

Evidence of Real-World Tire Flat-Spotting and Its Effect on Vehicle Performance

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ABSTRACT

Recent trends in vehicle light-weighting and tire design requirements have created an increased awareness to tire flat-spotting. Tire flat-spotting occurs when tires remain in a loaded condition without rolling for an extended period of time. Tire flat-spotting can either be temporary or permanent depending on the length of storage and other environmental factors. Tire non-uniformity caused due to flat-spots often induces shake and shimmy (back and forth oscillation of steering wheel) vibration in vehicles due to increased tire-wheel force variation input into the chassis. This can result in increased warranty costs for OEMs (Original Equipment Manufacturers) as well as customer dissatisfaction exhibited in third party quality surveys like the annual J. D. Power IQS (Initial Quality Survey). While tire flat-spotting can also occur during the vehicle shipping process, it is particularly of concern for slow moving vehicle inventory that remains at manufacturing plants and/or dealership parking lots for extended periods of time.

While the effects and mechanism of tire flat-spotting are understood, current literature mostly documents the effect of flat-spotting using only tire uniformity measurements from simulated tire loading conditions. The study in this paper documents the case of tire flat-spotting under real-world conditions and the resulting effect on the vehicle on-road shake and shimmy performance. Flat-spotting effects are known to be more pronounced at elevated temperatures. A mid-size sedan vehicle was tested in Arizona for varying storage durations over the course of the summer months. Data showing the flat-spotting effect at the tire level as well as the effect of temporary and permanent flat-spots at the vehicle level was acquired. The data clearly shows the detrimental effects of tire flat-spotting on vehicle shake and shimmy performance. The measured increase in steering and floor vibration levels demonstrate the risk for warranty claims and customer dissatisfaction. Improving vehicle sensitivity to protect against such large increases in wheel-end force variation is both mass and cost prohibitive for OEMs and can interfere with other dynamic performance requirements.

The results of this study highlight the importance of proper OEM vehicle inventory management and vehicle maintenance (mainly movement management) on plant and/or dealership parking lots, especially for slow moving products. This can minimize tire-related warranty costs and the resulting customer dissatisfaction. It is important that OEMs work with tire manufacturers to include tire flat-spotting characteristics as one of the key considerations in the multi-attribute set used during the tire design and selection process.

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INTRODUCTION

Tire flat-spotting has been receiving increased attention from automotive and tire manufacturers in recent years due to a variety of factors. Lighter vehicles, larger wheels, high performance tires, changing tire compositions, etc., have all contributed towards the increased awareness to tire flat-spotting [1]. Flat-spotted tires increase the tire-wheel input forces that excite the chassis and are likely to cause increased steering shimmy (also referred to as nibble) and/or steering/body shake. Shimmy is defined as the back and forth oscillation of the steering wheel about its rotational axis whereas shake is defined as vibration in a particular direction (up and down for vertical or Z direction, side to side for lateral or Y direction, and front to back for fore-aft or X direction as defined by SAE vehicle coordinate system). Although several tire low order harmonics are

affected by tire flat-spots [1], the effect on radial first order harmonic is clearly the highest. At the vehicle level, the tire first and second order vibrations are mainly increased due to tire flat-spots.

A schematic showing the causes and effects of tire flat-spotting is shown in Figure 1. Tire flat-spotting can occur during shipping due to excessive tie-down forces on vehicles in carriers or during long periods of transit on a ship. It can also occur when vehicles sit in plant or dealership parking lots for extended periods of time while being exposed to elevated temperatures. Slow moving vehicle inventory generally presents the greatest challenge due to inconsistent or non-existent dealership level inventory management during vehicle storage on the lots. Aggressive inventory push from OEMs to dealers and fluctuating vehicle sales volumes only adds to the issue. An increasing number of OEMs require or advise dealerships to follow

monthly inventory management routines that include moving the vehicle a small distance in the parking lot to prevent tire flat-spotting. However, these requirements and advisories are often ignored by over-stocked dealerships that have limited parking lot space and service personnel.

Examination of tire-wheel related warranty data on a geographical and seasonal basis shows that flat-spotting is exacerbated by elevated temperatures. Laboratory testing has confirmed this effect [1].

Flat-spotting can be either temporary or permanent. Temporary flat-spots can occur even after a weekend of residential parking, but they dissipate after a few miles of driving. Permanently flat-spotted tires may require replacement if original vehicle performance needs to be recovered, thereby invoking significant warranty costs.

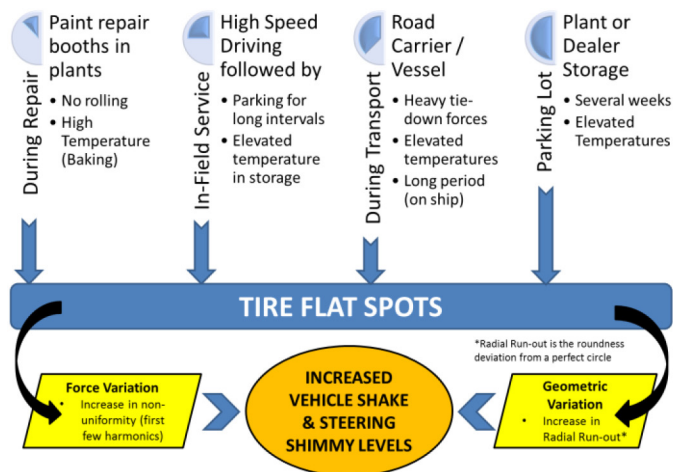


Figure 1. Schematic showing causes and effects of tire flat-spotting

The two biggest factors driving the increased OEM attention to tire flat-spotting are tire-wheel warranty costs and customer dissatisfaction. Quality surveys such as the annual J. D. Power IQS include a category for vehicle vibration that is directly impacted by tire flat-spotting. A dealership will typically address a vehicle shake or shimmy complaint on a vehicle by balancing its wheels. In fact, dealerships often balance wheels on vehicles immediately after the sale of a new vehicle due to a shake or shimmy complaint from the new buyer. While the cost impact of balancing wheels is low, this action is actually counterproductive because the balance of a tire-wheel assembly changes due to flat-spotting. If and when the flat-spot effect changes or dissipates, as in the case of temporarily flat-spotted tires, the newly corrected balance condition becomes inaccurate and can cause worse vehicle shake or shimmy than the original levels. For this reason, an increasing number of OEMs do not reimburse dealerships for wheel balancing claims unless the new vehicles accumulate approximately 300 km or more. This provides an opportunity for temporary flat-spots to dissipate and prevent repeated service visits for the consumer.

Tire non-uniformity generates a harmonic force whose frequency varies with vehicle speed, exciting responses from the vehicle body, steering column/wheel, and unoccupied seats when these structural

resonances coincide with the tire input frequency. The importance of tire uniformity and its effect on vehicle performance is well documented in literature [2], [3], [4], [5], [6]. However, there is limited literature published in the area of tire flat-spotting itself, most of it published well within the last decade. Even so, the mechanism and ramifications of tire flat-spotting are interpreted mainly from tire-wheel uniformity measurements in the laboratory conducted on loaded tires. A comprehensive laboratory investigation into tire flat-spotting has been conducted by Mani [1]. Mani, et. al. also documented a comprehensive laboratory method of tire flat-spot measurement [7]. Literature on real world tire flat-spotting and its effect on vehicle performance is scarce. Park, et. al. presented some data on flat-spotted tires from dealership parking-lots in a statistical sense and showed the effect of flat-spotting with mileage accumulation using a portable chassis dynamometer [8].

For the study in this paper, the real world effects of tire flat-spotting have been studied on a mid-size sedan over the course of a hot summer season in the southwestern state of Arizona, USA. The vehicle was stored for successive increasing durations over a time period of six months in an open asphalt parking lot. The effect of tire flat-spotting on vehicle shake and steering shimmy performance was measured on a smooth road at each storage interval. Tire-wheel component uniformities were measured at the beginning and end of the test period. The effects of both temporary and permanent flat-spots were determined using the data from the study.

The motivation behind the study was to produce real-world data that clearly quantifies the negative effects of tire flat-spotting on vehicle performance. This data can be used to drive a strategy for effective inventory management from OEM production, OEM sales & marketing and dealership personnel. The data from the study is also useful for estimating increased tire/wheel forces from flat-spotting that might drive better design at both the component (tire) and vehicle (chassis & body) level. A holistic approach that employs the aspects discussed above can contribute simultaneously to lowering the tire/wheel related warranty costs and improving customer satisfaction.

TEST PLANNING

The primary focus of the study was to investigate tire flat-spotting under real-world conditions. As such, it was necessary to account for aspects such as environmental conditions, parking location, tire conditions, vehicle selection, separating imbalance from uniformity forces, test speeds, etc. The test plan also had to account for testing both the temporary and permanent effects of tire flat-spotting.

Test Location

With the existing knowledge that tires flat-spots are exacerbated at high temperatures during storage, it was decided to conduct the study in Arizona. The vehicle testing could also conveniently be conducted on the smooth high speed track at Nissan's Proving Grounds, 80 km south of Phoenix. It is important to note that the environmental conditions in terms of temperature and humidity are some of the

worst in USA. During the peak summer months, maximum ambient temperatures can routinely reach 43° C (~110° F) with asphalt and tire sidewalls reaching temperatures of over 65° C (~150° F). Peak solar radiation levels can routinely hit 1400 W/m² during the day. Desert topography in that region provides a temperature swing of approximately 30-35° C between the high and low asphalt temperatures during a 24-hour period which accentuates tire flat-spotting [1]. Due to these factors, it should be recognized that the flat-spotting effects observed will arguably be close to worst case conditions anywhere in the USA.

Test Vehicle & Storage Intervals

A mid-size sedan was chosen as the vehicle for this project based on its large sales volume. The sedan was equipped with alloy wheels and P215/55R17 tires. Varying test intervals of successively increasing length were chosen for the study. The vehicle was tested at zero days (baseline performance) and after one, two and three months of lot storage. Storage intervals chosen align with warranty report intervals and dealer storage protocol timing. Some manufacturers advise car dealerships to move parked vehicles every 30 days which corresponded to the first storage interval chosen. The other two storage intervals are multiples of the first, chosen so that the project length does not extend into the colder months (since temperature was key driver for flat-spotting). Note that the storage intervals denote time sitting on the lot, so the total study lasted six months, from May to October of 2014. Between the tests, the vehicle was parked in an open asphalt lot with cold tire pressures set to placard (manufacturer recommended pressures posted on sticker label attached inside of the door opening) levels. These tire pressures during storage were chosen after some considerations:

1. OEMs usually ship vehicles from the plant with higher tire pressures (approximately 20% higher than placard), but require dealerships to reduce tire pressures to placard levels as part of delivery inspection procedure (unless vehicles are going to be stored at an off-site location).
2. There is no clear consensus amongst tire manufacturers regarding tire pressures for vehicles during shipping and storage. The lack of consensus amongst tire manufacturers may in fact be rooted in protection against temporary or permanent flat-spots; generally, higher pressures are assumed to be better for reducing temporary flat-spotting whereas lower pressures are preferred to limit permanent flat-spotting.
3. Mani, et. al. [1] suggest that higher pressures during storage might be favorable for flat-spot reduction, but caution that abbreviated load conditions were used in that study.

The test vehicle was parked in a north-south orientation to maximize the sun loading with no other vehicles parked on either side. Once again, this creates a worst case scenario for tire flat-spotting. Figure 2 shows the timeline for testing days and storage intervals used in this study spanning six months in total.

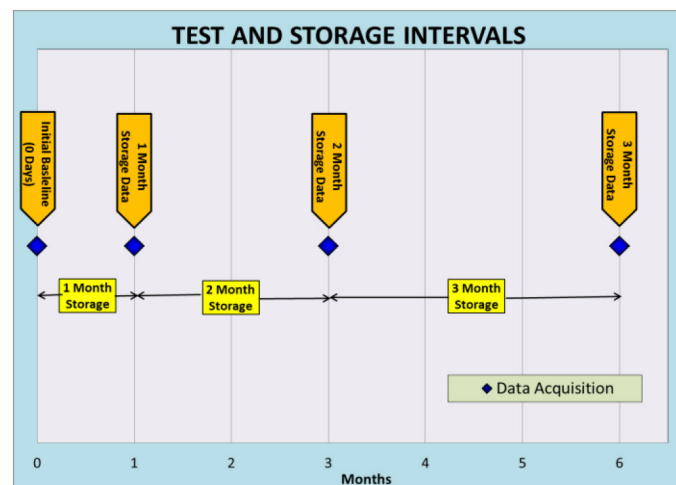


Figure 2. Vehicle test timing and storage duration details

Tires & Wheels

It is known from literature that virgin tires have the maximum potential for flat-spotting and after about 800 km the tendency to flat-spot decreases substantially [1]. With the aim of simulating real-world flat-spotting effects, virgin tires were chosen for each vehicle. Their uniformity characteristics would be measured twice during the study over a period of approximately six months - at the beginning of testing and end of all testing. Consideration was given to measuring tire uniformity characteristics more frequently (for each storage interval measured), however it was concluded that the wheel removal and re-installation could introduce unknown variation from varying hub gap effects [2] even if the indexing on the lugs was maintained. The initial measurements also ensured that no existing flat-spots were present at the start of testing. After the wheels are first installed on the vehicle, an on-car balance needs to be performed on each wheel to ensure that the imbalance forces from all rotating components are minimized and the measured changes are largely attributable to tire-wheel uniformity forces.

Another important aspect to consider during tire flat-spotting is the angular location of the contact patch with the asphalt. Because the testing involved multiple measurements and re-parking the vehicle for the next storage interval, there were three choices for the angular orientation of the flat-spot:

1. Random Orientation of Flat-Spot: Park the vehicle randomly after test is completed (flat-spot orientation changes randomly on all wheels at each parking interval).
2. Fixed Rotation of Flat-Spot: Rotate the tire contact patch by a fixed angle after each test (e.g. Tire contact patch rotates 60° on each wheel, every time the vehicle is parked).
3. Constant Orientation of Flat-Spot: Keep tire contact patch at same orientation for every storage interval for all wheels.

It is known that repeated flat-spotting at different angular locations on the tire such as would be produced by the random and fixed rotations discussed above, actually improves the radial force variation (RFV) [1]. While the random orientation makes most sense from a real-world standpoint, it would make data interpretation difficult. The fixed angular rotation between storage intervals would work, but has an artificial element to it and its effect on vehicle performance has not been clearly established. It was decided to park the vehicle at the same angular location for each storage interval because it provided the most consistent way for data interpretation when comparing the different storage intervals (considering that tire uniformity measurements were not conducted for each test interval but only at the start and end of study). Once again, this situation represents a worst case scenario for flat-spotting since the angular location of flat-spot remained the same for the entire test period.

Test Speeds

Smooth road vehicle shake and shimmy measurements conducted generally include the entire relevant speed range from approximately 70 km/h to 140 km/h. Shake and shimmy amplitudes while driving on the road oscillate between some minimum and maximum value depending on the relative phase of the high spots on the left and right wheels (in and out of phase) on each axle and even between the front and rear axles. In order to maximize the phasing, the tire pressures between the left and right sides were offset on each side of the placard values. The total data acquisition time for each speed was set at five minutes. This means that mileage accumulates quickly on the vehicle; at 120 km/h, data is acquired over a distance of 10 km. Because temporary flat-spots work themselves out with mileage accumulation, measuring data at many speeds would mean the tire input forces are constantly dropping during the acquisition. In order to limit this issue, it was decided to use only two speeds for each vehicle for intermediate storage interval acquisitions. The initial and final data acquisitions included all speeds between 70 and 140 km/h in 10 km/h increments. The test speeds selected facilitate the investigation of both the temporary and permanent flat-spot phenomena. The two test speeds selected were 90 and 130 km/h to capture the low and high ends of vehicle shake and shimmy performance.

TEST DETAILS

It is necessary to outline the details of the testing that was conducted in order to understand the results of the study.

Measurement Locations

Tire flat-spots increase the input force into the suspension which propagates to the tactile locations. In order to capture the increase in input force as well as the effects of tire flat-spotting on vehicle shake and steering shimmy performance, the force input and customer contact points were instrumented with accelerometers. One front and one rear spindle were instrumented to capture input force increase at the axles. For tactile locations, the steering wheel, driver floor and 2nd row floor were instrumented in the relevant directions to capture shake and shimmy response information.

Data Acquisition

As mentioned earlier, in order to facilitate faster phasing of high spots between the left and right wheels (and even the front to back axles), the tire pressures were offset side to side from nominal placard values. LMS Scadas hardware and TestLab signature acquisition software were used to acquire data tracked to wheel RPM. Time data was acquired from 70 to 140 km/h in 10 km/h increments for the baseline and final test iterations. For intermediate storage intervals, data was only acquired for two speeds per vehicle. On smooth road surfaces, shake induced by road surface irregularities is negligible whereas the shake due to tire-wheel imbalance and non-uniformity forces is dominant. Data acquisition was always conducted in the same sequence of decreasing speeds for each storage interval tested. Total data acquisition time was generally between 200 and 300 seconds to capture several phases of wheel high spots between left and right sides.

Data Analysis

The acquired time data was processed to extract the first and second tire orders. Even on a smooth road, there is some amount of road surface irregularity that gets included in the orders extracted due to the impact nature of the road excitation. Such non-order related content was filtered out using a proprietary running average scheme after the orders were extracted. The resulting peak vibration levels for tire first and second order for all measured locations were plotted against the vehicle speed.

Test Sequence

It is necessary to outline the main steps in the test sequence used in order to understand the test results well.

1. Virgin tires were selected at the start of testing. The tire-wheel assemblies were balanced and the tire-wheel component uniformity characteristics were measured. It was ensured that there were no existing flat-spots on any of the assemblies.
2. When wheels were installed on the test vehicle, the ones with higher levels of non-uniformity were installed on the front axle to better excite steering wheel shimmy. Because the study is trying to isolate the effects of tire-wheel uniformity, an on-car balancing was conducted to minimize the effects of rotating system imbalance.
3. The initial (0 days) shake and shimmy levels were established for each vehicle with on-road testing on a smooth surface of the high-speed oval track. For baseline performance, all speeds between 70 and 140 km/h in 10 km/h increment were measured.
4. The test vehicle was parked on an open asphalt lot exposed to sun loading at placard pressures. The tire contact patches in the parked condition were marked precisely on each wheel.
5. After each successive lot storage interval (one, two and three months), cold tire pressures were adjusted to placard values. The shake and shimmy performance was measured on the smooth surface at the two speeds (90 and 130 km/h), always starting at higher speed. The data was recorded for both speeds at 0, 64, 128 and 192 km intervals to investigate the effect of temporary flat-spotting.