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RECORDED RESPONSES OF A LIGHT TRUCK WITH RAPID LEFT FRONT AIR-OUT OF SUPER OVERSIZED MUD TIRES

Mark W Arndt
Transportation Safety
Technologies, Inc.
Mesa, AZ, USA

ABSTRACT

A closed-loop test of a 1974 Ford F-150 4WD truck equipped with super oversized off-road mud tires was conducted to demonstrate that steering was possible after a left front rapid air-out event. A rim was built with six remotely deployable orifices that activated simultaneously and caused the air pressure to decrease below 2.5 psi in less than one second. The truck was configured in OEM condition except for the tires and rims. The tires were 42-14X16 mounted to 8X16 rims with zero offset. The tires that were originally sold with the vehicle were probably 8.75-16.5. Three tests at increasing speed of 35 mph, 45 mph, and 55 mph were conducted on a large, remote, and closed parking lot in a two-lane travel way marked with surface paint. The truck, while monitored with a standard suite of instruments and video, was brought to speed in a straight-line. At a predetermined point, and while maintaining a straight path, the throttle was dropped and the left front tire air-out was remotely triggered. The driver, aware of the test conditions and with the benefit of experience, was instructed to steer the truck to maintain its position within the simulated traffic lanes. The truck was equipped with a four-speed manual transmission which remained in fourth gear throughout the response phase of the test. The clutch was depressed and brakes applied only after steering control had corrected the vehicle's leftward motion. The post air-out path of the truck evidenced by printing from the left front tire in each test was measured, photographed and plotted. The truck never left the simulated roadway travel lanes, which represented one direction of a typical four-lane California state highway. The test data was recorded at 200 samples per second and was post-processed with a 6 HZ, 12-pole, phaseless digital filter. Test results were plotted and presented. The test results are of interest because they are a demonstration of the concept that even under extreme conditions, if a test driver knows what is going to happen and knows what to do, a controlled vehicle motion is the likely outcome. In the tests, as the driver gained experience and the speed increased, lateral motion decreased. These findings are consistent with conclusions in a NHTSA tread separation study including, "when drivers had prior knowledge of the imminent tread separation, they were significantly less likely to sustain loss of vehicle control following the tread separation." And, "findings from test track studies in which test drivers were aware of an imminent tread separation may underestimate the extent to which tread separation occurring in the real world leads to instability and loss of vehicle control."

INTRODUCTION

Historical research of tire disablements consistently included the understanding that some form of external vehicle disturbance occurred. In his 1968 Illinois tollway study J. Stannard Baker and co-author, G. Declan McIlraith, described how drivers reported they knew a tire was disabled both before a crash and in non-crash situations (n=338). In Baker's study, drivers reported "blow out" (15.1%), vibration (51.2%), sideward pulling (15.4%) and other (18.3%), as how they knew a tire was disabled in all situations. Though Baker only studied thirteen crashes in which tire disablement was determined to have preceded a crash (and only ten of these crashes where the tire was available for examination), pulling to the side (41.1%) and "blow out" (23.6%) were reported at higher rates in these cases causally linked to a crash. Baker commented on variations in duration of tire disablements noting that "blow out" would "imply sudden as contrasted to slow failure." [1]

Tire disablements have been documented to cause insignificant to severe external vehicle disturbances. An insignificant response was reported by Car and Driver magazine in January of 2001 after testing a 1994 Ford Explorer XLT with a left rear tire rigged to rapidly deflate (blow out) at speeds between 30 mph and 70 mph. In the first test at 30 mph the Car and Driver test driver reported, "No big deal. It didn't really pull much at all. I just kept it going straight, eased my foot off the gas and onto the brake. A piece of cake." In their last 70 mph left rear blowout run the test driver removed both hands from the steering wheel and, again, the Explorer continued straight ahead. [2]

A severe response reported in a 2001 paper published at the Enhanced Safety of Vehicle (ESV) conference in Amsterdam, Netherlands resulted from a test of a 1996 Ford Explorer that had a “significant destabilizing response to a [right rear] tire tread separation” when the driver’s behavior was restricted to holding the steering steady. In the test with severe response the tire maintained its air pressure and did not blowout. “The test driver could not redirect the Explorer with a counter-steer. The result was that the Explorer left the paved test surface and tripped and rolled coming to rest 175 feet away.” [3]

This paper was motivated by tests conducted to evaluate a front tire blowout that preceded the loss of control and crash of a 1974 Ford four-wheel-drive (4X4) pickup truck. In the crash a front tire much larger than anticipated by the vehicle’s design suffered a rapid deflation because of its inner sidewall puncture. The puncture occurred when the left side tie-rod end disengaged from the steering knuckle because the castellated nut that held the parts together was not secured with a cotter pin. When the tire-rod end disengaged it fell away from the steer knuckle and contacted the inner side wall of the tire. The contact with the tire side wall shaved a groove and eventually produced a large hole in the tire. The disablement from the separated tie-rod was the significant cause of the crash; however, questions remained as to whether the failed tire size caused an unrecoverable disturbance and/or an un-steerable truck. The tests were conducted to evaluate whether the disturbance and/or change in vehicle response due to the tire failure was so great that steering to affect crash avoidance was not possible.

METHOD

The vehicle that was tested was a 1974 Ford four-wheel-drive (4X4) F150 pickup truck. The truck was equipped with a V8 engine (492), four-speed manual transmission and manual steering. The tires were 42-14X16 mud tires mounted to 8X16 rims with zero offset. The tires were inflated to 25 psi at the front and 18 psi at the rear. The tires were so large that the front fenders were removed so that interference while turning and jounce motion was eliminated (the front and rear fenders of the crash truck had been cut to eliminate tire interference). Photo 1 contrasts the tested tire to a tire listed in the trucks sales brochure.

To conduct the test a titanium outrigger built to the specifications described by NHTSA [4] was fitted to the front and rear. The outrigger was mounted at an angle because of the truck’s significant leftward roll when the left front tire was deflated. Photo 2 depicts the truck prior to testing. The truck was ballasted with 177.5 pounds in the right front seat position and 105 pounds bolted to the middle floor of the bed. The test driver weighed 220 pounds. The truck was instrumented with an AB Dynamics Omni Lite steering machine which was only used to measure hand wheel angle. Other instrumentation included the Crossbow IMU400CB-100 (measuring x, y, z acceleration and yaw, roll, pitch rates) and the Corrsys-Datron S-400 optical sensor (measuring speed and slip angle). Two cameras were mounted on the exterior of the vehicle documenting the tire and an external camera captured the overall truck motion. One camera was mounted in the interior of the truck documenting the hand wheel but only captured footage in the first air-out test.

Photo 1. Tested tire on left. Tire that was probably originally sold with the truck on right.

Photo 2. The truck prior to testing.

Three tests at increasing speed of 35 mph, 45 mph and 55 mph were conducted on a large, remote, and closed parking lot in a two-lane travel way marked with surface paint. The two-lane travel way represented one direction of a typical four-lane California state highway geometry. Photo 3 depicts the layout of the two-lane travel way and gate. The truck was brought to speed in a straight-line aligned with the center of the right lane. Before reaching a gate marked with small traffic cones, and while maintaining a straight path, the throttle was dropped. At the gate the left front tire air-out was remotely triggered. The truck remained in fourth gear throughout the response phase of the test. The clutch was depressed and brakes applied only after steering control had corrected the vehicle's leftward motion.

The testing involved the rapid air-out of the left front tire. To cause the rapid air-out a rim was built with six remotely deployable orifices that caused the air pressure to decrease below 2.5 psi in less than one second. The pressure versus time of the air-out was confirmed with a properly pressurized tire mounted to a stationary truck naturally sitting on flat ground. Pre-test characterization of tire deflation is shown in figure 1.

Photo 3. Layout of the two-lane travel way and gate.

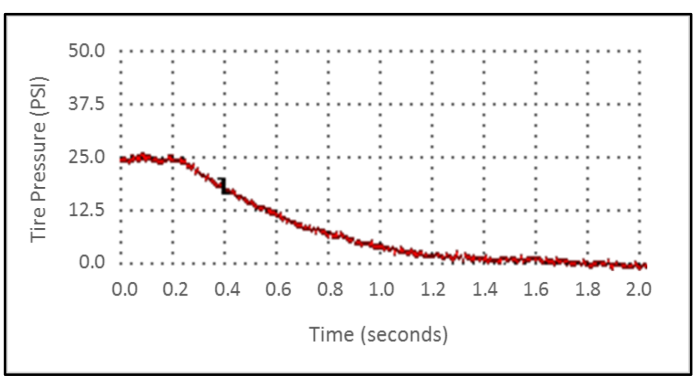

Figure 1. Pre-test characterization of tire deflation. Pressure (PSI) versus time (sec)

The driver of the truck was the author of this paper. The driver was knowledgeable regarding the consequences of tire disablements, experienced with driving a variety of vehicles during a variety of tests with tire disablements, aware of the test conditions, and benefited by gaining additional experience as the testing progressed. The test driver was instructed to attempt a steer of the truck to maintain a position within the simulated traffic lanes. Prior to conducting the first air-out test at 35 mph, neither the driver nor anyone associated with the test had driven an air-out event test with the test truck in any configuration or condition. In other words there was not any truck/tire/event specific knowledge about the response of the truck prior to conducting the first test at 35 mph.

In additional to digital recording of the instrumentation at 200 samples per second, photographs and measurements of the left front tire marks were made. Data recorded from the instruments was post processed with a 6HZ, 12-pole phaseless filter and zeroed.

RESULTS

Figures 2 through figure 4 are plotted results of the pertinent segment of each air-out test. The hand-wheel angle, speed, X and Y acceleration and yaw rate are plotted. Each test result figure has a vertical line at the left representing the start of steering and a vertical line at the right representing the start of brake/clutch application. The time of start of air-out was not electronically synchronized/recorded in the test data.

Photo 4 documents the left front tire mark after all three tests. The marks may not reproduce well in publication so for complete clarity photo 5 duplicated photo 4, but with the addition of overlaid shading depicting the three tire marks. The tire marks are highlighted in photo 5 with the lowest speed mark (35 mph) at the left side and the highest speed (55 mph) at the right side (red – 35 mph; blue – 45 mph; green – 55 mph). Figure 5 is a scale drawing of the three tire marks and figure 6 is an elongated drawing of the tire marks that distorts the X versus Y scale and may help with distinguishing the tire mark paths. Photo 4 depicts the truck at rest with the left front tire deflated following an air-out test.

In figure 2 through figure 4 the Y axis acceleration does not return to zero. This can be explained by the significant lean of the truck after the left front tire was flat as demonstrated in photo 6. Instruments were not fitted to the truck which would allow for the calculation of roll or pitch angle, so a correction of the X and Y acceleration for the time during and after the tire air-out was not performed.

DISCUSSION

Because of the extremely large tires, tires so large that the wheel wells had to be modified, the exact influence of a rapid air-out effect on leftward pulling and steerability of the truck was in question. During testing the truck never left the simulated

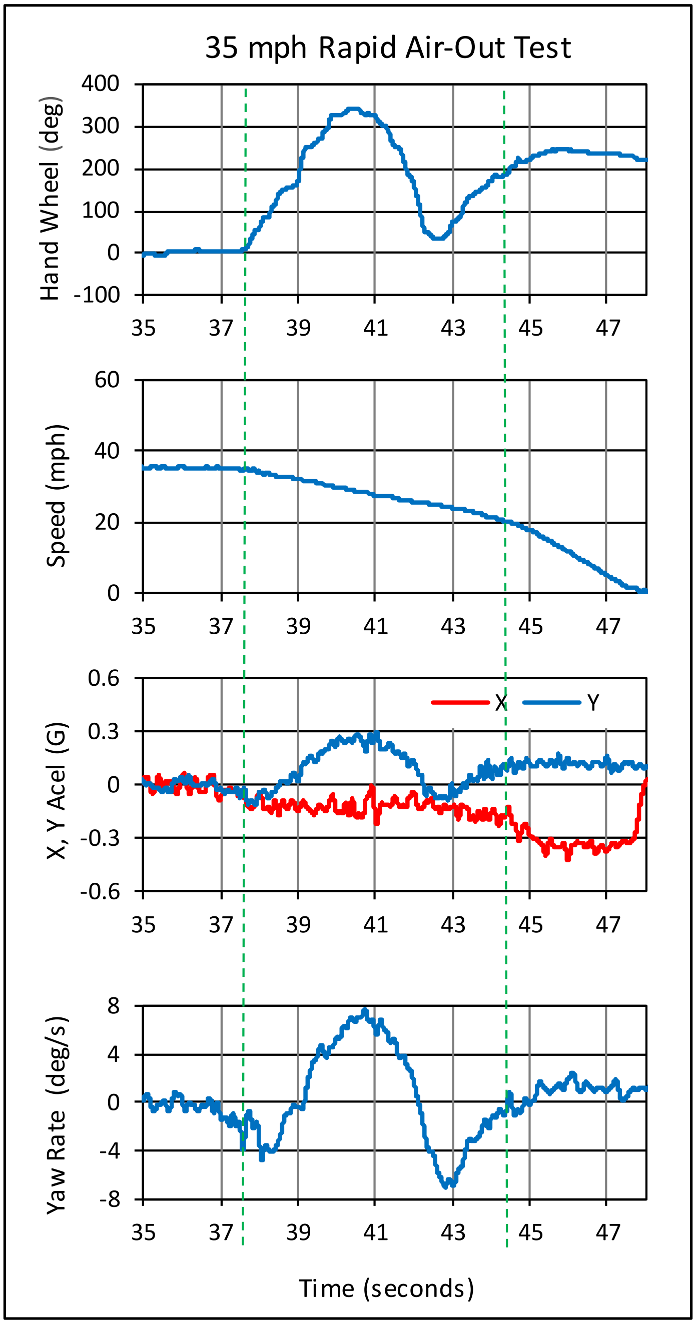

Figure 2. Plotted results from the 35 mph rapid air-out test. A vertical dashed line at the left represents the start of steering and a vertical dashed line at the right represents the start of brake/clutch application.

Photo 4. Left front tire mark after all three tests.

Photo 5. Tire marks from Photo 4 are highlighted with lowest speed mark (35 mph) at the left side and highest speed (55 mph) at the right side (red - 35 mph; blue - 45 mph; green - 55 mph).

Photo 6. Significant lean of the truck after the left front tire was flat.

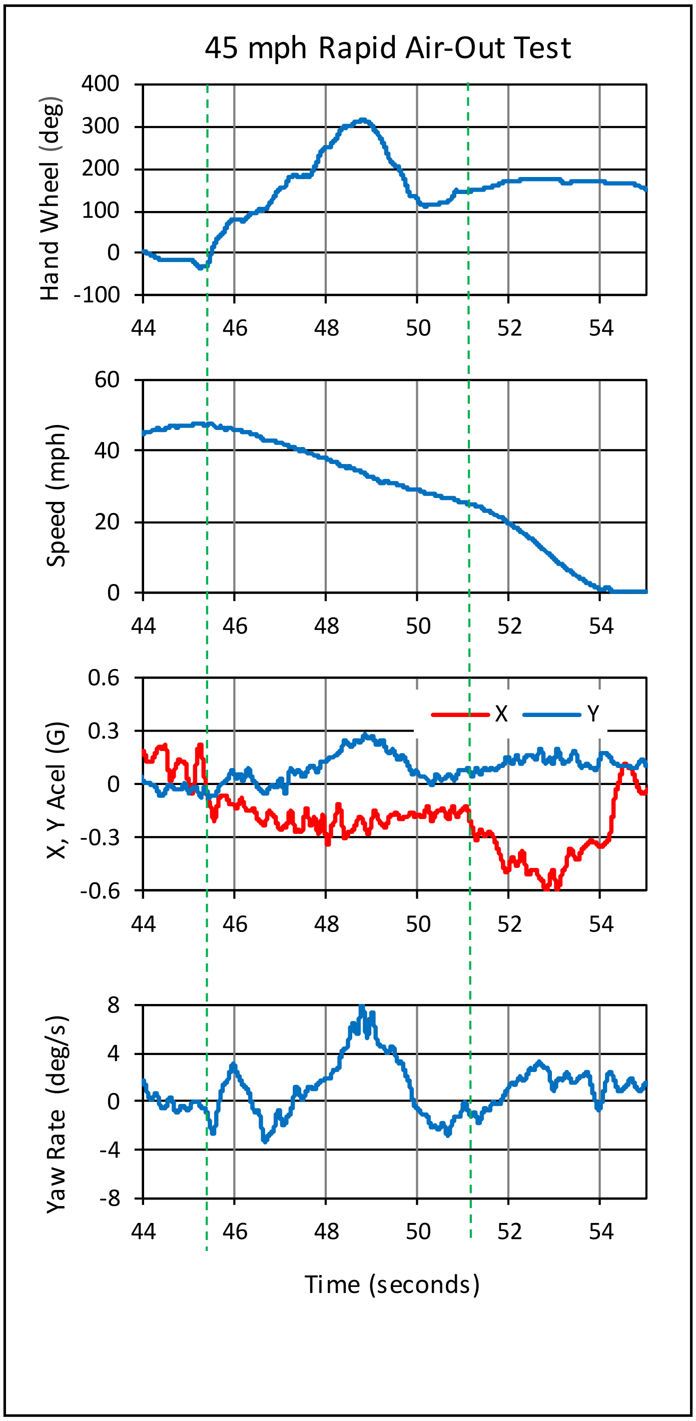

Figure 3. Plotted results from the 45 mph rapid air-out test. A vertical dashed line at the left represents the start of steering and a vertical dashed line at the right represents the start of brake/clutch application.

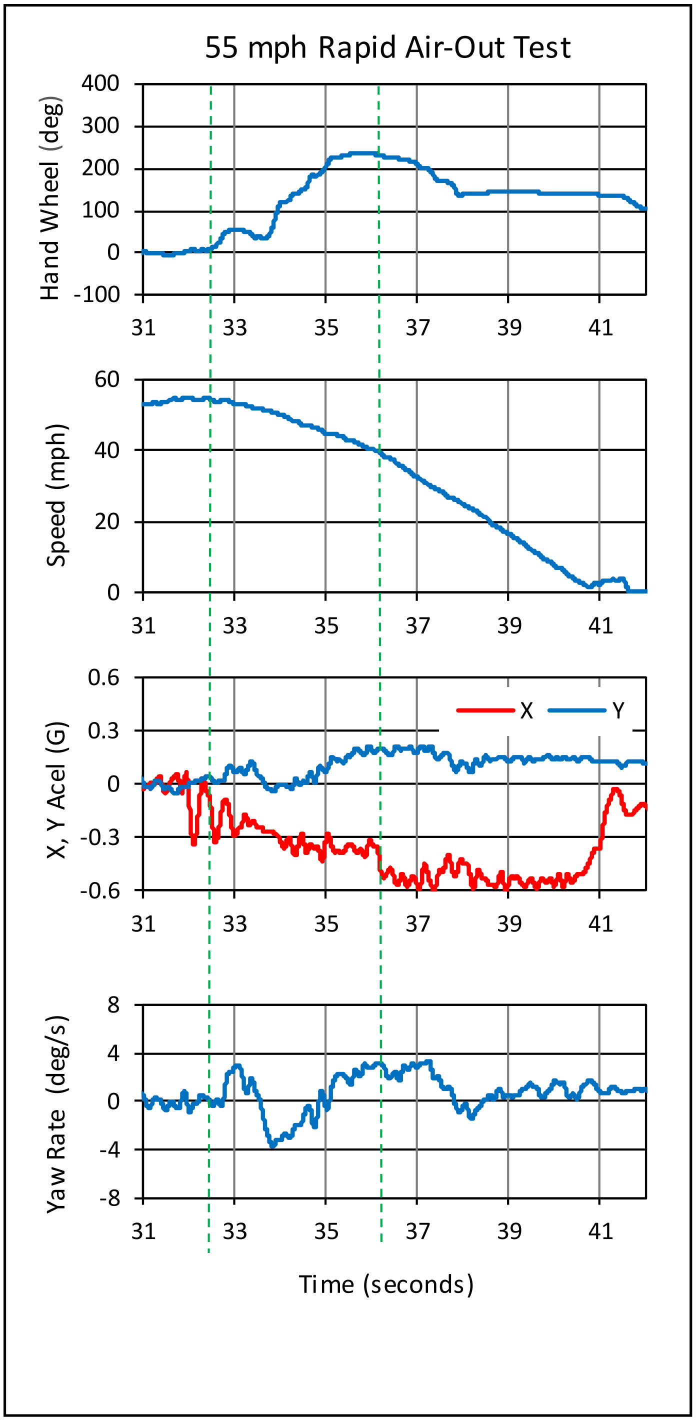

Figure 4. Plotted results from the 55 mph rapid air-out test. A vertical dashed line at the left represents the start of steering and a vertical dashed line at the right represents the start of brake/clutch application.

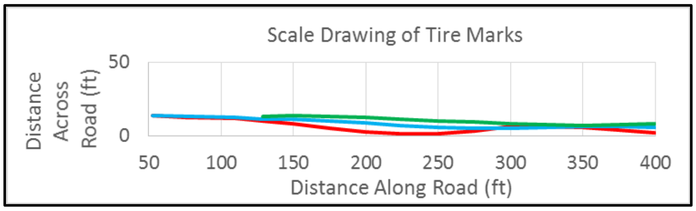

Figure 5. Scale drawing depicting path of left front tire. Red line is 35 mph. Blue line is 45 mph and green line is 55 mph.

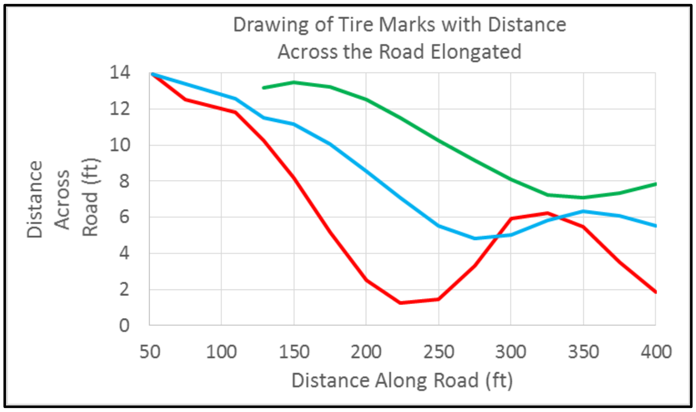

Figure 6. Drawing with distance across road elongated depicting path of left front tire. Red line is 35 mph. Blue line is 45 mph and green line is 55 mph.

travel lanes that represented one direction of a typical four-lane California state highway geometry. The tires did not cause an air-out response with an unrecoverable disturbance or render the vehicle unsteerable. The reader should consider these results in the context of the test purpose and method. As in many unanticipated tire failures on vehicles operated on the road by relatively unfamiliar and unpracticed drivers, the failed tire would have pulled the vehicle off the travel lanes except for the test driver and design.

The purpose of the test was to evaluate whether the disturbance and/or change in vehicle response was so great that steering to affect crash avoidance was not possible. In other words, did some disturbance or truck characteristic change with the fitment of the super oversized tires such that the disablement by itself invariably caused a crash? The clear answer to this question was no. The test was not designed to evaluate driver capability, nor was the test designed to evaluate the suitability of the tire/truck combination.

Regarding the method, historically two approaches have been used in evaluations of vehicles undergoing tire disablements. The approaches can be characterized as closed-loop versus open-loop.

The testing reported herein used a closed-loop approach. Closed-loop means that the driver is in the [control] loop using feedback from the vehicle's responses to actively decide how to control the truck. How the driver steered the truck was also influenced by experience and knowledge. A body of published technical literature described tire disablement testing that used a closed-loop approach. Not surprisingly, no modern published study using an "un-blind" closed-loop approach reported an uncontrollable vehicle response. The term blind means that the driver did not have prior experience or knowledge of the test or its parameters. Unfortunately, the same studies often concluded with inferences generalized to the driving behavior of all passenger-carrying vehicle drivers in all situations based upon the vehicle's performance at the hands of the experienced and knowledgeable (un-blind) expert driver operating in the study's controlled conditions.

Open-loop means that a test design was implemented that limited responses to those caused solely by the consequence of the stimulus – in this case a rapid air-out. In an open-loop test steering or other responses of the driver are prevented so that attempts to control the vehicle are not confused with the responses of the vehicle. A body of published technical literature described tire disablement testing that used an open-loop approach. Open-loop test results are by definition reproducible – meaning that test results could be replicated under the same conditions by different drivers or autonomously with no active driving. Comparison of open-loop test results are not based upon subjective interpretations, but rather objective measures and criteria.

Sequentially, the subject tests were conducted with target speed increasing in 10 mph. As the testing progressed the leftward motion of the left front tire decreased and peak hand wheel angle declined. These results are principally attributed to two effects: increasing speed and driver experience.

A similar result regarding the effect of increasing speed was published in 1968 by Professor Masaichi Kondo and co-authors based on testing results from simulated tire failures. [5] Testing a rear-engine passenger car, the Hino Contessa 1300, the researchers conducted simulated rapid deflation of left side tires at both the front and rear positions and in straight and circular paths (1.5 second and 2.0 second for front and rear tires, respectively). The authors described "somewhat" leftward deviation and "stable running converging to steady circular turn" in steering locked (open-loop) straight line front tire tests.[1] The

[1] The authors [5] conducted both open-loop and closed-loop testing in a robust test program presented at the XII Congress of the Federation Internationale des Societes D'Ingenieurs des Techniques de L'Automobile (FISITA). Additional conclusions include, in steering locked (open-loop) straight line rear tire tests "only a little" deviation occurred, but "side slip angle increases rapidly and the car manifests unstable behavior." Deviations were attributed to increased rolling resistance of the deflated tire. An interesting finding in the published conclusions was for the case of left rear tire deflation in steering locked (open-loop) right turns: the authors noted that, though oversteer occurred, the degree of oversteer was weaker compared to left turns. In other words the increased rolling resistance of the outboard rear tire mitigated oversteer by a mechanism analogous to Electronic Stability Control (ESC) Systems.

measured deviations were attributed to increased rolling resistance of the deflated tire, but the rate and extent of deviations was documented to be lower as speed increased. The authors concluded that as speed increased the force from rolling resistance decreased. This finding was not inconsistent with the driver's experience in the present study.

Other than common sense, perhaps the most authoritative example of the effect of driver experience on vehicle response following tire disablement was the 2002 driving simulator study by Ranney et al.[6] The study was statistically designed to select average drivers that were "blind" to the purposes of the study. A purpose was to investigate the effect of understeer gradients on the rates of vehicle loss of control following a simulated rear tire tread separation.[2] The study included a follow-up evaluation of each driver after having driven "blind" during a simulated tread separation and after having been instructed as to the most effective method to avoid loss of control following tread separation. In the follow-up study where the driver knew what was going to happen (un-blind) and how to respond, significantly less loss of control was measured. Ranney and co-authors noted [6, page 51], "when drivers had prior knowledge of the imminent tread separation they were significantly less likely to sustain loss of vehicle control following the tread separation." And, "findings from test track studies in which test drivers were aware of an imminent tread separation may underestimate the extent to which tread separation occurring in the real world leads to instability and loss of vehicle control." These finding were consistent with the author's driving experience in the present study.

Concern was expressed that with the configuration tested and presented in this paper, control would not be possible following a tire disablement with the oversized tire. A variety of factors contributed to and in combination aggravated the truck's steering control. These factors included not only the tires - which were outrageously larger than the vehicle could accommodate and substantially larger than specified by the vehicle manufacturer - but the lack of power steering, non-OEM rims, truck vintage and wear and tear (age/mileage).

In the body of published testing that utilized the closed-loop method with drivers aware and knowledgeable of the test and test conditions, the configuration of the truck with the oversized tire in this study represented a worst case condition and the tire disablement produced without question the largest turning force. Despite the size of the tire and the magnitude of its failure-inducing turning force, the truck was nonetheless controlled by the knowledgeable and experienced driver.

The results of the study are explained by the superior and scientifically reliable body of objective prior published research that used statistical experimental design, blind drivers, and controlled and open-loop testing. This body of reliable research objectively described a range of disturbances that occur in tire disablements, changed vehicle handling characteristics, and the effects of prior knowledge, experience, and instruction in best driving practices. The results from this study confirmed that even though factors at play during the tire disablement were most adverse, the driver controlled the vehicle because he knew what was going to happen, had experience with prior disablements and was driving on a controlled, closed course that negated environmental complications. In addition, decreased lateral displacement upon tire disablement was consistent with results from Professor Kondo's 1968 study in which he noted as speed increased the force from rolling resistance decreased.

CONCLUSION

In conclusion the results of the testing presented in this study demonstrated that it was possible to control a 1974, non-power-steering enabled pickup truck with super-oversized tires after a left front tire blowout. As speed was increased in the testing, lateral displacement and vehicle control demands decreased. The results were explained by and corroborated prior published objective testing presented by and Kondo [5] and Rainey [6].

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[2] In the course of the study the researchers [5] reported a statistically significant relationship between understeer gradient and the likelihood that a driver loses control of a vehicle following a rear tire tread separation.

