A STREAMLINED INITIAL TEST REGIME UTILIZING THE NHTSA NCAP ROLLOVER MANEUVER.

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ABSTRACT

An experiment was designed to evaluate the effect of changes to two vehicle parameters on rollover maneuvers. The changed parameters were tire size and static stability factor (SSF). The statistically designed experiment tested each vehicle condition utilizing the NCAP Dynamic Rollover Maneuver. The NCAP Dynamic Rollover Maneuver test procedure dictated a consistent tire condition, test order, vehicle load, and steer regime. Testing utilized an AB Dynamics steering robot. Results of testing demonstrated different and improved vehicle performance with changed vehicle parameters. Evaluation of the test results showed statistical significance in vehicle response due to changed SSF and no statistical significance in vehicle response due to changed tires for one of the steering sequences. Close examination revealed that for evaluation of effects in vehicle response due to changes of vehicle parameters no additional statistically significant information in vehicle response was observed for initial left turn versus initial right turn and default steer versus supplemental steer. When evaluating vehicle response to changed vehicle parameters an initial streamlined test regime utilizing the NCAP Rollover maneuver is suggested. The complete NCAP Dynamic Rollover test procedure for vehicle validation is recommended. Future investigations that build on these results could include changes in the roll moment distribution together with SSF.

INTRODUCTION

The Transportation Recall Enhancement, Accountability, and Documentation (TREAD) Act of 2000 required NHTSA to develop a dynamic test on rollovers by motor vehicles for the purposes of a consumer information program. After conducting a rulemaking to determine how best to disseminate dynamic test results to the public, NHTSA used results of the dynamic rollover test as supplementary information in combination with a vehicle's Static Stability Factor (SSF). Consumer information results are published in New Car Assessment Program (NCAP). The NHTSA NCAP dynamic rollover test specifies a consistent concept of vehicle load, specific method of steer characterization, tire break-in, tire use, test sequence and steering maneuver. The steering maneuver is a double-step-steer, fishhook, maneuver based upon roll rate feedback(1).

According to NHTSA, the original fishhook maneuver was developed by Toyota Motor Corporation and it is fully described in Toyota Engineering Standard TS-A1544 (2). Variations of fishhook maneuvers were suggested by Nissan and Honda. NHTSA experimented with several versions since 1997(1). An important feature of NHTSA's fishhook test is a steering maneuver that can only be preformed with a steering machine based upon roll rate feedback provide while a test is being preformed. The roll rate feedback identifies the moment of maximum roll angle by identifying when the roll rate oscillation first crosses zero, triggering a coincidental steer reversal.

For the testing presented in this paper a statistical test design is employed to evaluate the hypothesis that increased SSF and decreased tire size will reduce the occurrence of a simultaneous 2-wheel lift in a vehicle in a dynamic rollover maneuver.

METHOD

The statistically designed test matrix allowed for estimates of the relative importance of two vehicle factors. Evaluated factors were the SSF and tires. SSF0 refers to the unmodified base vehicle. SSF1 refers to the base vehicle modified with two-inch spacers at each wheel, a four-inch increase in track width. SSF2 was the vehicle with the four-inch increase in track width and a cg that was reduced by one-inch. Tire 0 was a Michelin X Radial LT P235/70R16LT OEM specified tire. Tire 1 was a Michelin X Radial LT P235/70R15LT tire and Tire 2 was a Michelin X Radial P205/75R15 tire. Because the smaller tires and wheels resulted in a lower vehicle cg height a corresponding upward adjustment of the vehicle cg was made utilizing a movable mass. Use of the movable mass allowed for testing of the three SSF conditions and three tires in isolation and combination consistent with the statistical experiment design.

A 2002 two wheel drive Ford Explorer Sport (two-door) with 39095 miles was purchase. The vehicle frame, suspension, steering and overall condition was inspected, measured and, where necessary, restored to manufacture specification with OEM parts by certified mechanics. For testing the vehicle was fitted with instrumentation and steering controller, ballasted and equipped with outriggers. Instrumentation measured speed, slip angle, three axis of acceleration, yaw rate, roll rate, hand wheel angle, rear wheel heights and body height behind the front tires. Roll angle was calculated from the front body height measurements. The motor for the steering controller replaces the steering wheel and was an AB Dynamics steering robot. Data was collected at 200 samples per second with a 100 Hz preacquisition filter.

Ballast in the right front seat included instrumentation and steering controller electronics combined in a configuration that replicated the cg position and mass of a 175 pound water dummy. The rear seat was replaced with a light steel fixture that allowed the vertical adjustment of a mass equivalent to the rear seat and two water dummies. The cg of the rear adjustable mass was laterally positioned at the vehicle centerline and longitudinally positioned identical to the installed rear seat containing two 169 lb water dummies. The rear adjustable mass was composed of lead weight distributed over an area approximately 40 inches from side to side and 15 inches from front to back. The moment-of-inertia of the rear seat with 169 lb water dummies was not replicated by the rear seat movable mass. The test driver weighed 175 lbs. As tested the vehicle weighed 4815 lbs which is 55 lb over the vehicle GVWR. The front and rear axle weights were under the GAWR. Individual wheel weights were: left front – 1225 lb, right front – 1137 lb, left rear 1232 lb and right rear – 1221 lb.

Adjustment of the rear seat mass compensated for changes in vehicle cg height due to different tire rolling radius and reduced cg height at the greatest SSF condition. The vertical adjustment was determined by the formula:

(1) $\Delta h_{cg(mm)} = W/W_{mm}(\Delta h_{cg} - \Delta h_t)$,

Where:

$\Delta hcg_{(mm)}$ is the calculated displacement of the movable mass,

W is the weight of the vehicle,
W_{mm} is the weight of the movable mass,
Δh_t is the change in height of the vehicle due to tire (reduced radius is negative),
Δhcg is the desired change in height of vehicle CG (reduced height is negative),

The calculated vertical displacement of the movable mass is shown in Table 1. The equivalent vertical position of the rear seat and water dummy was determined by measurement and analysis to be 40 inches above the ground in a loaded vehicle. The tested position of the movable mass in the Tire 1, SSF2 condition was 0.1 inches lower than calculated[1].

Table 1.
Calculated vertical displacement of rear seat movable mass.

	Change in rolling radius (in)	Desired change in CG (in)	$\Delta h_{cg(mm)}$ (in)
Tire 0, SSF0	0.00	0.00	0.0
Tire 0, SSF2	0.00	-1.00	-12.4
Tire 1, SSF0	-0.23	0.00	2.9
Tire 1, SSF2	-0.23	-1.00	-9.6
Tire 2, SSF0	-1.19	0.00	14.8
Tire 2, SSF2	-1.19	-1.00	2.4

Titanium outriggers designed by NHTSA replaced the vehicle front and rear bumpers. The outriggers were attached to the vehicle with custom fitted brackets. Attachment of the skid plates at the end of

[1] The effect of a 0.1 inch change in rear seat movable mass manifest as 0.008 inch change in vehicle cg height and no change in the calculated SSF rounded to two significant digits.

the outriggers were lightened and shortened reducing the outrigger mass and moment of inertia and lowering the mass of the outrigger relative to the vehicle cg.

Tires were Michelin X Radial LT for the P235/70R16LT and P235/75R15LT configurations, Tire 0 and Tire 1, respectively. Tire 2 was a Michelin X Radial for the P205/75R15 configuration. LT designated tire were not available in the 205/75R15 size. The tire distributor recommended the Michelin X Radial without the LT designation as an equivalent in the smallest size. All rims were either 16X7 or 15X7. Tires were fitted with radial tubes to prevent catastrophic tire debead. All tires were purchased new and broken in using the NHTSA tire break-in procedure. Tire pressures were set after break-in and before testing consistent with the vehicle placard at 30 psi for the front and 35 psi for the rear throughout testing. Tire pressures were checked but not changed during test sequences.

Steering characterization was conducted using the steering controller programmed to slowly increase steering at 13.5 degrees per second to a magnitude of 75 degrees. The steering was held constant for 2 seconds at 75 degrees. Utilizing the analysis method described in the NHTSA NCAP the resulting steering characterization CS was 32.1 degrees. The default steer was 209 degrees and the supplemental steer was 177 degrees. Five sinusoidal passes were conducted for tire break-in prior to the steer characterization testing because the first break in runs did not produce a 0.5 g to 0.6 g lateral acceleration.

Dynamic rollover tests were conducted using the NHTSA NCAP flow chart except all vehicle conditions except conditions at SSF0 were tested in both the Left-Right (LR) and Right-Left (RL) sequence. The SSF0 condition was only tested in the LR direction and the performance in the LR direction was presumed for the RL direction. The NCAP flow chart dictated cessation of testing if a failure conditions results in the LR sequence prior to RL testing. In addition a test sequence was conducted in one direction to its conclusion before testing in the other direction was started. A test sequence in one direction is concluded pursuant to the NCAP flowchart when simultaneous two wheel lift occurs (S2WL), a tire debeads, rim to ground contact occurs or all tests in the sequence are successfully completed. A sequence in one direction is complete when the vehicle has successfully passed both a default and supplemental steer at 50 mph. Simultaneous two wheel lift was determined when the rear wheel height sensors indicated wheel lift in excess of two inches. The vehicle's front roll stiffness forces the front wheels higher off the ground when the rear wheels are off the ground due to body roll.

Outrigger contact was determined by painting the skids on the end of the outrigger and checking for abrasion of the paint following a test. Tire to ground contact was evaluated by inspecting the tires and wheels and test track surface.

Testing was conducted on an asphalt parking lot at Southwest International Raceway (SIR) South of Tucson Arizona. The test surface peak friction coefficient (PFC) was measured in accordance with ASTM Method E 1337–90, at a speed of 64.4 km/h (40 mph), without water delivery using an American Society for Testing and Materials (ASTM) E1136 standard reference test tire. The peak friction coefficient was 0.91. The test surface has an East to West slope of minus 1.0% and has an North to South slope of 0.8%. Vehicle direction prior to first steer is approximately toward the Southwest and along the path of vehicle approach the slope is minus 0.1%.

RESULTS

The default steer magnitude was 209 degrees and the supplemental steer magnitude was 177 degrees. A master table of the fishhook test results is shown in Table 2. For each test condition the R-L sequence is listed first since it consistently resulted in simultaneous two wheel lift at a lower speed.

For the RL default steering experiment, SSF was tested at 2 levels and tires at 3, resulting in a 2 X 3 experiment. For the LR default steering experiment, SSF was tested at 3 levels and tires at 3, resulting in a 3 X 3 or 3^2 experiment. The response variable was the mph at which the design failed the test. Specifically, the possible values of the response were 35, 40, 45, 47.5, and 50. The value 55 was assigned when there was no failure. When there was a failure at 47.5 or 50 mph, the test was repeated. For analysis purposes, the second test result is considered a duplicate. While the tires were new for this duplicate run and therefore the experimental conditions yielding this duplicate observation were slightly different, it offered the possibility of examining an interaction term between tires and SSF.

Each of the steering sequences were analyzed separately. Table 3 provides the factors and p-values of significance. In both the default steering sequence directions, the SSF was significant at the 0.05 level,

Table 2. Summary of test results

Order of Test in Sequence: Test	# of tires	Baseline Tire (235/70R16)						Tire 1 (235/75R15)						Tire 2 (205/75R15)					
		SSF0		SSF1		SSF2		SSF0		SSF1		SSF2		SSF0		SSF1		SSF2	
		RL	LR	RL	LR	RL	LR	RL	LR	RL	LR	RL	LR	RL	LR	RL	LR	RL	LR
35 mph Default Steer	1		P	P	P	P	P		P	P	P	P	P		P	P	P	P	P
40 mph Default Steer	1		P	P	P	P	P		F	P	P	P	P		F	P	P	P	P
45 mph Default Steer	1		F	P	P	P	P			F	P	P	P			P	P	P	P
47.5 mph Default Steer	1			P	P	P	P				P	F	P			F	P	P	P
	2											F				F			
50 mph Default Steer	1			F	P	P	P				P		P				F	P	P
	2			P								P[1]					P		
45 mph Supplemental Steer	1				P	P	P				P		P					P	P
	2			P															
47.5 mph Supplemental Steer	1				F	P	P				P		P					P	P
	2			P	P														
50 mph Supplemental Steer	1					P	P				F		P					P	P
	2			P	P						P						P		
Did Configuration Pass NCAP Series?		N		Y		Y		N		N		N		N		N		Y	

Notes:
[1]Passing 50 mph RL Default at SSF2, T1 condition was an exception to the NHTSA NCAP sequence and not included in analys
"RL" and "LR" refer to the turn sequence directions from the NCAP test series
"# of tires" refers to situation when a new tire set was required to verify S2WL. New tires were not fitted for S2WL at <=45 mph
NCAP test sequence is followed except testing is completed in one direction before the second direction is initiated.
New tires are utilized at the beginning of each test sequence
A "F" and filled box denotes a configuration that resulted in Simultaneous Two Wheel Lift (S2WL). A "P" denotes no S2WL
A "F" or "P" denotes the result of a test that was actually conducted
S2WL is presumed in grey shading for all tests in sequence following the test of observed S2WL
S2WL is presumed in grey shading for all tests in RL sequence of the SSF0 conditions based upon LR result
Failure in default RL at 47.5 with the first tire in the SSF2, T1 condition is accompanied by rim to ground contact
The tested position of the movable mass in the SSF2, T1 condition was 0.1 inches lower than calculated

Table 3. Summary of Test Results.

Testing	Significant Factor and p-value	Not Significant
Default Steering RL $R^2 = 81.11$	Tires 0.020 SSF 0.042	Interaction
Default Steering LR $R^2 = 90.49$	SSF 0.001	Tires Interaction
Supplemental Steering	No factors	Tires SSF

however, tires were only significant for the RL sequence. Analysis of the supplemental steering results yielded no significant factors. The main effects plots in Figures 1 and 2 illustrate these results and indicate that the direction of the main effect of the SSF is the same for both steering sequences, LR and RL. In other words, as SSF increases, performance improves. While the LR sequence shows no effect of tires, the RL sequence results show the best performance for the baseline tires.

It is noteworthy that these simple models provide very good fits as summarized in the R-squared values, 81.11% for RL and 90.49% for LR.

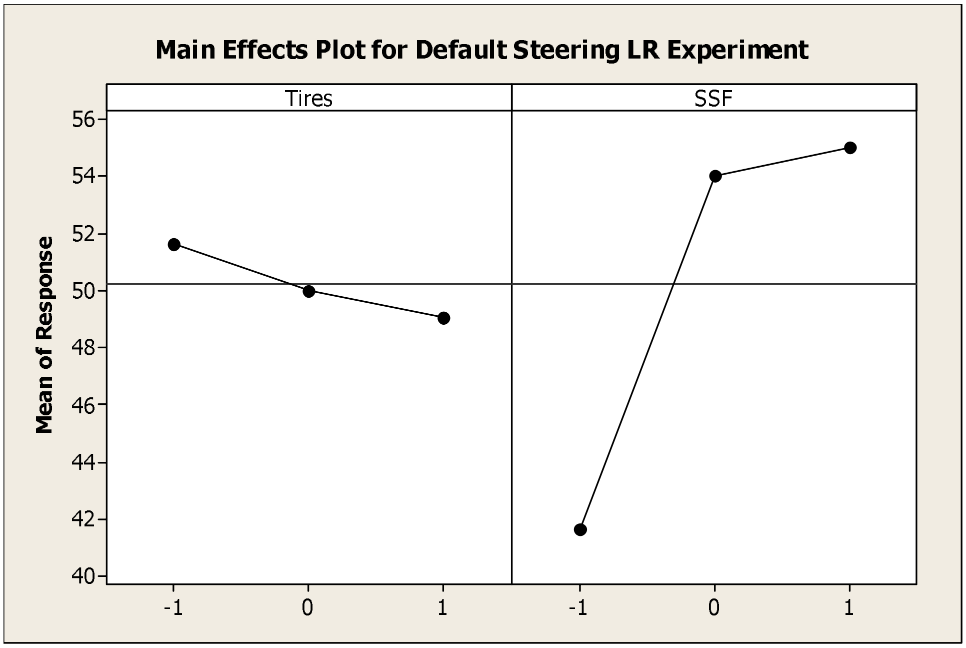

Figure 1. Main Effect Plot of Tires and SSF for Default Steering LR Experiment, Tires Insignificant and SSF Significant

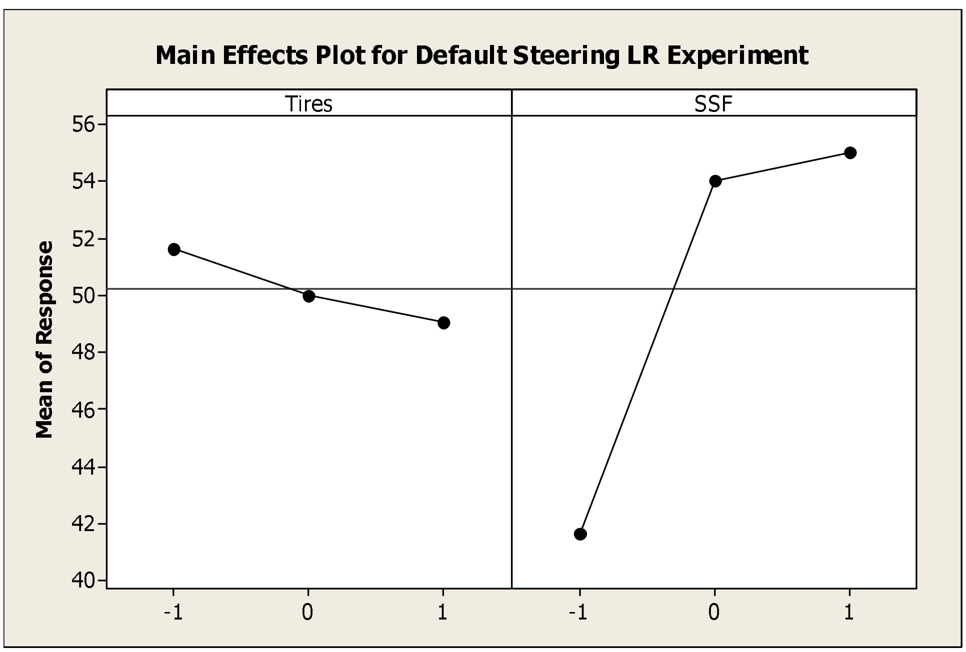

Figure 2. Main Effect Plot of Tires and SSF for Default Steering LR Experiment, Tires Insignificant and SSF Significant

Examination of the residual plots indicates no violations of the underlying modeling assumptions. While the order of the experimental runs was not random, no underlying pattern in the residuals according to run order was notable.

In summary, under the experimental conditions and procedures implemented, the conclusion is that an increase in SSF and a reduced tire size reduces the occurrence of a simultaneous 2-wheel lift in a vehicle in a dynamic rollover maneuver. By performing the separate analysis on the different default steering sequences and the supplemental steering, it was also found that the RL steering sequence provided the most information about vehicle sensitivity to changed vehicle parameters. Hence, these results suggest an initial streamlined test procedure.

CONCLUSION

Results of testing demonstrated different and improved vehicle performance with changed vehicle parameters. Evaluation of the test results showed statistical significance in vehicle response due to changed SSF and no statistical significance in vehicle response due to changed tires for one of the steering sequences. Close examination revealed that for evaluation of effects in vehicle response due to changes of vehicle parameters no additional statistically significant information in vehicle response was observed for initial left turn versus initial right turn and default steer versus supplemental steer. The testing performed under these experimental conditions concludes that increased SSF and decreased tire size reduces the occurrence of a simultaneous 2-wheel lift in a vehicle in a dynamic rollover maneuver. Furthermore, when evaluating vehicle response to changed vehicle parameters an initial streamlined test regime utilizing the NCAP Rollover maneuver is suggested. The complete NCAP Dynamic Rollover test procedure for vehicle validation is recommended. Future investigations that build on these results could include changes in the roll moment distribution together with SSF.

BIBLIOGRAPHY

1. Federal Register, 49 CFR Part 575, Consumer Information; New Car Assessment Program; Rollover Resistance; Final Rule, October 14, 2003.

2. W. Riley Garrott, J. Gavin Howe, and Garrick Forkenbrock, "An Experimental Examination of Selected Maneuvers That May Induce On-Road Untripped, Light Vehicle Rollover - Phase II of NHTSA's 1997-1998 Vehicle Rollover Research Program," VRTC-86-0421, July 1999.