicles	Percentage of fatalities in rollover crashes among passenger vehicle occupants killed in the year, according to vehicle type
2021	29%	pickups (41%), SUVs (37%), vans (26%), and passenger cars (21%)
2020	30%	SUVs (42%), pickups (41%), vans (23%) and passenger cars at 22%
2019	28%	SUVs (41%), pickups (38%), vans at 25%, and passenger cars at 20%
2018	29%	SUVs (43%), pickups (40%), vans (24%), and passenger cars (20%)
2017	30%	SUVs (46%), pickup trucks (42%), vans (28%), and passenger cars (21%)

Faudzi *et al*., [18] also highlighted that extensive residual damage due to rollover crashes typically provides limited survival space for occupants which affects almost all seating positions. Outcome of injuries are very much related to amount of survival space resulting from a specific collision. Research by Conroy *et al.*, [19] found out that even when safety belts are correctly used, individuals with a greater magnitude of intrusion at their seat position were roughly ten times more likely to suffer serious injury. Actual rollover accident condition for instance maximum intrusion and intrusion speed into passenger compartment are much more represented in dynamic rollover test as suggested by Stephenson [20]. The finding is coherence with findings by Seyedi *et al*., [21] which states that FMVSS-208 Dolly Rollover Test method widely used to replicate the single vehicle rollover. Mao *et al*., [22] quotes that the disadvantage of FMVSS 216 quasi-static Roof Crush Test is that it only reflects the roof strength, rather than the pillar’s strengths, if it is loaded along a fixed orientation and response in that direction.

In addition, Rains compare quasi-static roof resistance test with dynamic roof crush resistance test (Inverted drop test). They found out that peak force in the dynamic roof crush resistance test is always higher than the static roof resistance test of the same vehicle model [23]. Capitalizing the advantage of simulation test which offers the freedom of repeatability features [24], the purpose of this research is to evaluate vehicle structural integration in terms of peak force and maximum intrusion for different vehicle SSF value according to FMVSS 208 dolly rollover test using Finite Element Analysis (FEA). This study's primary contributions are highlighted in the following areas: (i) the incorporation of rigid body dynamics to enhance simulation speed, and (ii) the development of an evaluation technique for various indicators and tests related to rollover crashworthiness, considering available resources.

The subsequent sections of the article are structured as outlined below: Section 2 delineates the comprehensive evaluation process for alternative FMVSS 208 dolly rollover tests. Section 3 presents simulations, results, and analyses pertaining to the crashworthiness of vehicles during rollovers. The final section provides concluding remarks.

2. Methodology

The overall process of this research is illustrated Figure 4. There was a very limited number of Finite Element (FE) models which have both FMVSS 208 dolly rollover test & FMVSS 216 roof resistance test result available to be compared with. Therefore, the pickup vehicle Chevrolet Silverado model year (MY) 2014 was selected because of the FE model and FMVSS 216 roof resistance actual test result availability. A full-scale validated FE model of Chevrolet Silverado MY 2014 that is available in Center for Collision Safety and Analysis (CCSA) website was originally modelled in parts using LS-DYNA nonlinear explicit finite element code was translated into RADIOSS using Hypermesh software and refined through extensive employment of better elements and spot-welds formulation. The detail of the vehicle specification and the model properties are as indicated in Table 2 and Table 3 below.

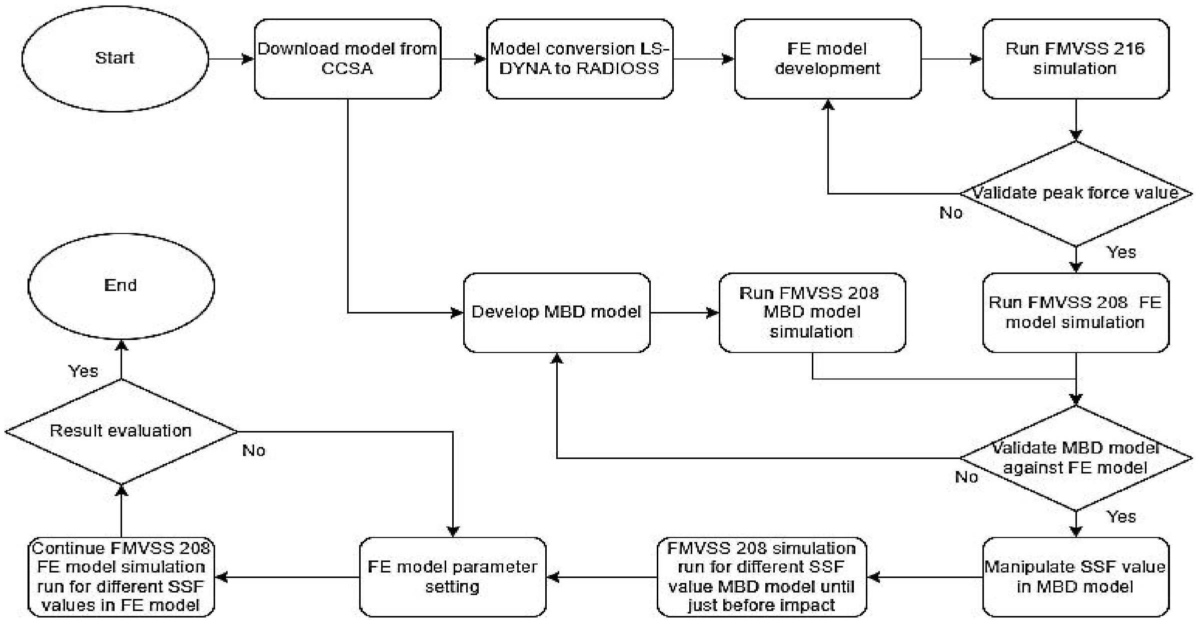

Fig. 4. Flowchart of the research

Table 2
Vehicle specification of Chevrolet Silverado 2014

Vehicle description	Details
Vehicle Identification Number (VIN)	3GCUKPEC7EG144266
Body type	4-door crew cab short box pick-up truck
Engine type	5.3L V8 Ecotec3
Transmission	6L80 hydra-Matic 6 speed automatic
Tire size	P255/70 R17

Table 3
Model properties [25]

Model properties	Details
Elements	2,960,781
Nodes	2,809,811
Parts	1,501
Features	Structural components details, Suspension system details, Uniform mesh throughout (to support multi-mode impacts)

The updated model is then compared to the actual FMVSS 216 roof resistance test to ensure the FE model mimics the actual vehicle structural integrity. The tuned model was then used in FMVSS 208 Dolly rollover test simulation in RADIOSS. However, the computer analysis is complex and requires plenty of computation time because it is done explicitly which is more suitable for extremely non-linear dynamic models. Due to the limited number of cores to process the complex simulation, the strategy is that the model is first simulated in Multi Body Dynamics (MBD) environment during the roll initiation and airborne phase until the model reaches position just before ground impact. Subsequently, the simulation is then continued in FE model RADIOSS software using translational & rotational motion parameters inherited from MBD model to investigate the rollover result. This approach is similar to the works by [26, 27], which they integrate MBD and FE simulation method in assessing rollover of bus. This is due to the reason MBD simulation capability to analyse the dynamic motion of a vehicle body as a rigid body with some contact setting and compliances could be set to compensate the deformation caused by moving parts.

Damping coefficient, c and stiffness, k parameter of contact between all tires and platform and compliant of joints between tires and vehicle body were set to correlate the vehicle rollover motion between MBD model and RADIOSS FE Model. The correlation of rollover behaviour of both FE model and MBD model are then assessed and MBD model is adjusted to reproduce the rollover occurrence accurately. Subsequently, the SSF value of the adjusted MBD model is varied to investigate the effect of SSF to the overall rollover behaviour. FE model for RADIOSS solver was analysed using the vehicle position and velocity (both translational and angular) data acquired from the MBD model dynamic simulation.

2.1 FE Model Development

Timestep 0.5μs is maintained from the original mesh sizes and setting during the LS-DYNA to RADIOSS conversion. Its element formulation and contact modelling are also converted considering its compatibility. A 4-noded reduced shell elements (Q4) is used as it is the most suitable for automotive full vehicle crash application. It is the lowest central processing unit (CPU) cost in the 4-noded shell elements category. Due to unavailability of FMVSS 208 published result for Chevrolet Silverado for comparison purpose, the correlated FE model via FMVSS 216 simulation serves as the basis of FE model for subsequent FMVSS 208 simulations due to comparable vehicle structure involved.

2.2 MBD Model Development

MBD model developed concurrently with the FE model development. The major purpose for model development in MBD model is to reproduce the rollover behaviour during roll initiation and airborne phase. The crucial parameter setting for the MBD model is in the contact definition. In this case, all tires and platform contact properties are set to stiffness, k value of 1,165 N/mm. Compliant fixed joint between wheel and vehicle body also has been optimized to ensure the rollover behaviour of MBD model is comparable to FE model as depicted in Figure 5. Subsequently, FMVSS 208 simulation is done in MBD software, and the rollover behaviour is observed. The crucial value of translational & rotational motion obtained from MBD model version of FMVSS 208 simulation just before ground impact is important as an input to FE model to recommence the FMVSS 208 simulation in FE environment.

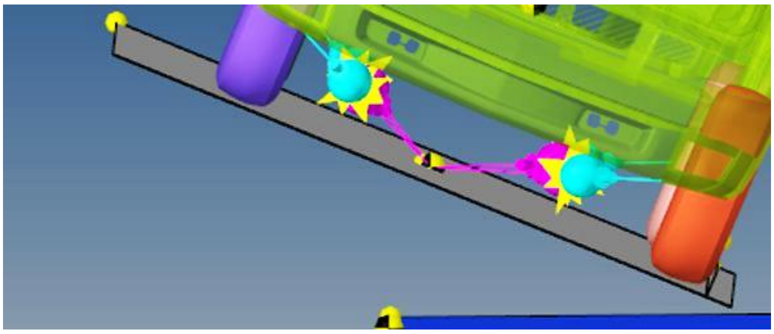

Fig. 5. Tire-platform contact definition in MBD

2.3 SSF Variation

Using the optimized MBD model, the minimum & maximum CG height is determined to evaluate the vehicle rollover behaviour for different SSF values. Two SUV models namely Ford Explorer MY 2004 & Dodge Magnum MY 2008 were selected with different SSF value are benchmarked. The SSF value for both SUV models are obtained from compilation of SSF value of passenger vehicle in Appendix A of Report No. DOT HS 812 444 [28]. It is proven that track width and vehicle CG height are the primary factors determining the rollover propensity of a vehicle [29]. In this study, using MBD model of Chevrolet Silverado MY 2014 while maintaining the track width dimension, only the CG height parameter is made modifiable based on reference vehicles as shown in Table 4 below to vary the SSF value for simplification .

Table 4
SSF variation based on CG height

SSF	Reference vehicle	Track width (mm)	CG height (mm)
1.2 (Original)	Chevrolet Silverado MY2014		1,441
1.41 (Maximum)	Dodge Magnum MY2008	1,730	1,227 (-214)
1.07 (Minimum)	Ford Explorer MY2004		1,617 (+176)

3. Results
3.1 Validation of Peak Force Value

This section discusses simulation result of Roof Resistance Test according to FMVSS-216 procedure. The percentage difference between simulation test and actual test of FMVSS 216 Roof resistance test is 20.21% as shown in Table 5 below.

Table 5
Comparison of FMVSS 216 roof resistance test result between actual and simulation

Results	Actual test FMVSS 216	Simulation test FMVSS 216 (RADIOSS)	Percentage difference
Peak force [kN]	94	113	20.21%
Strength to weight ratio (SWR)	4.10	4.92	

In FMVSS 216 test, the vehicle roof is crushed by an angled metal plate to a minimum displacement of 127 mm at a slow but constant speed. The force required to crush the roof is recorded along with the angled metal plate travel. The recorded force is then divided with measured vehicle curb weight to calculate the SWR value. The simulation provides maximum force value required to crush a vehicle roof during the angled impactor travel of 5 inches and strength to weight ratio (SWR) is then calculated based on peak force divided by the vehicle curb weight. SWR also had been ranked according to Insurance Institute for Highway Safety (IIHS) roof strength rating boundaries as specified in Table 6 below. According to the IIHS roof strength rating, the FMVSS 216 Roof resistance test result for Chevrolet Silverado MY 2014 is rated as Good because the SWR obtained is 4.10.

Table 6
Roof strength rating boundaries according to IIHS

SWR	Rating
≥ 4.00	Good
≥ 3.25 to < 4.00	Acceptable
≥ 2.50 to < 3.25	Marginal
< 2.50	Poor

The correlation between the actual FMVSS 216 test and simulation FMVSS 216 was established by the ability of the FE model to reproduce the crashworthiness behavior of the actual structure with minimal error. After iterations of evaluation, the smallest percentage difference of SWR value (20.21%) obtained is the result of refined through extensive employment of better elements, material models and spotwelds formulation. Similar situation had been encountered by Mao *et al.,* [30] where they found out that modelling of windscreen model affects their acceleration result of comparing the roof crush test between simulation and actual result especially between 0 to 0.02 seconds. Therefore, they suggested that employed material properties and the connection definition may affect the simulation result. Comparison of actual post-test photo of FMVSS 216 for Chevrolet Silverado model with simulation is as illustrated in Figure 6. It could be observed that the windshield crack behavior and pillar crash is comparable between actual post-test photo and simulation post-test photo.

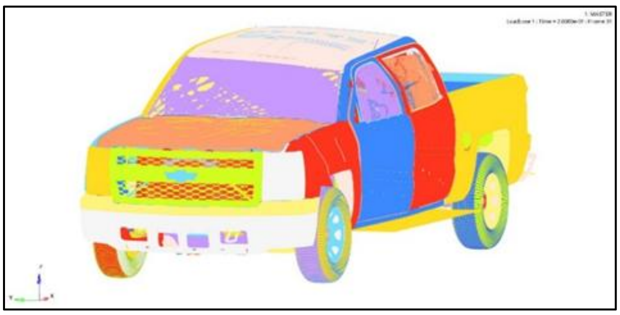

Fig. 6. Comparison of actual post-test photo (left) [31] of FMVSS 216 for Chevrolet Silverado model with simulation (right)

3.2 MBD Rollover Simulation

Using the similar vehicle model (Chevrolet Silverado MY 2014) with three different SSF values by manipulating its CG height parameter produces different rollover behavior. Rollover motion of base model with SSF value of 1.20 exhibits common rollover manners. Vehicle with higher SSF value (SSF 1.41) rotates to a position of approximately 90°. Vehicles with lower SSF value (SSF 1.07) rollover motion is significant which rotates near to 180°, with longer and further projection distance compared to others. Figure 7 shows rollover roll initiation motion of FMVSS 208 test in MBD environment at the start of simulation (t=0.3s) for the three different SSF values whereas Figure 8 below shows rollover motion of FMVSS 208 test in MBD environment in the end/middle of the airborne phase (t=1.14s) for the three different SSF values. The contact point of ground impact also varies for each SSF value model. The contact point of vehicle with SSF 1.20 is at the inner side front edge of the vehicle roof as shown in Figure 9. On the other hand, vehicle with SSF 1.41 contact point at ground impact is at the edge of outer side vehicle rear quarter panel as depicted in Figure 10. The front door became the contact point at ground impact for vehicle model with SSF 1.07.

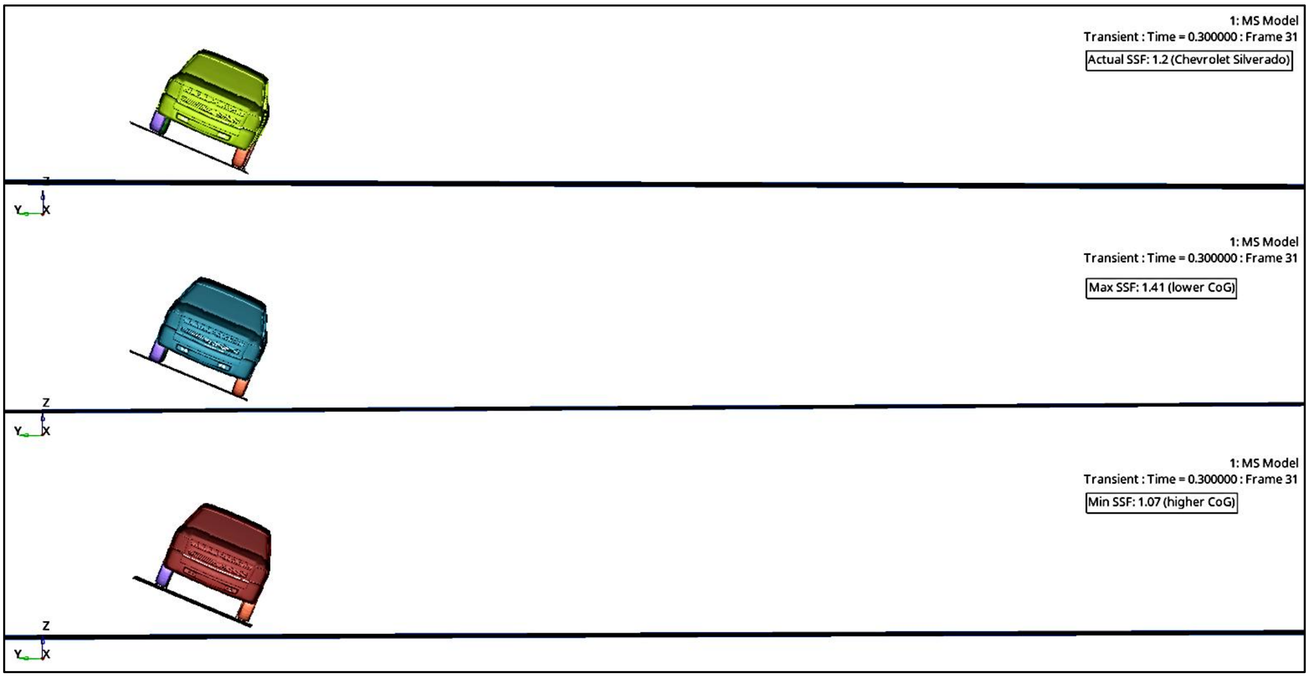

Fig. 7. Position of vehicle at the start of simulation (t=0.3s)

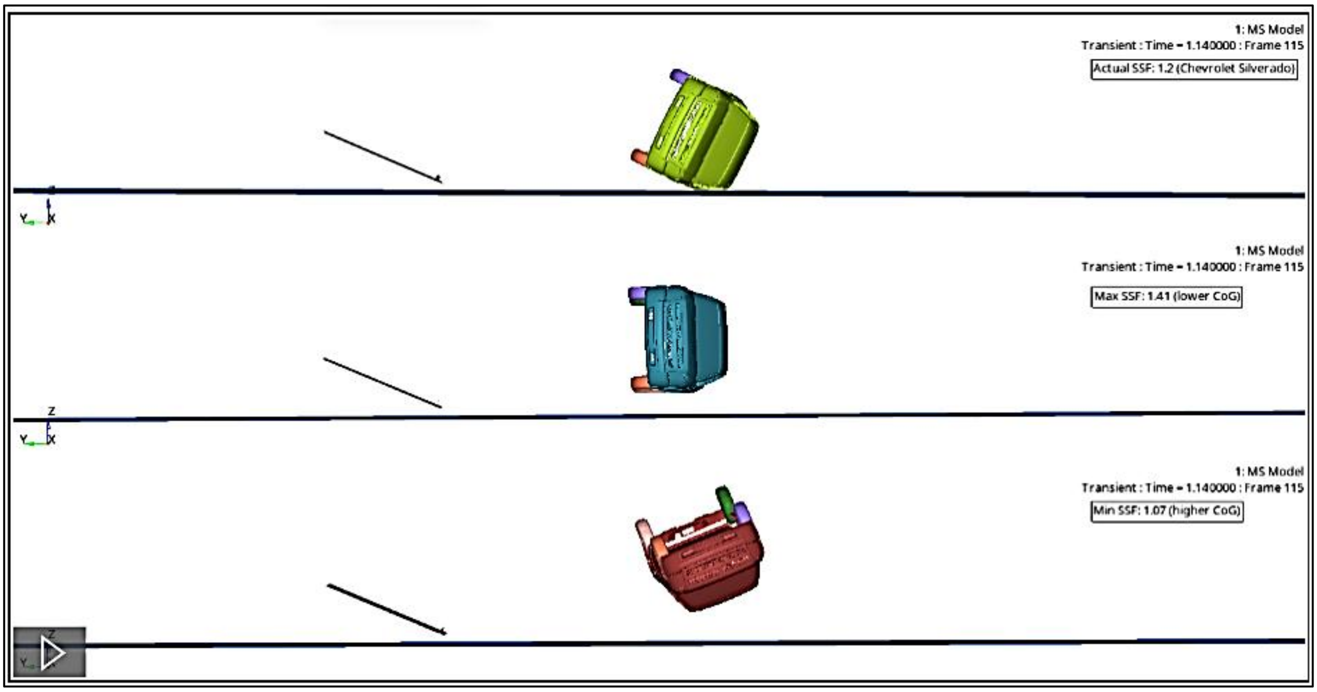

Fig. 8. Position of vehicle with SSF 1.2 end/middle airborne phase (t=1.14s)

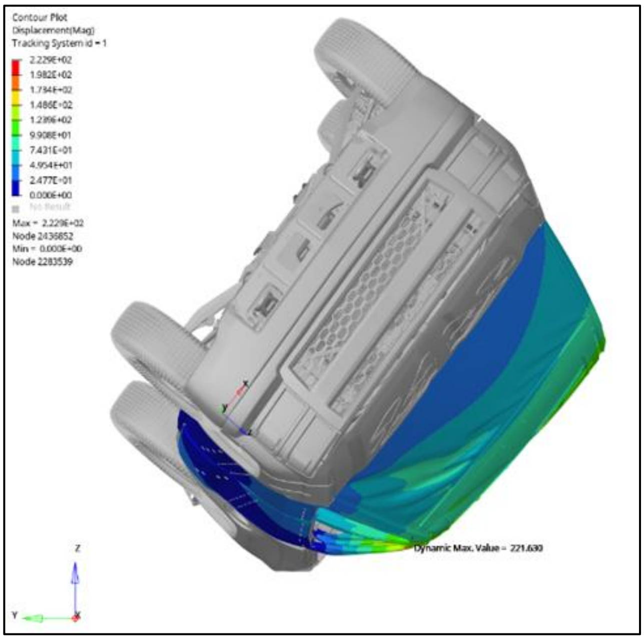

Fig. 9. SSF 1.2 ground impact location (Y-Z plane view)

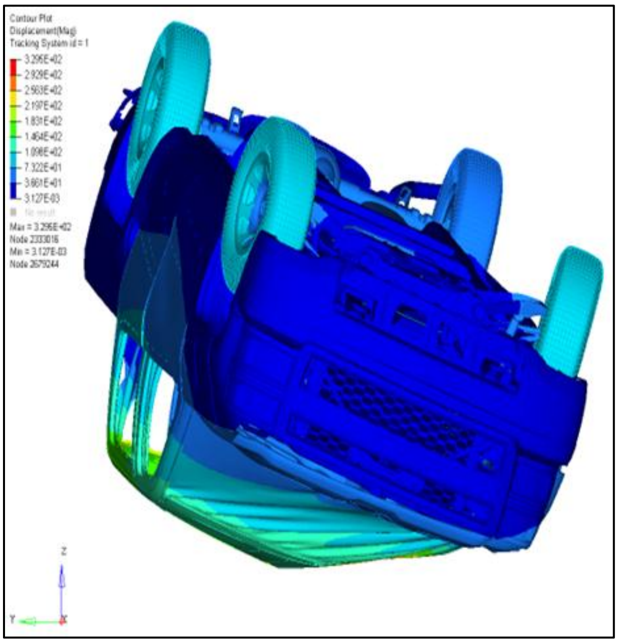

Fig. 10. SSF 1.4 ground impact location (Y-Z plane view)

3.3 FE Rollover Simulation

The result of FE rollover simulation is presented in this section. The vehicle to ground impact force, maximum structural deformation, and maximum intrusion were measured and presented. Table 7 presents the summary of results for Dynamic Rollover Test for three different SSF which is 1.2 (base model), 1.41 and 1.07. Peak force result is the maximum reaction force recorded at the vehicle body due to Newton's third law because of rollover ground impact force throughout the simulation duration.

Table 7
Result of Dynamic Rollover Test simulation for three different SSF 1.20 (Base model) 1.41, and 1.07

	FMVSS 208		
Results	SSF 1.07	Base model (SSF 1.20)	SSF 1.41
Peak force (kN)	231.00 (+136.68%)	97.60	99.10 (+1.54%)
Peak energy absorption (kN.mm)	25,175.96 (+113.36%)	11,800.00	10,237.08 (-13.25%)
Intrusion (mm)	332 (+49.55%)	222	109 (-50.90%)

On the other hand, the integration of the area under peak force versus displacement graph as shown in Figure 11 is defined as energy absorption. With reference to graphs as depicted in Figure 11 and Figure 12, it is apparent from these results that as SSF gets lower, the peak energy absorption and intrusion on the vehicle structure goes higher. Rollover for vehicle with SSF 1.07 show highest energy absorption (25,175.96 kN.mm) above all. This is due to the contact point of the vehicle at ground before impact is at the other side of the roof due to over-rotation of the vehicle before it touches the ground as illustrated in Figure 8. The results of energy absorption vs max. displacement have been offset to start at 0, as shown in Figure 12 to define intrusions caused by the rollover event. In addition, the highest intrusion recorded is 332 mm which denotes for the vehicle with lowest SSF value. Meanwhile, vehicles with SSF 1.41 present lowest energy absorption (10,237.08 kN.mm) and lowest intrusion of the rollover event (109mm). The most striking result to emerge from the data is that the SSF value which represents the vehicle stability affects the rollover behavior of the vehicle and thus impacts on the energy absorption and intrusion value caused by the rollover event. In comparative analysis, the research delineated in [32] reveals that the ultimate chassis of the prototype Formula of Student Automotive Engineers (FSAE) vehicle exhibits a specific energy absorptivity reaching as high as 130 kJ/kg upon normal to critical impact conditions by the incorporation of biomimicry beams.

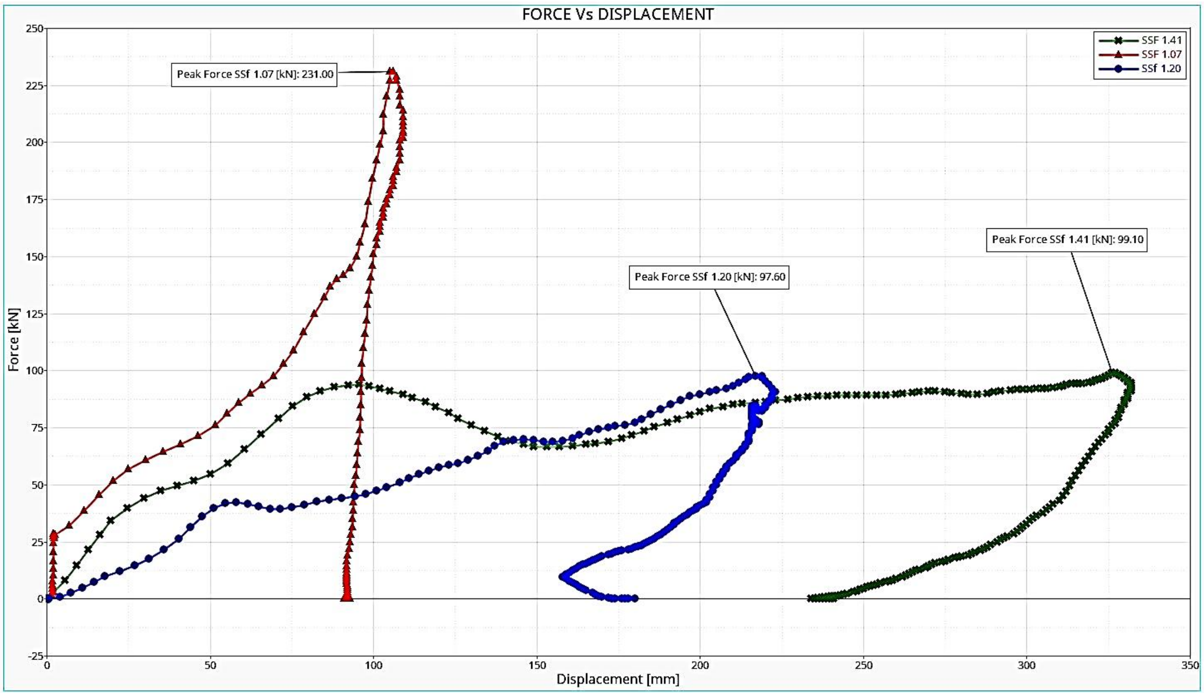

Fig. 11. Maximum force (kN) vs maximum displacement (mm) offset for three different SSF

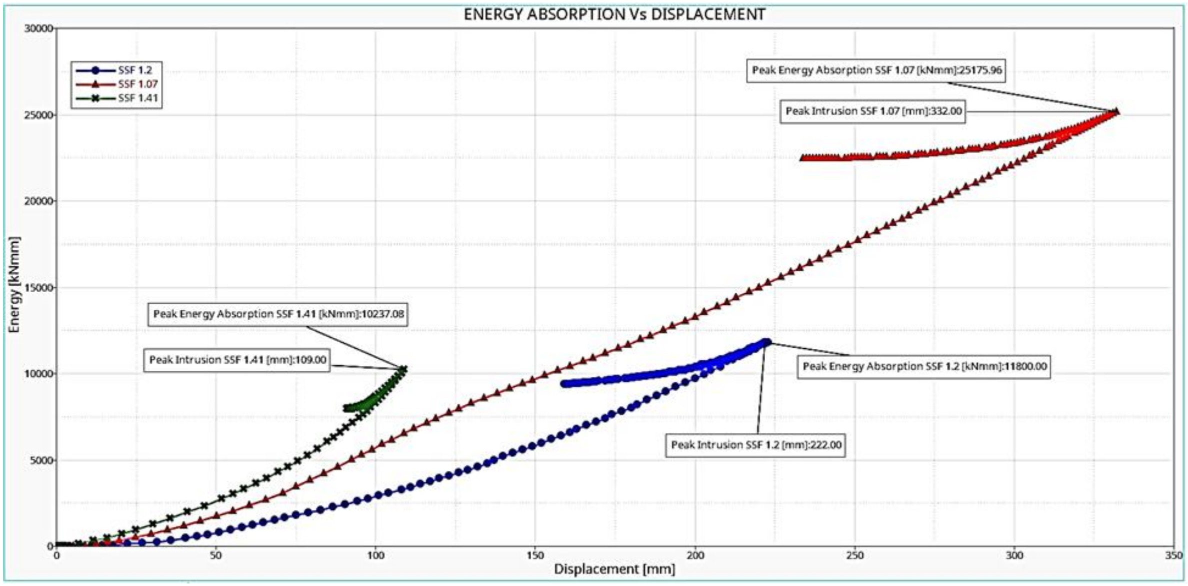

Fig. 12. Energy absorption (kN.mm) vs maximum displacement (mm) offset for three different SSF

Ground impact contact point on vehicle affect the peak force reading. Intriguingly, peak force result does not conform to the pattern of relation between SSF value with peak energy absorption and intrusion. According to the pattern, peak force value for SSF 1.41 model should be lower than

SSF 1.20, however in our study, it showed otherwise. 99.10 kN peak force recorded on SSF 1.41 model which is 1.54% higher than peak force value recorded by SSF 1.20 model. The vehicle orientation and position just before impact is as shown in Figure 10. The comparison to other vehicles with different SSF is as shown in Figure 8.

To assess structural integration by peak force factor, comparison of peak force result model run according to FMVSS 208 test with model run according to FMVSS 216 is made. The model run according to FMVSS 208 test recorded lower peak force value (97.6 kN) than model run according to FMVSS 216 (113 kN) although it is run using similar model with similar structural integrity. The simulation results implied that FMVSS 216 test is found to be more severe than FMVSS 208 in this case. Another discovery from the study is that SSF value also plays an important role in rollover behavior and rollover crash impact magnitude. For instance, an increase of 12.21% in SSF value would result in an increase of approximately 50% of intrusion which in return would affect survival space.

Preserving the occupant's "survival space" within a vehicle during a crash is a critical factor affecting their chances of survival in various collision scenarios. In rollover crashes, maintaining the integrity of this space becomes crucial, and it is achieved by combining a robust protective structure with an effective passenger restraint system to limit occupant movement. Researchers have noted that the primary determinant of the survival space's integrity during a rollover crash is the extent of roof intrusion experienced by the vehicle. Two independent studies investigating the relationship between roof intrusion and injury levels have indicated that injuries tend to increase significantly when roof crush exceeds 10 cm [1]. The cross-sectional analysis demonstrated a 64% increase in the odds of a life-threatening injury as estimated by the Head, Neck, and Spine New Injury Severity Score (HNS-NISS) with every 10 cm of increased roof crush. The results of the matched case–control analysis demonstrated a 44% increase in the odds of sustaining any injury to the head, neck, or spine with every 10 cm increase in roof crush. Roof deformation does affect injuries of head, neck and spine [33].

4. Conclusions

In brief, the evaluation of vehicle structural integration in terms of peak force and maximum intrusion for different vehicle SSF value according to FMVSS 208 dolly rollover test using Finite Element Analysis (FEA) is presented. Results indicate that vehicles with lower SSF values lead to higher energy absorption and intrusion, signifying increased rollover impact. Additionally, it is suggested that FMVSS 216 exerted more force reaction from ground impact than FMVSS 208 for the same FE model. Vehicle rating system based on SSF value is vital for market awareness to push for legislation standard uplift. Integrating the highest achievable SSF (Static Stability Factor) and employing Finite Element Analysis (FEA) for rollover assessments like FMVSS 216 and FMVSS 208 during the design phase greatly contributes to achieving exceptional crashworthiness in rollover incidents for a vehicle. Understanding the vehicle structural integration in rollover scenarios is essential for improving safety measures and vehicle design, especially for high-center-of-gravity vehicles prevalent in the market. It is worth asserting that the three different SSF models built are simplified because it is modified based on CG height only without considering the track width parameter. Therefore, it is recommended that further analysis is done using individual FE model for each SSF value for better representation.

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