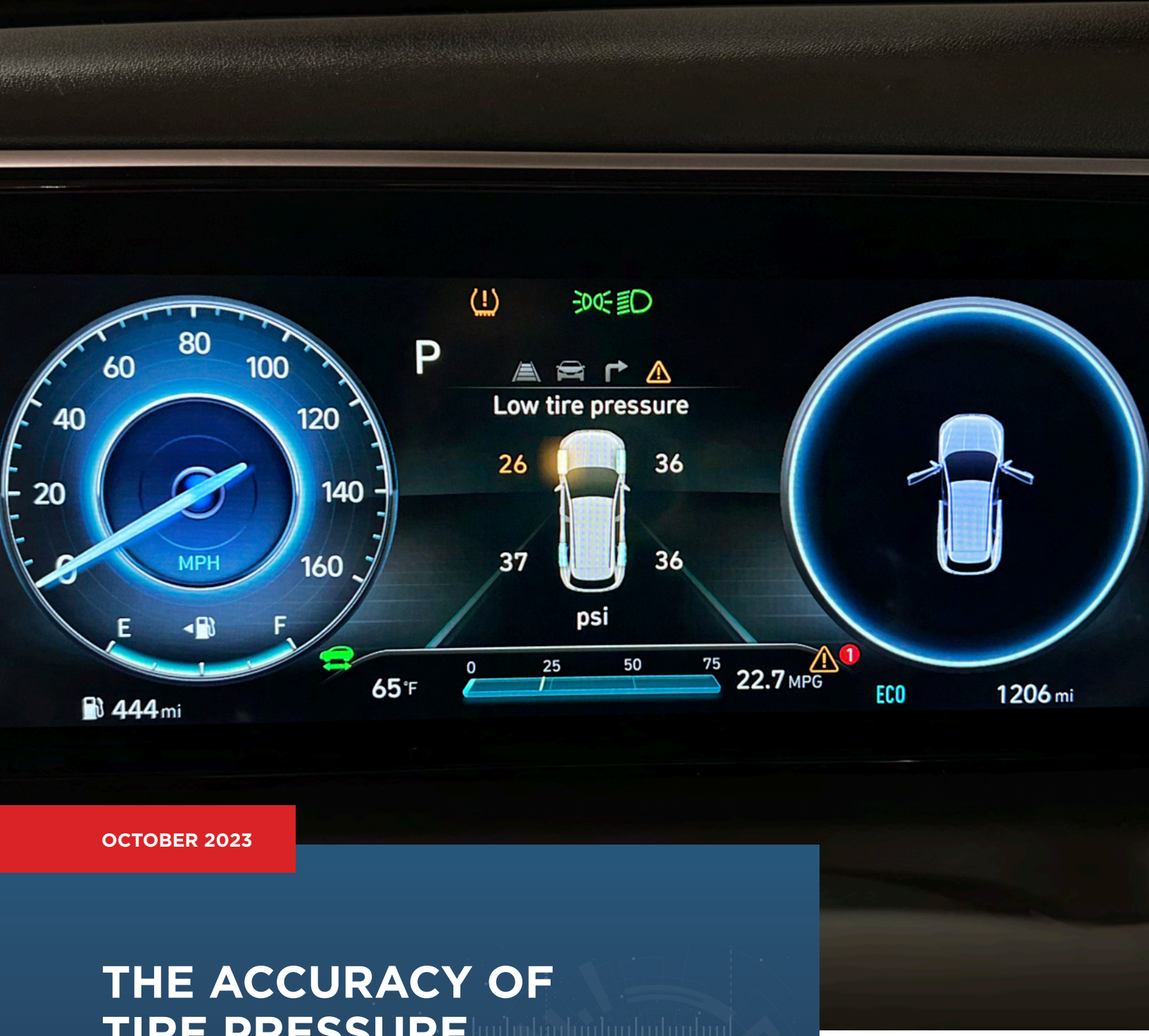

OCTOBER 2023

THE ACCURACY OF TIRE PRESSURE MONITORING SYSTEMS

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ABSTRACT

Since September 1, 2007, tire pressure monitoring systems (TPMS) have been standard in light vehicles sold within the United States with a gross vehicle weight rating (GVWR) of 10,000 lbs. or less [1]. These systems are effective in providing clear tire pressure information to the driver and warning against significant underinflation, contributing to safe vehicle operation.

AAA evaluated TPMS accuracy in a variety of passenger vehicles which were otherwise obtained for a variety of research projects. A calibrated tire gauge was utilized to verify reported tire pressures when inflated to placard pressure and when tires were deflated to 75 percent of recommended tire pressure as found on the placard inside the driver's door jamb.

Research Questions:

1. How do displayed tire pressure readings compare to actual tire pressure?
2. Does the TPMS light illuminate when tire pressure is lowered to 75 percent of placard pressure?

Key Findings:

1. On average, the absolute percent difference between displayed and actual tire pressure was between 1.2-1.5 percent, depending on tire location.
2. Five of eleven test vehicles immediately illuminated the TPMS light when tires were deflated to 75 percent of placard pressure. Of the remaining test vehicles, five of six illuminated the TPMS light when the left front tire was deflated an additional 0.8-2.9 psi, depending on the test vehicle. The remaining vehicle did not illuminate the TPMS light even when one tire was deflated to only 65 percent of placard pressure.

CONTENTS

I. INTRODUCTION

As automobiles continue to evolve in terms of technology, safety, and efficiency, the laws of physics continue to apply. Specifically, friction between the tires and the road dictate vehicle handling and stopping characteristics. Proper tire inflation is a critical contributor to overall tire performance; in addition to adverse effects on vehicle dynamics and fuel efficiency, incorrect tire pressure could cause a blowout resulting in a serious crash.

As far back as the 1970, the National Highway Traffic Safety Administration (NHTSA) considered requiring a "low tire pressure warning" device but ultimately determined the only suitable device available at the time was an in-vehicle indicator whose cost was too high [1]. The first TPMS system made a mainstream debut on the Chevrolet Corvette starting with the 1989 model year. Over the following years, TPMS systems gradually became available as standard or optional equipment within performance and luxury vehicles.

Figure 1: Tire pressure monitoring systems are designed to warn of significant underinflation. Image Source: AAA.

On November 1, 2000, Congress passed the Tire Recall Enhancement, Accountability, and Documentation (TREAD) Act, largely as a result of many rollover crashes of 1990s era Ford Explorers outfitted with Firestone tires. Section 13 of the TREAD act mandated the completion of "a rulemaking for a regulation to require a warning system in new motor vehicles to indicate to the operator when a tire is significantly under inflated" within one year of the TREAD Act's enactment.

Starting with the 2008 model year, TPMS systems have been standard in all passenger vehicles under 10,000 pounds GVWR. While some newer vehicles have additional functionality such as real-time display of pressure for each tire, the primary function of alerting a vehicle operator to significant underinflation in one or more tires remains the same. While TPMS systems tend to receive little attention in the wake of newer safety systems, they are essential to safe vehicle operation. AAA evaluated the accuracy of TPMS systems within various 2022 and 2023 model year light vehicles that were otherwise procured for separate research projects.

II. BACKGROUND

In 2011, NHTSA analyzed data related to the effectiveness of TPMS in promoting proper tire inflation. It was estimated that 23.1 percent of 2004-2007 model year vehicles without TPMS had at least one severely underinflated tire, but only 11.8 percent of 2004-2007 model year vehicles with TPMS had a severely underinflated tire. Based on all analyzed data, TPMS was estimated to result in a statistically significant 55.6 percent reduction in the likelihood that a vehicle will have one or more severely underinflated tires [2].

In addition to safety concerns, underinflation causes tires to build excessive heat that can damage tires over time and lead to failure. It can also degrade handling precision and increase stopping distances. Additionally, under-inflated tires are not fuel efficient. For every one PSI pressure drop in all four tires, gas mileage is reduced approximately 0.4 percent. Increasing tire wear is another result of driving on under-inflated tires and leads to uneven tread wear, reducing the life of the tire and requiring more frequent tire replacement.

There are two main types of TPMS systems; both system types will illuminate the TPMS light if one or more tires are underinflated by 25 percent or more of the recommended pressure.

A. Direct Systems

Direct systems utilize air pressure sensors mounted within each wheel; these sensors transmit tire pressure and battery state to a receiver which interfaces with the electronic control module (ECM). In addition to low tire pressure, the TPMS light will also illuminate if the battery in one or more sensors is low.

A TPMS sensor is designed to use as little power as possible to enable maximum battery life; this is important as batteries are usually heavily integrated within the sensor and cannot be replaced. In addition to an ultra-high frequency (UHF) transmitter, most sensors also contain a low frequency receiver.

The integrated pressure and in some cases, temperature and acceleration sensors generate analog signals which are converted to digital signals via analog to digital converters. Acceleration data is not usually transmitted; this component is simply included to detect rotation. In either case, the accelerometer or “roll switch” places the device in an energy saving mode when the vehicle is stationary.

Depending on the vehicle, a direct system can be either a “high line” or “low line” system. High line systems utilize low frequency transmitters installed around the vehicle to query pressure information from the sensors. These systems typically collect pressure information on a periodic basis and whenever is ignition is turned on. Low line systems consist of random or fixed reporting of pressure information dictated by the sensors rather than being queried by the vehicle. To ensure a low pressure event is quickly detected, a sensor will usually transmit more frequently upon a rapid change of pressure.

1. Valve Stem Type

These sensors are integrated into the back on the valve stem; the entire assembly can be thought of as two distinct parts: the valve stem and the sensor component. The sensor component is contained within a plastic enclosure and mounted inside of the tire. In addition to the pressure sensor, the enclosure contains other electronic components such as the transmitter and battery. In most cases, the internal components are not serviceable and the entire sensor must be replaced in the case of a low battery or other technical malfunction.

Unlike the sensor component, the valve stem can usually be replaced. In this case, it is required to install new hardware kits whenever a tire is changed; in addition to the valve stem, these kits consist of a new seal, washer, valve nut, valve cap, and a nickel-plated valve core.

2. Banded Type

Banded type sensors consist of the same sensor components and operate identically as the valve stem type. The primary difference relates to the placement of the sensor component; as the name implies, they are mounted directly to the wheel by a band and carrier 180º from the valve stem. This mounting allows for safe removal of the tires.

B. Indirect Systems

Indirect systems do not monitor the actual pressure in each tire and tend to be less sensitive than direct systems. These systems function by monitoring the anti-lock brake system wheel speed sensors to detect when one tire is significantly underinflated compared to the others. A tire with low pressure has a lower profile and therefore rotates faster than a properly inflated tire. As wheel speed at each corner is monitored for differences relative to the additional tires, numerical pressure readings on the instrument cluster are not available.

As relative speed is the measured parameter, some systems may not warn the driver when more than one tire is underinflated; this is certainly true if all tires are underinflated. It is important to note that indirect systems require some driving before the system can detect an under-inflated tire and illuminate a warning light; once the tire pressure is adjusted, it will also require driving at various speeds for the system to recalibrate and turn off the warning light.

III. VEHICLE SELECTION METHODOLOGY

Test vehicles were included in this work independent of formal selection criteria. Specifically, AAA researchers evaluated a random sample of eleven 2022-2024 model year passenger vehicles with direct TPMS that were otherwise procured for a variety of unrelated research projects. As TPMS systems are currently standard across all light passenger vehicles, a random selection of current model year vehicles provides a representative sample of new light passenger vehicles for sale in the United States. Test vehicles included within this evaluation and corresponding tire information is provided in Figure 2.

Year	Make	Model	Tire Make and Model	Front Tire Size	Rear Tire Size	Placard Pressure Front/Rear
2023	BMW	i760x	Pirelli P ZERO	255/40R21	285/35R21	41/44
2023	Cadillac	Escalade	Bridgestone Alenza	275/50R22	275/50R22	36/36
2022	Ford	F-150 Lighting	General Grabber HTS 60	275/50R22	275/50R22	42/42
2022	Ford	F-250	Michelin LTX A/T2	275/65R20	275/65R20	60/65
2023	Ford	Maverick	Michelin Primacy A/S	225/60R18	225/60R18	35/35
2023	GMC	Canyon	Goodyear Wrangler Territory AT	265/65R18	265/65R18	35/35
2024	GMC	Sierra 2500	Goodyear Wrangler Trailrunner AT	LT275/65R20	LT275/65R20	60/70
2023	Hyundai	Tucson	Michelin Primacy A/S	235/55R19	235/55R19	35/35
2023	Lexus	RZ450e	Dunlop SP Sport MAXX	235/50R20	255/45R20	38/35
2023	Tesla	Model 3	Hankook Kinergy GT	235/45R18	235/45R18	42/42
2023	Toyota	bZ4X	Bridgestone Turanza EL450	235/50R20	235/50R20	38/38

Figure 2: Test vehicle information Image Source: AAA.

No indirect systems were evaluated within this work as these systems were more common on older vehicles.

IV. TEST EQUIPMENT AND RESOURCES

A. Measurement Equipment

1. Intercomp Digital Air Pressure Gauge

The Intercomp Digital Air Pressure Gauge (model no. 360045-BC) has a range of 0-99.99 pounds per square inch (psi), a resolution of 0.1 psi, and accuracy of ± 0.1% of applied pressure.

V. INQUIRY 1: HOW DO DISPLAYED TIRE PRESSURE READINGS COMPARE TO ACTUAL TIRE PRESSURE?

A. Objective

Compare displayed tire pressure readings to actual tire pressure as measured by a calibrated pressure gauge.

B. Methodology

Prior to including a vehicle for evaluation, AAA researchers ensured no warning lights were illuminated. Each test vehicle was parked in the shade for a minimum of three hours before each tire was inflated to the placard pressure located on the door jamb of the vehicle's driver side door. Once the correct pressure at each corner was verified, the vehicle was driven at various speeds and distances. After the vehicle was driven, the displayed and measured tire pressure at each corner was recorded.

C. Test Results

			Left-Front		Left-Rear		Right-Rear		Right-Front	
Year	Make	Model	Displayed PSI	Actual PSI	Displayed PSI	Actual PSI	Displayed PSI	Actual PSI	Displayed PSI	Actual PSI
2023	BMW	i760x	41	41.5	44	44.4	44	44.4	41	41.5
2023	Cadillac	Escalade	37	38.2	37	38.1	37	37.9	38	38.3
2022	Ford	F-150 Lighting	45	44.5	46	45.2	45	45.2	45	45.0
2022	Ford	F-250	60	61.0	60	62.0	65	67.0	65	67.0
2023	Ford	Maverick	36	36.6	36	36.3	36	36.3	37	36.6
2023	GMC	Canyon	35	35.6	35	35.3	35	35.3	35	35.4
2024	GMC	Sierra 2500	61	62.0	71	71.7	71	71.6	61	61.8
2023	Hyundai	Tucson	37	36.5	36	35.7	36	35.8	37	36.4
2023	Lexus	RZ450e	39	38.5	36	35.2	36	35.3	39	38.4
2023	Tesla	Model 3	42	42.0	42	42.0	42	42.0	42	42.0
2023	Toyota	bZ4X	40	39.4	40	39.3	40	39.3	40	39.3

Figure 3: Displayed vs. actual tire pressure results for each test vehicle. Image Source: AAA.

Vehicle information and displayed vs. actual tire pressures for each test vehicle are provided in Figure 3. The average numerical and percent differences for each corner are provided in Figure 4. Negative or positive values indicate the displayed pressure is lower or higher than the actual pressure, respectively.

			Left-Front		Left-Rear		Right-Rear		Right-Front	
Year	Make	Model	PSI Difference	Percent Difference	PSI Difference	Percent Difference	PSI Difference	Percent Difference	PSI Difference	Percent Difference
2023	BMW	i760x	-0.5	-1.2%	-0.4	-0.9%	-0.4	-0.9%	-0.5	-1.2%
2023	Cadillac	Escalade	-1.2	-3.2%	-1.1	-3.0%	-0.9	-2.4%	-0.3	-0.8%
2022	Ford	F-150 Lighting	0.5	1.1%	0.8	1.7%	-0.2	-0.4%	0.0	0.0%
2022	Ford	F-250	-1.0	-1.7%	-2.0	-3.3%	-2.0	-3.1%	-2.0	-3.1%
2023	Ford	Maverick	-0.6	-1.7%	-0.3	-0.8%	-0.3	-0.8%	0.4	1.1%
2023	GMC	Canyon	-0.6	-1.7%	-0.3	-0.9%	-0.3	-0.9%	-0.4	-1.1%
2024	GMC	Sierra 2500	-1.0	-1.6%	-0.7	-1.0%	-0.6	-0.8%	-0.8	-1.3%
2023	Hyundai	Tucson	0.5	1.4%	0.3	0.8%	0.2	0.6%	0.6	1.6%
2023	Lexus	RZ450e	0.5	1.3%	0.8	2.2%	0.7	1.9%	0.6	1.5%
2023	Tesla	Model 3	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%
2023	Toyota	bZ4X	0.6	1.5%	0.7	1.8%	0.7	1.8%	0.7	1.8%

Figure 4: Pressure and percent differences for each test vehicle. Image Source: AAA.

For each test vehicle, the accuracy of the TPMS system was comparable for each corner. The consistency and small absolute error exhibited for each corner among all test vehicles suggest no systematic error is present among evaluated TPMS systems.

	PSI Difference	Percent Difference
Left-Front	0.6	1.5%
Left-Rear	0.7	1.5%
Right-Rear	0.6	1.2%
Right-Front	0.6	1.2%

Figure 5: Absolute mean pressure and percent differences for each test vehicle. Image Source: AAA.

Absolute mean psi and percent differences for each corner are provided in Figure 5. Absolute mean differences provided herein quantify error magnitude without regard to over or under-reporting of tire pressure.

D. Summary of Test Results

No significant error in displayed tire pressure readings was noted for any vehicles evaluated within this work. On average, the absolute mean percent difference for all corners was less than 2 percent. The largest absolute percent difference in reported vs. actual tire pressure was 3.3 percent; this vehicle had a significantly higher placard pressure relative to other test vehicles.

VI. INQUIRY 2: DOES THE TPMS LIGHT ILLUMINATE WHEN TIRE PRESSURE IS LOWERED TO 75 PERCENT OF PLACARD PRESSURE?

A. Objective

Determine if the TPMS light illuminates and/or other warning are provided when tires are deflated to 75 percent of placard pressure.

B. Methodology

To verify illumination of the TPMS light and/or other warning messages, each tire was deflated to 75 percent of placard pressure. While it is not likely that all four tires will be deflated to this extent in real-world use, this approach was utilized to verify pressure readings at each corner at a lower pressure and to give the most

opportunity for a TPMS light and/or other warning(s) to be displayed. Once each tire was deflated to the target pressure, the ignition was switched on and the status of the TPMS light was noted.

If the TPMS light did not illuminate, the vehicle was driven a short distance of no more than one mile. If the TPMS did not illuminate during or immediately after the drive, the left front tire was slowly deflated until the TPMS light illuminated or 65 percent of placard pressure was reached, whichever occurred first. If the TPMS light did not illuminate after the left front tire was deflated to 65 percent of placard pressure, the vehicle was again driven a short distance of no more than one mile to allow a final opportunity for the TPMS light to illuminate.

C. Test Results

Year	Make	Model	Target Pressure Front/Rear	TPMS Light On at Target Pressure	LF Pressure for TPMS Light Illumination	Percent of Placard Pressure at TPMS Light Illumination	Additional Messages
2023	BMW	i760x	30.8/33	Yes	30.8	75.1%	"Low tire pressure: stop carefully"
2023	Cadillac	Escalade	27/27	No	25.3	70.3%	"Tire pressure low add air to tire"
2022	Ford	F-150 Lighting	31.5/31.5	Yes	31.5	75.0%	"Tire low"
2022	Ford	F-250	45/48.8	No	N/A	N/A	N/A
2023	Ford	Maverick	26.3/26.3	Yes	26.3	75.1%	"Tire low"
2023	GMC	Canyon	26.3/26.3	No	24.9	71.1%	"Tire pressure low add air to tire"
2024	GMC	Sierra 2500	45/52.5	No	42.1	70.2%	"Tire pressure low"
2023	Hyundai	Tucson	26.3/26.3	No	25.5	72.9%	"Low tire pressure"
2023	Lexus	RZ450e	28.5/26.3	Yes	28.5	75.0%	"Please check tire when safe"
2023	Tesla	Model 3	31.5/31.5	Yes	31.5	75.0%	"Air pressure below recommendation for tires"
2023	Toyota	bZ4X	28.5/28.5	No	27.3	71.8%	"Tire pressure low"

Figure 6: TPMS light status and additional messages. Image Source: AAA.

For each test vehicle, TPMS light status at 75 percent of placard pressure and any additional messages within the instrument cluster are provided within Figure 6. Five of eleven test vehicles illuminated the TPMS light immediately upon deflating tires to 75 percent of placard pressure as measured by the calibrated tire pressure gauge. Five of six remaining test vehicles illuminated the TPMS light immediately upon lowering the left front tire pressure between 0.8-2.9 psi, depending on the test vehicle.

The 2022 Ford F-250 did not illuminate the TPMS light or provide any warning message after the left front tire was deflated to 65 percent of placard pressure and driven a short distance of no more than one mile. It is important to note that the tire pressure at each corner updated immediately after adjustment with no driving required.

Figure 7: 2022 Ford F-250 with left front tire inflated to 65 percent of placard pressure. Image Source: AAA.

D. Summary of Test Results

In aggregate, five of eleven test vehicles illuminated the TPMS light when each tire was deflated to 75 percent of placard pressure as measured by a calibrated tire gauge. Of the remaining test vehicles, five of six illuminated the TPMS light when the left front tire was deflated an additional 0.8-2.9 psi, depending on the test vehicle. These results suggest that TPMS systems generally warn the driver when tires are underinflated to 75 percent of placard pressure, with some small margins of error.

The 2022 Ford F-250 was the only test vehicle that did not illuminate the TPMS light even when one tire was only inflated to 65 percent of placard pressure. However, this vehicle has a GVWR of 10,000 lbs. which is at the upper limit of vehicles mandated to have TPMS.

It is important to note that all test vehicles displayed tire pressures with similar margins of error relative to measurements taken at placard pressure as described within Inquiry 1. Pictures of displayed tire pressures at 75 percent of placard pressure are provided in the Appendix.

VII. CONCLUSIONS

It was found that displayed tire pressures were generally accurate at both placard pressure and when all tires were inflated to 75 percent of placard pressure, with small margins of error. Additionally, the TPMS light illuminated when tires were underinflated to 75 percent of placard pressure for five of eleven test vehicles. Five of six remaining test vehicles illuminated the TPMS light when tires were deflated to 70.3-72.9 percent of placard pressure, depending on the test vehicle.

AAA is encouraged by this overall finding as TPMS systems have been found to significantly decrease the likelihood that a vehicle will be operated with one or more severely underinflated tires. However, one vehicle did not illuminate the TPMS light even when one tire was deflated to only 65 percent of placard pressure, despite the immediate update of pressure readings in the instrument cluster. Displayed tire pressures within

the instrument cluster can be convenient and should be utilized for keeping tires inflated to placard pressure, rather than relying solely on the TPMS light to determine when a tire needs to be re-inflated.

VIII. KEY FINDINGS

1. On average, the absolute percent difference between displayed and actual tire pressure was between 1.2-1.5 percent, depending on tire location.
2. Five of eleven test vehicles immediately illuminated the TPMS light when tires were deflated to 75 percent of placard pressure. Of the remaining test vehicles, five of six illuminated the TPMS light when the left front tire was deflated an additional 0.8-2.9 psi, depending on the test vehicle. The remaining vehicle did not illuminate the TPMS light even when one tire was deflated to only 65 percent of placard pressure.

IX. SUMMARY RECOMMENDATIONS

1. TPMS lights only illuminate when one or more tires are severely underinflated; drivers should regularly check the displayed tire pressure at each corner and keep tires inflated to the placard pressure found on the driver's door sill.

2. Even with TPMS, drivers should periodically inspect their tires for visual signs of damage to the tread surface and sidewall.

3. While displayed tire pressures were found to be generally accurate for all test vehicles, drivers should consider checking their tire pressure with a handheld gauge periodically to verify proper operation of the TPMS system.

X. REFERENCES

[1] National Highway Traffic Safety Administration , "Federal Motor Vehicle Safety Standards; Tire Pressure Monitoring Systems; Controls and Displays," United States Federal Register, Washington, 2002.

[2] National Highway Traffic Safety Administration, "Evaluation of the Effectiveness Of TPMS in Proper Tire Pressure Maintenance," US Department of Transportation, Washington DC, 2012.

XI. APPENDIX

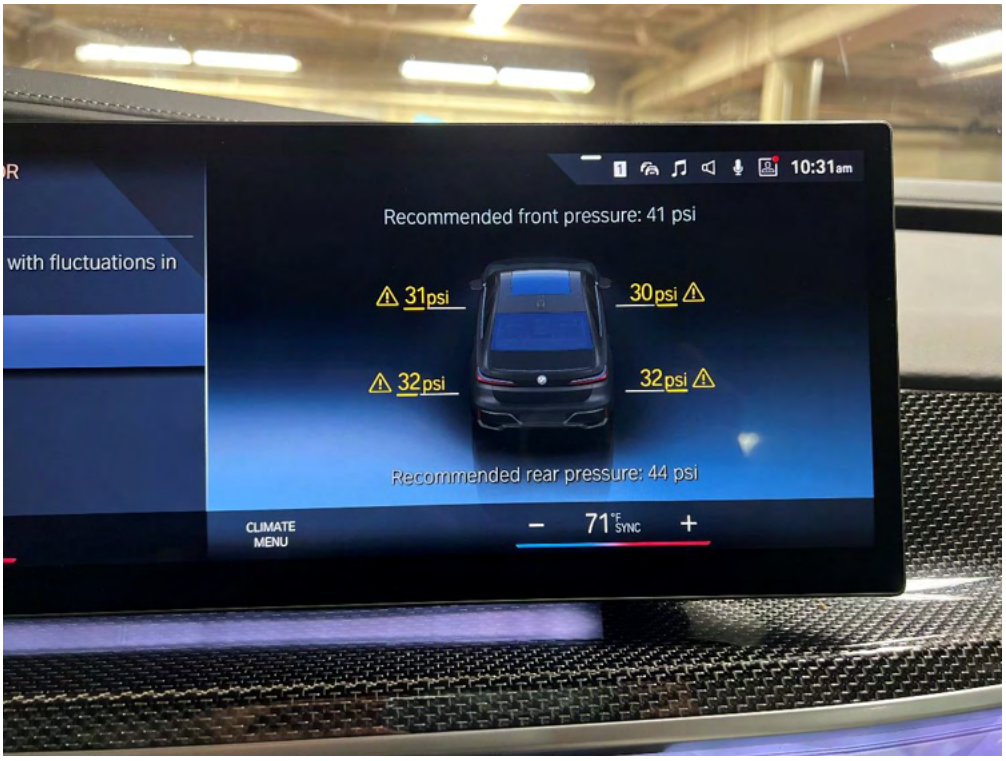

Figure 8: 2023 BMW i760x display at 75 percent of placard pressure. Image Source: AAA.

Figure 9: 2023 Cadillac Escalade display at 75 percent of placard pressure. Image Source: AAA.

Figure 10: 2022 Ford F-150 Lightning display at 75 percent of placard pressure. Image Source: AAA.

Figure 11: 2022 Ford F-250 display at 75 percent of placard pressure. Image Source: AAA.

Figure 12: 2023 Ford Maverick display at 75 percent of placard pressure. Image Source: AAA.

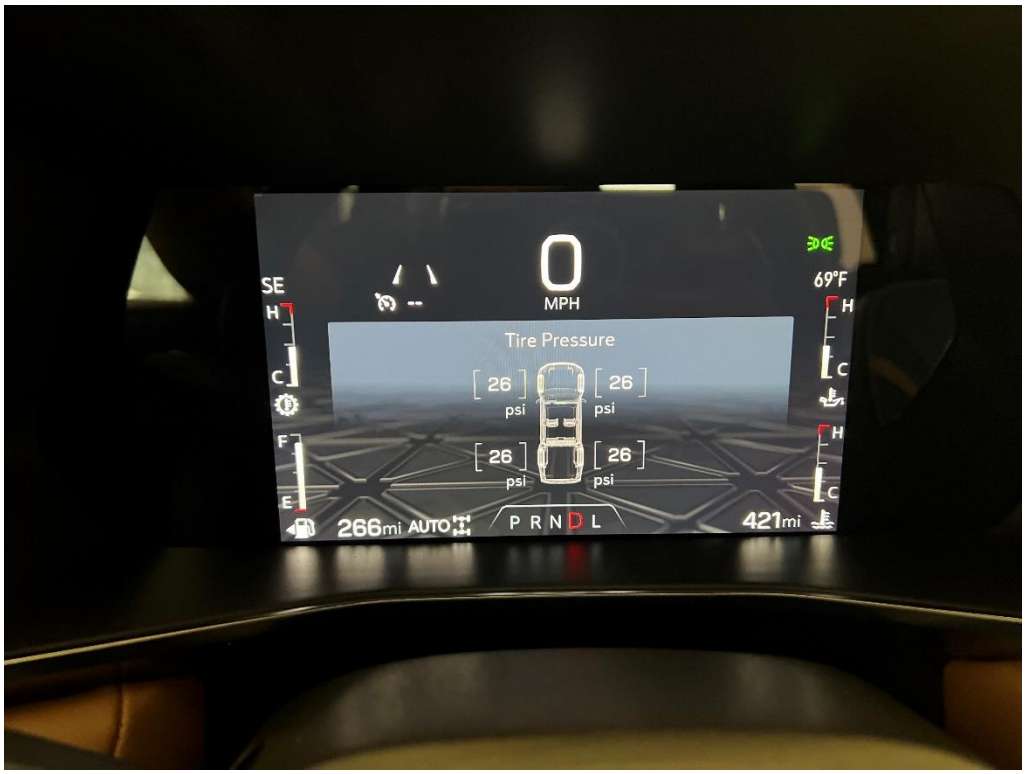

Figure 13: 2023 GMC Canyon display at 75 percent of placard pressure. Image Source: AAA.

Figure 14: 2024 GMC Sierra 2500 display at 75 percent of placard pressure. Image Source: AAA.

Figure 15: 2023 Hyundai Tucson display at 75 percent of placard pressure. Image Source: AAA.

Figure 16: 2023 Lexus RZ450e display at 75 percent of placard pressure. Image Source: AAA.

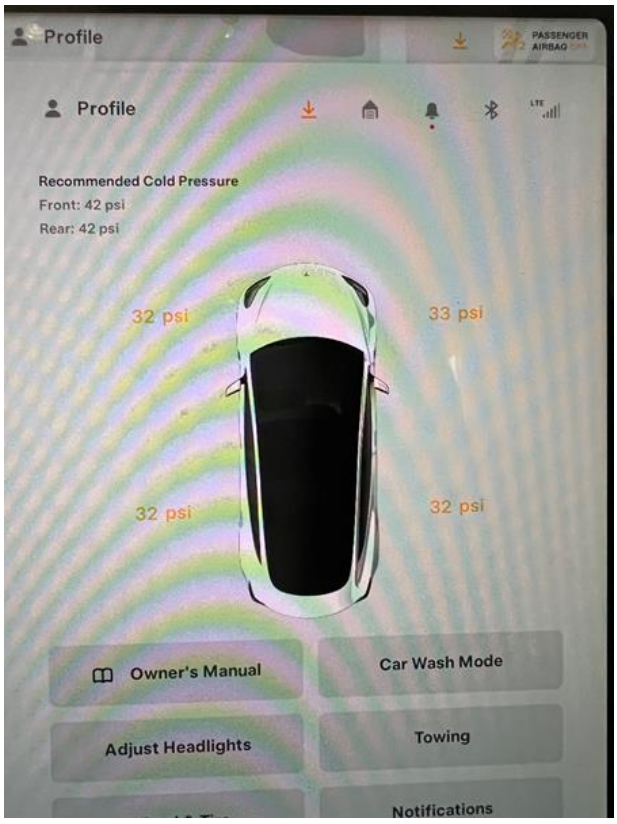

Figure 17: 2023 Tesla Model 3 display at 75 percent of placard pressure. Image Source: AAA.

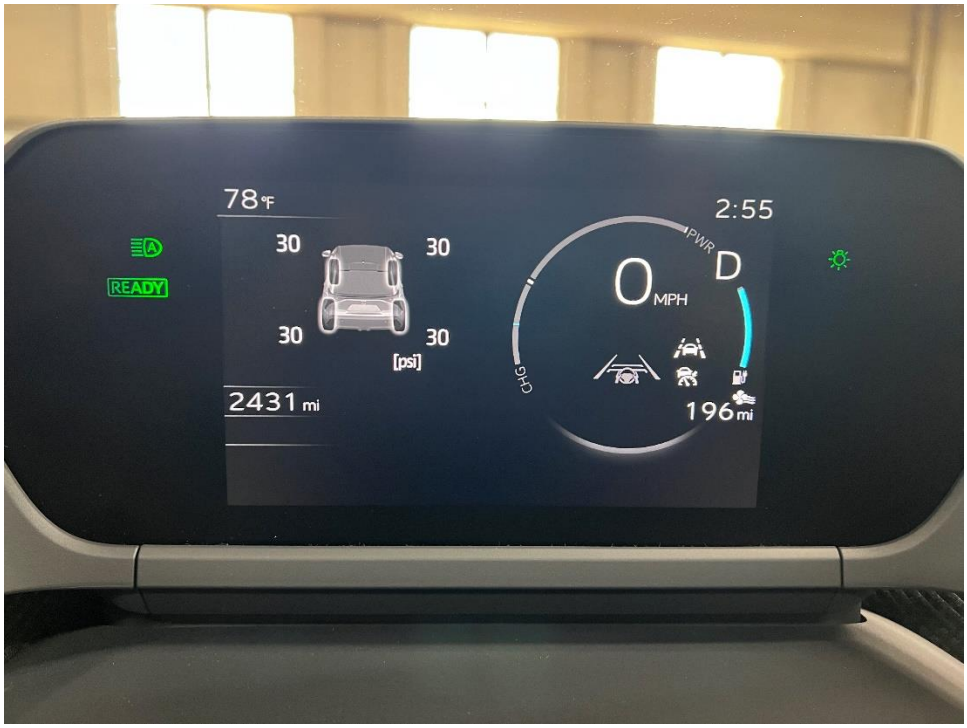

Figure 18: 2023 Toyota bZ4X display at 75 percent of placard pressure. Image Source: AAA.