

A Design Methodology to Assure Safe On-Road Handling Dynamics for Vehicles with Aftermarket Chassis Modifications

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ABSTRACT

The U.S. NHTSA has established the FMVSS 126 standard that requires all vehicles sold in the U.S. to include an ESC system as standard equipment after September 1st, 2011. There is growing concern among aftermarket suppliers specialized in development and installation of vehicle performance parts that chassis modifications may cause the ESC systems to be inoperative or can create unforeseen issues with stability and safety systems. This industry is in need of a process to support the development and validation of chassis modification. The authors propose the implementation of SIL and HIL simulations as a solution to the problem statement. Based on the results of a sensitivity analysis, guidelines for safe aftermarket modifications will be presented.

INTRODUCTION

The United States National Highway Traffic Safety Administration (NHTSA) has established the Federal Motor Vehicle Safety Standard (FMVSS) 126 [1] that requires all vehicles sold in the U.S. weighing less than 4,536 kg (10,000 pounds) to include an Electronic Stability Control (ESC) system as standard equipment after September 1st, 2011. FMVSS 126 ensures that a particular vehicle with ESC installed meets the lateral responsiveness and lateral stability criteria and has been found to be highly effective in preventing single-vehicle loss-of-control, run-off-the-road crashes, of which significant portions are rollover crashes. With this regulation in place there is growing concern among the aftermarket suppliers specialized in development and installation of vehicle performance parts such as suspension and body lift kits, modified sway bars and oversized tires. These chassis modifications may cause the ESC systems to be inoperative, might cause false warnings through the ESC malfunction telltale or can create unforeseen issues with

stability and safety systems. Altered vehicles must comply with FMVSS 126 after September 1st, 2012. Legally, should an accident occur, the aftermarket parts manufacturer and installer could be held liable, whether the accident was caused by the alterations or not. Therefore, the aftermarket suppliers are in need of best practice tools and processes to assess the impact of chassis modification regarding FMVSS 126 compliance.

The chassis modifications may in addition have a significant impact on the rollover propensity of that particular vehicle. ESC is a highly effective device to maintain control of the vehicle and will primarily prevent single-vehicle accidents. Both NHTSA and the Insurance Institute for Highway Safety (IIHS) estimated that ESC could prevent 80-88% of all SUV un-tripped rollover crashes [2, 3]. These numbers imply that despite ESC about 12-20% of all un-tripped rollover crashes cannot be avoided. This makes it necessary for the aftermarket industry to completely understand the influence of any modification on the yaw as well as roll stability of the vehicle. In order to sustain this business and prevent possible litigation cases, it is of great importance that the chassis design modifications can be assessed and validated during the product development phase before final implementation in a customer's vehicle. A critical factor for the aftermarket industry is that the ESC system must be regarded as a 'black box' since the code and control parameters of the ESC algorithms are of a proprietary nature and differ from supplier to supplier. These ESC algorithms will be unknown for the aftermarket industry and the proper design of chassis modifications and functional assessment of yaw and roll stability becomes even more challenging, as the design must incorporate the electronic stability control actions.

Several studies have been conducted on assessment of altering vehicle design parameters (height of center of gravity, track width, tire diameter, suspension kinematics) on rollover

propensity. Other studies have looked into the impact of tire characteristics (cross section size, aspect ratio) on generic vehicle handling and stability. None of the existing studies have addressed aftermarket chassis modification and compliance with FMVSS 126 (yaw stability) yet.

The authors propose the implementation of Software-in-the-Loop (SIL) and Hardware-in-the-Loop (HIL) simulations as a solution to the problem statement. The simulations will consist of a non-linear vehicle model coupled with either a software based generic ESC algorithm or an external ESC-ECU in the loop. The effect of modifications such as suspension lift kits, altered anti-roll bars, and oversized tires can readily be studied through the simulations, and the compliance of the modified vehicle as stipulated in FMVSS 126 can be assessed as well. Furthermore, it will be possible to obtain more insight on the rollover characteristics of the modified vehicle by additionally simulating the fishhook maneuver.

As a first step, a non-linear vehicle model representing a full-size pickup truck was modeled in CarSim and validated against actual field test results. The validated CarSim model with a generic SIL ESC modeled in SIMULINK [4] was then used for conducting sensitivity analyses towards possible chassis alterations. With this preliminary setup, the influence of the above-mentioned chassis modifications on the yaw and roll stability were assessed supporting the proper choice of the various alterations possible. To support the possible chassis design choices objective handling metrics were defined which account for vehicle responsiveness, driver controllability and overall system damping. These metrics will assist the aftermarket suppliers in creating a desired on-road vehicle handling “DNA” and also have a high correlation with the vehicle’s yaw and roll stability (and performance in FMVSS 126).

The modified vehicle will be tested for FMVSS 126 as well as the NHTSA fishhook maneuver. By simulating the FMVSS 126 test, sensitivity of chassis modifications towards yaw instability will be addressed. Similarly, a sensitivity analysis of these modifications towards roll instability will be conducted based on the fishhook maneuver. Based on the results of sensitivity analyses, the vehicle dynamic system parameters that correlate to the vehicle’s performance in FMVSS 126 (yaw stability and responsiveness criteria) are assessed and guidelines for safe aftermarket modifications will be presented.

Additional steps were taken to define the best combination of aftermarket chassis products. An optimization strategy was formulated to aid this selection of aftermarket chassis upgrades. The optimization scheme can be developed with an objective to attain a specific desired “DNA” for the vehicle. The desired “DNA” can be set up as a function of both, ride and handling characteristics for the vehicle. For this report a desired DNA based only on the handling characteristics (i.e. objective metrics of yaw rate gain, natural frequency, damping ratio and lateral acceleration phase lag) was used. This optimized

selection of chassis products was then again tested for FMVSS 126 and NHTSA Fishhook to ensure safe on-road behavior.

MODELLING AND VALIDATION

VEHICLE DYNAMICS MODEL

A 2003 Toyota Tundra was used for this study. The Tundra has a 4.7 L V-8 engine, with a 4-speed automatic transmission. This vehicle has a limited edition TRD off-road suspension package with P265/70R16 tires. The vehicle was modeled using the vehicle dynamics simulation tool CarSim [5] and consists of dual independent front suspension and a solid rear axle. The roll, pitch and yaw inertia values for the vehicle were estimated based on previous studies [6]. The steering ratio and other kinematic steering parameters such as caster angle and kingpin inclination were obtained by Kinematics & Compliance (K&C) measurements of the actual vehicle [7]. Both front and rear shock absorbers were tested on a shock dynamometer. The tire model used in the simulations is based on ‘Pacejka Magic Formula’. The tire model also includes the effect of camber thrust, overturning moments and relaxation lengths.

VALIDATION

The vehicle dynamics model in CarSim was validated against actual field tests. The vehicle was instrumented with a full set of vehicle dynamics sensors: four ride height sensors, a longitudinal/lateral velocity sensor and a steering wheel position/torque sensor was used for the field tests. The vehicle was tested for various maneuvers including step steer, single lane change, random steer and swept sine steer. Figures 1, 2, 3 show, as an example, the results from a slalom maneuver. The peak steering wheel angle during the slalom maneuver at 80 km/h equals +70 to -60 degrees. The measured steering and velocity profiles from the test maneuvers were used in the simulations for validation purposes. As can be seen from the plots the overall behavior of the CarSim model matches quite well with the measured behavior on the track. The minor discrepancies between the simulation and actual field test results can possibly be attributed to the estimated values of inertia parameters (yaw and roll).

GENERIC ESC MODEL

A generic SIL ESC software model was developed as part of the simulations for the purpose of tuning and assessing vehicle performance in critical handling situations (such as FMVSS 126). The controller used for this research is a simplified 1st order representation of the fundamental ESC algorithm based on a yaw rate PD-controller. The yaw rate from the actual vehicle is compared with the desired yaw rate from a single-track vehicle model with desired handling behavior. Based on the yaw rate error (desired minus actual), the ESC controller will determine a required yaw moment for stable vehicle operation and the actual yaw motions will be induced by

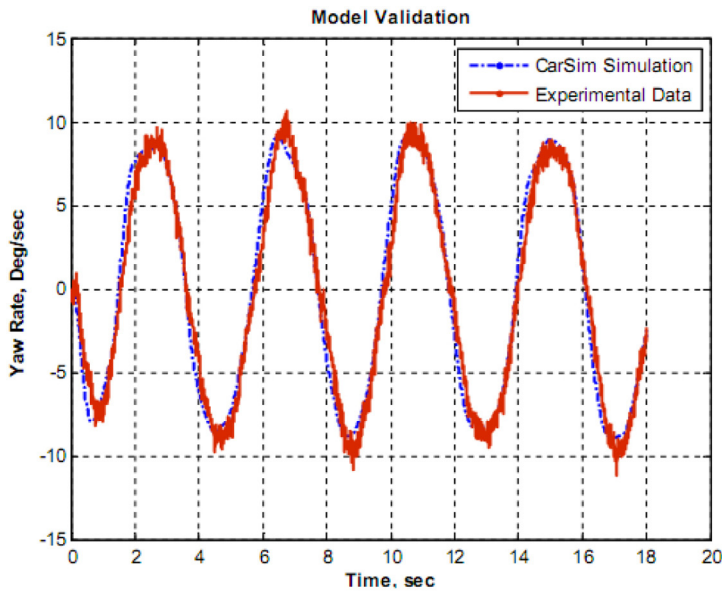


Fig. 1. Yaw Rate: Slalom Maneuver ($V=80\text{kph}$)

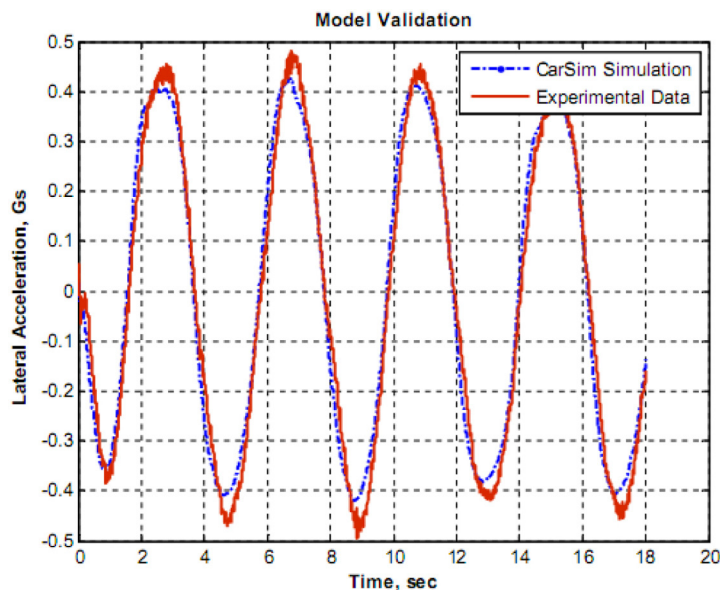


Fig. 2. Lateral Acceleration: Slalom Maneuver ($V=80\text{kph}$)

selective brake activation. The yaw rate error threshold for the ESC controller has been set to 0.18 rad/sec for 80 km/h. This value of yaw rate error threshold was selected based on test results for a similar vehicle [8]. The controller algorithm can be described with the following sequence: firstly, the controller detects the direction of the turn (left or right); secondly, it determines the yaw rate error and interprets if the vehicle is in a state of “apparent” understeer or oversteer. If the controller perceives an apparent understeer, it takes the action of braking

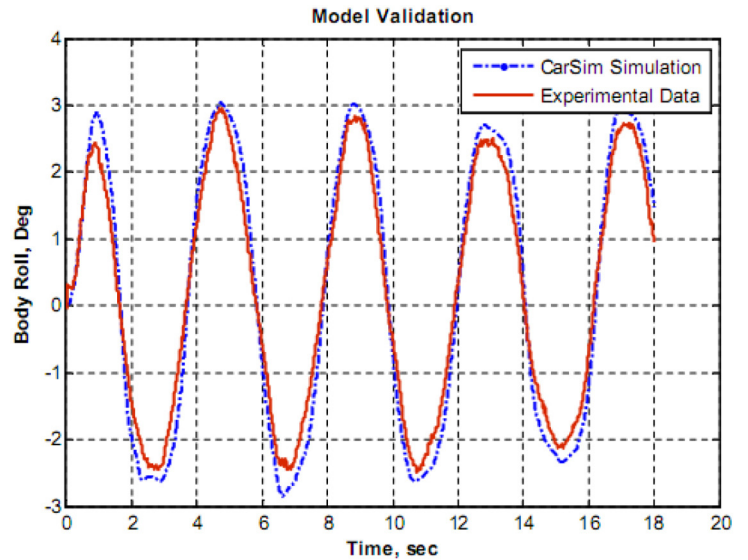


Fig. 3. Roll Angle: Slalom Maneuver ($V=80\text{kph}$)

the inside rear wheel and for an apparent oversteer, the controller takes the action of braking the outside front wheel.

SIMULATIONS

To understand the influence of aftermarket modifications on yaw and roll stability, a variety of simulations were carried out. The influence of 3 specific aftermarket modifications are presented in this paper: These include 1) A suspension lift kit for pickup trucks raising the sprung mass by 2 inches, 4 inches and 6 inches, 2) upgraded anti-roll bars with higher stiffness values, and 3) replacement of the on-road tires with dedicated off-road tires and oversized all-terrain tires.

A variety of suspension lift kits are available on the market today. Most commonly the aspired lift is achieved by adding an application-specific spacer to the top of the factory strut assembly at the front and adding lift blocks for the rear. The primary goal of such a lift kit is to raise the vehicle’s ride height for off-road application ensuring more ground clearance and larger ramp angles. The impact on the vehicle’s characteristics is a raise in center of gravity (CoG) of the sprung mass, however without any significant change in suspension kinematics. For this study, the influence of these kits is evaluated by increasing the sprung mass CoG height (i.e. the influence of a 4-inch lift kit is simulated by raising the sprung mass CoG by 4 inches in the simulations).

The vehicle in its stock configuration was equipped with a front anti-roll bar of 1 inch diameter. A common upgrade for the vehicle under consideration is replacing the front anti-roll bar with a stiffer anti-roll bar (in this case from 1 to 1.25 inch in diameter). It is assumed that the anti-roll bars have the same length, same modulus of rigidity and are installed without

affecting the installation ratios. With these assumptions, the contribution of the anti-roll bar to the roll stiffness is directly proportional to the fourth power of diameter of the bar [9].

Other popular upgrades among the pick-up trucks include the installation of special purpose aftermarket tires. The most common in this category is replacement of the nominal passenger car tires with special off-road “mud” tires or oversized all-terrain tires. These off-road tires generally have an aggressive tread pattern and increased sidewall strength. In this case the stock BF Goodrich Rugged Trail P265/70R16 tires were replaced with BF Goodrich Mud-Terrain T/A® KM2 Off-Road tires. A variety of tire sizes are available in this category, a LT 235/85R16 tire was selected for this study. To represent the case of oversized all-terrain tires, LT 325/60 R 20 ProComp all-terrain (X’treme A/T) tire was selected. In all simulations, Pacejka’s Magic Formulae characteristics of the tires were used to accurately predict the tire force and moment behavior.

Each of the 4 chosen lift kit configurations (nominal, +2 inches, +4 inches, and +6 inches) was assessed with three sets of tires and two sets of anti-roll bar setups. All together this results in 24 different vehicle configurations. The on-road handling performance of each configuration has been simulated for the FMVSS 126 maneuver (yaw stability) as well as NHTSA’s fishhook maneuver (roll stability), each with and without ESC present. Lastly, in order to support appropriate design choices a possible optimization strategy is discussed, and sample results are presented.

DESCRIPTION OF FMVSS 126 AND FISHHOOK TEST

The FMVSS 126 maneuver assesses the lateral stability and responsiveness of on-road vehicles and the result of the test is either a PASS or a FAIL. A detailed description of the FMVSS 126 test in CarSim can be found in [4].

Fig. 4 describes the fishhook test used in this research. The vehicle is driven at a constant target speed, while executing a steering maneuver as depicted in Fig. 4. The steering wheel angles used for the test are based on the hand wheel angle required to attain 0.3 g’s of lateral acceleration (resulting in different steering input for different chassis configurations). The numerical qualifier of this test equals the maximum speed at which the vehicle can successfully perform the maneuver (i.e. without simultaneously lifting 2 wheels or rolling over).

DESCRIPTION OF TIRE CHARACTERISTICS

As described above, three different tires i.e. BF Goodrich Rugged Trail P 265/70 R 16, ProComp (X’treme All Terrain A/T) 325/60 R 20, and Mud Terrain LT 235/85 R 16 were used in this study. These tires are among the most popular choices for the pickup trucks. Two of the most important characteristics

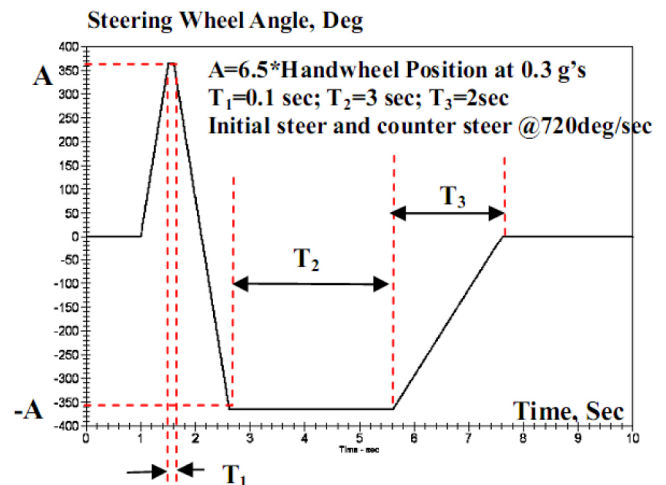


Fig. 4. Steering Wheel Angle for Fishhook Test.

of pneumatic tires are the cornering stiffness coefficient (CSC) and the peak lateral coefficient of friction (μ_{yp}). The CSC represents the predominant tire contribution to directional stability under normal driving conditions (less than 0.5 g lateral acceleration) [10]. Under emergency maneuvering conditions where vehicles can exhibit transient oversteer (leading to fishtailing or spinout), saturation properties of tires are important which are characterized by peak lateral coefficient of friction [10]. The peak coefficient of friction also plays a part in the tip up propensity of utility vehicles [11]. Vehicles with marginal static stability factors (i.e. the ratio of half track width, $T/2$, to center of gravity height, H , or $SSF=T/2H$) tend to be sensitive to tire aggressiveness. The large lateral forces that occur at tip-up are typically generated by the tires under limit maneuvering conditions. These forces occur at high slip angle conditions and high load due to maneuver induced load transfer. For a given set of maneuvering conditions, the more aggressive a tire, the more it will contribute to tip-up [10].

Figures 5, 6 and 7 show the plots for the peak lateral coefficient of friction vs. normal load, cornering stiffness coefficient (CSC) vs. normal load and the cornering stiffness vs. normal load for the three tires used during this study. As expected, both CSC and peak lateral coefficient of friction show an inverse relationship with vertical load. It is observed that the large section width, low aspect ratio (i.e. more aggressive) LT 325/60 R 20 A/T tires have lower values of cornering stiffness coefficient until around 12,000 N, but then the CSC values for the LT 325/60 R 20 A/T tires become larger than the CSC values for the P 265/70 R 16 tires. The more aggressive A/T tires also exhibit higher values of peak lateral coefficient of friction as compared to the Rugged Trail P 265/70 R 16 and the Mud Terrain LT 235/80 R 16 tires. The LT 235/85 R 16 is the least aggressive among the three tires used in this study. The LT 325/60 R 20 All-Terrain tires and the LT 235/85 R 16 Mud-

Terrain tires mark the extremes for the tires used for off road activities. Table 1 shows the approximate values of vertical stiffness of the three tires used.

Table 1. Vertical Stiffness of the Tires.

Tires	Tire Pressures(psi)	Vertical Stiffness(N/mm)
LT 325/60 R 20 Pro Comp (X'treme A/T)	50	508
P 265/70 R 16 BF Goodrich Rugged Trail	32	300
LT 235/85 R 16 BF Goodrich Mud Terrain	50	428

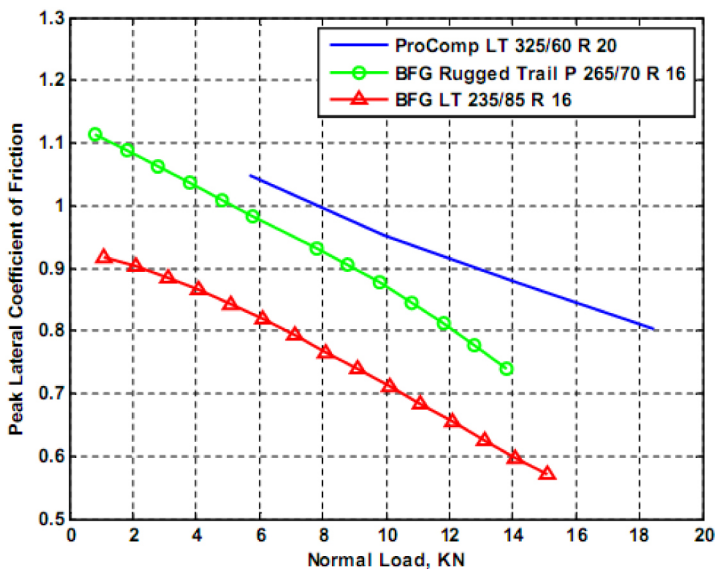


Figure 5. Peak Lateral Coefficient of Friction vs. Normal Load

RESULTS

RESULTS FOR FMVSS 126

For each of the four lift kit configurations (the nominal, +2 inches, +4 inches, and +6 inches) a full simulation of the FMVSS 126 maneuver was carried out. An important aspect here is the status of the FMVSS 126 if the vehicle has a wheel lift-off situation while performing the test. According to the official procedure [12], incidents such as wheel lift-offs should

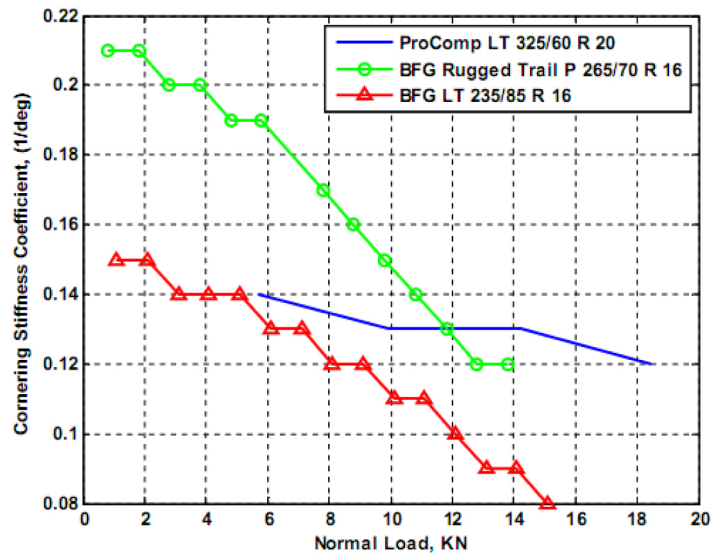


Figure 6. Cornering Stiffness Coefficient vs. Normal Load

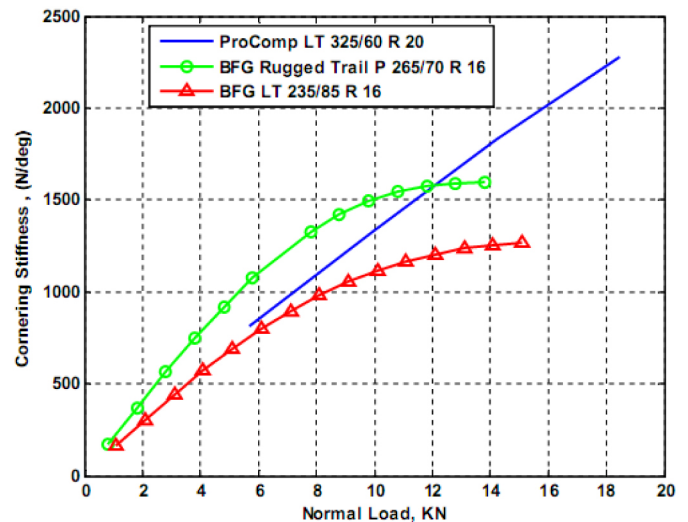


Figure 7. Cornering Stiffness vs. Normal Load

be reported to Contracting Officer's Technical Representative (COTR). The authors have applied FMVSS 126 as a measure of yaw stability and lateral responsiveness only, and therefore wheel lift-off has been assessed as a 'PASS'; if the vehicle meets the yaw rate and lateral displacement criteria (as required by the FMVSS 126 test).

Table 2 shows example results for the lift kit variation only. Table A1 (in Appendix) shows results for all possible configurations. It can be observed that the baseline vehicle and the configuration with a 2-inch lift kit passes FMVSS 126 for all its configurations (with and without ESC) except when the vehicle is installed with the more aggressive, larger LT 325/60 R 20 tires. It can be noticed that every vehicle configuration