Effect of underinflation on tire operating temperature

By Jenny Paige
Cooper Tire & Rubber Co.

A tire uses its inflation pressure for many functions. It allows the tire to carry load, transmit forces, absorb shock, provide grip and resist wear.

For a tire to provide optimum performance characteristics, it has to contain the right amount of pressure. This pressure is what gives the tire the majority of its stiffness to carry the weight of the vehicle as it travels down the road.

It has been stated in previous work, that a tire’s structure only accounts for 10-15 percent of a tire’s load carrying capacity.1

Tires are designed to handle a certain level of deflection against the road. When a tire is underinflated or overloaded, it will deflect beyond its designed deflection.

A tire operating in this state is referred to as overdeflected.

The relationship between load and inflation pressure for which a tire is designed is not manufacturer specific. It is guided by the tire and wheel industries.

Tables exist which can be referenced to determine the maximum load a specific tire size can carry and the inflation pressure necessary to carry that load.2

Also, the Federal Code of Regulations requires that tire manufacturers include the maximum load capacity and inflation pressure on the sidewall of every tire legal for highway use in the U.S.3

Common knowledge recognizes and numerous technical articles discuss underinflation as a leading cause of tire failure.4,5

Much less has been published that documents or depicts how a tire is affected by underinflation or overloading. This study documents how tires respond to different inflation conditions as well as speeds.

Three different methods are used to capture and measure the effect of applying different stress and strain cycles in the form of inflation conditions and speeds to tires: (1) static footprint or contact patch measurements; (2) dynamic profilometry; and (3) thermographic surface temperature measurements.

Experimental design

Two groups of four new passenger tires were involved in this study. A representative photo of each tire is shown in Figs. 1 and 2.

All tires were initially inspected and found to be free of any design issue or manufacturing anomaly.

Each tire was then mounted on its design rim width per the 2012 Tire and Rim Association Yearbook.6

Each tire was inflated to a specified pressure on a flat surface for each condition listed in Table III. This was done using a pressure mapping system.

One tire of each group was used to establish static contact (footprint) pressure on a flat surface for each condition listed in Table III.

Thermography testing was performed to record operating temperatures for each condition listed in Table III, except for test 4, which will be discussed in the results section.

Thermography testing was carried out using a single position of a two-position machine.

The test machine was located in a room that was climate controlled to 75°F.

The machine contained a smooth surface steel test wheel, 67.23” in diameter.

The test machine used a mechanical loading system with a feedback control loop to load the tires to 1,448 pounds.

Each tire was tested at 65 mph for 45 minutes. Thermographic images were captured every five minutes.

After 45 minutes, the tire was stopped and a final thermographic image was taken. The final inflation pressure and ambient temperature were recorded.

The tire was allowed to cool back to ambient temperature.

The tire was then retested at 90 mph for 45 minutes using the same test procedure, including the same load and inflation pressure, as the 65 mph test.

A schematic of the test setup is shown in Fig. 3.

One tire of each group was used to acquire dynamic tire profiles, operating at 65 mph and 90 mph for each inflation pressure listed in Table II.

This is done by operating the tire on the test wheel with a load of 100 pounds, and using a laser profilometer to measure the dimensions of the tire as it operates.

The profile is taken at the top of the tire, about 90° from the contact patch.

Results

Static deflection

Results for the tires are shown in Fig. 4.

Thermographic images

The thermographic images are shown in Figs. 7 and 8.

The maximum temperature is marked on the image.

The images in Figs. 7 and 8 are those taken of the stopped tire, after 45 minutes of operation.

Figs. 7 and 8 omit the condition of highest overdeflection, as specified in Table III (test 4).

No thermographic data was taken for the highest overdeflection condition. This condition specified 140 percent load (15 psi).
It raised concern as to whether the tire would fail and possibly harm the thermographic camera.

Out of caution, tire A was run at 15 psi and 90 mph without the thermographic camera in the room. The tire failed after running 25 miles. A forensic inspection revealed a separation below the No. 1 belt and a 1.0-inch radial split on the serial side shoulder. There was also a separation between belts at the same location, and intermittent visible trapped air at the belt edge around the tire.

It was decided to remove this operating condition from thermographic testing.

Figs. 9, 10 and 11 show the failed tire.

Dynamic cross sectional profiles
Laser profiles were taken at 65 mph and 90 mph for tires at each inflation pressure listed in Table II.

Figs. 12 and 13 show the data for the highest and lowest inflation pressures only. The figures overlay the profiles for 45 psi and 15 psi, for both 65 mph and 90 mph. There are insets on the figures of both the shoulder and sidewall area of the tires, for ease of comparison.

Tables V and VI then list the measurements taken from all profiles, for the dynamic tire’s maximum section width, maximum section height, and shoulder section height. Height measurements are taken from the top of the rim flange, shown as the zero location on the figures. The shoulder section height was measured on the profile at -3 inches from the tire centerline. This places the measurement on the serial side of the tire.

Discussion
As the inflation pressure decreased, the temperature of the tire increased. The maximum temperature occurred in the shoulder area for all tests. This increase in temperature is attributable to an increase in deflection of the tire. Consider the tire to be like a simple spring. The principles of Hooke’s Law apply:

\[ F = kx \]

Where \( F \) is equal to the load placed on the tire, \( k \) is the stiffness of the tire, largely because of the inflation pressure \( x \) is the deflection of the tire.

As the inflation pressure is decreased, the stiffness of the tire \( (k) \) decreases. In order for the tire to carry the load \( (F) \) when \( k \) is decreased, the deflection \( (x) \) must increase.

Fig. 4, a graph of the measured static deflection, shows this trend.

As deflection increases, there are associated changes in the footprint.

The length of the footprint in the circumferential direction increases, as seen in Figs. 5 and 6.

Tire B shows an increase of 83 percent in length from 45 psi to 15 psi.

Tire A increases 85 percent.

There is also movement of the contact pressure toward the shoulders as the in-See Tire, page 1

Table IV. Tire footprint dimensions.

<table>
<thead>
<tr>
<th>Inflation Pressure (psi)</th>
<th>Tire A</th>
<th>Tire B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Length (in)</td>
<td>Length (in)</td>
</tr>
<tr>
<td></td>
<td>Lateral Direction</td>
<td>Circumferential Direction</td>
</tr>
<tr>
<td>45</td>
<td>6.7</td>
<td>5.3</td>
</tr>
<tr>
<td>35</td>
<td>6.7</td>
<td>6.2</td>
</tr>
<tr>
<td>25</td>
<td>6.7</td>
<td>7.4</td>
</tr>
<tr>
<td>15</td>
<td>6.7</td>
<td>9.8</td>
</tr>
</tbody>
</table>

Fig. 5. Tire A static footprint pressure profiles (45 psi, 35 psi, 25 psi, 15 psi, respectively).

Fig. 6. Tire B static footprint pressure profiles (45 psi, 35 psi, 25 psi, 15 psi, respectively).

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The inflation pressure in a tire causes tension in the carcass cords which, in turn, pull the belt edges radially downward. As the tire rolls, any given section of the tire enters the contact patch (becoming deflected), the tension on the carcass cords is lessened, allowing the belts to flatten and causing some lateral and circumferential movement of the belt wires. This phenomenon is explained in detail in Chapters 6 and 7 of The Pneumatic Tire.

When this same section of tire rolls out of the contact patch, the cord tension is restored until the section makes another revolution into the contact patch. This cyclic tension/relaxation of the carcass and belt cords causes stress and strain reactions in the rubber matrix surrounding the cords. Rubber compounds generate heat as a result. The heat generation is directly proportional to both the amplitude and frequency of these tension/relaxation cycles.

The amplitude of the cycles is affected by inflation pressure. Greater deflection causes larger cord and wire movement in the footprint region, causing more stress and strain within the rubber matrix and more heat generation. The frequency of the cycles relates to the tire’s rotating speed. The faster the tire is traveling, the more times per minute the tire will cycle through tension and relaxation, thus the more often the rubber matrix is cycling through stress and strain, and generating heat.

The trend in the data shows that for a tire with lower inflation pressure, an increase in speed causes a greater increase in temperature than for a tire with higher inflation pressure. Stated another way, the overdeflected tires are more sensitive to speed and run hotter at an increased speed than those properly inflated. Figs. 12 and 13 show the impact of speed on the tire profiles. The data reveals that at a constant inflation pressure, an increase in speed results in growth in the shoulder diameter of the tire, and a reduction in the section width.

Table V. Tire A dynamic profile measurements.

<table>
<thead>
<tr>
<th>Injection Pressure (psi)</th>
<th>Max Section Height (in)</th>
<th>Max Section Height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>4.50</td>
<td>11.43</td>
</tr>
<tr>
<td>35</td>
<td>4.60</td>
<td>11.71</td>
</tr>
<tr>
<td>25</td>
<td>4.61</td>
<td>11.71</td>
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Table VI. Tire B dynamic profile measurements.

<table>
<thead>
<tr>
<th>Injection Pressure (psi)</th>
<th>Max Section Height (in)</th>
<th>Max Section Height (cm)</th>
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<tbody>
<tr>
<td>45</td>
<td>4.34</td>
<td>10.97</td>
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<tr>
<td>35</td>
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<td>10.97</td>
</tr>
<tr>
<td>25</td>
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Table VII. Percent increase in shoulder temperature from 65 mph to 90 mph.

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<td>29.4%</td>
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Rubber is also not a good conductor of heat, so the heat tends to build up inside of the tire structure. The shoulder area of the tire is traditionally the thickest section of the tire, which makes it prone to greater heat buildup. Also, as the inflation pressure decreases, the contact pressure in the footprint transfers toward the shoulders of the tire. This, combined with the shoulder’s ability to insulate heat, is the reason for the maximum surface temperature at the shoulder during overdeflected tire operation. Again referencing the thermographic images, another trend in the data shows that at the higher operating speed, 90 mph, the tire temperature is greater than at 65 mph.

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It makes sense because the centrifugal force on the tire is a result of the velocity squared. Furthermore, the section width decrease is more pronounced in tires of lower inflation pressure. The tire is less stiff and more responsive to the centrifugal force acting on it. As was stated before, the pressure inside the tire creates a tension on the fabric cords that extend around the length of the tire structure.

Table VII. Percent increase in shoulder temperature from 65 mph to 90 mph.

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Conclusions

- The footprint or contact patch of a tire increases or lengthens and moves the contact pressure outward to the shoulders as the overdeflection in a tire worsens.
- The operating profile of a tire alters resulting in greater stress and strain cycles in the shoulders as the overdeflection in a tire worsens.
- Thermographic imaging reveals heat generation increases in the tire shoulders consistent with the increased stress and strain from the longer footprint and altered profiles.
- At all pressures and speeds measured, the maximum temperatures generated were in the shoulder or belt edge area.
- Forensic examination of the tested tires finds observable failures to be incipient and actual belt edge separations and failures in the shoulder area consistent with the increased contact pressure, altered operating profile and more severe heat generation in the shoulder area.
REFERENCES

PRODUCT
Bluestar Silicones releases new foam control additives
EAST BRUNSWICK, N.J.—Bluestar Silicones USA Corp. has introduced a line of Silcolapse-brand foam control additives for food and industrial applications. These foam control additives are available locally, and will be manufactured in South Carolina. Silcolapse-brand foam control products are available in a range of dilutions to meet customer-specific anti-foaming needs, the company said.

These products also are effective at wide-ranging pH levels and are particularly effective in alkaline conditions, Bluestar said.

Silcolapse 623 and 621 are designed for industrial applications, such as oil and petroleum, textiles, pesticides, pulp and paper, plastics recycling, synthetic rubber processing, wastewater treatment and sea water distillation.


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