

Trends in Tire Pressure: An Analysis of Time-Series TPMS Data

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ABSTRACT

This paper presents findings based on the examination of time-series tire pressure data. Tire pressure is important to vehicle safety due to its effects on vehicle handling and stability, as well as the impact that inappropriate tire pressure has on tire wear and tire failures. Previous research such as NHTSA's 2001 Tire Pressure Special Study sampled vehicle populations and recorded tire pressures at a single point in time. Such studies yield important insights into tire pressures on individual vehicles and across the vehicle populations, but cannot provide insights into the behavior of tire pressures over time.

The data presented in this paper was measured using the tire pressure monitoring system (TPMS) data from Tesla Model S vehicles. Using Tesla's on-board diagnostic data logging and remote data retrieval capabilities, the time history of each vehicle's tire pressures was recorded and fleet-wide data was analyzed. The resulting analysis provides insights into tire pressure changes caused by permeation and slow leaks as well as temperature fluctuations at both drive-cycle and seasonal time scales. The paper also includes examples of tire punctures with resulting pressure data.

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INTRODUCTION

Tire under inflation is a widely-recognized danger with well-researched consequences. Underinflated tires can exhibit increased tread wear, provide reduced protection against impact damage, and are more susceptible to overheating, which increases the risk of tread separation and sudden tire failure. Tire under inflation can also adversely influence vehicle handling and stability, increase stopping distances, and reduce energy efficiency [1] [2] [3].

Tire pressure monitoring systems (TPMS) warn drivers when a tire is significantly underinflated, and have been required by Federal Motor Vehicle Safety Standard (FMVSS) 138 on all light-duty vehicle manufactured since 2007 [4]. FMVSS 138 was created in response to a mandate in the Transportation Recall Enhancement, Accountability, and Documentation (TREAD) Act enacted by the U.S. Congress in 2000. The current edition of this standard requires a TPMS capable of detecting tires 25 percent or more below the manufacturer's recommended cold inflation pressure.

As detailed in the Background section below, previous studies have surveyed vehicles on the road to determine the distribution of tire pressures, often with a focus on determining the prevalence of tire under inflation. However, such research cannot provide data on leak rates and other changes in tire pressures over time. As a result, NHTSA noted in the final rule making of the 2002 version of FMVSS 138 that they had no data indicating how often slight tire damage such as a nail in the tire results in a slow tire leak [2].

This paper is intended to address this deficit in existing tire pressure research by using Tesla's data and telematics capabilities to perform the largest-known analysis of temporal tire pressure data. The paper is based on over 180 million vehicle miles of tire pressure data collected from more than 15,000 vehicles worldwide. The next section of this paper provides background including an overview of prior research into vehicle operating tire pressures and background on tire pressure monitoring systems. The paper then includes results and discussion of Tesla's data and concludes with a summary of observations from this data.

BACKGROUND

As dictated by the ideal gas law, the pressure of the gas within a tire is dependent on the amount of gas within the tire and the gas' temperature. Gas temperature will converge to ambient temperature when the vehicle is stationary, but gas temperature can exceed ambient temperature when the vehicle is driving due to the heating effects of tire flexion. The amount of gas can be increased by inflation or decreased through intentional deflation, unintentional leaks including punctures, and permeation through the rubber tire.

Permeation through the tire results in slow air losses similar to the air losses that can occur due to leakage at the rim flange seal or leakage at the valve stem. To quantify these different leak paths, a 1979 Exxon Chemical study carefully submerged tires to see where bubbles collected and measured the leak rates of tires with and

without ultra-low permeability liners. Both of these techniques demonstrated that permeation through the tire sidewall is the primary mechanism of slow air loss [5].

Previous Tire Pressure Studies

Previous research studies have sought to determine the tire pressures present in vehicles on the road by measuring pressures of a random sample of vehicles. A 1978 study by IIT Research Institute surveyed Chicago-area cars by measuring the tire pressure in parked cars [6]. The study surveyed approximately 2000 vehicles during a midsummer period and 400 vehicles during a midwinter period, and required that the vehicle remain stationary for a minimum of 3 hours in order to ensure that the tires reached a stable ambient temperature. The study found that the mean tire inflation pressures were 1 to 2 psi (7 to 14 kPa) below the manufacturer's recommended inflation pressure, with a standard deviation of 5 to 6 psi (34 to 41 kPa). The study also found that tires in the winter were more underinflated and had a greater variation in pressure than tires in the summer.

A 1979 study by Transport Canada measured tire pressures during interviews with 745 randomly-chosen urban householders [7]. The tire pressures were measured after the car had been stationary for at least one hour. The study found that 54.7% of all tires were at least 2 psi (14 kPa) below the recommended tire pressure. Rear tires were an average of 1.6 psi (11 kPa) more underinflated than front tires, an observation that the study attributed to the greater pressure typically required in rear tires. The study also found that mean pressures were higher in British Columbia than the rest of Canada, which the study attributed to the higher mean temperature in British Columbia during the study compared to other parts of Canada (+4°C vs -5°C).

In support of the FMVSS 138 rulemaking, NHTSA undertook the Tire Pressure Special Study which used tire pressures collected over a two-week period in February 2001 from over 11,000 passenger vehicles [8]. The study included measuring tire pressures of randomly selected vehicles arriving at gas stations. Similar to the Transport Canada study two decades earlier, the study found that rear tires were more likely to be underinflated than front tires. For passenger cars, half of the left front tires were underinflated by at least 0.8 psi (5.5 kPa), and half of the left rear tires were underinflated by at least 2.0 psi (14 kPa).

In order to evaluate the effectiveness of TPMS in reducing underinflation in the on-road fleet of passenger vehicles, NHTSA conducted the Tire Pressure Monitoring System Special Study, collecting data from August 2010 through April 2011 [3]. Similar to the Tire Pressure Special Study, data was collected at gas stations. Pressure data was corrected for tire temperature by measuring the sidewall temperature of the tire and adjusting the pressure to the equivalent pressure at 65°F (18°C). The study found that of 2004 to 2007 vehicles, 23.1% of those without TPMS had at least one tire that was 25% or more underinflated, whereas only 11.8% of TPMS-equipped vehicles had a similarly underinflated tire.

METHODOLOGY

All data presented in this paper is from the Tesla Model S, a fully electric sedan. Consistent with FMVSS 138, the Tesla Model S is equipped with a TPMS that is capable of alerting the driver if a significant drop in tire pressure is detected in any tire.

Data Analyzed

The TPMS system on the Tesla Model S detects tire pressures using individual tire pressure sensors mounted to the inside of each rim. These sensors communicate via radio frequency (RF) communication with the TPMS ECU, have a rated accuracy of approximately +/- 10 kPa (1.5 psi), and transmit pressure measurements with a resolution of approximately 3 kPa (0.4 psi). The measured tire pressures are compared to thresholds that are based on the vehicle's recommended tire pressure in order to determine if a user-facing underinflation alert needs to be displayed.

The recommended tire pressure for the Tesla Model S depends on factors such as the vehicle's wheel size (19" or 21"), drive configuration (rear wheel drive or all-wheel drive), and suspension (coil spring, air suspension, or air suspension with performance package). The diverse available vehicle configurations result in many different recommended tire pressures for the Tesla Model S, though most are in the range of 275 to 310 kPa (40 to 45 psi). Because of its near equal weight distribution, most configurations of the Tesla Model S have equal front and rear tire recommended tire pressures. Those configurations with different recommended tire pressures recommend 2 psi greater pressure on the rear axle.

The data in this paper comes from vehicles with different recommended tire pressures, which creates a challenge in displaying aggregate fleet pressure distributions. In order to make use of data from any vehicle in the Model S fleet, we normalized each tire pressure by that tire's recommended tire pressure. The tire pressure plots in this paper therefore display tire pressures as percent increase or decrease relative to the recommended tire pressure.

TPMS data reveals changes in tire pressure, which can result from both changes in the amount of gas within the tire and changes in the temperature of this gas. If the temperature of the gas in the tire is known, the effect of temperature changes can be removed by calculating a temperature-adjusted tire pressure. This temperature-adjusted pressure can be calculated as:

$$P_{adjusted} = P_{measured} \left(\frac{T_{adjusted}}{T_{measured}} \right) \quad (1)$$

In this equation $P_{measured}$ is the measured pressure, $T_{measured}$ is the absolute temperature of the gas at the time of the measurement, and $T_{adjusted}$ is the absolute temperature to which the pressure is to be adjusted. The temperature-adjusted pressures in this paper were calculated by adjusting to an absolute temperature of 293K / 20°C (68°F).

The TPMS sensors used by Tesla are capable of measuring internal tire temperature, but this data is not logged by the vehicle and was not available for this analysis. Instead, the vehicle's ambient external temperature was used to calculate temperature-adjusted cold tire pressures. In order to filter for cold pressures, we selected only the first pressure measurement of each day, when the tires are most likely to be at ambient temperature.

Diagnostic Log Data

The tire pressure monitoring system in the Tesla Model S consists of four rim-mounted sensors and a TPMS ECU that communicates with the sensors. Figure 1 is a conceptual diagram showing the tire pressure monitoring system and other components used to store and transmit TPMS data. The TPMS ECU communicates with other vehicle components over the vehicle's Controller Area Network (CAN) bus. The TPMS ECU sends a CAN alert message if any of these pressures fall outside the range specified. The TPMS ECU also regularly sends messages containing individual tire pressures, and it is the data from these messages that is used in this paper.

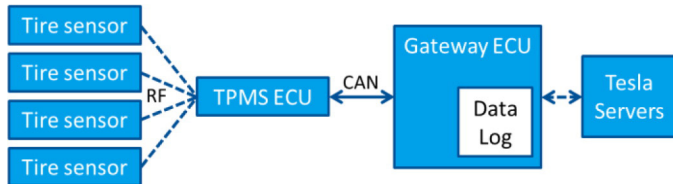


Figure 1. Conceptual diagram showing the tire pressure monitoring system and other components used to transmit and store TPMS data.

The Tesla Model S has a gateway ECU that serves to transfer messages between the vehicle's communications buses. The gateway ECU writes some of the information it reads to a diagnostic log file that is stored on non-volatile memory located within the gateway. Computational, data transfer, and data storage constraints as well as privacy considerations limit the variables that are logged, the rates at which they are logged, and in which conditions they are logged. For example, although the TPMS system sends CAN messages containing the tire pressure values at 1 Hz, the Gateway only writes the tire pressure values to the diagnostic log approximately once every 10 minutes while the vehicle is in drive, which is therefore the update rate of the data used in this paper.

There are three methods by which the diagnostic log file can be retrieved from a vehicle. The data can be securely transferred using Tesla's over-the-air data communication, the data can be downloaded directly from the vehicle by a technician with a valid vehicle-specific key, or the data can be accessed directly by physically disassembling the vehicle's dash to remove the gateway's non-volatile memory.

Over-the-air data transfer is the most common method, and was the method used to retrieve most of the data analyzed in this paper.

Tesla's over-the-air communication occurs over a Wi-Fi connection if the vehicle is in range of a recognized Wi-Fi router, or using the 3G cellular communication capability of Model S. Regardless of which method is used, the communication between the vehicle and Tesla's servers takes place over a Virtual Private Network (VPN) to ensure the security and integrity of the communication. Once uploaded, the data is stored on a redundant database architecture that ensures data persistence.

In processing data for this paper, diagnostic log files were read from Tesla servers to extract tire pressures and ambient temperatures. Each log file also contains the vehicle configuration, including wheel size, at the time that the diagnostic log was uploaded. If the wheel size in

the vehicle configuration was the same as when the vehicle was delivered, the recommended tire pressure was determined based on vehicle manufacturing records. If the tire size was different from when the vehicle was delivered, the recommended tire pressure was determined using the new size. If the wheel size was found to have changed since the vehicle's previous log file, data from that log file was ignored, so as to avoid using data during a time period in which the vehicle's wheels were changed. The wheel size parameter in the vehicle configuration is updated manually by a Tesla technician when changing wheels. Therefore, if the wheels were changed outside of a Tesla service center, the wheel size in the vehicle configuration may no longer be accurate, and this is potential source of error in the data. In order to avoid any bias caused by new vehicles, all tire pressure measurements used in this study were recorded at least 180 days after initial customer delivery.

EXAMPLE TPMS DATA

This section provides two examples of TPMS data in order to illustrate some of the features visible in this data. The examples are from customer-owned Tesla Model S vehicles with flat tires that were repaired by Tesla service centers. The subsequent section of the paper presents results from analyzing bulk TPMS data.

Figure 2 and Figure 3 each show 20 days of TPMS pressure data. The vehicles each suffered a tire puncture during this period, and a nail and a screw were found in the punctured tires respectively. After servicing the vehicles, the diagnostic log data was retrieved and analyzed. The TPMS pressure plots in Figure 2 and Figure 3 show data from the punctured tires in red and the other tires in blue. The black, dashed line shows the recommended tire pressure.

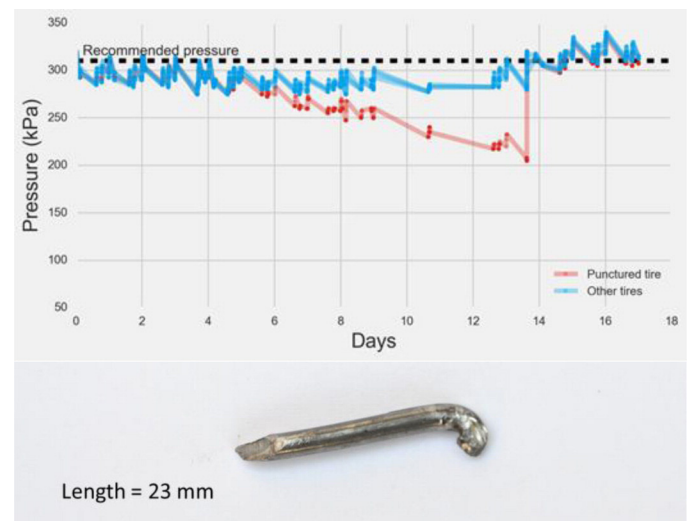


Figure 2. TPMS data associated with a puncture and the nail responsible for the puncture.

The pressures in Figure 2 show that the puncture occurred on approximately day 4 of the plot. During the first 4 days of the plot the pressures in all 4 tires were similar: the pressures increased in unison during daily drive cycles and decreased in unison at night. Beginning the evening of day 4, the pressure in one tire began to drop and diverge from the other tires. Over the next 9 days the punctured tire's