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Tire Pressure Maintenance - A Statistical Investigation

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<tr><td colspan="4">16. Abstract
Past studies on tire pressure monitoring have revealed that about 28 percent of light vehicles on our Nation's roadways run with at least one underinflated tire. Only a few psi difference from vehicle manufacturer's recommended tire inflation pressure can affect a vehicle's handling and stopping distance. Poor tire maintenance can increase incidences of blowouts and tread separations. Similarly, underinflation negatively affects fuel economy.

In 2005, NHTSA's FMVSS 138 required automobile manufacturers to install tire pressure monitoring systems (TPMS) on light passenger vehicles with phase-in period from 2006 to 2008. Prior to the regulation, NHTSA's National Center for Statistics and Analysis conducted several surveys and studies to estimate and compare the benefits of Direct and Indirect TPMS. The results of the most recently conducted survey, Tire Pressure Monitoring System Study, are presented in this report. Data collection in this survey ceased prior to its completion. This study outlines a Bayesian approach to compute the case weights so that the estimates could be representative of the universe considered for the survey. Subsequently, effectiveness of TPMS is studied by comparing estimates of percentages of underinflated and overinflated vehicles with and without TPMS, as well as the average underinflation and overinflation over vehicles in the two groups: vehicles with and without TPMS. Testing some relevant hypotheses provides statistical support to claims made in favor of TPMS based on the above comparisons. The analysis also covers comparison of direct and indirect versions of TPMS, concluding that direct type of TPMS is more effective as compared with the indirect. Since this data collection, improvements have been made to both kinds of TPMS, so different results are to be expected if the study were to be conducted presently.</td></tr>
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EXECUTIVE SUMMARY

Background and Objective

Past studies on tire pressure monitoring have revealed that about 28 percent of light vehicles on our Nation's roadways run with at least one underinflated tire. Only a few psi difference from vehicle manufacturer's recommended tire inflation pressure can affect a vehicle's handling and stopping distance. Poor tire maintenance can increase incidences of blowouts and tread separations. Similarly, underinflation negatively affects fuel economy.

In 2005, NHTSA's FMVSS 138 required automobile manufacturers to install tire pressure monitoring systems (TPMS) on light passenger vehicles with phase-in period from 2006 to 2008. Prior to the regulation, NHTSA's National Center for Statistics and Analysis conducted several surveys and studies to estimate and compare the benefits of Direct and Indirect TPMS; the most recent being Tire Pressure Monitoring System Study. Data collection in this survey ceased prior to its completion, thereby loosing its credibility of yielding a national representative sample. The objective of this study is to calculate case weights that can be used to obtain nationally representative estimates of the under- and over-inflated vehicles that include both with and without TPMS.

Methodology

Using a Bayesian approach, this study develops case weights that take into account the PSU size, strata sizes, planned sample sizes, as well as the actual sample sizes. The proposed weights are useful in making the best of the information that would otherwise be considered merely anecdotal. The data are analyzed by comparing the recommended pressures of each vehicle with its measured tire pressures, thus arriving at vehicle underinflation and overinflation. The proposed weights are used to obtain several estimates, such as percentages of underinflated and overinflated vehicles for TPMS and Peer groups, as well as their subcategories, Direct and Indirect. The significance of the differences in these percentages is statistically tested.

Results

The analysis results show that the percentage of vehicles with correct pressure are much higher (57%) for the TPMS group as compared with 43 percent for the Peer group. Regarding underinflation, while about 45 percent of the underinflated vehicles belong to TPMS group, a much higher percentage (55%) is attributed to the Peer group. In terms of the average underinflation, the TPMS-equipped vehicles have significantly lower average (14%) as compared with 16 percent for the Peer vehicles. The difference between averages is more significant when Direct type of TPMS and Peer vehicles are compared, while the difference in the case of Indirect types is insignificant.

Analysis conducted for overinflation shows that more of TPMS-equipped vehicles are overinflated (53%) as compared with 47 percent Peer vehicles that have at least one tire overinflated. Comparison of averages for the two groups shows that while the overall difference is insignificant, the average overinflation 12 percent for the Direct TPMS is significantly lower than 14 percent for the Direct Peer vehicles.

Further, analysis conducted to assess the effectiveness of TPMS shows that while this tire pressure monitoring device is highly effective in aiding the operator of a vehicle to prevent it from significant underinflation, it is likely to result in overinflation, though within the safe limits. Statistical analysis performed on the survey data provide sufficient evidence in favor of the TPMS, especially in the favor of the direct TPMS. Since this data collection, improvements have been made to both kinds of TPMS, so different results are to be expected if the study were to be conducted presently.

1 INTRODUCTION

In order for a vehicle to handle safely and use fuel economically, proper tire inflation, as recommended by the vehicle manufacturer, needs to be maintained in a vehicle's tires. Pressure below the recommended pressure (i.e., underinflation) can cause high heat generation that in turn can cause rapid tire wear, tire blowout, and loss of vehicle control that may cause a crash. TPMS is believed to be an effective means to monitor the tire pressure - a claim that is statistically tested in this study. Comparison of vehicles equipped with TPMS with the vehicles without TPMS can throw light on the effectiveness of this device. Further, there are two types of TPMS, Direct and Indirect. Direct systems operate with a tire pressure sensor in each tire cavity, while Indirect systems monitor tire pressure by comparing characteristics of tires, such as wheel speeds using the anti-lock braking system. Indirect systems do not distinguish between overinflation and underinflation. Therefore, it is also of interest to assess whether Direct TPMS is more effective as compared with Indirect TPMS.

In support of rulemaking activities mandated by Section 13 of the TREAD Act, the National Highway Traffic Safety Administration's National Center for Statistics and Analysis conducted the Tire Pressure Special Study (TPSS) and the Tire Pressure Monitoring System Study (TPMSS). The TPSS was designed to assess to what extent passenger vehicle operators are aware of the recommended tire pressures for their vehicles, the frequency and the means they use to measure their tire pressure, and how significantly the actual measured tire pressure deviated from the manufacturer's recommended pressure. This study is focused on the last aspect of the tire pressure maintenance.

The TPMSS was designed to gather tire-pressure-related information on vehicles equipped with different kinds of tire pressure monitoring systems so that their respective effectiveness could be evaluated. The main objective was to assess the effectiveness of TPMS, in general and investigate if Direct TPMS is more effective as compared with Indirect TPMS. The present study conducts statistical analysis to estimate some tire-pressure-related statistics, as well as make inferences about the effectiveness of TPMS devices. Section 2 of this paper discusses data collection methodology. In section 3 details about the data collected in TPMSS are provided. The break-up of the population size and the size of the actual sample collected in TPMSS is discussed in section 4. Section 5 probes the issue of assigning case weights and outlines statistical methodology used in revising weights that is required due to early termination of the survey. Section 6 is devoted to statistical analysis focused on estimation of tire-pressure-related parameters, as well as test certain hypotheses that are relevant to tire pressure maintenance issue. In section 7, the data are further analyzed with the objective of assessing the effectiveness of TPMS. The last section, section 8, summarizes the findings of this study. Additionally, the appendix provides analytical details of the weighting methodology.

2 DATA COLLECTION METHODOLOGY

The objective of TPMSS was to assess real-world tire pressure maintenance of vehicles in the United States. Accordingly, the data collection was planned to obtain a nationally representative sample of passenger vehicles, including passenger cars, light trucks, pickups, and sport utility vehicles. The target population for the survey consisted of two categories of vehicles: vehicles equipped with the tire pressure monitoring system, to be referred to as the "TPMS group" and the ones that were not equipped with TPMS, to be referred to as the "Peer group." As mentioned earlier, there are two types of tire pressure monitoring systems, Direct and Indirect. Therefore, care was taken to include both types of TPMS systems in the sampling frame. Finally, the vehicle age was also taken into account by including vehicles from model years 1997 through 2003 in the two groups.

The survey was conducted through the infrastructure of the National Automotive Sampling System

(NASS) Crashworthiness Data System (CDS). As in NASS-CDS data collection system, the TPMSS data were collected from 24 primary sampling units (PSU). The sample was selected from the State registration files and was comprised of vehicles from the TPMS group as well as from the Peer group as determined with the assistance of the Alliance for Automobile Manufacturers. The Peer group was formed by including vehicles that were not equipped with TPMS, but were of the same model years and of similar body styles and price ranges as the vehicles selected in the TPMS group. A computer program randomly selected study vehicles (TPMS and Peer) from the list of those eligible.

3 TARGET INFORMATION (DATA)

The information on several tire-pressure-related variables, such as actual pressure in all the tires, the recommended tire pressure levels for the vehicle, ambient temperature, age of the vehicle, and age and sex of the vehicle owner/operator was collected in this survey. In order to assess the effectiveness of monitoring devices, the information on the categorical variables: TPMS (presence or absence), TPMS type (Direct or Indirect) was documented as well. This study is focussed on assessing effectiveness of TPMS and uses the tire-pressure-related variables only.

4 SAMPLE SIZE

Originally, the data were planned to be collected on a sample of 12,001 vehicles. Anticipating the response rate of the survey to be 60 percent, the data on 7,000 vehicles was the actual target. However, the survey was not completed and data was collected on 2,316 vehicles only. The allocation of the originally planned sample of 12,001 vehicles over Peer and TPMS groups, as well as their subcategories, Direct and Indirect, is shown in Table 1. This table also shows (within parentheses) similar allocation of the final sample of 2,316 vehicles.

Table 1: Sample segmentation by vehicle groups and their subcategories

<table>
<tr><td colspan="4">TOTAL SUBJECT VEHICLES
12,001†
(2,316)*</td></tr>
<tr><td colspan="2">TPMS-equipped (TPMS)
5,977†
(1,259)*</td><td colspan="2">Without TPMS (Peer)
6,024†
(1,057)*</td></tr>
<tr><td>Direct TPMS
1,261†
(213)*</td><td>Indirect TPMS
4,716†
(1,046)*</td><td>Direct Peer
1211†
(243)*</td><td>Indirect Peer
4,813†
(814)*</td></tr>
</table>

Planned sample size† (Actual sample size)*

Given the reduced sample size, it was of interest in this study to assess how well the actual sample could represent the population. This is done by comparing the ratio, $R_{planned}$ of planned sample size to the corresponding PSU size with the ratio R_{actual} of actual sample size to the corresponding PSU size. Figure 1 presents profiles of these two ratios over PSUs in which data were collected. The patterns of the two ratios in this figure shows that the number of vehicles actually documented in the sample is consistently proportional to the planned PSU sample sizes. However, this does not completely make the sample nationally representative in certain other aspects of the sample design. Therefore, an adjustment needs to be made through case weights to achieve a reasonable level of national representation. The following section is devoted to developing these weights.

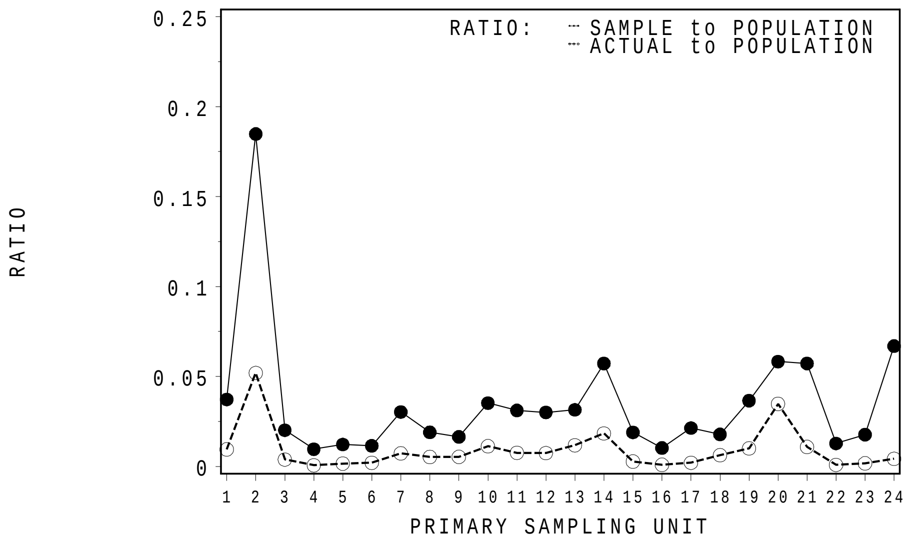


Figure 1: Comparison-actual sample sizes and planned sample sizes for the 24 selected PSUs

5 SAMPLE DESIGN AND CASE WEIGHTS

<u>SAMPLING SCHEME</u>

A two-stage stratified sampling scheme was used to select the study vehicles:

- The first stage of sampling consisted of selecting geographic areas, such as counties, groups of counties, or cities forming PSUs. These PSUs are a probability sample selected from a frame of all geographic areas in the continental United States. Twenty-four PSUs were selected for this survey from amongst the 1,195 determined by the NASS system. The selection is based on the number of motor vehicle traffic crashes occurring within these regions.
- At the second stage, stratification was done with respect to the vehicle's age (model year) and vehicle category (in terms of the presence or absence of TPMS) in each selected PSU.
- Finally, from the selected PSU as in the first stage, a simple random sample of vehicles was selected from each stratum formed at the second stage.

<u>CASE WEIGHTS</u>

The objective of the TPMSS was to collect a sample of vehicles with and without TPMS that is representative of the U.S. fleet. A survey conducted according to a designed sample and the use of appropriate case weights would help achieve this objective. Although, the sample actually selected in this survey has some affinity with the population as discussed earlier, due to early termination the probabilities of selection at different stages of the design are no longer valid. Consequently, the case weights based on these probabilities would fail to make the sample representative of the population. This study proposes the methodology to compute case weights for the terminated survey that can be used for estimating the tire-pressure-related parameters of the target population.

Typically, the case weights in a sample survey are based on the scheme used for the case selection - in the two-stage sample design used in this survey, it would be the inverse of the product of the probability of PSU selection and the probability of vehicle selection from a stratum. Originally, the weight for the i^{th} case selected randomly form the j^{th} stratum of the k^{th} selected PSU was defined as

$$W^o_{ijk} = \left(\frac{1}{P_k}\right)\left(\frac{1}{P_{ij/k}}\right), \tag{1}$$

where P_k = Prob $\{k^{th}$ PSU is selected $\}$, $P_{ij/k}$ = Prob $\{i^{th}$ vehicle is selected from j^{th} stratum, given that k^{th} PSU has been selected$\}$.

Although the survey was terminated prior to completion of data collection based on the laid-down sample design, the PSU selection had already been made. This preserves the probability P_k of PSU selection. However, due to early termination, the selection of vehicles in the strata was disturbed - fewer than planned vehicles could be selected in the strata. This questions the validity of the corresponding selection probability $P_{ij/k}$. To introduce a reasonable amount of national representation, revision of these probabilities is imperative. What is needed is to account for what was actually selected in a stratum as against what was supposed to be selected. This suggests that the posterior rather than the prior distribution should be used for computing the vehicle selection probability $P_{ij/k}$ to be used in computing weights as in (1). Based on this rationale, this study proposes a Bayesian methodology to compute case selection probabilities $P_{ij/k}$, and hence the case weights W_{ijk}.

Consider the sampling design layout for an exemplar PSU as shown in Table 2, where n_{ij} is the sample size originally planned to be collected from the stratum (ij) of the PSU and m_{ij} is the sample size actually collected from the ij^{th} stratum.

Table 2: Stratification in an exemplar PSU.

Vehicle Age	**Vehicle group**	
	With TPMS (Study group)	**Without TPMS** (Peer group)
Less than 3 years (New vehicles)	n_{11} m_{11}	n_{12} m_{12}
3 years or older (Old vehicles)	n_{21} m_{21}	n_{22} m_{22}

The case selection at each stage is basically a Bernoulli process with probability of selection (success) determined by the ratio of the number to be selected to the number from which to be selected. Thus, if in a stratum of N_{ij} vehicles, n_{ij} are to be selected, then the probability of selection (success, speaking in terms of bernoulli trials), is the ratio ($\pi = n_{ij}/N_{ij}$.) However, instead of n_{ij} vehicles, only m_{ij} ($m_{ij} \leq n_{ij}$) could be selected by the time the survey was terminated. Speaking in terms of the bernoulli trials, this amounts to having m_{ij} successes in n_{ij} trials with probability of success given by π. It is this probability that needs to be revised using the prior information about the sample size. Bayesian approach is used for this purpose as outlined in the appendix. The probability that maximizes the selection of i^{th} vehicle from the j^{th} stratum of the k^{th} PSU, that is the mode of the posterior distribution [1], is given by

$$\pi^* = \frac{(m_{ij} - 1/2)}{(n_{ij} - 1)} \tag{2}$$

Finally, in the two-stage selection process used in the survey, the probability of selection of a vehicle is the product of the probability of selection P_k of the k^{th} PSU and the posterior probability given by (2), that is

$$P^*_{ijk} = P_k * \left(\frac{m_{ij} - 1/2}{n_{ij} - 1} \right). \tag{3}$$

However, some adjustments are needed before this posterior probability of case selection could be used in calculating case weights. It should be noted that the strata in which the number of vehicles actually selected is equal to the number that was originally planed for a stratum do not require the Bayesian treatment. Thus, the case weights are calculated using the formula (1) or (3), depending upon whether the number of vehicles actually selected is equal to or less than the number of vehicles planned to be selected. Further, non-response in a survey is not uncommon. To account for this contingency, the weights need to be adjusted by using the response rates in the selected strata. Finally, the case selection probabilities and hence the case weights are calculated by

$$W_{ijk} = \begin{cases} \left(\frac{1}{P_k}\right)\left(\frac{N_{ij}}{n_{ij}}\right)\left(\frac{1}{r_j}\right), \text{ if } m_{ij} = n_{ij} \\ \\ \left(\frac{1}{P_k}\right)\left(\frac{n_{ij}-1}{m_{ij}-\frac{1}{2}}\right)\left(\frac{1}{r_j}\right), \text{ if } m_{ij} < n_{ij}, \end{cases}$$

where $r_j \times 100$ ($r_j \leq 1$) percent is the response rate in the j^{th} stratum.

Using these weights, the number of vehicles in the Peer and TPMS categories and their subcategories Direct and Indirect are estimated as shown in Table 3. The statistics presented in Table 3 show that in

Table 3: Allocation of sampled vehicles and their estimates over vehicle groups

<table>
<tr><td colspan="4">SAMPLED NUMBER OF VEHICLES AND THEIR WEIGHTED ESTIMATES
(2,316)*
[654,817]‡</td></tr>
<tr><td colspan="2">TPMS-equipped (TPMS)
(1,259)*
[332,046]‡</td><td colspan="2">Without TPMS (Peer)
(1,057)*
[322,771]‡</td></tr>
<tr><td>Direct TPMS
(213)*
[74,595]‡</td><td>Indirect TPMS
(1,046)*
[257,451]‡</td><td>Direct Peer
(243)*
[71,693]‡</td><td>Indirect Peer
(814)*
[251,078]‡</td></tr>
</table>

(Actual sample size)* [Weighted estimate]‡

an estimated total number 654,817 of vehicles, 332,046 are estimated to be TPMS-equipped and 322,771 without TPMS. Of the TPMS-equipped, 74,595 vehicles are estimated to be equipped with Direct TPMS, while an estimated 257,451vehicles with Indirect TPMS.

6 ANALYSIS

The measured tire pressure being below or above the recommended pressure level is all that matters. There are two ways an improper tire inflation could be hazardous: overinflation and underinflation. While overinflation can be dangerous for vehicle handling, underinflation can become a safety hazard not only due to blow-outs and tire destruction, but also due to the development of dangerous driving scenarios, such as directional loss of control. This brings out the importance of some means by which vehicle operators can determine if the tires need to be inflated or deflated. One of the devices that can be used for this purpose is TPMS. This study is focused on assessing the effectiveness of TPMS as a means to maintain tire inflation at the recommend levels, as well as study the comparative effectiveness of Direct and Indirect TPMS. One of the ways this can be done is to compare the TPMS group of vehicles with the Peer group and TPMS Direct subgroup with TPMS Indirect subgroup. This study makes these comparisons in terms of the frequencies of underinflated and overinflated vehicles for the two groups, as well as their average underinflation and overinflation. Statistical analysis is conducted to estimate some tire-inflation-related parameters using the proposed weights and test certain hypotheses to compare groups of vehicles with and without TPMS, as well as their respective subgroups, Direct and Indirect.

The tire-pressure-related parameters that can be used to determine underinflation and overinflation are the manufacturer's recommended tire inflation pressure and the one actually measured in the survey for each tire of a vehicle. The difference between the two is used to determine the extent of underinflation and overinflation of a tire:

- Underinflation = Recommended pressure - Measured pressure (≥ 0, recommended exceeds measured)
- Overinflation = Measured pressure - Recommended pressure (≥ 0, measured exceeds recommended)

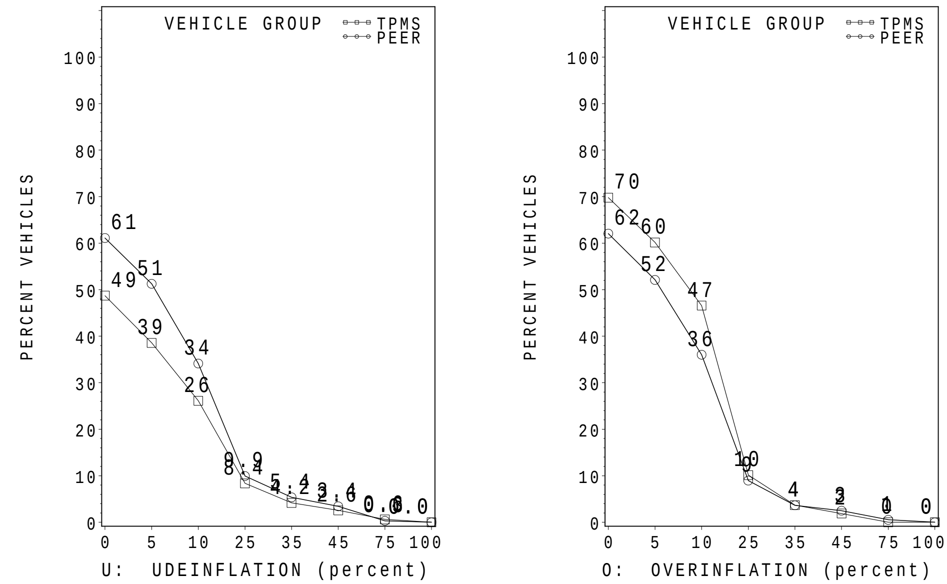
For the analysis purpose, these are converted into percentages (percentage of the corresponding recommended pressure of the subject tire) for each tire of the vehicle.

With regard to the tire pressure status of a vehicle on the whole, an underinflated vehicle in this study refers to a vehicle that has at least one tire underinflated. The same criterion is used in the case of overinflation. It should be noted that a vehicle can have both underinflated and overinflated tires.

While the variables Underinflation and Overinflation are computed for all the tires of a vehicle, the minimum of all tire pressures in the case of underinflation and maximum of all tire pressures in the case of overinflation are used as measures of vehicle underinflation and overinflation, respectively.

6.1 Preliminary Analysis

As a preliminary analysis, the profiles of two groups over underinflation and overinflation with threshold values 0, 5, 10, 15, 25, 35, 45, 75, and 100 percent (expressed as percent of the recommended pressure) are presented in an Ogive. An Ogive is a line graph that depicts the percentage of cases (vehicles) that have values of the variable (underinflation or overinflation) less than or equal to a certain threshold value. In this study, to assess the effectiveness in terms of reduction in underinflation or overinflation the percent of cases greater than a certain threshold value is used. Hence, instead of Ogive, its image, to be referred to as reverse Ogive, is used. Obviously, a reverse Ogive is a line graph depicting the number of vehicles greater than the threshold value. Figure 2(a) and Figure 2(b), respectively, show underinflation and overinflation profiles of the two groups. Figure 2(a) shows that about 61 percent of the Peer vehicles were found underinflated (Underinflation ≥ 0), while a much smaller percentage (48.2) of TPMS vehicles had one or more underinflated tires. For other levels of under inflation (5, 10, 15, 25, 35%), too, the TPMS-equipped vehicles demonstrate lower frequencies of underinflated vehicles than the Peer vehicles. The overinflation profiles of the two groups over the threshold values 0, 5, 10, 15, 25, 35, 45, 75, and 100 presented in Figure 2(b) indicate lower percentages of Peer overinflated vehicles as compared with the TPMS-equipped vehicles that were overinflated.



(a) Percent vehicles with Underinflation > U (b) Percent vehicles with Overinflation > O

Figure 2: Percent frequency distributions of Underinflated and Overinflated vehicles

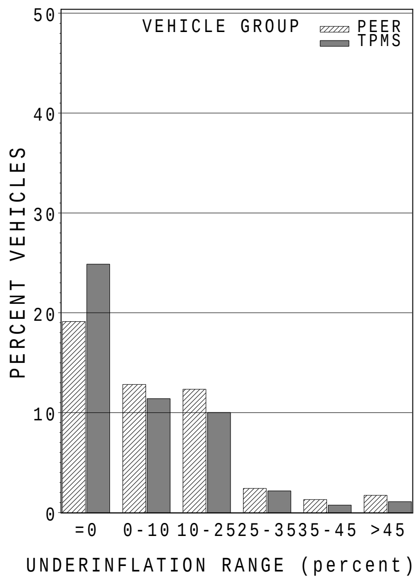
The performance of the TPMS group is compared with the Peer group also over different ranges of underinflation. The results of this comparison are presented respectively in Figure 3(a) and Figure 3(b). Figure 3(a) shows that while the percentage of vehicles with zero underinflation is higher for the TPMS group, it is lower for other ranges of underinflation. In the case of overinflation, the frequency distributions in Figure 3(b) show that more of the Peer vehicles had no overinflation as compared with the TPMS-equipped vehicles.

6.2 Analysis: Comparison of Vehicle Groups and Their Subcategories

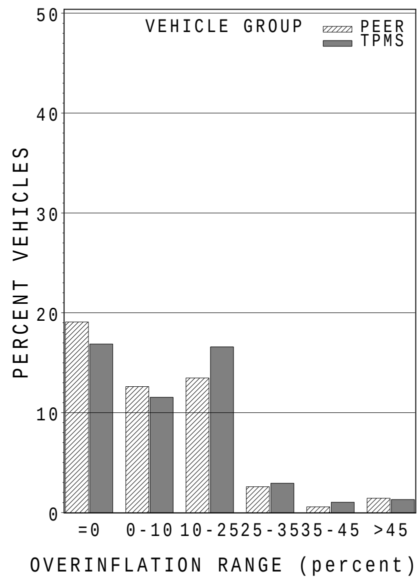
The efficacy of a tire pressure monitoring device is reflected primarily in the level of underinflation it allows before illuminating the low pressure warning lamp. The following analysis is focused on three aspects of tire inflation - correct tire inflation, underinflation, and overinflation and compares the TPMS and Peer group of vehicles for each of these three tire conditions. Specifically, the TPMS and Peer group of vehicles are compared with respect to:

- **Correct tire inflation**:
  - None of the vehicle's tires is underinflated or overinflated
- **Underinflation**:
  - No underinflation
  - Underinflation > 0 percent
  - Underinflation > 25 percent
  - Underinflation > 30 percent

- **Overinflation**:
  - No Overinflation
  - Overinflation > 0 percent
  - Overinflation > 25 percent
  - Overinflation > 30 percent



(a) Frequency Distribution of Underinflated Vehicles



(b) Frequency Distribution of Overinflated Vehicles

Figure 3: Percent vehicles with Underinflation and Overinflation exceeding threshold values, 0, 5, 10, 25, 35, 45 percent.

6.2.1 Correct Pressure

One of the indicators of effectiveness of TPMS would be its contribution in aiding the operator of a vehicle to keep inflation of its tire at the correct level which means none of its tires is underinflated or overinflated with reference to the recommended tire inflations. The estimates based on the TPMSS data show that among vehicles with correct pressure (in the above sense,) about 57 percent are TPMS-equipped, which is much higher than 43 percent for the Peer vehicles. However, correct pressure on a vehicle is an ideal scenario. The following analysis determines how effective TPMS could be in warning the vehicle operator against underinflation or overinflation a vehicle's tires.

6.2.2 Underinflation

With regard to TPMS function in warning against underinflation, the pressure characteristics considered in this analysis include: 0 (no underinflation), underinflation more than 25 percent, and underinflation more than 30 percent. The percent frequency distribution of vehicles is presented in Table 4.

The statistics in this table show that 57 percent TPMS vehicles have no underinflation as compared with 43 percent Peer vehicles without an underinflated tire. Further, among vehicles with no underinflation, there are 7.6 percent Peer (Direct) and 12.8 percent TPMS (Direct) vehicles. Similarly, only 35 percent of the vehicles are without an underinflated tire in the Peer (Indirect) group and about 45 percent in the TPMS (Indirect) group. These statistics show that whether the TPMS device is Direct or Indirect type, it does aid in preventing vehicle underinflation to a large extent.

The estimates presented in Table 4 also project how the two groups compare in terms of underinflation (i.e., underinflation > 0). Among such vehicles, the percentage 44.9 of TPMS vehicles (9.5% Direct and 35.4% Indirect) is well below the percentage 55.1 of the Peer vehicles that consists of 13.7 percent Direct and 41.5 percent Indirect type. These percentage differences between the underinflated TPMS and Peer vehicles further support the claim that TPMS is effective in preventing underinflation.

Table 4: Underinflation status by vehicle group and device type

VEHICLE GROUP	**DEVICE TYPE**	**UNDERINFLATION**			
		No	Yes	More than 25%	More than 30%
Peer	Direct	7.6	13.7	9.7	11.2
	Indirect	35.0	41.5	44.1	45.0
	Sub-total	42.6	55.2	53.8	56.2
TPMS	Direct	12.8	9.5	8.0	10.9
	Indirect	44.6	35.4	38.2	32.8
	Sub-total	57.4	44.9	46.2	43.7

The two groups are also compared for underinflation above threshold levels of 25 and 30 percent. Among vehicles with more than 25-percent underinflation, the percentage (46.2%) for the TPMS vehicles is much smaller than the percentage (53.8%) for the Peer vehicles. Similarly, among vehicles with more than 30 percent underinflation, the percentage (43.8) of TPMS vehicles is much smaller than the percentage (56.2%) of the Peer vehicles. Statistical tests performed on these differences show (with 95% confidence level) that the data provide sufficient evidence in favor of the TPMS in tire pressure maintenance in terms of underinflation. However, no significant difference was observed between the two groups for underinflation greater than 35 percent. This is obvious, as underinflation to that extent cannot go unnoticed, whether or not the vehicle is equipped with the TPMS.

Additionally, another parameter of tire inflation has been looked at in this study; namely the average underinflation - the two groups are compared in terms of the average underinflation. As a word of caution, an average presented in this table is an average over the vehicle group rather than the average over the vehicle. The estimates of averages presented in Table 5 are used for this purpose. These results show that on the average, TPMS vehicles have only 14.3-percent underinflation as compared with 16 percent for the Peer vehicles. The difference between 15.8 percent for the Peer (Direct) group and 12.6 percent for the TPMS (Direct) group further shows that on the average, Direct type of TPMS contributes to a significant reduction in underinflation.

6.2.3 Overinflation

The statistics showing comparison between the two vehicle groups in terms of overinflation are presented in Table 6. These results show that, in general, the TPMS-equipped vehicles tend to be overinflated. For example, there are 55.2 percent Peer vehicles and 44.8 percent TPMS vehicles among vehicles that have no overinflation (Overinflation=0). Similarly, among the overinflated (Overinflation¿0) vehicles, 46.5 percent are Peer vehicles in contrast with 53.5 percent TPMS vehicles. Also, among vehicles with more

Table 5: Average underinflation (percent) by vehicle group and device type

VEHICLE GROUP	DEVICE TYPE	UNDERINFLATION	
		Average	95% Conf. Interval
Peer	Direct	15.77	[14.02, 17.51]
	Indirect	16.10	[14.34, 17.87]
	Overall	16.01	[14.52, 17.50]
TPMS	Direct	12.61	[10.16, 15.06]
	Indirect	14.70	[13.15, 16.24]
	Overall	14.30	[12.85, 15.75]

than 25 percent overinflation, TPMS vehicles have larger representation, 54 percent as compared with 46 percent for the Peer vehicles. Similarly, among vehicles with more than 30 percent overinflation, TPMS vehicles have larger representation 51.8 percent as compared with 48.2 percent for the Peer vehicles.

In terms of the vehicle group averages, there is insignificant difference between the averages: 15.4 percent for the Peer vehicles and 15.5 percent for the TPMS vehicles (Table 7). However, the comparison between the averages 12.3 and 13.9 percent, respectively, of the TPMS (Direct) and Peer (Direct) groups shows that on the average, Direct type of TPMS aids in keeping the level of underinflation low. Thus, although a higher percentage of overinflated vehicles belong to TPMS, on the average, the overinflation is lower for Direct TPMS vehicles as compared with Direct Peer vehicles.

Table 6: Overinflation status by vehicle group and device type

VEHICLE GROUP	DEVICE TYPE	OVERINFLATION			
		No	Yes	More than 25%	More than 30%
Peer	Direct	13.6	9.6	8.1	11.3
	Indirect	41.6	37.0	37.9	37.0
	Sub-total	55.2	46.6	46.0	48.2
TPMS	Direct	8.5	12.3	8.1	2.0
	Indirect	36.3	41.2	45.9	49.7
	Sub-total	44.8	53.5	54.0	51.8

7 TPMS EFFECTIVENESS ANALYSIS

In this section, the overall effectiveness of TPMS is studied by considering ranges of underinflation/overinflation, simultaneously. A simultaneous test is performed to test if TPMS retains its effectiveness as underinflation/overinflation increases from 0 percent through 100 percent. Descriptive analysis of the data shows that estimates of the skewness coefficients (2.9 for the Peer and 5.2 for the TPMS group) differ significantly from 0 which is the skewness of a Normal distribution. This suggests using multicategory-based nonparametric analysis to compare the two groups with respect to TPMS effectiveness. Specifically, the nonparametric test called Wilcoxon Rank-Sum Test [2] is used to test the significance of the effect of TPMS, i.e., to test the hypothesis

$$H_0 : \mathrm{m}_{\text{tpms}} = \mathrm{m}_{\text{peer}} \quad \text{against the alternative} \quad H_A : \mathrm{m}_{\text{tpms}} < \mathrm{m}_{\text{peer}}$$

Table 7: Average Overinflation (percent) by vehicle group and device type

VEHICLE GROUP	DEVICE TYPE	OVERINFLATION	
		Average	95% Conf. Interval
Peer	Direct	13.93	[11.08, 16.79]
	Indirect	15.80	[14.26, 17.33]
	Overall	15.37	[13.91, 16.83]
TPMS	Direct	12.26	[10.54, 13.97]
	Indirect	16.39	[14.81, 17.96]
	Overall	15.52	[14.19, 16.85]

where m stands for the average underinflation or overinflation, with subscript indicating the group. This test assumes that the models associated with the two samples differ in terms of location, the difference being attributable to the effect of TPMS. Assuming that the distributions of U_{peer} and U_{tpms} have the same shape and spread, the testing is done only in terms of shift Δ in location. The test basically concerns testing the hypothesis $H_0 : \Delta = 0$ against the alternative $H_A : \Delta < 0$. Due to large sample size, Normal approximation of the rank sum statistic is used, i.e., the statistic

$$W^* = \frac{W - \left[n_{\text{tpms}}\left(n_{\text{peer}} + n_{\text{tpms}} + 1\right)/2\right]}{\left[n_{\text{peer}} \times n_{\text{tpms}}\left(n_{\text{peer}} + n_{\text{tpms}} + 1\right)/12\right]^{1/2}}, \quad (4)$$

where n_{tpms} and n_{peer} are the numbers of TPMS and Peer vehicles, respectively, in the samples. The statistic W^* has an asymptotic $N(0,1)$ distribution.

7.1 Effectiveness - Controlling Underinflation

To conduct the above analysis for underinflation, all subject vehicles are categorized depending on the level of underinflation. The analysis is conducted using the variable Effectiveness, defined as

$$\text{Effectiveness} = \begin{cases} 6, \text{ if Underinflation} = 0\% \\ 5, \text{ if } 0\% < \text{Underinflation} \leq 10\% \\ 4, \text{ if } 10\% < \text{Underinflation} \leq 25\% \\ 3, \text{ if } 25\% < \text{Underinflation} \leq 35\% \\ 2, \text{ if } 35\% < \text{Underinflation} \leq 45\% \\ 1, \text{ if Underinflation} > 45\% \end{cases}$$

The Wilcoxon two-sample test statistic W^* equals $9.817 * 10^{10}$ which is the sum of the Wilcoxon scores for the smaller group (Peer). This sum is greater than the expected value $1.050 * 10^{11}$ under the null hypothesis of no difference between the two groups. This difference, with Z-value= -95.3894 and one-sided p-value < 0.0001 shows that TPMS is significantly effective in keeping the underinflation low for all ranges of underinflation.

7.2 Effectiveness - Controlling Overinflation

To conduct similar analysis for overinflation, all subject vehicles are categorized depending on the level of overinflation. The analysis is conducted using the variable Effectiveness, defined as

$$\text{Effectiveness} = \begin{cases} 6, \text{ if Overinflation} = 0\% \\ 5, \text{ if } 0\% < \text{Overinflation} \leq 10\% \\ 4, \text{ if } 10\% < \text{Overinflation} \leq 25\% \\ 3, \text{ if } 25\% < \text{Overinflation} \leq 35\% \\ 2, \text{ if } 35\% < \text{Overinflation} \leq 45\% \\ 1, \text{ if Overinflation} > 45\% \end{cases}$$

The Wilcoxon two-sample test statistic W^* equals $1.108 * 10^{11}$ which is the sum of the Wilcoxon scores for the smaller group, Peer. This sum is greater than the expected value $1.049 * 10^{11}$ under the null hypothesis of no difference between the two groups. This difference, with positive Z-value = 80.6136 and the one sided p-value < 0.0001 shows that vehicles equipped with TPMS tend to be more overinflated as compared with those that are not.

8 RESULTS AND DISCUSSION

Although the TPMS survey collected data only on a portion of the original sample size, the tire-pressure-related information is available for over 2,000 vehicles. This study found that when this sample was distributed over all PSUs, it resulted in almost the same proportions as the originally planned sample. The actual sample consists of about 200 vehicles equipped with the Direct TPMS and about 1,000 vehicles equipped with the Indirect TPMS. Similar categories of Peer vehicles are proportional to those in the TPMS group. However, the actual sample in hand at the time of termination could not conform to the second stage sample design, thereby lacking national representation - the case weights based on the original sample design could no longer be used for estimation purpose. Using a Bayesian approach, this study develops case weights that take into account the PSU size, strata sizes, planned sample sizes, as well as the actual sample sizes. The proposed weights are useful in making the best of the information that would otherwise be considered merely anecdotal. The data are analyzed by comparing the recommended pressures of each vehicle with its measured tire pressures, thus arriving at vehicle underinflation and overinflation. The proposed weights are used to obtain several estimates, such as percentages of underinflated and overinflated vehicles for TPMS and Peer groups, as well as their subcategories, Direct and Indirect. The significance of the differences in these percentages is statistically tested.

The analysis results show that the percentage of vehicles with correct pressure are much higher (57%) for the TPMS group as compared with 43 percent for the Peer group. Regarding underinflation, while about 45 percent of the underinflated vehicles belong to TPMS group, a much higher percentage (55%) is attributed to the Peer group. The analysis conducted for more than 25 and 30 percent underinflation shows similar differences. The differences between percentages are even more prominent when Direct types of the two groups are compared with respect to no underinflation, underinflation greater than 0 percent and 25 percent. In terms of the average underinflation, the TPMS-equipped vehicles have significantly lower average (14%) as compared with 16 percent for the Peer vehicles. The difference between averages is more significant when Direct type of TPMS and Peer vehicles are compared, while the difference in the case of Indirect types is insignificant.

Analysis conducted for overinflation shows that more of TPMS-equipped vehicles are overinflated (53%) as compared with 47 percent Peer vehicles that have at least one tire overinflated. The difference between percentages of the direct type TPMS and Peer vehicles with overinflation more than 25 percent is not significant. The difference between 11 percent for the Direct Peer subgroup and 2 percent for the Direct TPMS is highly significant. Comparison of averages for the two groups shows that while the overall difference is insignificant, the average overinflation 12 percent for the Direct TPMS is significantly lower than 14 percent for the Direct Peer vehicles.

Further, analysis conducted to assess the effectiveness of TPMS shows that while this tire pressure monitoring device is highly effective in aiding the operator of a vehicle to prevent it from significant underinflation, it is likely to result in overinflation, though within the safe limits as supported by the above analyses.

Statistical analysis performed on the survey data provide sufficient evidence in favor of the TPMS, especially in the favor of the direct TPMS. NHTSA recommends that vehicle operators check their tire pressures at least once a month and before long trips. The vehicle manufacturer's recommended tire pressure (located on a placard on B-pillar of the driver's side door) can be referenced for this purpose. TPMS should be used as a supplement to regular tire maintenance and care. It should be noted that TPMS studied in this analysis not be representative of the current designs.

9 APPENDIX

This appendix provides analytical details of the methodology used in revising case weights based on the rationale discussed in section 5. Speaking in terms of the Bernoulli trials, obtaining m_{ij} vehicles instead of planned number n_{ij} amounts to having m_{ij} successes in n_{ij} trials. This in turn means that the probability of selection of m_{ij} vehicles from n_{ij} vehicles in the j^{th} stratum of the k^{th} PSU is given by the Binomial distribution

$$p(m_{ij}/\pi) = \left\{ \frac{n_{ij}!}{(n_{ij} - m_{ij})! \;\; m_{ij}!} \right\} \pi^{m_{ij}} (1-\pi)^{(n_{ij}-m_{ij})}, m_{ij} = 0, \ldots, n_{ij} \tag{5}$$

To use a Bayesian approach, a nearly noninformative prior for π is used and is proportional to

$$p(\pi) \propto [\pi(1-\pi)]^{-1/2}\,. \tag{6}$$

This further results into the posterior distribution which is proportional to

$$\pi^{m_{ij}-1/2}(1-\pi)^{n_{ij}-m_{ij}-1/2}, 0 < \pi < 1 \tag{7}$$

After substitution of the appropriate normalizing constant, the corresponding posterior distribution for π assumes the form of Beta distribution, i.e.,

$$p(\pi/m_{ij}) = \frac{\Gamma(n_{ij}+1)}{\Gamma(n_{ij}-m_{ij}+1/2)\Gamma(m_{ij}+1/2)} \pi^{m_{ij}-1/2}(1-\pi)^{n_{ij}-m_{ij}-1/2}, 0 \leq \pi \leq 1 \tag{8}$$

$p(\pi/m_{ij})$ in (8) is maximized at

$$\pi^* = \frac{(m_{ij}-1/2)}{(n_{ij}-1)} \tag{9}$$

π^* given by (9) is the mode of the posterior probability distribution associated with the selection of i^{th} vehicle from the j^{th} stratum in the k^{th} PSU. This is the probability that maximizes the selection of the ij^{th} case and can be used as the revised probability of selection of a vehicle.

References

[1] Box, G.E.P (1980). *Bayesian Statistical Analysis*, New York: John Wiley & Sons.

[2] Hollander, M. and Wolfe, D. A. (1972). *Nonparametric Statistcal Methods* New York: John Wiley & Sons.

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