

An Objective Analysis of the Effect of Tire Tread Depth on Crash Causation and Wet Road Vehicle Dynamics

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ABSTRACT

This paper explores tire placement with given tread depths on vehicles from two distinct perspectives. The first area explored is an analysis of crash data recently reported by the National Highway Traffic Safety Administration (NHTSA). In this report, thousands of tire-related crashes were investigated where the tread depth and inflation pressure were logged for each tire and assessments were made as to whether tire condition was a factor in the crash. The analysis of the data shows that in regards to accident causation, it is not statistically significant which axle has the deepest tread. What is significant is that a tread depth at or below 4/32" anywhere on the vehicle leads to an increased rate of crashes. To understand the physics implied by the NHTSA data, a study was performed on how the placement of tires of various tread depths affects the steering, handling, and braking performance of a modern sport utility vehicle. The test vehicle was instrumented with on board video equipment and a computer with transducers to measure driver inputs as well as vehicle responses during the testing. The vehicle was tested on a uniform wet test surface at a test track specifically designed for this purpose. Specific repeatable tests were performed to study the wet surface steady-state and transient handling performance as well as the straight line stopping distance during limit braking. These tests included an SAE J266 one hundred foot circle test, a closed loop single lane change, a slowly increasing steer test, and a limit ABS brake stop. These tests were each performed three times on the vehicle with tires of various makes and manufacturers and different levels of real world customer wear. A pair of "shaved" tires was also evaluated. The results show that placement of tires has a definite effect on the vehicle dynamic performance of the utility vehicle tested and that deeper tread depth on the rear suspension is not always the best configuration for overall vehicle performance.

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INTRODUCTION

When a customer enters a tire store to purchase only two tires, a decision must be made as to where to place the two new tires and the two other tires on the vehicle. Many times it is recommended to place new tires on the rear suspension and the more worn tires on the front. In general, the thinking behind this strategy is that it is believed tires with more wear have less traction in wet conditions. Therefore, it is somehow better for a vehicle to plow out during a loss of control situation than to spin out. There have been several papers and studies that have looked at how vehicles steer and handling on wet surfaces and/or how tires behave on wet surfaces of varying water depths and translational velocities [1,2,3,4,5,6,7,8,9,10,11,12,13,14]. Some of the papers which

concentrated on vehicle handling employed "shaved" tires when the effect of various tread depths was studied. Not a lot of emphasis has been placed on what happens to the braking performance of a motor vehicle when equipped with tires of dissimilar tread depths.

This paper focuses on how a vehicle handles, steers, and brakes when driven at highway speed on a surface with uniform but significant water depth with a variety of tires of different tread depths. A 2004 rear wheel drive sports utility vehicle which was not equipped with an electronic stability control system was employed for all testing (see [Figure 1](#)). The vehicle was instrumented with on board video equipment and a data acquisition system to measure driver inputs as well as vehicle responses during the testing (see [Figure 2](#)).



Figure 1. Test Vehicle: 2004 Sport Utility Vehicle

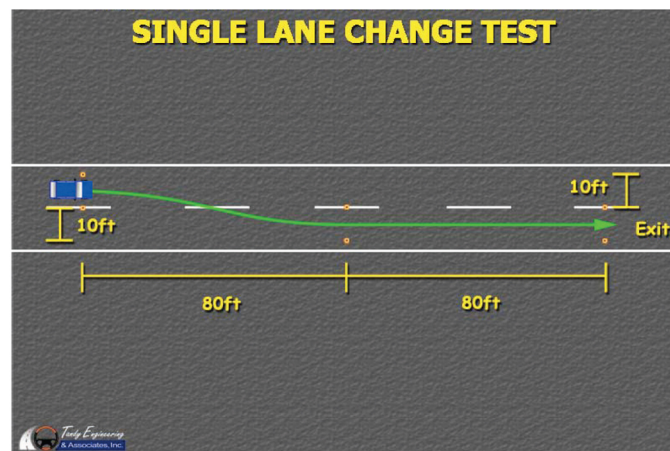


Figure 3. Course Layout for Single Lane Change Test



Figure 2. Photograph of Test Instrumentation

All tests were conducted on two consecutive days on the wet pad and wet circle at the Continental Tire Proving Grounds in Uvalde, Texas. The first test involved a straight line full ABS brake stop from highway speeds. The next two tests were quasi static and run to determine understeer at low speeds and high speeds. The first of these tests was an SAE J266 [15] one hundred foot circle test run until the vehicle could no longer stay on the course. The second understeer test involved slowly increasing steers at various speeds until the vehicle either spun out or plowed out. The last test involved a single lane change which was run at ever increasing speeds until the vehicle either plowed off the course or spun out (see Figure 3 for course layout). A single experienced and trained driver was used so that repeatable tests could be performed. The purpose of this study was to measure how various tires at various tread depths affect the braking, steering and handling characteristics of vehicle on a surface with significant standing water. Speeds were selected to go beyond what is reasonable for normal everyday driving.

CRASHES ON WET ROADS

Accident data recently reported by NHTSA where tire-related factors were considered in the pre-crash phase has been analyzed¹. In the NHTSA report, thousands of tire-related accidents were investigated where the tread depth and inflation pressure were logged for each tire and assessments were made as to whether tire condition was a factor in the accident. Since only accident data was analyzed by NHTSA, the tread depth distribution on average, non-accident vehicles was not considered. In 2001, NHTSA published a research note on the data collected during the Tire Pressure Special Survey where tread depth was captured². By combining the data from the two NHTSA studies, the risk of crash involvement as a function of the difference between front axle tire tread depth and rear axle tire tread depth was estimated.

Crash Data Analysis

The National Motor Vehicle Crash Causation Survey (NMVCCS) is a collection of on-scene information on the events and associated factors leading up to crashes that involve light vehicles. To be included in the survey, several criteria for the accident had to be met. For example, crashes had to occur between 6 a.m. and midnight. The crash must have resulted in a harmful event associated with a vehicle in transport on a roadway. EMS must have been dispatched to the crash scene. At least one of the first three crash-involved vehicles had to be present at the crash scene when the NMVCCS researcher arrived, in addition to the police being present at the scene of the crash when the NMVCCS researcher arrived. One of the first three vehicles involved in the crash was a light passenger vehicle that was towed. A completed police accident report for this crash must be available. Data was collected from July 1, 2005 to December 31, 2007 for the nationally representative sample of 5,470 crashes representing 2,188,969 crashes involving 3,944,621 drivers and 4,031,075 vehicles.

The Tire Pressure Special Survey (TPSS) was designed to assess what extent passenger vehicle operators were aware of the recommended tire pressures for their vehicles, the frequency and the means they used to measure their tire pressure, and how significantly actual measured tire pressure differs from the manufacturer's recommended tire pressure. During the survey process, the NHTSA researchers also measured the tread depth of all four tires and noted their position. For both studies, the tread depth measurement was taken from the shallowest groove of the tread. Data was collected on light passenger vehicles at gas stations from 8am - 5 pm February 1, 2001 through February 14, 2001. A nationally representative sample of 11,530 vehicles was measured, representing 41,562,984 vehicles.

The data from the two previous studies was then combined to estimate the risk of crash involvement as a function of the difference between front axle tire tread depth and rear axle tire tread depth. For each database the difference between average front axle tire tread depth and rear axle tire tread depth was calculated and the tread depth measurements from the TPSS were converted from 1/32" to mm. Tread differences were calculated as front tread depth minus rear tread depth, meaning:

- Negative values imply deeper tread in rear
- Positive values imply deeper tread in front

Vehicle crash data was matched to vehicle population data using tread depth differences in 11 categories (-5 or more, -4, ..., +4, +5 or more). Rates are number of crashes in category divided by population in category and represent the crash rate in the 2 1/2 year period from July 1, 2005 to December 31, 2007. The rates calculated are for:

- All Tow-Away Crashes per 100 Vehicles
- Tire/Wheel Related Tow-Away Crashes per 100 Vehicles
- Loss of Control Tow-Away Crashes per 100 Vehicles

It is also important to note that no data from either of the studies was excluded from this analysis.

Results

Figure A1 in the Appendix shows the tread depth difference between front and rear tires for both distributions of tires, the 2001 TPSS (or vehicles that were surveyed at gas stations and *not* involved in accidents) and the NMVCCS, where *all* vehicles were involved in accidents. Vehicles involved in tow-away crashes are more likely to have differences in tread depth between front and rear axles as compared to non-accident vehicles.

Figure A2 in the Appendix shows the detail for the rate of tow-away crashes vs. tread depth differences. In all cases, the rate of tow-away crashes is higher for vehicles that have any difference in tread depth between front and rear, regardless of how small the difference may be or whether the higher tread depth tires are on the front or the rear.

The NMVCCS data allows for a more in-depth accident analysis regarding the tire as a contributor to the accident.

The data identifies a subset of accidents where tire/wheel deficiencies are identified as a pre-crash contributing factor. Figure A3 in the Appendix shows that the crash rate increases significantly when there is a difference between front and rear axle tread depths. Figure A4 in the Appendix is another way to slice the NMVCCS data. By looking at all loss of control accidents, one can also see that the crash rate increases significantly when there is a difference between front and rear axle tread depths.

Discussion

In the past several years, tire companies have been strongly recommending that when purchasing two new tires, the new tires should be mounted on the rear axle of the vehicle. The reasoning behind the recommendation is that if one is going to lose control of a vehicle, it is easier to recover from losing control of the front as opposed to the rear. Unfortunately, other than demonstrative videos produced by tire companies and limited experiments by Blythe² et al, there is a paucity of data to rely on when attempting to validate whether there is any science to back up the tire industry recommendation. The analysis in this paper shows that there is no correlation between tread depth, axle placement and accident causation. In the case of accident causation, the simplest correlation (to tread depth) has been shown to be the best. To quote from the NMVCCS¹:

"The results...show that significantly more than expected vehicles experienced tire problems when they were running on tires with tread depth between 0 and 4/32", where expected frequencies were obtained under the assumption that tire's crash role has no association with tire tread depth."

The analysis of the data shows that in regards to accident causation, it is not statistically significant which axle has the deepest tread. What is significant is that a tread depth at or below 4/32nds of an inch anywhere on the vehicle leads to an increased rate of accidents.

ON TRACK TESTING METHODOLOGY

The methodology employed in the testing in this study is divided into four sections. The first section describes the tire selection and the second section describes the test surface. The third section describes the vehicle preparation, including the instrumentation and video equipment used to document the tests. The fourth and final section describes the test procedures employed.

TIRE SELECTION

All tires used in this testing were of the size P235/70R16 and were inflated to 35 psi, the recommended size and

pressure for the test vehicle. Four new tires were purchased and many customer worn tires were obtained from Tire stores in Texas. These used tires were of various manufacturers and were selected to be part of the study if they had consistent wear (not excessive irregular wear or wear on only one side of the tire). It is important to note that the customer worn tires were taken off vehicles within a couple weeks of the testing. Tires were grouped together in pairs so that on a given axle, the same make and brand of tire would be used and those two tires would have a similar amount of wear. This tire selection process was chosen because data suggests that people who only replace two tires may not necessarily seek out the same make and model of tire as is on their vehicle. [Figures A5, A6, A7, A8, A9, A10, A11, A12, A13](#) in the Appendix contain photographic documentation of an example tire of a given set used in this testing.

Since several previous studies have relied on tires cut down to a given tread depth to approximate a real customer worn tire, a set of “shaved” tires were also employed in this study. The “shaved” tire was made from a customer tire by placing it on a tire shaver and cutting down the tread to a desired tread depth of $5/32$ ". [Figures 4 and 5](#) each show a photograph of one of the specially prepared “shaved” tires. Note the roughness of the tread blocks which is due to the cutting action of the shaver. This roughness is clearly not similar to a real world customer worn condition.



Figure 4. ‘Shaved’ Tire Used in Testing



Figure 5. Close-up Photograph of “Shaved” Tire

TEST SURFACE

All tests except the SAE J266 circle tests were performed on the wet pad at the Continental Tire Proving Grounds in Uvalde, Texas. The wet pad is approximately a 250 by 250 meter square, extremely consistent asphalt surface that has water pipes on two sides that allow water to slowly drain across it from one end to the other. The pad was recently repaved and made such that the water depth is very uniform in the test area (see [Figure 6](#)). The SAE J266 circle tests were performed on a special paved circle that has water draining across it as well (see [Figure 7](#)). The water was turned on hours before any tests were conducted to allow for the test track surface to fully flood and do so in a consistent manner and generate a consistent depth of just over $2/32$ of an inch. In their SAE publication 720471 “Testing and Analysis of Tire Hydroplaning”, by Robert Yeager and Jack Tuttle⁷ included a study of surface water depth and concluded that the depth used in this study is between the “brief thundershower” and “heavy downpour.” Therefore, the amount of water chosen for this study is indicative of a roadway with significant water depth.



Figure 6. Uvalde 250 × 250 meter Wet Pad

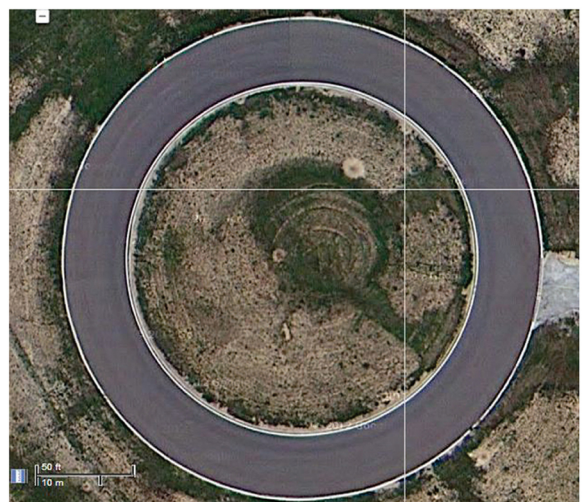


Figure 7. Uvalde Wet Circle

VEHICLE PREPARATION / TEST DOCUMENTATION

The test vehicle was equipped with video equipment and instrumentation and was loaded with only a driver and front seat passenger for all tests conducted. Four tires making up a set were selected from the group of tires and were marked and placed at all four locations.

Vehicle Instrumentation

The test equipment consisted of a set of instrumentation capable of measuring the following signals:

- Longitudinal, lateral, and vertical acceleration at approximately the vehicle center of gravity (cg)
- Vehicle longitudinal speed
- Steering wheel angle
- Slip angle
- Brake pedal force
- Yaw rate, roll rate, and pitch rate

Vehicle Video Equipment

Video equipment consisted of cameras that recorded the following views:

- Steering view over the driver's shoulder
- View of a digital display that recorded the longitudinal velocity
- An elevated view from a lift on the edge of the test surface

TEST PROCEDURES

The braking tests, SAE J266 circle tests, and the lane change tests were all performed on a course set up so that the test vehicle would travel over the exact location on the test track in each run. The following steps were followed:

Straight Line Braking Tests

- Place the chosen set of tires at the proper positions on the vehicle and record.
- Initiate data acquisition and video.
- Accelerate vehicle to highway speeds (around 100 kph) on a run up area that entered at the side of the wet pad.
- Drive through a set of two traffic cones which located the pre determined location where all brake stops should be performed.
- Brake to a stop with a very hard brake application and maintain it so that the Antilock Brake System (ABS) would immediately cycle and would continue to cycle through the whole stop.
- Repeat the test two more times for a total of three runs.

- Turn off data acquisition and video equipment.

SAE J266 100 Foot Constant Radius Circle Tests

- Place the chosen set of tires at the proper positions on the vehicle and record.
- Initiate data acquisition and video.
- Drive vehicle around the circle, starting at very low speeds and then accelerating very slowly until a limit condition is reached.
- Turn vehicle around and repeat the test in the other direction.
- Slow vehicle to a stop and turn off data acquisition and video equipment.

Slowly Increasing Steer Tests

- Place the chosen set of tires at the proper positions on the vehicle and record.
- Initiate data acquisition and video.
- Accelerate vehicle to highway speeds (around 80 kph) on a run up area that entered at the side of the wet pad.
- Vehicle speed must be kept constant during the entire test run.
- Slowly turn the steering wheel to the right using a slow, constant steer rate until the driver senses the vehicle breaking loose in a plow out or spin out.
- If a limit condition was not reached (i.e. the vehicle did not plow out or spin out), repeat the test at a higher speed. The test speeds are 80, 88, 92, and 96 kph (or 50, 55, 57.5, and 60 mph).
- Slow vehicle to a stop and turn off data acquisition and video equipment.

Closed Loop Single Lane Change Tests

- Place the chosen set of tires at the proper positions on the vehicle and record.
- Initiate data acquisition and video.
- Accelerate vehicle on a run up area that entered at the side of the wet pad.
- Drive into lane change at a constant speed of 80 kph (50 mph).
- Vehicle speed must be kept constant during the entire test run.
- Drive into the entrance gate to the lane change then steer to the right into the exit opposing lane.

- Steer back to the left to straighten vehicle in the exit chute.
- Slow vehicle to a stop and turn off data acquisition and video equipment.
- If a limit condition was not reached (i.e. the vehicle did not plow out or spin out), repeat the test at 8 kph (5 mph) faster.

GENERAL RESULTS AND DISCUSSION

Studies into wet traction of tires indicate that water not only acts as a lubricant between the tire and road surface but it also must be expelled allowing the tread blocks to grip the road. The latter condition can lead to hydroplaning if the water begins to build up under the tire. Hydroplaning is a condition where the tire rides up on a film of water and leaves contact with the road. Hydroplaning is dependent on many factors including water depth, vehicle speed, tread design, tread depth, and type and polish of the roadway to name a few.

Straight Line Braking Tests

In the previous studies referenced, more effort was devoted to studying the wet handling characteristics than braking performance on wet roads. The brakes on a vehicle constitute an important safety system for a driver when an emergency occurs. Slowing down is helpful in many situations since it reduces the kinetic energy stored in the vehicle and it may make a vehicle easier to control for a lay driver. Therefore, only looking at vehicle handling or steering performance on wet roads will not provide the whole picture on total safety.

The straight line braking performance of several tire combinations on the test vehicle was evaluated using a panic ABS brake stop from around 100 kph (see [Figure A14](#) in the Appendix for example data plot of driver inputs and vehicle responses). The data was reduced by computing stopping distance from approximately 97 kph (60 mph) to zero speed and the braking distance from 96 kph to 65 kph (60 to 40 mph) then calculating an average of the three runs. Processing the data in this manner provided insight into not only total stopping distance but also the more important performance characteristic of slow down capacity since most drivers don't typically need to come to a complete stop on a highway.

[Figure A15](#) in the Appendix contains a bar chart of the total stopping distance (97 kph to zero). The data confirms that the braking performance of the test vehicle was improved with higher tread depth tires on the front and was degraded with the lower tread depth tires on the front of the vehicle. This finding makes sense since most of the braking force of a vehicle is generated at the front suspension. The results also seem to be insensitive to tire make and design and even to the amount of wear. The average stopping distance with new front tires fall in the 47 to 52 meters range and 59 to 77 meters when the new tires are on the rear. The case with the largest stopping distance was when new tires were on the rear

suspension and the most worn tires tested were on the front. In that example, it took approximately 25 meters more to stop than if the new tires were placed on the front. It is also interesting to note that the case of the 6/32" tires on the front and 4/32" tires on the rear stops similar to 6/32" on the front and new on the rear as does the case with 4/32" tread depth all around. Once again, not a surprising finding since the stopping distance is mostly dependent on the front tires.

[Figure A16](#) in the Appendix contains a bar chart of the braking distance from 97 to 65 kph. The performance of the vehicle is much more affected by tire sets in this case over the stopping distance to zero. Note that the data spans from 27 to 31 meters with the new tires in the front and increases to a range of 39 to 55 meters with the new tires in the rear. This is a significant degradation of vehicle performance. As in the case in the stopping distance tests, the longest braking distance was the most worn tires on the front suspension and the new tires on the rear.

Overall, the braking performance of a vehicle is highly dependent on the front tires. The data indicates that as the front tires wear, the braking distance in a severe water condition degrades. It is also important to note that the "shaved" tire performed similar to the customer worn tires in the braking tests.

SAE J266 100 Foot Radius Circle Test

As discussed above, two separate tests were employed to investigate the steady state handling performance of the test vehicle with different tire sets. The SAE J266 one hundred foot circle test was chosen to measure the linear range understeer and evaluate limit response in a test where the vehicle was traveling relatively slow (less than 50 kph). In this speed range, the tires would not hydroplane so that the limit response would be more dependent on how the compounding and design of the tires grips a wet surface. Two performance metrics were computed to study the low speed steady state behavior, one being the linear range understeer which was calculated between 0.1 and 0.4 g's of lateral acceleration. Note that 0.4 g's is only 40 kph (or 24 mph) which is far below the speed needed to hydroplane and therefore the tires are firmly on the ground and not slipping. The second metric was the observed limit response of the vehicle, one being a plow out response and the other a spin out response when the limit was reached. This is when the vehicle finally breaks loose. [Figure A17](#) in the Appendix contains an example of a time history data plot of driver inputs and vehicle responses for one of these test runs and [Figure A18](#) shows a plot of steering wheel angle versus calculated lateral acceleration.

The understeer gradients were calculated in both the counterclockwise and clockwise directions. It should be noted that this vehicle, like most, does not have the exact same understeer when turning right as when turning left. The data for the case with the new front and rear tires shows an understeer of 3.9 degrees per g in a counterclockwise direction and 3.4 degrees per g in a clockwise direction. The

understeer gradient differences highlighted in the test results should be a directly related to changes in the cornering stiffness of the different tires since the vehicle is held constant.

Figure A19 in the Appendix contains the understeer gradients for the counterclockwise turn and Figure A20 for the clockwise turn. Note first that in general placing worn tires on the front suspension and new tires on the rear reduces the magnitude of understeer and conversely, new tires on the front and worn tires on the rear increase the understeer gradient. In fact, in some cases the vehicle loses all of its understeer when worn tires are on the front and new tires are on the rear suspension. This should not be surprising since new tires deflect more and therefore have a lower cornering stiffness on average than worn tires due to the increase in tread block stiffness when tires are worn. It is also interesting that tires of similar wear on the front and rear suspension will have understeer comparable to four new tires. This fact provides firm support for the notion of performing routine tire rotations which will act to even the wear on the tires on a vehicle. The data also confirms that vehicle handling is not always improved with a "new tires on the rear" tire mounting policy.

Another interesting find in the circle test was the performance of the "shaved" tires. The change in understeer with the "shaved" tires was not as great as that with the customer worn tires when they were placed on the front or rear suspension which indicates that using a "shaved" tire is not necessarily a proper substitute for a real world worn tire.

The circle test also found that nearly all of the conditions evaluated exhibited a limit plow out response. The front tires would reach their limit first and slide on the lubricated surface to a larger radius circle. In several cases this was not true, namely when new tires were on the front suspension and customer worn 6/32" and 4/32" tires on the rear. The vehicle also spun with the tires "shaved" to 5/32" on the rear suspension in the counter clockwise direction. Note that the case with new tires on the front and 2/32" worn tires on the rear did not spin in either direction.

Slowly Increasing Steer Tests

The slowly increasing steer test objectively measured the quasi steady state handling properties of the test vehicle with various tire sets. The vehicle was driven onto the test track at constant speeds of 80, 88, 92, and 96 kph (or 50, 55, 57.5, and 60 mph). The test was terminated when the test driver felt the front of the vehicle hydroplane in a plow out response or the rear of the vehicle hydroplane in a spin out response. The metrics chosen for comparison were what type of hydroplaning limit response was achieved, the speed at which the vehicle plowed or spun, and the lateral acceleration level when that limit response occurred. Figure A21 in the Appendix contains a sample time history data plot of driver inputs and vehicle responses for a run that resulted in a hydroplane plow out where as Figure A22 contains a plot of a run where spin out occurred. These figures also show how the

lateral acceleration value was selected (i.e. when the yaw rate begins to deviate from the expected steady state value). Figure A23 in the Appendix shows a bar chart of all the tire sets and their corresponding performance metrics for the slowly increasing steer test sorted with increasing limit speed. Figure A24 shows the same data but with ascending lateral acceleration when the limit was reached. Figure A25 in the Appendix only shows the lateral acceleration data for tires tested.

The first metric to be discussed is the speed at which a hydroplane response was achieved. Here, the 2/32" tires and some runs with 4/32" and 5/32" tires break loose at the lower speeds. The highest speed runs were with the 4/32" or 6/32" tread depth tires on the front suspension and the new tires on the rear. In fact, these conditions achieved a higher speed run than the case with new tires at all positions. The "shaved" tire did not exhibit any real odd behavior in this metric.

The type of limit response encountered followed in general with plow outs with more worn tires on the front suspension and new tires on the rear. The case with the front and rear tires having 4/32" also experienced a plow out response. However, it is interesting to look at what matched sets of tires experienced a spin out in this quasi steady state test. The case with four new tires spun out as did the 6/32" tread depth tires on the front and new on the rear. The 5/32" "shaved" tires performed similar to the 2/32" customer worn tires when they were placed on the rear suspension with new tires on the front.

The lateral acceleration level when the limit response is achieved highlights an interesting difference between the plow out and spin out conditions. When the vehicle hydroplanes at the front suspension, it breaks loose and slides at lower lateral acceleration levels. These are in the range of 0.25 to 0.45 g's. In fact, the 2/32" tread depth tires actually generated more lateral acceleration than the two 4/32" tire sets when on the front with new tires on the rear. When the vehicle spun out, it actually could generate more lateral acceleration before the limit condition was experienced. These lateral accelerations ranged from 0.55 to 0.80 g's. The tires "shaved" to 5/32" on the rear suspension with new tires on the front performed similar to the four new tires condition. The results of this metric indicate that in general having more worn tires on the rear suspension allows a driver to take a steady corner at higher speed before the limit is encountered. This indicates to that if a vehicle spins out with more worn tires on the rear suspension and deeper tread depth tires on the front in a given maneuver, then it stands to reason that had the more worn tires been on the front instead, a plow out response would likely have occurred in that same maneuver at a lower lateral acceleration level. Both are loss of control events.

Closed Loop Single Lane Change Tests

In order to fully evaluate the steering and handling of the vehicle with different tire sets on a road with significant amount of water, thought must also be given to transient events. A closed loop single lane change was selected for this study for that purpose. The vehicle was run through the course at a constant speed starting at 80 kph (50 mph) and if a limit response was not experienced, the speed was increased by 8 kph (or 5 mph) for the next run. The metrics chosen in order to evaluate the transient performance of the vehicle were the speed through the lane change where the limit response was experienced and the type of limit response (i.e. spin out or plow out). [Figure A26](#) in the Appendix contains a sample time history data plot of driver inputs and vehicle responses for a run that resulted in a successful lane change where as [Figure A27](#) contains a plot of a run where spin out occurred and [Figure A28](#) contains a plot where plow out occurred. [Figure A29](#) in the Appendix shows a bar chart of all the tire sets and their corresponding performance metrics. The height of the bar represents the capacity of the tire set in terms of maximum successful speed and the color of the bar indicates the limit response. [Figure A30](#) in the Appendix provides the data sorted for only the spinout response and [Figure A31](#) contains only the data for the plow out runs

As opposed to the braking and understeer tests, the findings in the lane change do not consistently follow common expectations relating to tire placement. In terms of capacity (maximum successful speed), the fact that the most worn tires on the front were found to have the lowest capacity is no surprise. It clearly shows the degradation of worn front tires with significant wear. However, what is surprising is that many of the tire combinations had a similar 88 kph limit. It did not seem to matter where the worn tires were placed once the tire wear was at 4/32" or above. In fact, the highest speeds recorded were for the four new tires case as well as the 6/32" tread depth front with new tires on the rear suspension. This is not true for the "shaved" tires when placed on the rear suspension. This set could only get to the 80 kph limit.

The data is even more interesting when the limit response metric is analyzed. There are some tire sets with worn tires on the front and new on the rear that did not spin at speeds where other combinations of new on the rear and worn on the front suspension spun. There are also cases of spinout with new on the rear and worn tires on the front. Note also that the vehicle with four new tires exhibited a spin out response at the limit. This would be the performance of the vehicle out of the factory which can be compared to the case with 6/32" tread depth on the front and new on the rear which did not spin out at the same speed. Another interesting finding is the case with the "shaved" tires on the rear and the new tires on the front suspension. This condition had the lowest spinout speed of all sets tested which indicates once again that shaving a tire does not necessarily provide similar performance to an actual real world worn tire.

SUMMARY/CONCLUSIONS

1. In the past several years, tire companies have been strongly recommending that when purchasing two new tires, the new tires should be mounted on the rear axle of the vehicle. The reasoning behind the recommendation is that if one is going to lose control of a vehicle, it is easier to recover from losing control of the front as opposed to the rear. The analysis of actual crash data shows that in regards to accident causation, it is not statistically significant which axle has the deepest tread. What is significant is that a tread depth at or below 4/32nds of an inch anywhere on the vehicle leads to an increased rate of accidents. In all cases, the rate of tow-away crashes is higher for vehicles that have any difference in tread depth between front and rear, regardless of how small the difference may be or whether the higher tread depth tires are on the front or the rear.

2. Tires are a very important component in wet road vehicle dynamics. Their design, condition, and wear do have an effect on how a vehicle will perform up to and at its limits. Overall, this study indicates that a proper tire rotation schedule is important to keep the vehicle dynamic characteristics of a vehicle from deviating too much when wet roads are encountered. The response of vehicles at limit conditions clearly shows that drivers have a responsibility to be extra cautious and to slow down when driving on wet surfaces.

3. How a vehicle performs during braking is a very important aspect of total vehicle safety. This aspect of vehicle dynamics has not been given the focus it deserves in previous studies. The data shows that stopping distance and braking distance from 96 to 65 kph is very sensitive to tire placement. The common practice of placing tires with more wear on the front suspension degrades the stopping power of the vehicle significantly.

4. The SAE 100 foot radius circle test used to measure the low speed steady state handling performance of the different tire sets tested found that the common practice of placing tires of greater wear on the front suspension actually reduces the understeer gradient. Sometimes that understeer reduced to around neutral steer. When the new tires were placed on the front suspension, the understeer gradient increased as expected. Only a couple cases resulted in a spinout response at the limit of vehicle performance. The circle test data once again supports the use of a good tire rotation policy in order to keep the vehicle as close to original specifications as possible.

5. High speed understeer tests showed that even with four new tires, a spinout can be achieved in a steady turn maneuver. The type of limit response encountered follows in general with plow outs with more worn tires on the front suspension and new tires on the rear. The case with the front and rear tires having 4/32" also experienced a plow out response. In terms of spin outs, the case with four new tires

spun out as did the case with 6/32" tread depth tires on the front and new tires on the rear. The 5/32" "shaved" tires performed similar to the 2/32" customer worn tires when they were placed on the rear suspension with new tires on the front. Also, when the vehicle hydroplanes at the front suspension, it breaks loose and slides at lower lateral acceleration levels.

6. The findings in the lane change do not consistently follow common expectations relating to tire placement. In terms of capacity (maximum successful speed), the fact that the most worn tires on the front were found to have the lowest capacity is no real surprise. It clearly shows the degradation of worn front tires with significant wear; however, many of the tire combinations had a similar 88 kph limit. It did not seem to matter where the worn tires were placed once the tire wear was at 4/32" or above. In fact, the highest speeds recorded were for the four new tires case as well as the 6/32" tread depth front with new tires on the rear suspension. In terms of the limit response, some tire sets with worn tires on the front and new tires on the rear did not spin at speeds where other combinations of new on the rear and worn on the front suspension spun. There are also cases of spinout with new on the rear and worn tires on the front, not to mention that the vehicle with four new tires exhibited a spin out response at the limit. Clearly the "new on the rear" policy not always provides the best performance.

7. When evaluating the effects of tire tread depth on wet handling performance, it is imperative to obtain real world customer worn tires and not employ "shaved" tires as a substitute. Although the braking performance was similar between "shaved" and customer worn tires, the "shaved" tires did not experience the same understeer changes in the circle test and even spun out in one direction. They also reached their transient handling limits earlier and spun out in that test. These findings cast serious questions on previous studies that employed "shaved" tires.

8. It is important to note that at no time did the test vehicle go out of control in a limit response unless the test driver applied significant steering inputs. Said another way, the vehicle wants to go straight no matter where the tires are placed. It is equally important to understand the role of vehicle speed. At a low enough speed, all conditions where controllable and the vehicle followed the commands of the driver. Therefore, following the rule set forth in many driving manuals of slowing down when driving during rain storms or over roads with significant water is important and should be followed.

9. The results of this study cast some serious doubts on the idea that more worn tires should always be on the front suspension. It really depends on what type of maneuver the driver will need to employ. Will the driver be required to brake hard or steer rapidly in a transient handling maneuver? The answer to that question leads to two different tire mounting strategies.

REFERENCES

1. Dinges, J., Tandy, D., Hanba, S., and Bae, J., "Effect of Water Depth and Translational Velocity of Tire Force and Moment Characteristics," SAE Technical Paper 2010-01-0770, 2010, doi: 10.4271/2010-01-0770.
2. Blythe, W., and Day, T., "Single Vehicle Wet Road Loss of Control; Effects of Tire Tread Depth and Placement," SAE Technical Paper 2002-01-0553, 2002, doi: 10.4271/2002-01-0553.
3. Gillespie, T., "Fundamentals of Vehicle Dynamics," Society of Automotive Engineers, Inc., Warrendale, PA, ISBN 978-1-56091-199-9, 1992, doi: 10.4271/R-114.
4. Salaani, M., Heydinger, G., and Grygier, P., "Measurement and Modeling of Tire Forces on a Low Coefficient Surface," SAE Technical Paper 2006-01-0559, 2006, doi: 10.4271/2006-01-0559.
5. Pacejka, H., "Tire and Vehicle Dynamics," Society of Automotive Engineers, Warrendale, PA, ISBN 978-0-08097-016-5, 2006, doi: 10.4271/R-418.
6. Navin, F., "Hydroplaning and Accident Reconstruction," SAE Technical Paper 950138, 1995, doi: 10.4271/950138.
7. Tuttle, R., Yeager, J., "Testing and Analysis of Tire Hydroplaning," SAE Technical Paper 720471, 1972, doi: 10.4271/720471.
8. Wong, J.Y., "Mechanics of Pneumatic Tires," Theory of Ground Vehicles, Third Edition, John Wiley & Sons, Inc., Danvers, MA, 2001.
9. Cleveland, W.S., Devlin, S.J., "Locally-Weighted Regression: An Approach to Regression Analysis by Local Fitting", Journal of the American Statistical Association, Vol. 83, No. 403, pp. 596-610.
10. Hayes, G., "Passenger-Car Cornering and Braking Tests on Wet Pavements," SAE Technical Paper 760350, 1976, doi: 10.4271/760350.
11. Pottinger, M., Pelz, W., Pottinger, D., and Winkler, C., "Truck Tire Wet Traction: Effects of Water Depth, Speed, Tread Depth, Inflation, and Load," SAE Technical Paper 962153, 1996, doi: 10.4271/962153.
12. Speyer, A., "Evaluation of Various Passenger Tire Constructions for Wet Traction Performance," SAE Technical Paper 780197, 1978, doi: 10.4271/780197.
13. Kelley, J., "Factors Affecting Passenger Tire Traction on the Wet Road," SAE Technical Paper 680138, 1968, doi: 10.4271/680138.
14. Gilbert, M., Olmstead, J., Woessner, E., Mueller, T., "Wet Pavement Handling Tests," The Source, Autumn 2005, pp. 4-13.
15. "SAE International Surface Vehicle Recommended Practice "Steady-State Directional Control Test Procedures for Passenger Cars and Light Trucks," SAE Standard J266, Rev. Jan. 1996.

CONTACT INFORMATION

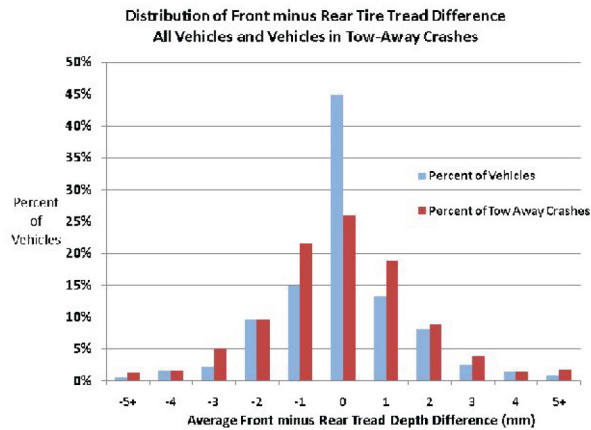
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APPENDIX

Distribution of Average Front to Rear Tread Depth Differences All Vehicles and Tow-Away Crash Vehicles

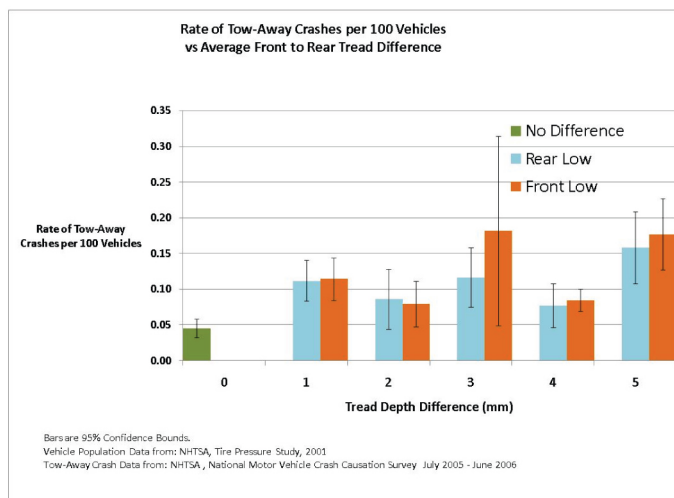


Vehicles in Tow-Away Crashes are more likely to have tread depth differences between front and rear axles.

Sources: TPS and
NMVACCS

FIGURE A1. CRASH DISTRIBUTION CHART

Rate of Tow-Away Crashes- Detail Vs. Tread Depth Differences



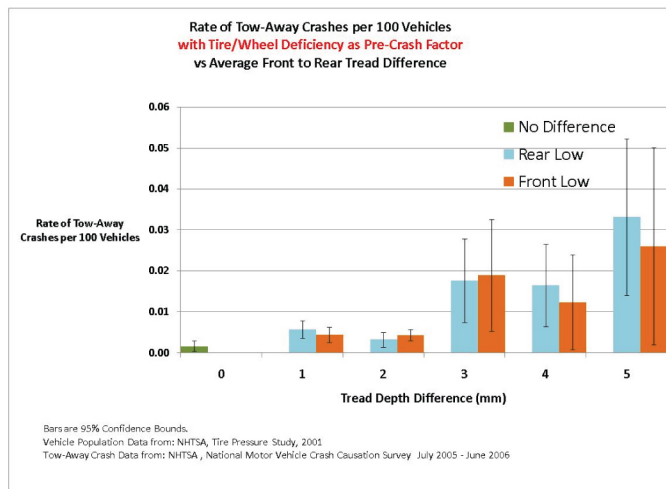
- Crash rate is higher for vehicles with tread depth difference between front and rear.

- Irregularity of pattern is partly due to conversion from 1/32" to mm.

Sources: TPS and NMVACCS

Figure A2. Rate of Tow Away Crashes

Rate of Tow-Away Crashes- Detail with Tire/Wheel Deficiency as Pre-Crash Contributing Factor Vs. Tread Depth Differences



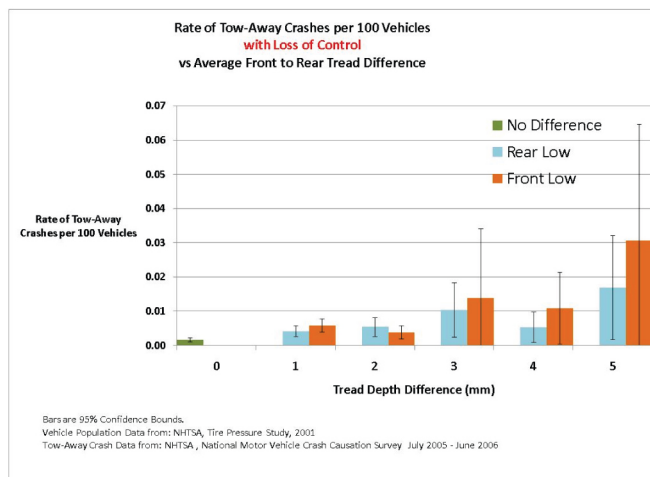
- Crash rate is higher for vehicles with tread depth difference between front and rear.

- Irregularity of pattern is partly due to conversion from 1/32" to mm.

Sources: TPS and NMVACCS

Figure A3. Tire/Wheel Deficiency Crash Chart

Rate of Tow-Away Crashes-Detail with Loss of Control as Pre-Crash Contributing Factor Vs. Tread Depth Differences



- Crash rate is higher for vehicles with tread depth difference between front and rear.

- Irregularity of pattern is partly due to conversion from 1/32" to mm.

Sources: TPS and NMVACCS

Figure A4. Loss of Control Crash Chart

Test Tire W2

Michelin Cross Terrain P235/70R16



DOT B37P-PA7X2311

Tread Depths



APPENDIX A5. TEST TIRE PHOTOS