

Inflation Pressures at Less-Than- Maximum Tire Loads

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ABSTRACT: One of the most important parameters to be established for tire operation, whether on a new vehicle being designed by a vehicle manufacturer or on a plus-size fitment, is the recommended cold inflation pressure for the tire. The tire carries a maximum inflation pressure label, but operation at lower loads and pressures is generally beneficial for overall vehicle performance. Recommended inflation pressures have historically been provided by tire standards organizations in the form of tables of load versus pressure or in the form of simple mathematical models. This paper reviews these models, and develops a new formulation based on a tire stiffness model. It is shown that the stiffness model predicts higher inflation pressure requirements at lower-than-maximum loading conditions than some of the models in use in the industry.

KEYWORDS: Inflation pressure, stiffness model

Tire pressure selection in instances where the tire loads are lower than the maximum load allowed can be done by numerous methods. However, the selection of a correct inflation pressure is critical to the successful operation of the tire. It is well-known that operation of a tire at higher than required pressures may cause uneven tread wear, degrade vehicle ride and comfort, and increase susceptibility to impact damage. Operating the tire at lower than required pressures may also cause uneven tread wear, but can potentially lead to fatigue breakdown of the tire’s internal structure resulting in tread separation or other structural failure. Lower-than-optimal operating pressures also decrease fuel economy. Obviously, inflation pressure at a given load has been shown to affect a tire’s deflection, contact footprint pressure distribution, and hysteretic heat generation. The correct setting of the cold inflation pressure is therefore critical to achieving the design intent of the tire in the field. For vehicles being fitted with the Original Equipment (OE) tire, the recommended operating pressure is listed on the placard.

The normal methods employed for arriving at the correct inflation pressure are by interpolation in tables published by tire regulatory bodies, like the Tire & Rim Association (T&RA), or by computation using methods published by those same regulatory bodies. This paper will survey the computational procedures as they are currently published for passenger and light truck tires, along with a newly-developed method. An analysis of the results of such computations will be presented along with the impact on tire deflection.

Tire Pressure Determination

The placard pressure indicated on a vehicle is supposed to provide the optimal inflation pressure for the OE tires on any vehicle. This value will generally be higher than the minimum pressure required to support the maximum load on a given axle of the vehicle and lower than the tire's maximum inflation pressure rating. The inflation pressure on the vehicle placard is generally the result of significant performance testing on the part of the vehicle manufacturer along with the tire manufacturer. Tire makers, on the other hand, typically subject tires to a standard set of proprietary tests which field return experience has shown to provide adequate screening for development purposes. There are many instances, however, where tire inflation pressure must be determined in the absence of significant testing. This is especially true when tires are fitted to a vehicle that are a different size than those supplied as OE.

There are several approaches to determining the correct operating pressure for a vehicle's tires. The first is to find the tire listed in tabulated pressure-versus-load tables such as those published by the T&RA in annual Yearbooks. Tire manufacturers normally distribute these tables to tire sellers for their use. Using these tables requires 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 front and rear axle GAWRs will likely be different). Note that, if passenger tires are used on a multi-purpose vehicle (MPV), the tire load must be increased by 10% to conform to Department of Transportation (DOT) requirements. This approach will generally be followed by vehicle manufacturers when selecting an appropriate tire size and minimum inflation pressure for a given vehicle. The pressure finally adopted for the placard may likely be higher than the minimum inflation pressure in order deal with maximum vehicle speed or to optimize handling, rolling resistance, or a number of other vehicle performances. The same values found in yearbook

tables can be obtained mathematically using the Engineering Design Information (EDI) formulae that underlie those tabulations, or formulae provided by organizations like the European Tyre and Rim Technical Organisation (ETRTO). These formulations are supposedly 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 pressure is then given by:

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

where MaxLoad is the maximum load indicated on the tire sidewall, MaxPressure is the pressure used to determine the maximum load, and n is equal to a constant (assuming vehicle speeds less than 160 kph (100 mph)). Note that MaxPressure is not necessarily equal to the maximum pressure on the tire sidewall (this is discussed below). There are numerous values of the exponent n in common use in the tire industry today.

The T&RA has historically stated that the maximum load on a tire being designed to operate at a certain maximum inflation pressure could be stated as:

$$\text{MaxLoad} = G \times \text{Maxpressure}^n \quad [2]$$

The empirical origins of this form, where G represents a constant function of tire geometry, have been covered in detail by S. Padula [1]. The first formula adopted by the T&RA in 1928 established a value for n as 0.585. At that time, pressure at lower-than-maximum loads was obtained simply as a ratio, or using Equation 1 with $n = 1$. At some point in time, Equation 2 was deemed to apply to any pressure; the pressure-load relationship at lesser loads was then obtained by dividing the load at any pressure by the maximum load, resulting in elimination of the G term and yielding Equation 1. A value of 0.5 was adopted for P-metric tires in the 1970's. A perusal of a recent edition of the T&RA's EDI guide shows that the value of n is 0.7 for light truck radial tires, 0.585 for flotation tires (and bias tires), and various other values for truck tires depending upon the type and aspect ratio. Since the beginning of 2006, the T&RA has been working on harmonizing its standards with other international organizations like the ETRTO. For passenger car tires standardized after January 1, 2006, the value of n in Equation 1 is 0.8 for tires with Load Index (LI) less than 100, and 0.65 for tires with LI greater than 100.

This makes the computation of inflation pressure simple, but tires standardized by the T&RA prior to the beginning of 2006 still reflect pressure values in yearbook tables developed with the older rules. This does not seem to be either consistent or physically sound, since the load a tire can carry is proportional to its inflation pressure and its internal volume. Tires having the same internal volume and the same maximum inflation pressure should require the same inflation at lower-than-maximum loads. However, yearbooks have pressures tabulated for reduced load operation, and these values were generated based on the values of n in use at the time the given tire size was first entered into the document.

The approach based on the standards organization approach is simple, but the underlying formulae have been shown by Padula [1] to overestimate the proper maximum load as rim diameter increases. Padula's analysis was based on an empirical tire vertical stiffness formulation by Rhyne [2]. Based on Rhyne's analysis, Padula showed that tire vertical stiffness could be reduced to a simple function of tire geometry that was broadly applicable,

$$K_z = \text{Pressure} \times F + 3.45 \quad [3]$$

where K_z is the tire's vertical stiffness (i.e., load divided by deflection), and the function of tire geometry, F , contains the tire parameters of section width, S_N , aspect ratio, AR , and rim diameter, D_R :

$$F = 0.00028 \times \sqrt{(1.03 - 0.004 \times AR) \times S_N \times \left(\frac{S_N \times AR}{50} + D_R \right)} \quad [4]$$

where all the parameters are in metric units. Note that Equation 3 asserts that the tire stiffness is a linear function of the inflation pressure, and this concept was shown empirically by Rhyne's work to apply across numerous tire sizes and types. If the same iso-deflection assumption that is used in the tabulations by T&RA, ETRTO, and so on, is made, the pressure at a given load can be computed as:

$$\text{Pressure} = \frac{\left(\frac{\text{Load}}{\text{Maxload}} \times (\text{Maxpressure} \times F + 3.45) \right) - 3.45}{F} \quad [5]$$

Obviously, all the computational approaches above will yield slightly different values, especially since there is a wide range of values for the coefficient n in Equation 1. Of interest is the fact that the stiffness formulation described above was developed from data taken from a large number of tires of different sizes and types. The stiffness data therefore can be interpreted to be a representation of how tires actually behave at less-than-maximum inflation pressures rather than how the maximum-inflation models of load capacity might predict that they work. The deflection of the tire is one of the more significant operating parameters in terms of the tire's resistance to long-term fatigue breakdown, since deflection generates strain in the skim rubber at the belt edge. If the tire is over-deflected, i.e., deflected more than it would be if it were loaded to its maximum load and operated at its maximum inflation pressure, then the tire may incur strains beyond those envisioned by its developers. These strains are more likely to arise in the critical belt-edge area of a steel-belted radial tire where they can contribute to heat-related issues including increased rolling resistance and the development of tread separation.

A sample calculation can best illustrate the principle. Consider a P235/75R15 standard load tire. This tire has a T&RA maximum load of 920 kg (2028 lbs) at a maximum inflation pressure of 240 kPa (35 psi). Using Equation 3, the tire stiffness at the maximum load, maximum inflation pressure condition is 27.3 kg/mm, and the deflection at this condition is 33.7 mm. When such a tire is used on a multipurpose passenger vehicle (MPV) having a Gross Axle Weight Rating (GAWR) of 1315 kg (2900 lbs), the load applied to the tire for pressure rating purposes will be half the GAWR, or 658 kg (1450 lbs), and this value will be increased by 10% to conform to the rating standards of the DOT for passenger tires used on MPVs. Therefore, the required tire capacity will be 723 kg (1595 lbs). The vehicle placard for this particular vehicle lists the cold inflation pressure for the tire as 180 kPa (26 psi). Consulting the T&RA tables for this tire, the rated load at 180 kPa is given as 795 kg. Since the rated load capacity of 795 kg at 180 kPa is greater than the required capacity of 723 kg, one would assume that the tire will be operated at a deflection that is smaller than its maximum deflection, i.e., in an under-deflected state (the tire has excess capacity).

However, the tire stiffness at 180 kPa (26 psi) given by Equation 3 is 21.2 kg/mm. At the required load of 723 kg, the deflection of the tire would be 34.2 mm, which is larger than the deflection at the maximum load, maximum pressure condition (33.7 mm). In short, if the load applied to the tire were 723 kg, the tire will be slightly over-deflected, so the inflation pressure of 180 kPa (26 psi) is slightly below that required to maintain the iso-deflection state (that state where the deflection of the tire is just equal to its deflection at the maximum load, maximum pressure condition). Since a properly-maintained tire will have the benefit of the DOT's 10% safety margin (i.e., at GAWR, the actual load is only 658 kg), the bulk of the tires operated in this condition will still be running in an underdeflected state. However, lack of tire pressure maintenance, severe vehicle loading conditions, and other field experience issues could have a more severe effect on the tire in this application than in one where the expected tire deflection is well below the maximum.

Comparison of the Various Models

In order to compare the pressure prediction of the various models, it is interesting to recast them into a ratio format. That is, Equation 1 becomes

$$\frac{\text{Pressure}}{\text{MaxPressure}} = \left(\frac{\text{Load}}{\text{MaxLoad}} \right)^{\frac{1}{n}} \quad [6]$$

Equation 6 can be plotted for various values of n to see the influence of the various models on the pressure prediction. Figure 1 shows this relationship plotted for values of n equal to 0.65, 0.7, and 0.8. Note that the pressure ratio required to support any given load ratio increases as the value of n increases. For example, if a certain tire is required to support 75% of its maximum load, the pressure required would be 64.2% of the maximum inflation pressure for $n = 0.65$, 66.3% for $n = 0.7$, and 69.8% for $n = 0.8$. Again, there does not appear to be any significantly compelling reason to believe that the required inflation pressure could range between 64.2% and 69.8% of maximum inflation pressure for the same physical load on the same tire. Nor is there any compelling physical reason to believe tires of the same size (or more correctly, internal volume) governed by different standards organizations, would have substantially different pressure requirements to support less-than-maximum loads.

The stiffness formulation shown in Equation [5] can be recast in a similar fashion, albeit with slightly more work, as:

$$\left(\frac{\text{Pressure}}{\text{MaxPressure}}\right) = \left(\frac{\text{Load}}{\text{MaxLoad}}\right) \times (1 + k) - k \quad [7]$$

Where k is a constant for any tire given by:

$$k = \left(\frac{3.45}{\text{MaxPressure} \times F}\right) \quad [8]$$

where MaxPressure is given in kPa to be consistent with the original stiffness formulation. Equation 7 is, as expected, the equation of a straight line with slope $1+k$ and intercept $-k$. However, since the value of k depends upon the tire size and the tire's maximum inflation pressure, the slope will vary with the tire size and type. In order to explore the significance of this variation, numerical assessments were done across a wide range of tire sizes in P-metric, light truck, and medium truck. It was found that, generally, the geometry function, F , ranges between about 0.07 for very small passenger car sizes to about 0.18 for large medium duty truck sizes. Table 1 shows this trend for several tire sizes. Using these extremes, the value of the k parameter was plotted against various maximum inflation pressures as shown in Figure 2. This shows that the value of k is larger for small tires at low maximum inflation pressures and becomes smaller for large tires at high maximum inflation pressures.

From Figure 2 and Table 1, the expected range of values of k is from about 0.02 for large tires having high maximum inflation pressures to about 0.22 for small tires having low maximum inflation pressures. These values were substituted into Equation 7, with the results plotted in Figure 3 against Equation 6 with $n = 0.8$. From Figure 3, it is clear that when k is close to its minimum (i.e., for very small tires at low maximum inflation pressures), Equation 6 with $n = 0.8$ and the stiffness prediction are very nearly identical down to the point where the imposed load is about 70% of the maximum rated load. However, as tire sizes increase and maximum inflation

pressures increase, the stiffness prediction moves away from $n = 0.8$ line. In fact, for large size tires at high pressures, the stiffness prediction approaches:

$$\left(\frac{\text{Pressure}}{\text{MaxPressure}}\right) = \left(\frac{\text{Load}}{\text{MaxLoad}}\right) \quad [9]$$

which is Equation 6 with $n = 1$ (this line is also shown on Figure 3). Figure 3 shows that inflation pressures required at less than maximum loading predicted by the stiffness formulation will generally lie between that predicted by the $n = 0.8$ relationship and the pure ratio relationship given by Equation 9 ($n = 1$).

It is interesting to consider the deflections resulting from the choice of inflation pressure. Since the tire's vertical stiffness is the ratio of load to deflection, Equation 3 can be used to compute the static deflection, d , at any pressure as:

$$d = \frac{\text{Load}}{K_z} = \frac{\text{Load}}{\text{Pressure} \times F + 3.45} \quad [10]$$

Using Equation 10 at a given pressure, then, the ratio of the deflection, denoted d' , at the load allowed by the use of power rules based on Equation 2, denoted as L' , to the deflection, d , given by the load allowed by the stiffness formulation, L , is given simply as:

$$\frac{d'}{d} = \frac{L'}{L} \quad [11]$$

Substituting Equation 6 and Equation 7 into Equation 11, and noting the the pressure used for both rules is identical, the relationship between the deflections predicted by the two methods can be shown to be:

$$\frac{d'}{d} = (1 + k) \frac{\left(\frac{\text{Pressure}}{\text{MaxPressure}}\right)^n}{\left(\frac{\text{Pressure}}{\text{MaxPressure}} + k\right)} \quad [12]$$

The relation given by Equation 12 is shown graphically in Figure 4 for various values of the power rule exponent n from Equation 3. The graph on the left has $k = 0.22$, so it applies to very small tire and rim combinations at low maximum inflation pressure. The graph on the right has $k = 0.02$, so it applies to large tires at high maximum inflation pressures. Positive values of the ratio d'/d indicate that at a given pressure, the deflection resulting from allowable loads generated by formulations like Equation 3 is larger than that obtained when allowable loads are generated using the stiffness formulation. In other words, the loads allowed by the power rule type formulations are higher at a given pressure than those allowed by the stiffness formulation. The exception is that for $n = 0.8$, when the inflation pressure is less than about 70% of the maximum inflation pressure, the stiffness formulation allows slightly higher loads. This is essentially the same result noted in the discussion of Figure 3. The size of the overdeflections predicted by Equation 12 are somewhat disturbing. For example, when inflated to 70% of the maximum pressure, the load allowed by using Equation 3 with a value of $n = 0.65$ would create a deflection 5% to 12% larger than the tire's maximum deflection at its maximum load and maximum pressure condition, depending upon the size of the tire and its maximum inflation pressure.

In the special case of Extra Load tires, the increased maximum load capacity is developed from the EDI curves either by increasing the LI by 4 for tires with LI values less than 100, or by extending the load-pressure curve to the required higher pressure. For example, on a P255/70R16 tire, the Standard Load version has a maximum rated load capacity of 1030 kg (2271 lbs) at 240 kPa (35 psi), while the Extra Load version's maximum rated load capacity is 1120 kg (2469 lbs) at 280 kPa (41 psi). As shown in Figure 5, the EDI curve for the Extra Load tire follows that of the Standard Load tire and then continues from 240 kPa (35 psi) to 280 kPa (41 psi). Using the stiffness formulation for pressure suggests that the Extra Load tire requires more pressure at any given load than the Standard Load tire because the stiffness model always starts at the maximum load and maximum pressure point. The stiffness curves for the Standard and Extra Load versions of the tire are also shown on Figure 4. This result is not entirely satisfactory, and it is due to the selection of the maximum load capacity of the Extra Load tire. If the tire stiffness has a linear relationship with pressure, then at the same maximum deflection (recall that all the models are iso-deflection types), the load must vary linearly with pressure as well. Use of a stiffness-type model will yield a lower load capacity (and a correspondingly higher pressure requirement) for an Extra

Load tire relative to the Standard Load tire it is based on, given the current definition of the maximum load and maximum pressure for Extra Load type tires.

Discussion

The selection of an inflation pressure for tire operation at less than maximum loads is critical to the success of the tire in that service. Models of the form of Equation 2 were originally developed, as discussed by Padula [1], from empirical relationships governing the selection of a tire's maximum load capacity at some maximum inflation pressure. As Padula noted, in the early days of the T&RA, tire inflation pressure at less-than-maximum load conditions was obtained by using Equation 9, and the move to forms of Equation 1 was not clearly explained in the record. What is of interest for the modern radial tire at this point is that it has been shown that the stiffness of the tire is linear with pressure, at least in the range of "normal" operating pressures. Establishment of the linearity of stiffness with pressure suggests that the relationship between inflation pressure and load should follow a linear relationship for a given tire even if the maximum load capacity is related in a non-linear fashion to the maximum inflation pressure across many tires of the same type.

Equation 2 represents an empirically-developed relationship between the maximum load and the maximum pressure, and is essentially a function of the volume of the tire. Since the relationship was developed empirically, it is not clear that the same relationship would be useful to describe the relationship between less than maximum loads and corresponding inflation pressures for a given tire. Indeed, if this were a regression problem, it is clear that the value of maximum inflation pressure does not have significant variation for a given type of tire (i.e., passenger car tires), and therefore would appear as a constant to any regression algorithm. From this perspective, it does not seem that models like Equation 1 would be valid, since they were derived from an empirical model where pressure was essentially a constant. On the other hand, the stiffness methodology presented here was developed from an empirical model representing load versus pressure across a range of pressures.

It is also intuitive that, similar tire sizes at similar partial loads should require similar inflation pressures, regardless of the standards organization that is responsible for the tire. Hence, different

values of n in Equation 1 across different standards organizations do not seem consistent with the physical reality that the load capacity of a tire is related to its volume and its internal pressure. Further, the stiffness-based formulation for less-than-maximum load conditions suggests that all of the power rule type formulations yield pressures that are too low for the load in question. The relationship in Equation 1 with n equal to 0.8 appears to provide appropriate minimum inflation pressure for small tires at low maximum inflation pressures. In today's market, most passenger car tires fit on 15-inch diameter rims and larger, at a maximum inflation pressure of 240 kPa (35 psi) for standard load tires. These tires (along with all light truck tires at maximum inflation pressures of 340 kPa (50 psi) and higher, as well as all medium duty truck tires) would require higher inflation pressures, as defined by the stiffness model, than would be indicated by the use of power law rules.

In all these discussions, of course, "maximum inflation pressure" is taken to be the pressure at which the tire develops its maximum load capacity. For most tires, this is the maximum pressure shown on the tire's sidewall. However, for passenger car tires, there are many types of tires that are labeled with a higher maximum inflation pressure than the pressure at which the tire develops its maximum load capacity. Table 2 summarizes these types of labeling.

The appropriate inflation pressure for a tire operating at a lower-than-maximum load condition can be computed from the stiffness relationship derived in this paper. Alternatively, the simple model shown in Equation 9, while indicating a higher pressure than the stiffness model, would provide a safe value that is easily computed in the field.

Conclusions

1. Tire pressure required to support partial loads is predicted by the stiffness model to vary linearly with the load.
2. Power rule models, having n equal to or less than 0.8, put forward by tire standards organizations and indicated in tabulated values in annual yearbook publications may not provide adequate inflation pressure for certain tires at partial load conditions.
3. Adequate inflation pressure is essential to prevent overdeflected operation of a tire so that it can deliver its intended performances over the lifetime envisioned by the manufacturer.

4. The stiffness model formulation provides a conservative, but computationally intensive, method of developing the proper inflation pressure for operation at less than maximum loads.
5. The simple ratio method given by Equation 9 provides a slightly more conservative, but computationally simpler, method of developing a safe operating pressure for tires operating at less than maximum loads.

References

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[2] Rhyne, T.B., "Development of a Vertical Stiffness Relationship for Belted Radial Tires," *Tire Science and Technology*, TSTCA, Vol. 33, No. 3, July-September 2005, pp. 136-155.

List of Tables

TABLE 1 – *Parameter Values for Sample Tire Dimensions*

TABLE 2 – *Various Maximum Cold Inflation Pressure Markings Permitted*

| Dimension | Pmax (kPa/psi) | F | k |
|-------------|----------------|-------|-------|
| 155/80R13 | 240/35 | 0.071 | 0.204 |
| 235/75R15 | 240/35 | 0.099 | 0.145 |
| 325/75R20 | 350/50 | 0.136 | 0.074 |
| 455/55R22.5 | 900/130 | 0.176 | 0.022 |

| Passenger Tire Type | Labeled Maximum Pressure Marking | Maximum Pressure for Load Rating |
|---------------------|----------------------------------|------------------------------------|
| Standard Load | 240 kPa (35 psi) | 240 kPa (35 psi) |
| | 300 kPa (44 psi) | 240 kPa (35 psi), 250 kPa (36 psi) |
| | 350 kPa (51 psi) | 240 kPa (35 psi), 250 kPa (36 psi) |
| Extra Load | 280 kPa (41 psi) | 280 kPa (41 psi) |
| | 340 kPa (50 psi) | 280 kPa (41 psi), 290 kPa (42 psi) |

Note: Tires with 250 kPa (36 psi) and 290 kPa (42 psi) reference pressures have internationally harmonized load ratings

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FIGURE 5. *Extra-Load versus Standard Load tire capacities for a P255/70R16 using EDI and stiffness formulations.*

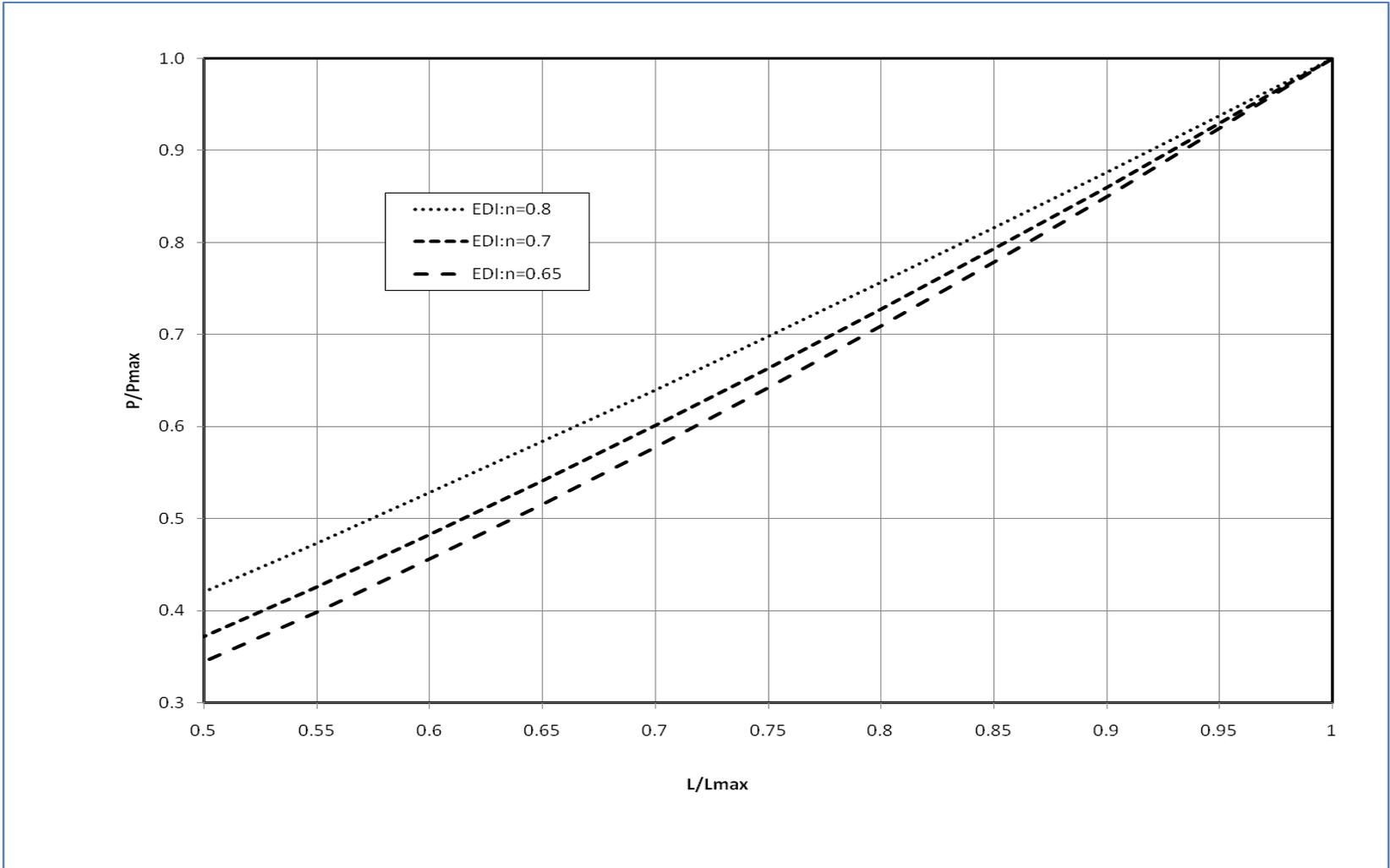


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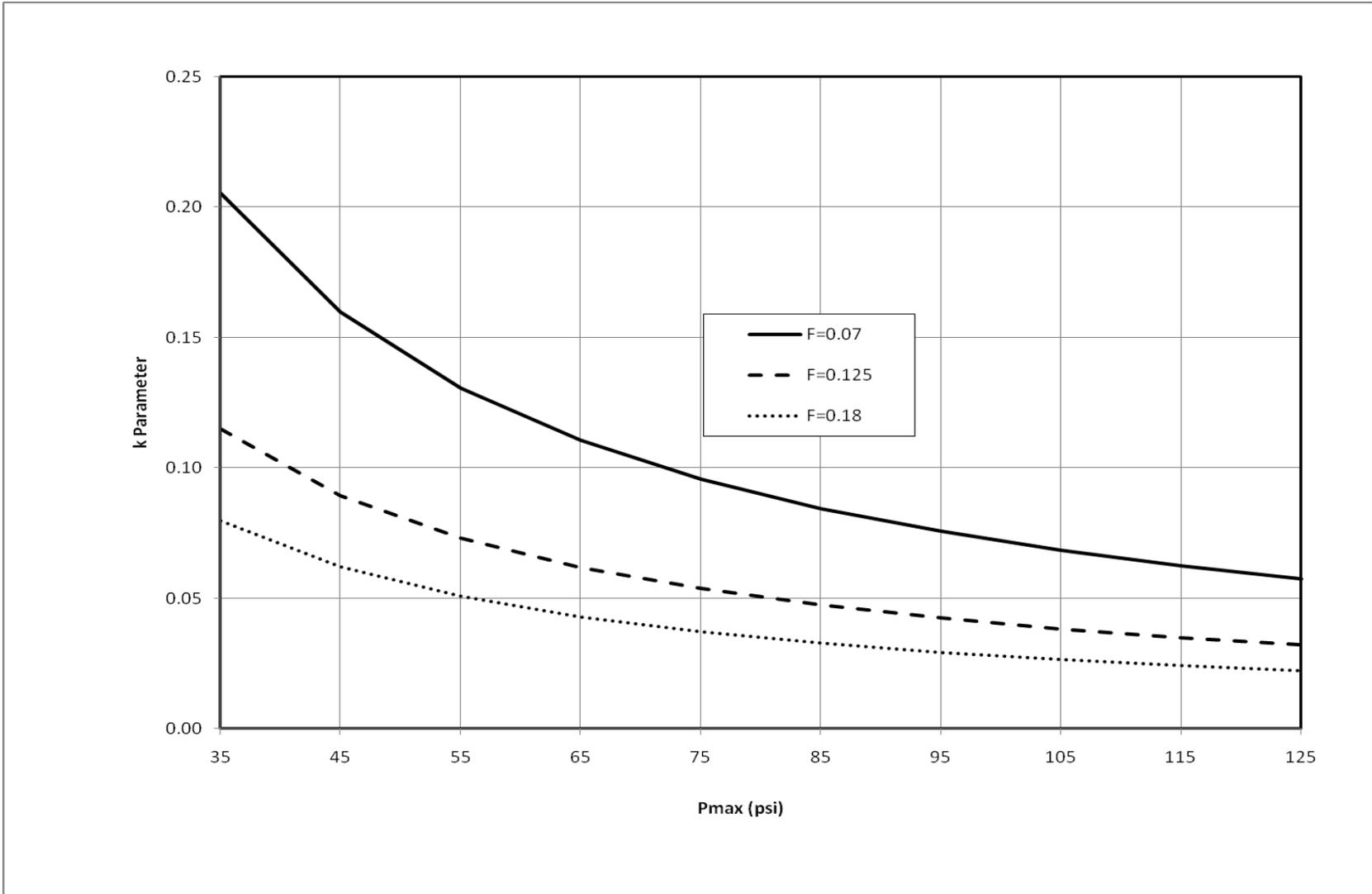


FIGURE 2. *Maximum Pressure Influence on Stiffness Model k Parameter*

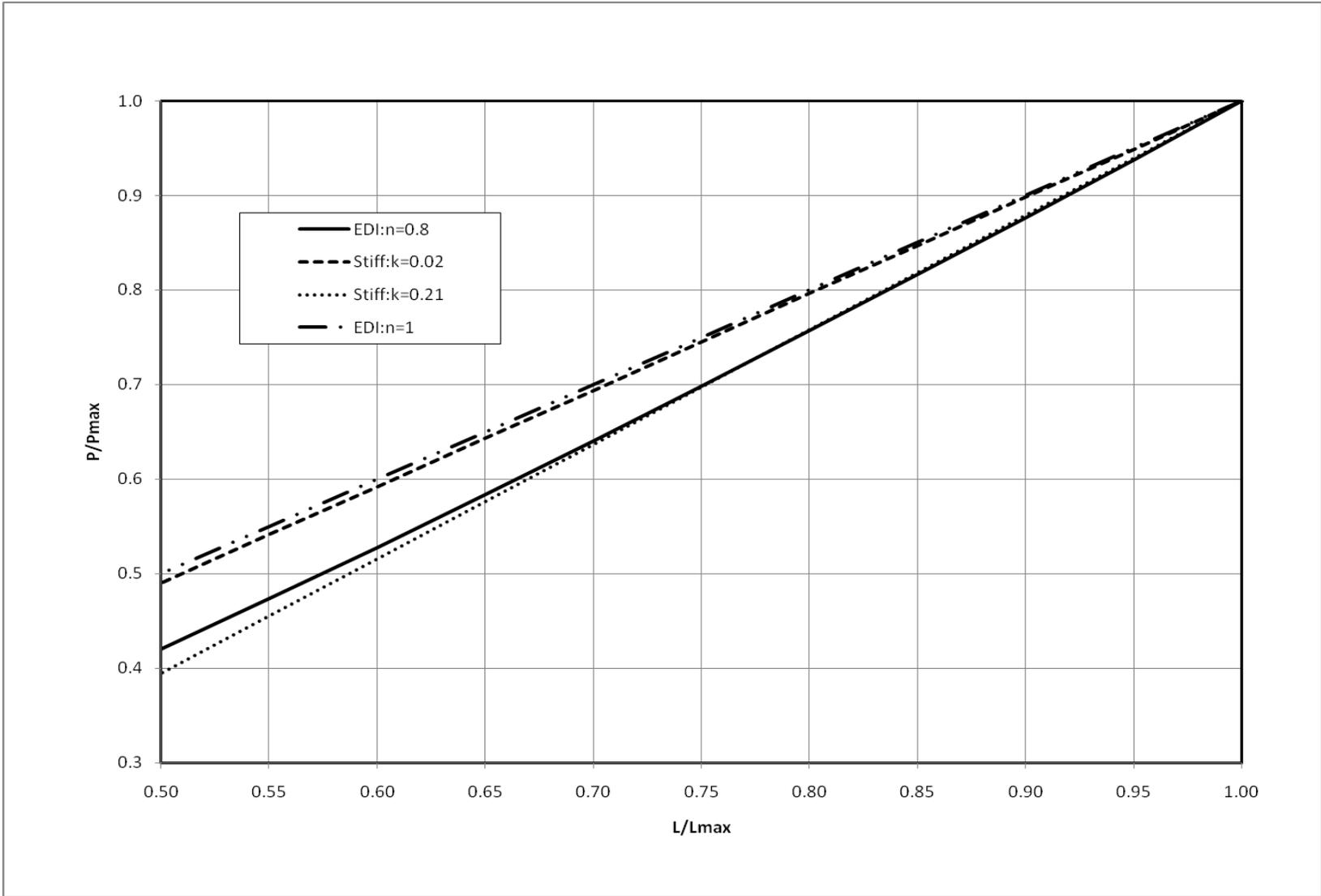


FIGURE 3. Range of Stiffness Model Pressure Predictions Compared to Industry Standards

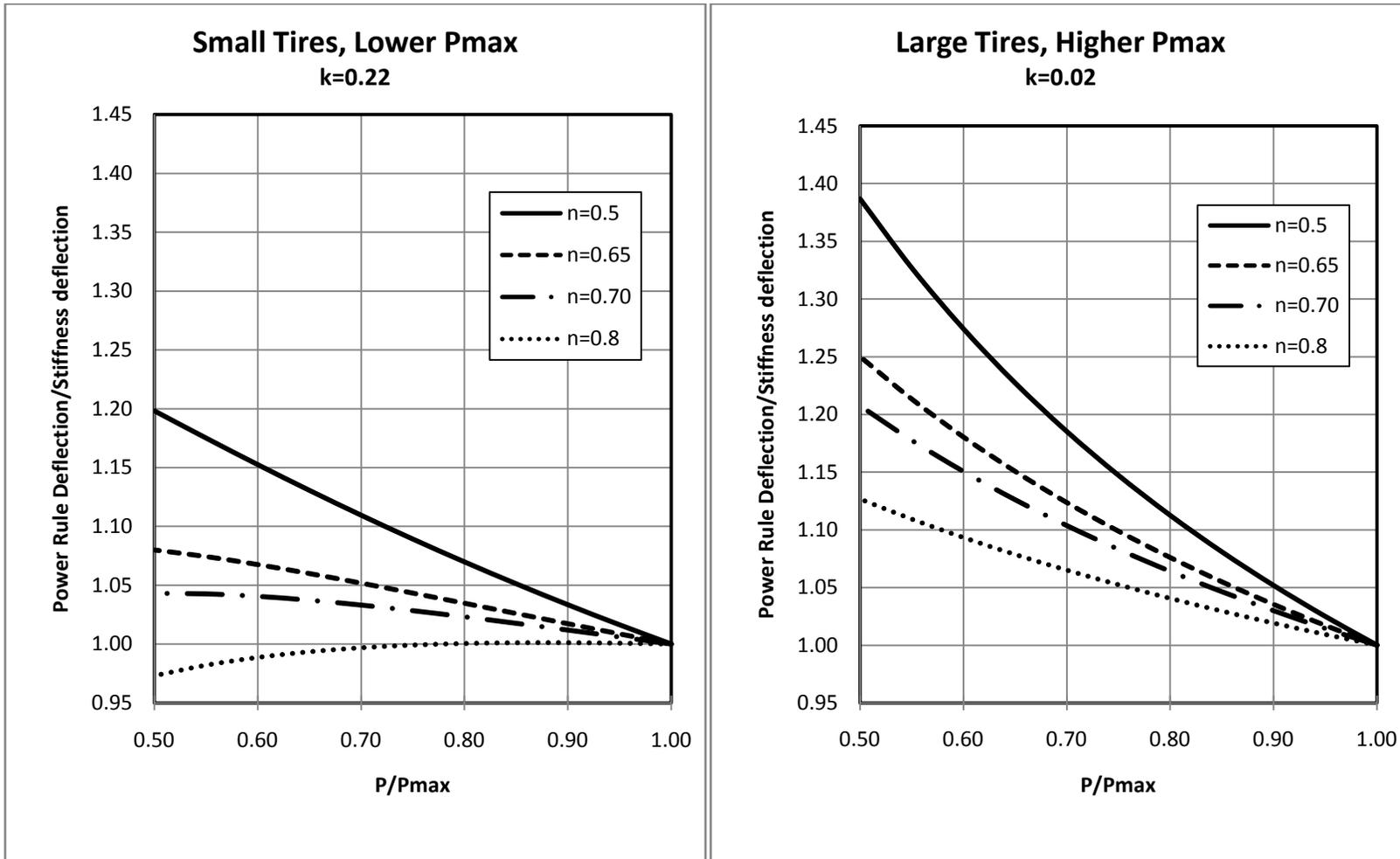


FIGURE 4. Comparison of deflections resulting from Power Rule Model Loads versus Stiffness Model Loads at extreme values of the parameter k .

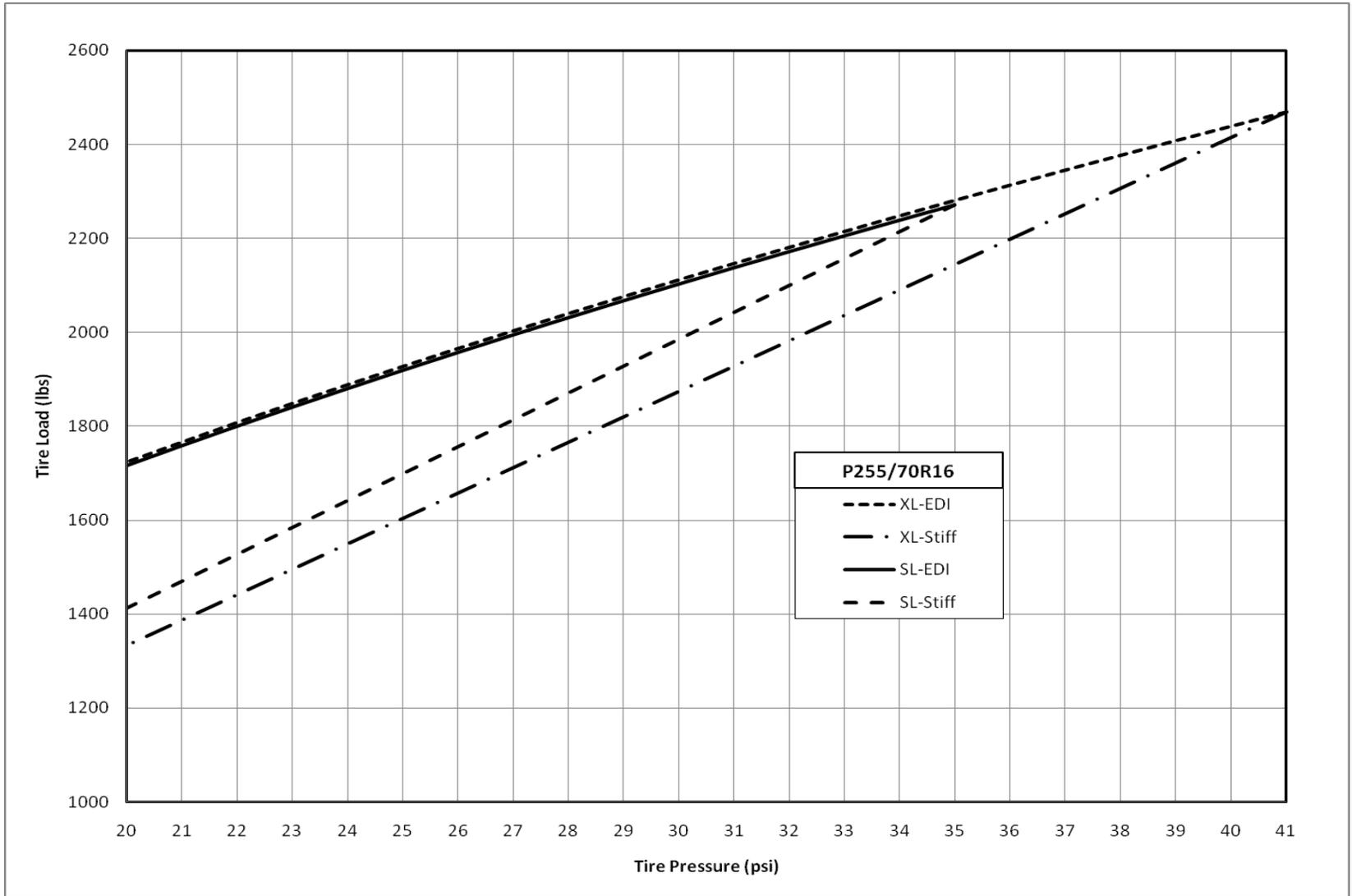


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