

Technical Considerations for Plus-Sizing

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ABSTRACT: Plus-sizing, or the fitting of larger diameter rims and lower profile tires to vehicles, continues to be a significant commercial force in the tire marketplace. When offering plus-size fitments to customers, many sellers simply offer "what fits" on a given vehicle. However, the various choices made by the seller, such as wheel width, wheel offset, inflation pressure, and so on, have the potential to influence the life of the tires and the dynamic performance of the vehicle itself. This presentation will discuss the influence of these larger and wider tires and wheels on basic vehicle handling and limit stability. In addition, matching tire size to wheel width and tire pressure to vehicle load will be covered, since these easily overlooked parameters must be correct to protect tire durability. Potential risks from the change of wheel/tire weight and inertia, as well as steering geometry, will also be covered.

KEYWORDS: Plus-size tire fitment, vehicle stability, Road Edge Recovery Maneuver, NHTSA star rating, scrub radius, inflation pressure, wheel width, wheel offset

The fastest-growing segment of the tire market today is what is called the "tuner" market. Another rapidly growing segment is that of low profile tires for light trucks and sport utility vehicles. The market for aftermarket wheels, tires, and suspension components in 2001 represented over \$6 billion in sales. In these applications, the consistent theme is to replace the original equipment wheel and tire with a larger diameter wheel and a lower profile, usually wider tire. The outside diameter (OD) of the tire-wheel assembly, i.e., the OD of the tire itself, is generally kept as close as possible to the OD of the original equipment tire and wheel system.

The driving force behind this market is the vehicle owner's desire to personalize the vehicle, while improving the performance and appearance. The term "plus-sizing" refers to the number of inches increase in the wheel diameter. For example, if a 16-inch diameter wheel is replaced with an 18-inch diameter aftermarket wheel, the change is considered a "Plus-2 Fitment". Beyond the change in look of the vehicle, the selection of both the tire and the wheel to be used on a given vehicle has the potential to change the vehicle's performance. Also, matching the wheel to the tire and determining the correct

inflation pressure for the tire are essential to obtaining proper long-term durability for the customer.

Selection Issues for Plus-sizing

When selecting tires and wheels for an upgrade on a given vehicle, there are several aspects that should be considered. First, the desired wheel diameter is selected based on the customer's preferences, where both appearance and pricing obviously play large roles. Then, a tire size must be selected that fits the given wheel and has adequate load capacity. Since tire load capacity varies with inflation pressure, the new tire fitment may require a change in the placard pressure for the vehicle. Also, a given size tire must be fitted to a wheel having appropriate width, so the wheel selection may be limited by this parameter. The last wheel selection parameter, offset, is perhaps the most difficult due to the many aspects of the vehicle's dynamic performance that this parameter effects.

Tire Selection

Given that conventional wisdom usually suggests that any difference in diameter should be within $\pm 3\%$ of the original equipment (OE) tire, there are usually a number of wheel diameters for which tires are available to achieve this goal. Since customer choice is often based more on appearance and cost, rather than proper sizing, it is not unusual to see tire fitments where the diameter of the replacement tire exceeds that of the OE tire by a wider margin than is ideal. Tire selection often appears to be based on maximizing the size of the tire that will fit in the wheel well of the vehicle without interference. Load capacity is another factor that can influence a customer to choose larger overall diameter tires, since load capacity goes down with decreasing aspect ratio for a given tire design. The issue of the load capacity of the tires has been discussed by Edington [1] in some detail. Following industry recommendations, the replacement tires should have a load rating equal to or larger than that of the original equipment tires.

In the 1970's and 1980's, plus-sizing was typically done by increasing tire width by 10 mm for every inch increase in wheel diameter and decreasing the aspect ratio by 10%. Following this procedure usually works well for Plus-1 and Plus-2 sizes, but tends to

yield tires with insufficient diameter and load capacity, or produce tire dimensions that do not exist, beyond that point. The approach tends to produce fitments with declining load capacities as the wheel diameter gets larger, since a tire's load capacity is related to its inflation pressure and its volume. With today's market extending to Plus-7 sizes and beyond, fitments can be developed in consultation with standard load tables developed by organizations like the Tire & Rim Association (T&RA) for tires having nomenclatures beginning with "P" or "LT" [2], and the European Tyre and Rim Technical Organization (ETRTO) for metric tires [3]. Table 1 shows tires that would be indicated for a 2002 Chevrolet Avalanche RWD using the "10%" method. Note that there are no tires currently in the list of standard dimensions for the Plus-3 and Plus-4 dimensions listed in Table 1. With this method, as the plus-size is increasing, the load capacity of the tire and its diameter, are both decreasing. Contrast this result to that shown in Table 2, where the tires are being selected based on rim diameter and load capacity. There is still no tire suitable for the Plus-3 size, but all the other sizes meet or exceed the load capacity of the original equipment tire. In the recent past, however, tire manufacturers have responded to this need with large, low profile tires with higher-pressure ratings (i.e., extra-load tires) in order to meet the load requirement for large sport utility vehicles. Of course, higher-pressure tires create other ride and durability issues for consumers. Also, if customers set their tire pressures based on the vehicle placard, there may be an effective reduction in the tire's load capacity that negates the benefits of using the extra-load tire.

Tire Pressure Determination

Regardless of the tire selected for a plus-size fitment, it is essential that the tire be operated at a pressure that provides as close to optimal performance as possible. Higher than optimal pressure results in a harsh ride and increases the potential for road hazard damage to the tire. Lower than optimal pressure reduces precision in handling and can result in fatigue failure of the tire. Either higher or lower than optimal pressure will also give rise to abnormal wear on the tire. The placard pressure indicated on the vehicle provides the optimal pressure for the OE tires. It is rare, however, to have a plus-size fitment tire that has the same Load Index (LI) as the OE tire. The correct pressure for the plus-size tire will therefore very likely be different from the placard pressure indicated on

the vehicle. There are several approaches to determining the correct operating pressure for the plus-size tires. The first is to find the tire listed in pressure-versus-load tables such as those published by the T&RA [2]. This would require locating the pressure in the table where the tire's load capacity exceeds one-half of the Gross Axle Weight Rating (GAWR) of the vehicle for the particular axle (the vehicle's front and rear axle GAWRs will likely be different). Note that, if passenger tires are used on a multi-purpose vehicle (MPV), the load must be increased by 10% to conform to Department of Transportation (DOT) requirements. The same values can be obtained mathematically using the Engineering Design Information that underlies the tabulations, as shown in references [4] and [5]. These standards organization formulations are based on the deflection at the maximum load for any pressure being the same as that of the tire at the maximum load, maximum pressure condition. The optimal pressure is therefore given by:

$$\text{Pressure} = \text{MaxPressure} \times \left(\frac{\text{Load}}{\text{MaxLoad}} \right)^{\left(\frac{1}{n} \right)}$$

where MaxLoad and MaxPressure are the maximum load and pressure indicated on the tire sidewall (35 psi for standard load tires, regardless of labeling), and n is equal to 0.5 for P-metric tires, 0.7 for LT tires, and 0.8 for ETRTO metric tires. Load is equal to one-half the GAWR of the particular axle, and Pressure will be the required inflation pressure. This approach is simple, but the underlying formulae have been shown by Padula [6] to underestimate the proper inflation pressure as rim diameter increases and tire aspect ratio gets smaller, i.e, for the very tires that will likely be used in plus-sizing. An alternate approach can be developed based on the tire vertical stiffness formulation by Rhyne [7]. Rhyne showed that tire vertical stiffness could be reduced to a simple function of tire geometry that was broadly applicable:

$$K_z = \text{Pressure} * f(\text{TireGeometry}) + 3.45$$

where K_z is the tire's vertical stiffness. The function of tire geometry contains the tire parameters of section width, S_N , aspect ratio, AR , and rim diameter, D_R :

$$f(\text{TireGeometry}) = 0.00028 \times \sqrt{(1.03 - 0.004 \times AR) \times S_N \times \left(\frac{S_N \times AR}{50} + D_R \right)}$$

where all the parameters are in metric units. If the same iso-deflection assumption is made, the pressure at a given load can be computed as:

$$\text{Pressure} = \frac{\left(\frac{\text{Load}}{\text{MaxLoad}} \times (\text{MaxPressure} \times f(\text{TireGeometry}) + 3.45) \right) - 3.45}{f(\text{TireGeometry})}$$

Obviously, all the computational approaches above will yield slightly different values. One conservative approach would be, for each axle on the vehicle, to select the maximum pressure from among the values given by the vehicle placard, the standards organization formula, or the stiffness formulation. Such an approach could easily be integrated into a computer program for use by the tire fitter.

Wheel Width Determination

The maximum and minimum widths allowed for the wheel used to support a given tire are given either as tabulated values in standards literature, i.e., references [2] and [3], or as a fraction of the tire's section width, where these fractions depend upon the aspect ratio of the tire. The most common problem found in the industry is the use of a rim that is narrower than recommended, since wider wheels are generally more expensive. Such a rim causes the tire beads to be run closer together than desirable, resulting in higher operating stresses in the sensitive area of the tire shoulder. Table 3 shows the fractions of section width to be used to compute the minimum and maximum wheel width acceptable for a given tire size, following references [4] and [5]. Once the fraction is multiplied by the section width and converted to inches, the value is rounded off to, in general, the nearest 0.5 inch. The passenger car aspect ratios of 25 and 30 are flagged in Table 3 because the T&RA and ETRTO handle the rim widths for these aspect ratios in a slightly

different manner. As with the computation of pressure, wheel width computation can easily be integrated in a simple computer program for use by the tire fitter.

Wheel Offset Selection

The last issue for plus-size selection is the choice of wheel offset. Wheel offset is the measure of the distance from the wheel-mounting surface to the centerline of the wheel. The vehicle manufacturer selected a certain amount of offset on the original equipment wheel in order to place the center of the tire (the action point for the tire forces) at a specific location in relation to the pivot axis of the steering arm, thereby optimizing the steering forces with respect to vehicle dynamics. Aftermarket wheels are available in a wide range of offset values. For example, perusal of a large tire distributor's web site for 20-inch wheels to fit a 2002 Ford F150 Supercrew truck yielded wheel offsets from +25 mm to -25 mm, all for a vehicle with a 14 mm offset in the standard OE wheel. The reasons for this are numerous. In some cases, wheels with offsets equal to that of the original equipment wheel are available. Wheels with larger offsets can be used to move the tires inboard in cases where fender clearance is important, as is the case in some states where the tire must be completely covered by the fender. Wheels with smaller, or even opposite sign value, offsets are often used to move the tire out from the vehicle in order to provide room for wider tires or to provide a "deep dish" look on vehicles like light trucks and sport utility vehicles where outer fender clearance is not an issue. Moving the tires outboard increases the vehicle track width at the expense of potentially increased steering effort and increased stresses on the spindles and other suspension components. Moving the tire inboard decreases track width. Changing the wheel offset away from that used on the OE wheels changes the track width and scrub radius, which may affect both on-center handling and limit stability.

A significant issue in offset selection is that the value for a particular wheel may not be available to the purchaser, but rather the wheel is sold as being "appropriate" for a given vehicle. The consumer is very likely to not know what changes, if any, have been made to the track width of his or her vehicle. Even if the consumer knows that there is a change in the wheel offset, he or she may have no idea what this change will do to the

vehicle's handling or stability. This suggests a need in the industry for better information on the wheel offsets on OE vehicles and the offsets on aftermarket wheels.

Performance Changes with Plus Sizes

There are other issues surrounding the use of plus-sized tires and wheels on an existing vehicle. General Motors Corporation stated in a recent publication [8] that wheels used for their upgrade packages have the “same mass, same offset, same width, same mounting flange, same tire pressure monitoring requirements, same brake clearance, [and] same dimensional tolerances” as the original equipment wheels. Implicit in this tight specification are the impacts of the plus-sized fitment on anti-lock brake systems, electronic stability control systems, and so on. Obviously, a wheel with the same mass at a larger OD has a larger rotational inertia than the OE wheel. Generally, as wheel diameter increases, the mass of the tire and wheel for equal load capacity generally increases, as does the inertia of the rotating system. This change in unsprung weight may affect the response of the suspension system. The change in rotational inertia may affect the response of systems like antilock braking and electronic stability control. Tire pressure monitoring based on antilock brake sensors may also be effected by changes in tire size and vertical stiffness. At this time, there is a significant lack of public domain data available to assess these effects.

It is generally agreed that fitting a vehicle with plus-size tires and wheels will change certain performance characteristics of the vehicle. Obviously, handling performance parameters like response, precision, and grip typically improve. This is because the lower aspect ratio tire will have increased lateral stiffness. As the plus-size increases, it would be expected that the lateral stiffness would continue to increase, so these improvements would also increase. However, since the tire is typically getting wider, the on-center tracking is very likely to degrade at the same time.

Another area that is of concern is the sensitivity of the vehicle to large bumps. Ride harshness typically increases with reduction in the tire sidewall height, so the comfort of the vehicle can be expected to degrade. This is especially true if the tire inflation

pressure has dramatically increased in order to provide sufficient load capacity. In addition, incidents of rim-pinch damage on the tire, as well as rim impact damage on the wheel, are also likely to increase as the tire's sidewall height is decreased. This sort of damage is very dependent upon the condition of the road surface in a given region and the speed limits in place on roads where potholes are prevalent.

The risk of hydroplaning with the wider tires used for plus-sizing is also likely to increase, as the tire's contact patch becomes shorter and wider relative to the OE tire. Of course, tread compound selection and tread pattern design can be very effective in mitigating this effect when the tires are relatively new. However, given the cost of plus-size tires and the tendency of consumers to try to get the last bit of use out of any tire, wet traction performance is likely to be an area of increasing risk as the tire tread wears. For this reason, recommending replacement of plus-sized tires at $\frac{4}{32}$ inch tread depth would likely improve the overall operating safety of the vehicle.

Wear of selected mechanical parts on the vehicle is also likely to increase with the use of plus-sized fitments. Brake pad wear is sensitive to the rotational inertia of the tire and wheel combination, and, as discussed previously, these likely increase. It is also possible that brake performance, in terms of brake fade and perhaps in terms of stopping distance, may suffer. The relationship between the rotational inertia of the tire-wheel and the vehicle's antilock brake system performance or electronic stability control also has not been studied in detail (at least not in any published studies). Another part that is likely to see increased wear is the steering gear, especially if the wheel offset has been altered. Moving the tire further inboard or outboard by changing offset changes the moment arm over which the tire forces act when steering is demanded.

Limit Stability Issues

Static Rating of a Vehicle

The issue of vehicle limit stability has been the subject of extensive work by all the vehicle manufacturers as well as the National Highway Transportation Safety Administration (NHTSA) over the past several years. Most of this work has focused on

the resistance of a vehicle to rolling over when involved in an avoidance maneuver or loss of control situation. The NHTSA has implemented final rules for its star rating for stability as part of its New Car Assessment Program (NCAP), in fulfillment of a requirement of the TREAD Act of 2001. In this system, vehicles are awarded a star rating of from one to five stars (more is better) based on the value of their Static Stability Factor (SSF) and whether or not they tip up when run through a defined rollover resistance test. This testing maneuver was originally called a “fishhook” test due to the path the vehicle follows during the test, and is now referred to as the “Road Edge Recovery Maneuver”. The test is designed to perform repeatable aggressive steering reversal maneuvers, with the intent being to differentiate between those vehicles that will and will not tip-up on pavement with a severe steering reversal. The detailed specifications for the test are given in reference [9]. Of particular note is the fact that the NCAP rating system was developed by analyzing rollover frequency in accidents involving vehicles having different SSF values. The SSF is simply defined as the track width (T) divided by twice the height of the center of gravity (h) of the vehicle, or $SSF=T/(2h)$. This purely static characteristic is obtained by measuring the track width and height of the center of gravity of vehicles as part of the NCAP testing process. The NHTSA has correlated the percentage of vehicles involved in single vehicle accidents that rolled over, based on historical crash data, with the vehicle’s SSF. The resulting curve fit of these data showed that, in general, the lower the value of SSF, the higher the percentage of single vehicle accidents predicted to result in rollovers.

NHTSA’s star rating system begins by awarding more stars for vehicles with higher values of SSF. The dynamic portion of the assessment is the determination of whether or not the vehicle will tip up in NHTSA’s pre-defined rollover resistance test procedure. NHTSA has separately correlated SSF with rollover frequency for vehicles that tip up in the Road Edge Recovery Maneuver and again for the group of vehicles that do not tip up. Vehicles that tip up are penalized by being rated with a curve based only on vehicles that tipped up in the Fishhook maneuver. This more stringent rating may result in a vehicle receiving a lower star rating than other vehicles with the same SSF that do not tip up.

Figure 1 shows the basic rating system. The two curves are used to establish rating values. The lower curve in Figure 1 applies if the given vehicle being tested does not tip up in the test at any speed up to 50 mph. The upper curve applies if the vehicle tips up. Note that there are regions in which the difference between tipping up and not tipping up will not change the rating value, and there are other regions where the tipping up will reduce the rating. For example, if a vehicle has a SSF value of 1.3, there is no change in the NCAP rating resulting from its performance on the dynamic test. However, if the vehicle has a SSF value of 1.2, then the rating does depend upon whether or not the vehicle tips up on the dynamic test.

The impact of plus-sizing on vehicle stability begins with the relationship between the section height of a tire and the working deflection expected on that tire. Normally, tires are expected to operate, when fully loaded, at a maximum static deflection equal to approximately 20% of the sidewall height. When installing plus-size tires and wheels on a vehicle, the outer diameter of the tire and wheel theoretically remains constant while the sidewall height decreases. Since the sidewall height of the plus-size tires is smaller than those that were original equipment, the static deflection of the plus-size tires will be lower than what was present when the height of the center of gravity was measured in the NCAP tests. In short, the axle height, and consequently the CG height, of the vehicle increases even though the unloaded diameter of the tires is not necessarily different.

In order to illustrate this effect, data for the 2002 Chevrolet Avalanche 1500 were selected from the 2002 NCAP study vehicles tested by NHTSA. The NCAP data included the original tire type and size, as well as the track width and center of gravity height for the vehicle. Plus-size tire fitments available were found by consulting a national tire outlet chain's web site. The change in center of gravity height was computed for each vehicle for each available plus-size tire by computing the change in deflection, assuming a static deflection of 20% of the section height for each tire. In order to simplify the analysis, the track width was assumed to remain constant, i.e., the wheel offsets would remain unchanged when moving to higher plus-sizes.

Figure 2 shows the result of the analysis. Both the rear-wheel drive (RWD) and the all-wheel drive (AWD) versions of the vehicle are included in Figure 2. The SSF value ($T/2h$) is plotted for each plus-size fitment on this graph. As expected, the SSF value for each vehicle tends to decrease as the plus-size fitment increases. (Plus-0 indicates the use of a lower aspect ratio, wider tire on the original equipment wheel). The AWD version of the vehicle has a higher center of gravity height and consequently a lower SSF value. The AWD version also has a larger size OE wheel than the RWD version, so there is no Plus-8 fitment for the AWD version even though the largest tire size is the same on both vehicles.

Also indicated in Figure 2 are star rating limit values between two-star and three-star ratings. Essentially, a vehicle having a SSF value of greater than 1.070 would receive a three-star rating if it does not tip up in the dynamic test. If the vehicle tips up in the dynamic test, a SSF value greater than 1.110 is necessary to receive the same three-star rating. The result of the dynamic influence on the star rating system can be seen in Figure 2. For the RWD version of the vehicle, the vehicle would receive a three-star rating for any plus-size tire fitment if it does not tip up in the dynamic test. If it tips up, the Plus-6, Plus-7, and Plus-8 fitments would make the vehicle receive a two-star rating. For the AWD version of the vehicle, the Plus-6 and Plus-7 fitments make the vehicle have a two-star rating regardless of the results on the dynamic test. However, if the vehicle tips up in the dynamic testing, then all the plus-size fitments make the vehicle have a two-star rating as opposed to its three-star rating with the original equipment tires.

The static analysis reported above has shown that the static stability characteristics of vehicles may be influenced by the addition of plus-size tires and wheels. Further, this change may be sufficiently large to move the vehicle from the NCAP star rating value with OE tires to a lower one with the plus-size tires. The potential for change in track width suggests that these impacts can be mitigated, but only with other potential influences in vehicle behavior.

The risk-of-rollover sensitivity curves employed by the NHTSA were developed from analyses of the percentage of single vehicle accidents involving rollover versus the SSF of the particular vehicle. These curves indicate that the rate at which the risk of rollover increases is larger at lower values of SSF. This means that incremental changes in the SSF value of a sedan-type vehicle having relatively higher SSF values will result in smaller changes in rollover risk according to the NHTSA. Conversely, incremental changes in SSF values for vehicles like SUVs with relatively lower SSF values will produce larger changes in rollover risk. Also, the underlying data for the NHTSA curves are actual data from single vehicle crashes. This means that every unique value of SSF in the data set was a different vehicle with its own set of dynamic performances. There is some question, however, about whether or not this analysis applies directly to SSF changes made to a single vehicle as was illustrated above for plus-sizing.

Dynamic Testing

As described above, the NHTSA Road Edge Recovery Maneuver test subjects a vehicle to a severe steering reversal maneuver on pavement. Testing done to determine the effects of plus-sized fitments was described by Daws, et al. [10]. For the purposes of that study, a 1992 Isuzu Rodeo V-6 4WD was set up as the test vehicle. The vehicle was fitted with NHTSA-specified outriggers and wheel-lift sensors as shown in Figure 3. The test vehicle was also fitted with cameras on each tire to show the tire deformation throughout the test maneuver. This vehicle was originally available with either P225/75R15 or an optional 31x10.50R15 tire fitment. The OE wheels had offsets of zero for both the P225/75R15 tire and for the 31x10.50R15 tire. For the purpose of this study, a Plus-5 fitment, 285/50R20, was selected to represent a plus-size application. The aftermarket wheels available for this plus-size fitment had an 18 mm (0.71 in) offset, resulting in a narrowing of the track width by 36 mm (1.42 in). In order to examine the effect of wheel offset, 20 mm (0.79 in) spacers were used to be able to test the plus-size tire fitment at an offset of -2 mm (0.08 in). Table 4 shows the four test conditions that were defined from the tire and wheel combinations available with both OE sizes and the plus-size fitment.

In order to compute the SSF for the various tire-wheel combinations used in this study, the basic values of track width and center-of-gravity (CG) height were measured. The measurements yielded a CG height of 26.6 in (676 mm) for the test vehicle when equipped with the 285/50R20 tires. The track width was determined to be 57.5 in (1460 mm) at the manufacturer's wheel offset of zero. Table 5 shows a comparison of the computed SSF values for the test configurations. The SSF value ranges from a high of 1.1512 for the P225/70R15 tire fitment to a low of 1.0518 for the 285/50R20 tires on the 18 mm offset wheel setup. This represented a change of over 9% in the SSF value. Based on the vehicle tipping up below 50 mph in the NHTSA dynamic testing, which it did in all configurations, the vehicle would receive a 3-star rating with both OE tires, but only a 2-star rating with the Plus-5 tire regardless of wheel offset.

Effect of Tire Size

A comparison of the vehicle response as a function of tire size alone refers to the response of the vehicle with wheel offset at or near zero. Changes in the tire size used will result in changes in the SSF value if the diameters of the tires are different. In Table 4, the SSF values range from 1.1512 for the P225/75R15 tire to 1.0814 for the 285/50R20 tire, a change of over 6% in SSF, with the track width remaining essentially constant for all three tire-wheel combinations.

Figure 4 shows the linear velocity of the CG of the vehicle for the test representing the minimum tip-up speed for each of the three tire conditions. Note that the test entry speed required to tip up the vehicle with the P225/75R15 tires was slightly higher than the other fitments. The speed data also shows a clear indication that the vehicle deceleration decreased (i.e., the speed decreased more slowly) as the tire size increased. This is expected, since the smaller tires had a lower lateral stiffness and a larger tire slip angle was generated in the maneuver, thereby producing more braking force on the vehicle. Interestingly, the vehicle tip-up occurred in the range between 1 and 2 seconds for all tire-wheel combinations. At the point of tip-up, the speed of the vehicle in each case was almost identical. The NHTSA procedure takes the run speed as the velocity at the start of the first steering maneuver (the test entry speed). From Figure 4, it is clear that the run

speed is only slightly different and the tip-up speed of the vehicle was very close to the same value for each tire/wheel combination.

Figure 5 shows a front tire comparison between the P225/75R15 and the 285/50R20 tires at maximum wheel lift. In Figure 5, there is a very clear distinction between the tire deformation on the two tires. The P225/75R15 tire is heavily distorted in the cornering. In fact, pavement abrasions from cornering were observed from the tire shoulder down to the equator of the sidewall. Contrast this to the 285/50R20 tire in Figure 5, where the tread system of the tire essentially retains its normal shape, even during this extreme cornering maneuver. Pavement abrasions on this size tire were limited to the shoulder region of the tread only. All the front tires were being driven at slip angles in excess of 15 degrees. These photographs generally support the hypothesis that the larger and more rigid tires actually create an effective track width that is wider than the actual track width, which, in this case, is offsetting the increase in CG height as the tire size is increased.

Effect of Wheel Offset

In order to look at the wheel offset effect, the 285/50R20 tires and wheels with 18 mm offset were run both with and without 20 mm spacers installed. In this case, the CG height was identical for each test, but the track width was 40 mm wider for the case with the -2 mm offset (with 20 mm spacer installed) compared to the 18 mm offset case (without the spacer). The tire size for both these cases was the 285/50R20, so any contribution to effective track width was identical in each case. The overall change in track width was slightly less than 3%. From Table 4, the SSF was 1.0814 for the -2 mm offset case, and 1.0518 for the 18 mm offset case.

Figure 6 shows the velocity of the vehicle for the two cases. The 18 mm offset case slowed down at a slightly greater rate. However, there was a distinct difference in the vehicle velocity for tip-up, and the only difference between the two test cases was the width of the track. Both the run speed and the tip-up speeds were distinctly different. This suggests that the vehicle dynamic performance is much more sensitive to track width changes than to changes in CG height.

Relationship to NHTSA NCAP Curves

The NHTSA NCAP curves shown in Figure 1 related a vehicle's NCAP rating to its SSF value. This approach was based on every vehicle in the underlying data having a single SSF value. The testing and data presented in reference [10] showed that the sensitivity to an SSF change due to track width is much larger than that due to a change in CG height. In that testing, a change in CG height of around 6% produced no significant change in the dynamic performance of the vehicle, while a 3% change in track width produced a significant dynamic performance change. Since $SSF = T/(2h)$, it can be shown that:

$$\% \Delta(SSF) = \% \Delta(T) - \% \Delta(h)$$

That is, the percentage change in SSF value is equal to the percentage change in track width less the percentage change in CG height. More importantly, it suggests that track width and CG height percentage changes have the same magnitude effect on the percentage change in SSF. More importantly, the NHTSA curves only assess the change in limit stability in terms of a change in SSF, regardless of the source. Since the dynamic testing reported in reference [10] indicates that vehicle dynamic performance does not follow the same rule, it can be concluded that the NHTSA NCAP curves do not apply to the case of SSF changes induced by tire changes with plus-sizing. That data also suggests that, for plus-sizing in general, track width changes are extremely important, while CG height changes due to tires, within the small ranges normally found in plus-sizing, have only small effects on performance.

On-Center Handling Issues

Wheel offset selection has been shown to play a significant role in the dynamic performance of the vehicle with its direct effect on the vehicle track width. Wheel offset also has an impact on an important steering parameter, the scrub radius. The scrub radius is the lateral offset between the intersection of the steering axis with the ground and the center of the tire. The scrub radius can also be influenced by the tire OD, since the steering axis is always inclined from the ground toward the center of the vehicle.

Figure 7 shows the general layout of a steering system. The mechanical trail is the distance defined by the castor setting and any spindle offset in the vehicle design.

Scrub radius is an important vehicle steering parameter. As scrub radius goes to zero, the driver loses road feel, and small angle steering becomes imprecise. Scrub radius is normally positive (the tire center is outboard of the steering axis intersection) on RWD vehicles. This causes the front tires to move in a toe-out direction on rolling. On Front Wheel Drive (FWD) vehicles, the steering axis is normally more inclined, and the scrub radius is negative. This means that the steering axis ground intersection is outboard of the tire center. This causes the tires to toe-in on rolling, but more importantly, causes the vehicle to have more stable handling in the event of a front tire blowout. Allowing the scrub radius to go to zero or to change sign will dramatically influence the handling of the vehicle in a negative manner. In plus-sizing, if the tire OD is within 3% of the OE tire OD, then the major contributor to scrub radius change is wheel offset. As previously discussed, however, tire OD often becomes larger or smaller than the OE tire OD for reasons of load capacity.

In the context of plus-sizing, RWD vehicles normally are fitted with wider tires with a lower aspect ratio than the OE tire. As previously discussed, this generally results in a tire with a larger OD to obtain a satisfactory load capacity. Figure 8 shows this type of fitment. With the OE wheel offset, the scrub radius becomes slightly smaller due to the increased tire OD. It is obvious in the schematic that, if the offset is changed to move the tire shoulder farther inboard, i.e., to place it within the fender well, the scrub radius will become smaller yet. Note that, if the offset is changed to move the tire inboard, the track width is also becoming smaller. It is therefore conceivable that the on-center handling as well as the limit stability of the vehicle would both be degraded.

FWD vehicles are often fitted with a much lower profile tire having much greater width than the OE tire in order to attain a significantly higher cornering power. Figure 9 shows this geometry. The smaller OD tire reduces the scrub radius. In this case, however, changing the offset to move the tire further inboard increases the negative value of the

scrub radius. The track width has been reduced, which has an effect on limit stability, but the on-center handling of the vehicle has been preserved.

Conclusions

Successful plus-sized fitting depends upon providing adequate tire load capacity, adequate tire inflation pressure, and adequate wheel width.

The use of plus-size tire and wheel fitments on a given vehicle will tend to decrease the SSF for that vehicle.

The SSF change due to increased tire diameter (increased CG height) has little influence on the limit stability of the vehicle, while SSF change due to changed wheel offset (reduced track width) may be significant.

The use of plus-sized fitments may change the vehicle's scrub radius due to both tire OD and wheel offset changes. These changes need to be reviewed to ensure that scrub radius does not go to zero or change sign.

Plus-sizing can affect many performance issues like cornering, harshness, potential for rim impact, and so on.

Hydroplaning resistance likely degrades when using plus-size fitments, especially as the tire tread wears, so recommending replacement at $\frac{4}{32}$ inch tread depth is prudent.

Plus-sizing can affect vehicle systems like antilock braking and electronic stability control, but the magnitude of these effects is unknown. Brake pad and steering gear wear rates may increase.

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TABLE 5 – *SSF Values for Tested Configurations*

Plus-Size	Tire Dimension	Diameter (mm)	Load (kg)
OE	265/70R16	778	1120
Plus 1	275/60R17	762	1060
Plus 2	285/50R18	743	1030
Plus 3	295/40R19	N/A	N/A
Plus 4	305/30R20	N/A	N/A

Plus-Size	Tire Dimension	Diameter (mm)	Load (kg)
OE	265/70R16	778	1120
Plus 1	285/65R17	762	1120
Plus 2	285/60R18	799	1250
Plus 3	N/A	N/A	N/A
Plus 4	285/50R20	794	1120

		Light Truck	
Passenger Car		Aspect Ratio	Tire Width Ratio
Aspect Ratio	Tire Width Ratio	95, 90, 85	65% to 80%
80, 75, 70	65% to 85%	80, 75, 70	65% to 85%
65, 60, 55, 50	70% to 90%	65, 60, 55, 50	70% to 90%
45	80% to 95%	45	80% to 95%
40, 35	85% to 100%	40, 35	85% to 100%
30*	90% to 100%	30	90% to 100%
25*	92% to 98%		

Tire ¹ Size	Speed Rating	Tire OD (mm)	Wheel Size	Wheel Offset (mm)
P225/75R15 102S M+S	S	719	15x6.0	0
31x10.50R15LT 109Q M+S	Q	775	15x7.0	0
285/50R20 116H M+S	H	794	20x8.5	-2
285/50R20 116H M+S	H	794	20x8.5	18

¹ All tires are Goodyear Fortera HL

Tire Size	Wheel Size/Offset	Computed SSF / Star Rating
P225/75R15 102S M+S	15x6.0 / 0	1.1512 / ★★★
31x10.50R15LT 109Q M+S	15x7.0 / 0	1.1119 / ★★★
285/50R20 116H M+S	20x8.5 / -2	1.0814 / ★★
285/50R20 116H M+S	20x8.5 / 18	1.0518 / ★★

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NCAP Rollover Ratings

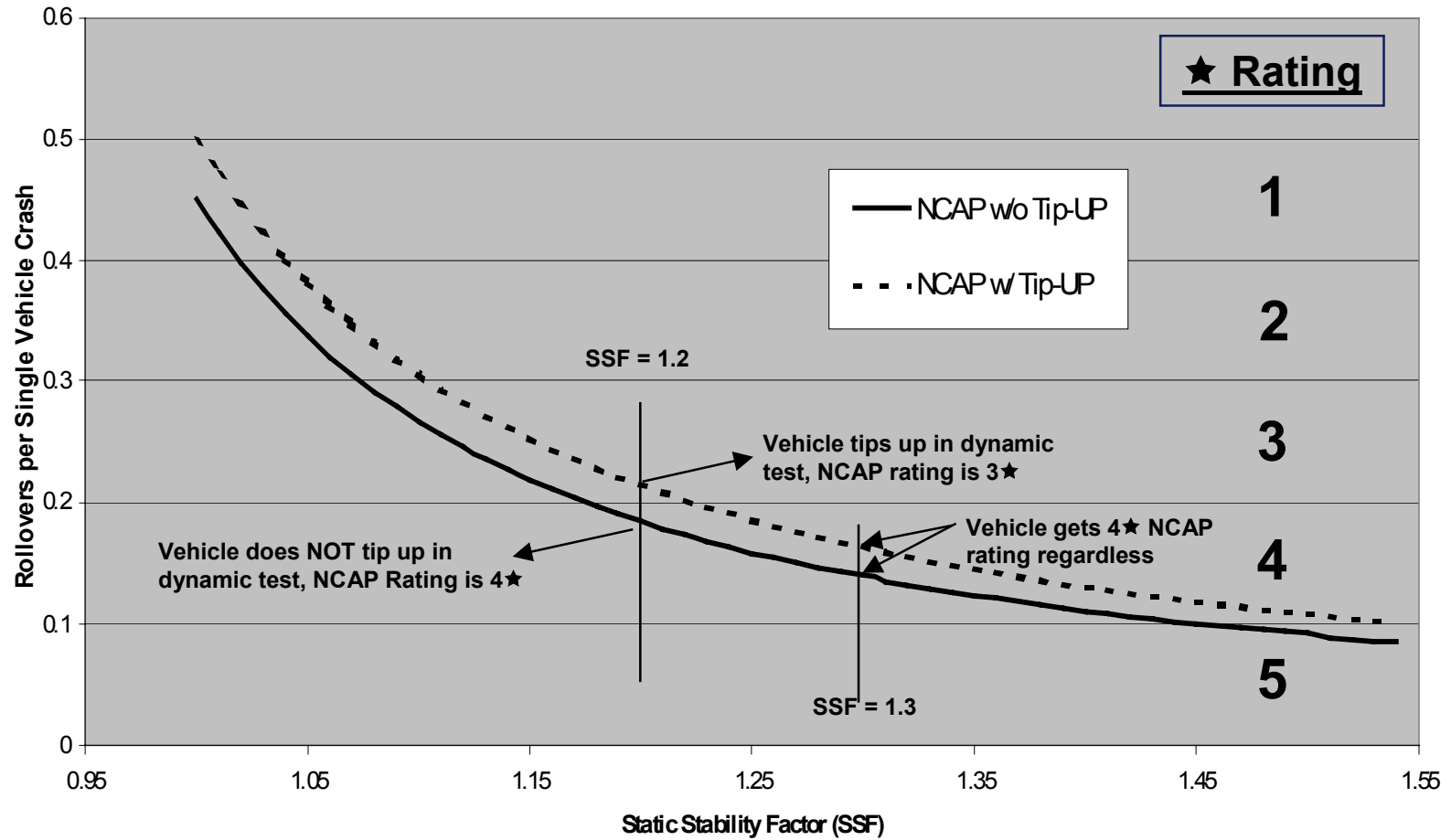


FIGURE 1. NHTSA New Car Assessment Program Rating System. Note the effect of tipping up in the dynamic testing may or may not change the NCAP rating received.

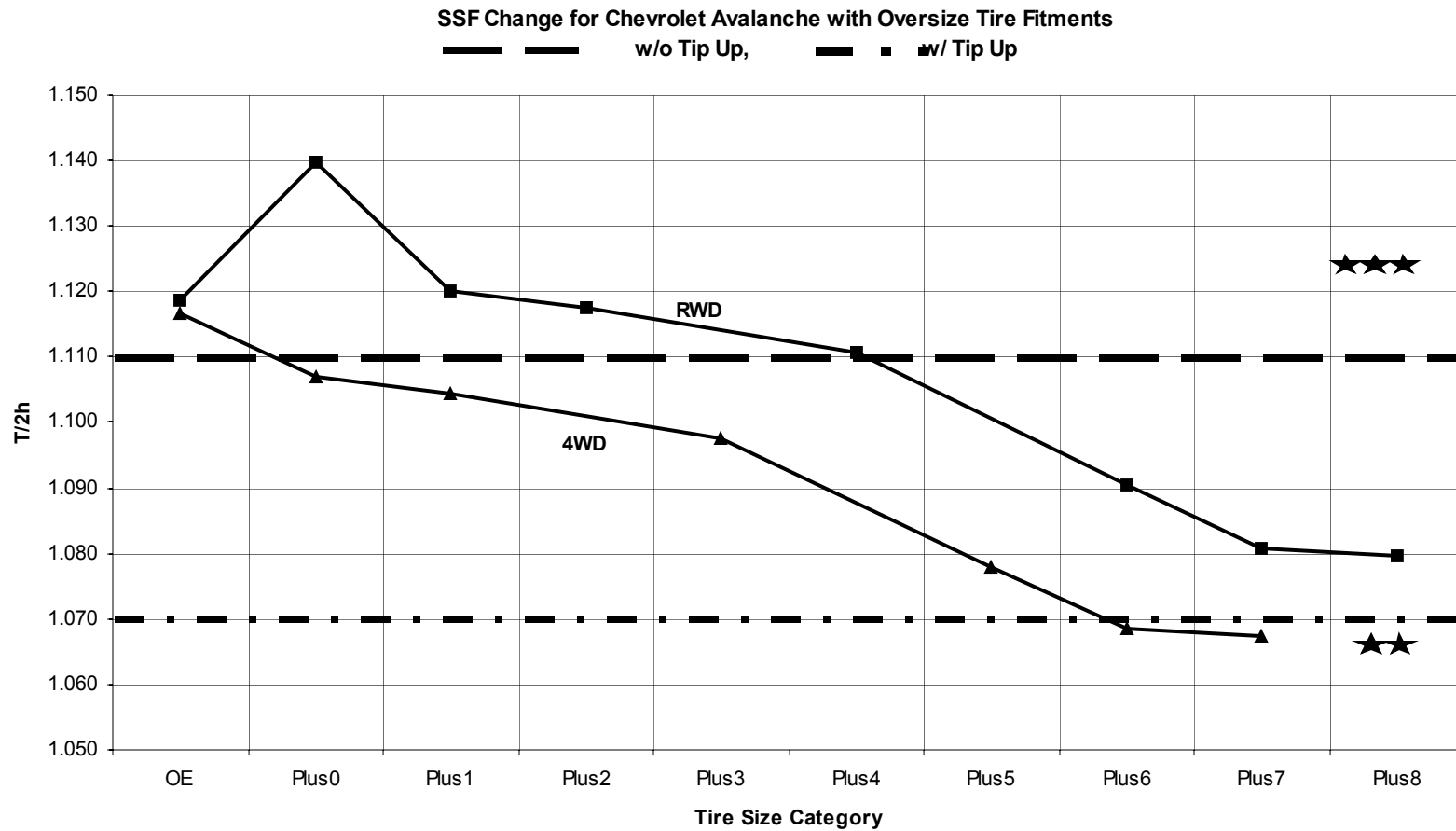




FIGURE 3. *Test Vehicle with NHTSA-style outriggers and wheel lift sensors. The steering controller and tire video equipment are specific to the specific test center.*

CGVelocityX

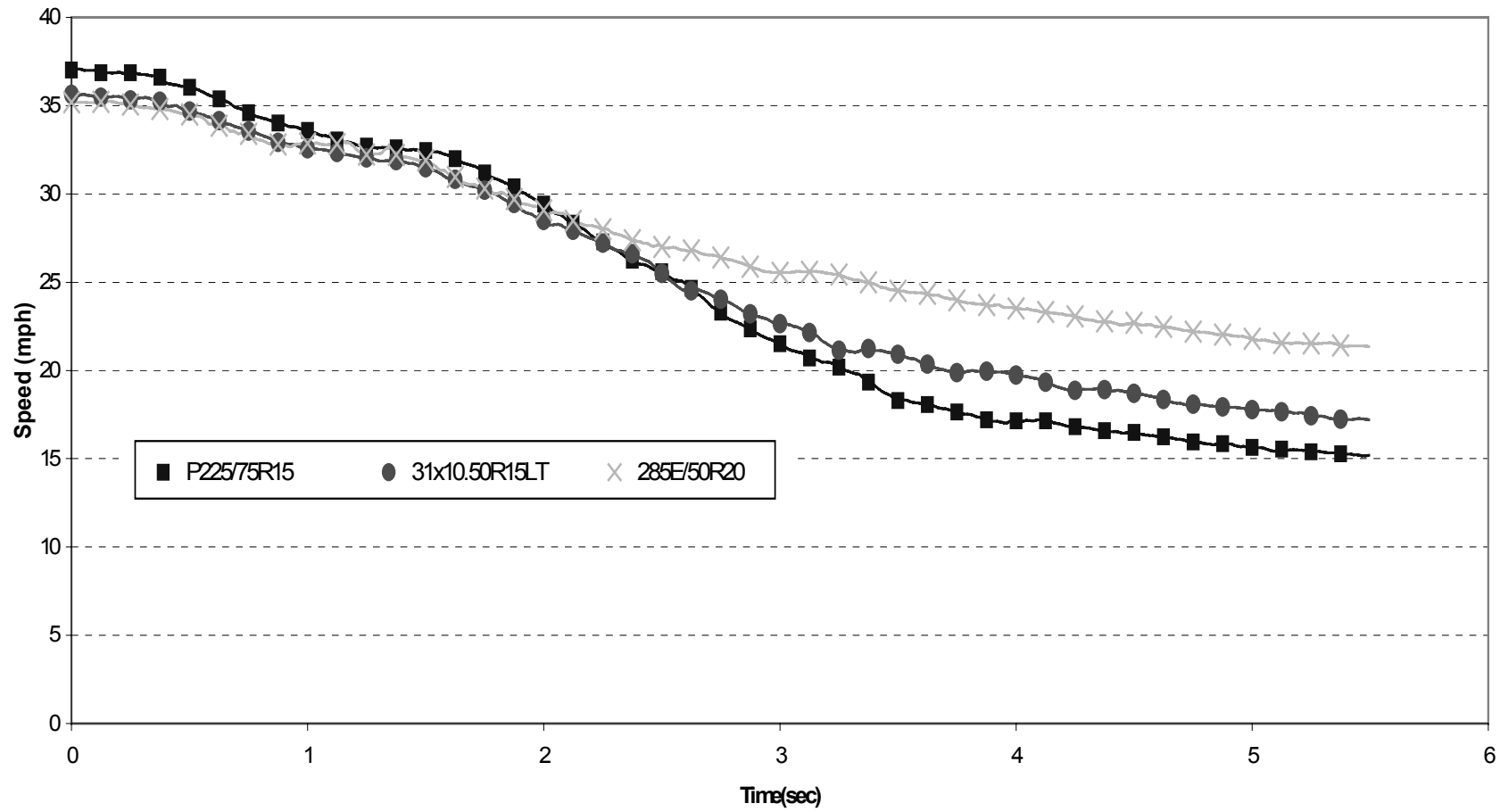


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FIGURE 5. *Comparison of front tire deformation of P225/75R15 (left) and 285/50R20 (right) at maximum tip-up. Wheels are zero offset on left and -2 mm offset on right.*

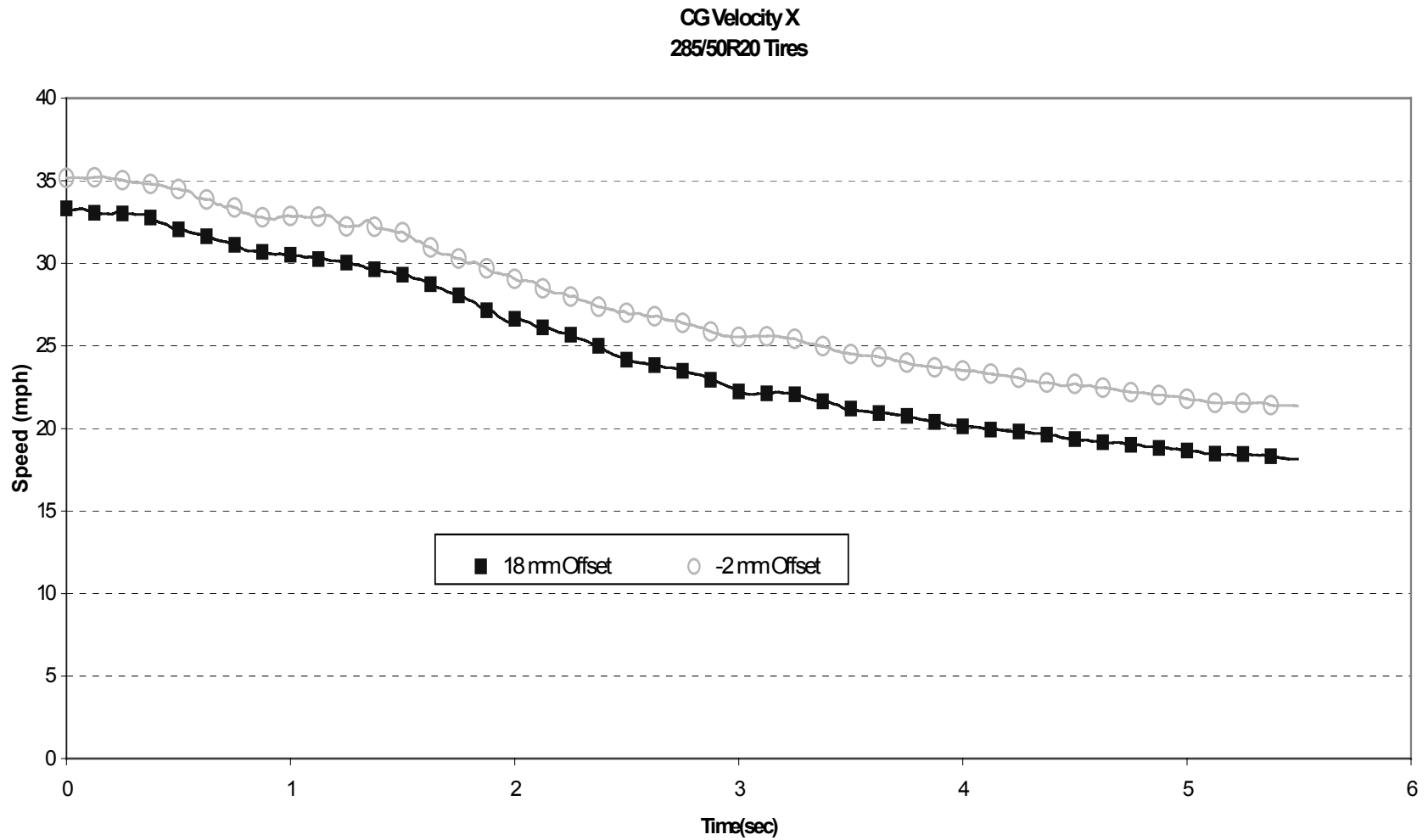


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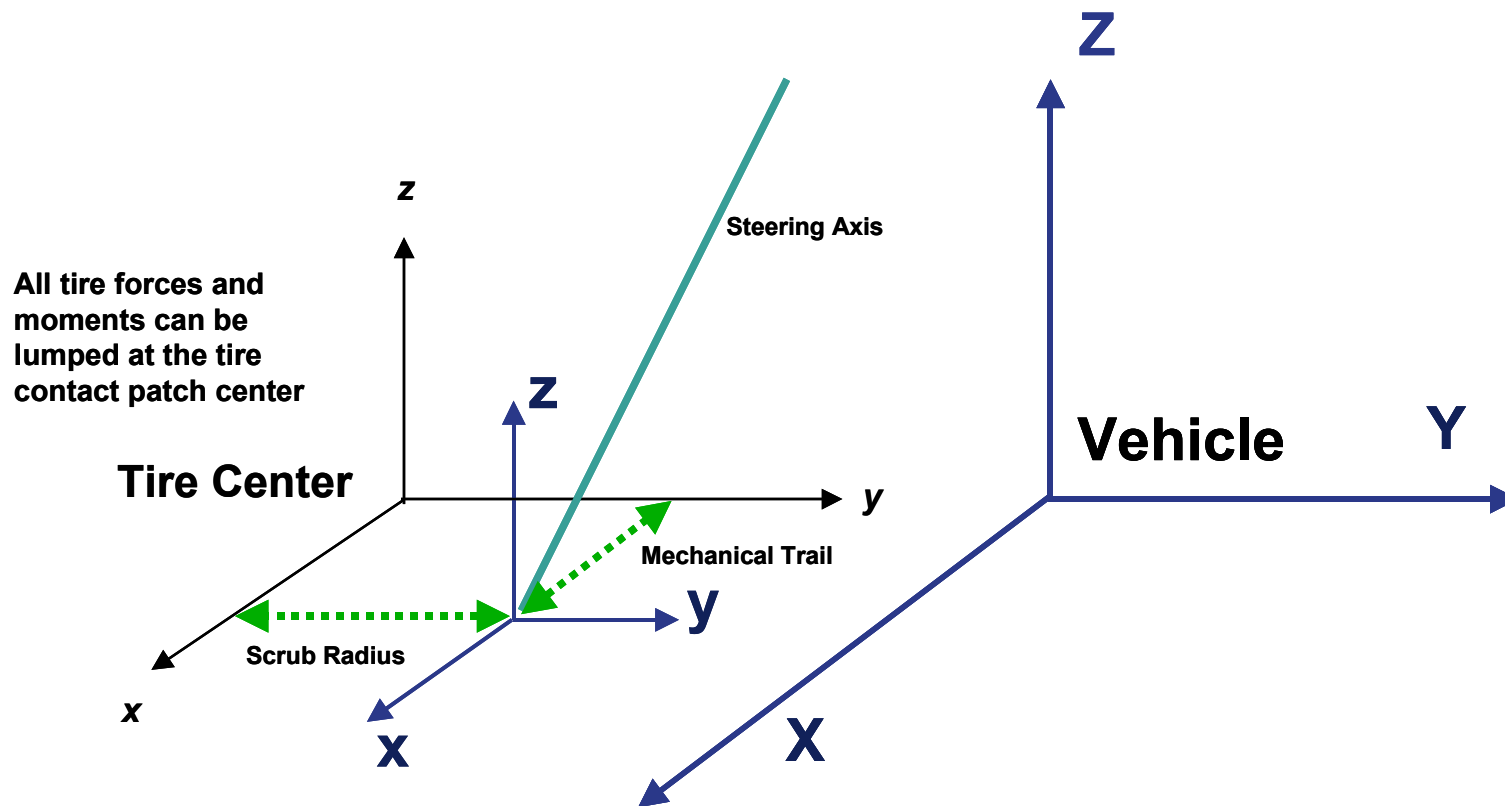


FIGURE 7. *Schematic of steering geometry on a vehicle. Mechanical trail is made up of castor setting plus spindle offset, and may be different from one side of the vehicle to the other.*

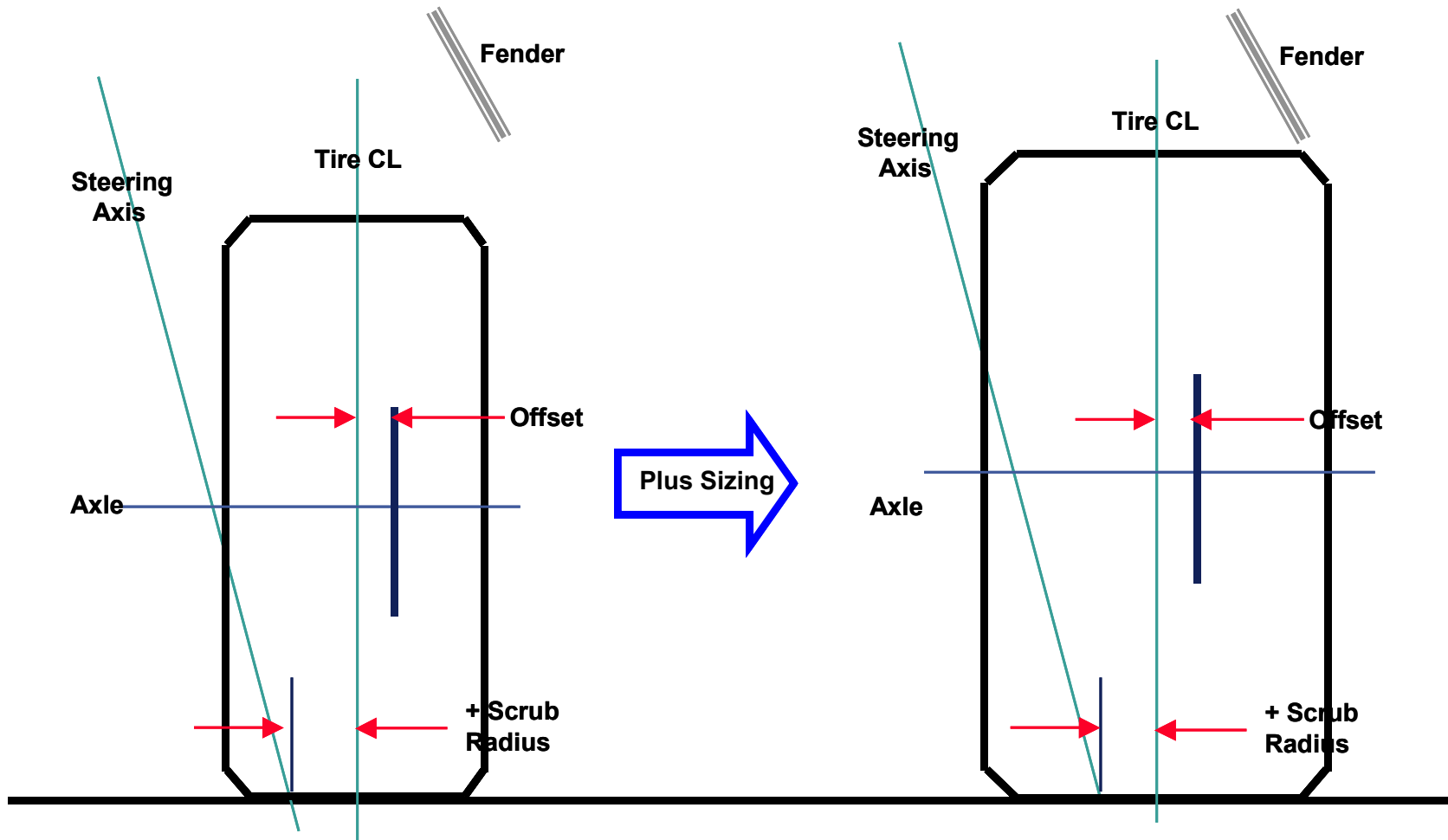


FIGURE 8. *Rear wheel drive plus-sizing setup using OE offset. Note that scrub radius gets smaller as tire OD gets larger. Changing wheel offset to move the tire under the fender will further reduce scrub radius.*

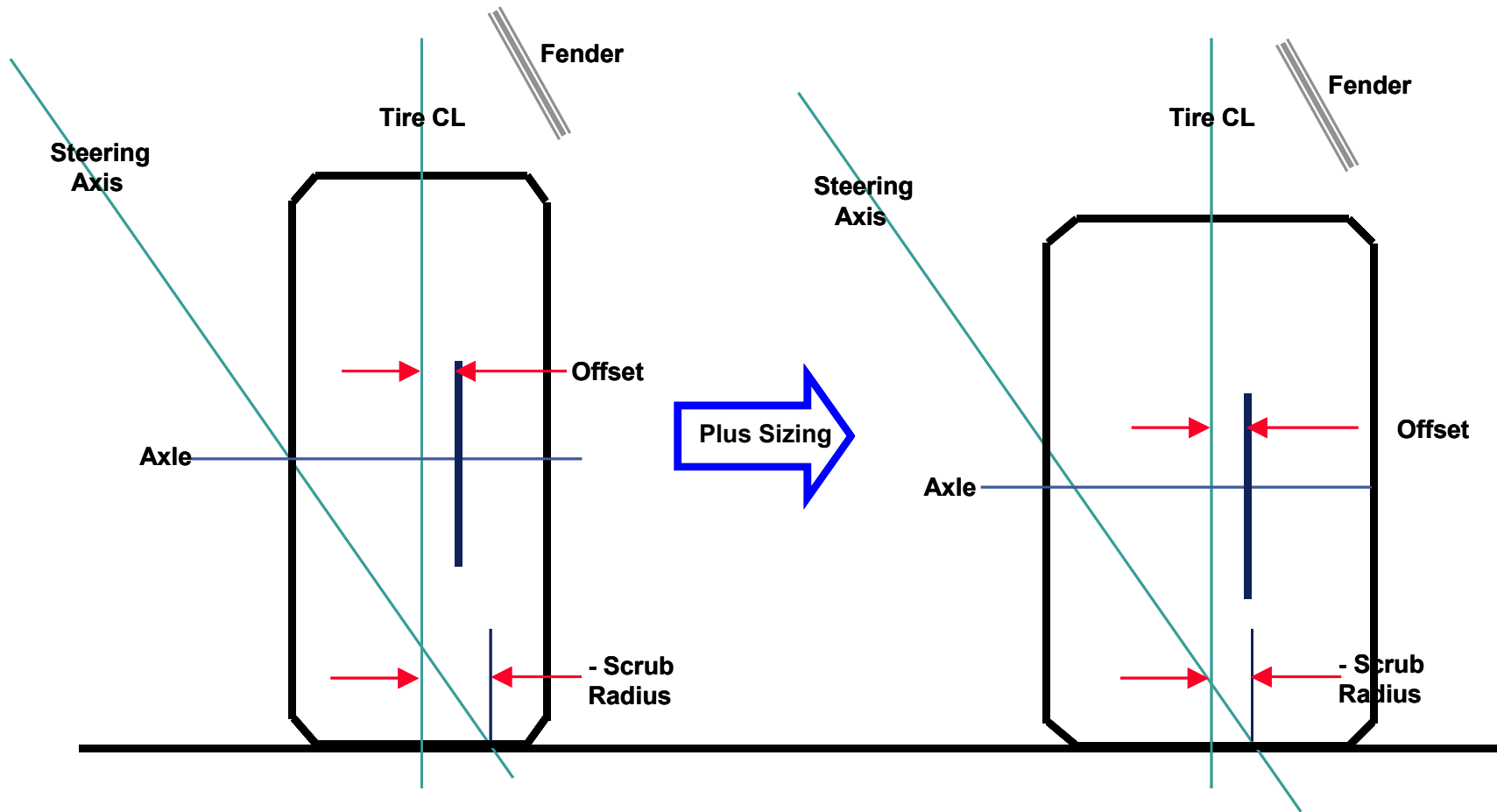


FIGURE 9. *Front wheel drive plus-sizing setup using OE offset. Note that scrub radius gets smaller as tire OD gets smaller. Changing wheel offset to move the tire under the fender will increase scrub radius.*