Proper Tire Inflation Increases Fuel Economy and Reduces Greenhouse Gas Emissions

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Abstract California has recognized the threat from global warming and has put forth legislation to curb greenhouse gas (GHG) emissions. Because transportation is the largest source of greenhouse gas emissions in California, regulating this sector could provide substantial benefits. Tire pressure has been shown to have a measurable impact on fuel economy, and thus has an impact on GHG emissions. Tire pressure is also easily monitored, corrected, and can produce savings for individuals through reduced fuel consumption. To determine the expected level of individual savings and statewide GHG reduction that might occur if every car in California had accurate tire pressure, I gathered data on tire pressure from car repair shops in Berkeley, California. I then established mathematical relationships between tire pressure, rolling resistance and fuel economy, and state data on automobiles to determine the impact that accurate tire pressure could have on fuel consumption and GHG emissions. My results show that individuals could expect $37-$77 of annual savings and that GHG's could be reduced by 1.42%-0.69% statewide. My study provides useful information for legislators looking to find economical ways of reducing GHG's. Reducing GHG emissions is an important goal due to the serious implications that global warming holds for the future and economic concerns are currently the largest obstacle to addressing this problem.

Introduction

Earth's climate is changing rapidly due to anthropogenic global warming (Intergovernmental Panel on Climate Change 2001). Climate changes can alter economic activities and lead to economic harm (Farrell, et al. 2005). The State of California has recognized this threat and has introduced legislation that would require greenhouse gas emissions be reduced by 25% of the projected level for 2020 (Holusha 2006). Since only nine nations emit more greenhouse gas than California (Busch et. al 2005), reducing these emissions could result in a significant impact on global warming. If California successfully reduces GHG emissions at a negligible cost or with economic benefits, it could serve as a model for the rest of the nation.

In an effort to see how GHGs might be reduced without economic repercussions, the California Climate Change Center at UC Berkeley analyzed eight different approaches to reducing GHG emissions. Their study demonstrated that greenhouse gas emissions can be reduced with a net economic benefit stemming from increased fuel efficiency reducing the demand for fossil fuel (Farrell et. al 2005). Reducing fossil fuel use would have a large impact on overall emissions because they are the main source of greenhouse gas emissions (Intergovernmental Panel on Climate Change 2001).

Fossil fuel use occurs in many sectors of the economy from industry to transportation. Personal cars and light duty trucks account for 40% of all emissions (Auffhammer et. al 2005) and 63% of transportation emissions, (U.S. Environmental Protection Agency 2006). Even though transportation makes up the bulk of emissions, only one of the eight factors studied by the California Climate Change Center focused specifically on the transportation sector (Farrell et al. 2005).

One unexamined method to increase fuel economy and thereby reduce emissions is through proper tire inflation. (Farrell et al. 2005). Under-inflated tires increase the rolling resistance of tires, which increases the amount of fuel needed to power the car (National Highway Transportation Safety Administration 2002). Proper tire inflation therefore optimizes the level of rolling resistance, which minimizes the amount of fuel needed. Recognizing this impact, the National Highway Transportation Safety Administration (NHTSA) set standards for tire pressure monitoring systems (TPMS) that will be included in all new cars starting in 2007. A recent study, released after the new standard for TPMS were set, shows that a 2 psi decrease in all four tires will lead to a 1-2% decrease in fuel efficiency of the vehicle. Even with this evidence however, little research has been conducted on this topic since the late 1970's (Transportation Research Board 2006). This lack of information and regulation is troublesome because 27% of regular automobiles have one or more tires that are under-inflated by at least 8 psi (National Highway Traffic Safety Administration 2001A).

While 85% of drivers are concerned about optimal tire pressure, only 25% of drivers correctly check tire pressure and 43% do nothing to address their concern (National Highway Traffic Safety Administration 2001B). The Tire and Rim Association (2002) states that standard tire pressure levels range from 26 psi to 35 psi. If every car's tires were under-inflated by 6 psi each, (i.e., roughly by 25% of the lower end of that spectrum and the level below which the NHTSA's requirements about monitors are not required to report), it would lead to a roughly 6% decrease in fuel efficiency[1]. The extra gasoline needed due to a 6% decrease in fuel economy quickly adds up with more than 31 million cars in California (Federal Highway Administration 2004).

Since ensuring accurate tire pressure has the ability to be beneficial for both individual consumers, in terms of reduced fuel costs, and the region that implements pressure monitoring, through reduced pollution and greenhouse gas emissions, monitoring is an excellent candidate for reducing emissions with negligible costs to society. Even with regulations requiring tire pressure monitoring in all new cars however, the large fleet of existing cars will continue to contribute to increased concentrations of greenhouse gases.

In this study I analyzed the costs of installing tire pressure monitors in existing cars relative to the savings from the average reduced fuel consumption. These calculations were based on a sample of tire pressures of actual cars in California. I then aggregated the fuel savings over the California economy and translated that into a reduction of greenhouse gas in CO_2. I hypothesize that the fuel savings from maintaining optimal tire pressure over the life of a car is greater than the costs associated with a tire pressure monitoring device. I further hypothesize that the reduction in CO_2 due to reduced fuel consumption could achieve 10% of the 25% reduction in GHG presented in the bill to the California State Assembly.

Methods

Data Collection To determine tire pressure deviation, I gathered data from Ed's Best Auto Service, LLC located on 1931 Addison St. in Berkeley, and the Honda Service Center located on

[1] This results from a calculation that I performed.

2600 Shattuck Ave. in Berkeley[2], from September 19th to December 19th [3]. These shops recorded the tire pressure of vehicles when they came into the shop and what the ideal pressure should be (Appendix A).

My data are heavily weighted towards Hondas, which is not representative of statewide data. However discussions with people in the industry revealed that correlation between under-inflated tires and brand of automobile is very small. Due to this minimal correlation, I assumed that my sample is representative. Gathering data from a specific dealership will also select for people who prefer that brand of automobile, however I assumed that any correlation between car selection and the likelihood of checking tire pressure is negligible.

Per Car Gasoline Savings due to Accurate Tire Inflation After the tire pressure data were collected, I calculated the average deviation from proper tire inflation for each tire. This calculation was performed for each tire, because the relationship for tire pressure, rolling resistance (the force on the axle required to move the tire once the car is already in motion) and fuel economy exist for an individual tire.

To determine the percent change in rolling resistance due to under-inflated tires I used data from the Transportation Research Board's Tires and Passenger Vehicle Fuel Economy: Special report 286 (2006). For each decrease in psi of a tire between 24 and 36 psi, the rolling resistance increases by 1.4%. For pressures lower than 24 psi, the increase in rolling resistance is greater than 2%. For each increase in psi from ideal pressure of a tire, there is no set relationship to rolling resistance (therefore my study will only look at under-inflated tires). To calculate the percent change in rolling resistance for tire pressure falls within the range of 36-24 psi, the tire pressure deviation is multiplied by the rolling resistance factor of 1.4%. To calculate the percent change in rolling resistance if the tire pressure falls below the range of 24 psi, the deviation from ideal to 24 psi is multiplied by 1.4% and then added to the remaining deviation which is multiplied by 2%. Formulas for all calculations can be found in Appendix B.

Fuel economy is measured in miles per gallon (mpg). According to the Transportation Research Board, a 10% reduction in a tire's rolling resistance can increase the fuel economy of the car by 1-2%. The recommended tire pressure for all passenger vehicles, from trucks, cars and

[2] The selection of these sites was based on the fact that most people take their vehicles to the dealership during the warranty period, and afterwards take the vehicle to independent repair shops, so I sampled one of each.
[3] Data were collected from September 19th to December 19th to attempt to capture temperature variation of late summer to early winter, though temperature was not specifically engaged in this study.

SUV's all lie within the range in which the linear relationships between rolling resistance and tire inflation are applicable, so at this stage, I did not differentiate between types of vehicles.

To fully account for the range of a 1-2% change in fuel economy I created three separate scenarios: High (a 2% change in fuel economy per 10% change in rolling resistance), Medium (a 1.5% change in fuel economy per 10% change in rolling resistance), and Low (a 1% change in fuel economy per 10% change in rolling resistance). These scenarios were kept separate through the rest of my calculations. To calculate the change in fuel economy I multiplied the change in rolling resistance by the percent change in fuel economy per 10% change in rolling resistance. Each tire acts on the axle separately therefore, the overall deviation of fuel economy can be summed over all four tires.

Using data from the California Department of Transportation's California Motor Vehicle Stock, Travel, and Fuel Forecast (2005) on the average number of miles driven per car per year and the average fuel economy of the fleet of cars in California, I calculated the gallons used in an ideal situation, where every car has perfectly inflated tires. I then used the percent reduction in fuel economy to calculate the number of gallons used when tires are under-inflated. The difference between the number of gallons in the ideal case and the case of under-inflated tires is the number of gallons the average driver could expect to save through maintaining accurate tire pressure

The calculations using California State data were conducted for the categories Car and Truck due to the difference in miles driven and gas mileage between the two categories. These categories are defined by federal classifications. In my study, Truck refers to Class 1 Trucks, or trucks that weigh less than 6,000 pounds. Class 1 trucks include most passenger trucks.

While using averages for miles driven per car per year and the fuel economy of the fleet of cars may seem overly simplified, one job of the Department of Transportation is to collect and consolidate data that accurately reflects the manufacturer mileage, the different models of the existing fleet, and differences between those who drive a lot and hardly at all. Re-aggregating the data on miles driven and mileage would be redundant therefore the values in the California Motor Vehicle Stock, Travel, and Fuel Forecast can be used.

Cost-Benefit Analysis To determine the benefits of TPMS, the gallons saved per year were translated into a dollar amount by multiplying the number of gallons saved by the average price of a gallon of regular unleaded gasoline over the past year ($2.87 per gallon of gasoline, from February 2006 to January 2007 (Automobile Club 2007)).

Using the standard discounting formula (Appendix B, #11), I calculated the present value of the yearly savings due to accurate tire pressure for each of ten years following the installation of TPMS. In my discounting formula, I used 5% as the discount rate, to reflect the current risk-free rate[4]. I then summed the present value of the yearly benefits in year increments to reflect the amount that people might expect to save over time.

The costs will be determined through looking at the prices of direct Tire Pressure Monitoring Systems (TPMS), since they can detect a drop of only one or two psi (Department of Transportation 2004). According to the Department of Transportation, prices for tire pressure monitoring systems range from $69 - $109 (this price includes every item needed for the TPMS including costs of installation/maintenance). The Department of Transportation (2004) believes prices will converge to the lower band as the systems become more efficient with use and experience. Currently TPMS are not widely available to individual consumers and as such must be specially ordered. Prices of specially ordered items do not accurately reflect the potential price with greater availability. Due to these factors, I used the lowest cost of TPMS to manufacturers and applied a retail markup of 100% to determine the retail cost to individual consumers[5]. This cost can then be compared to the calculated benefits to determine the net effects in different time periods.

Greenhouse Gas Reduction To determine the amount of GHG's that could be reduced through statewide accurate tire pressure, I first determined the total number of gallons of gasoline saved by aggregating the number of gallons of gasoline saved per vehicle (from earlier part of my study) across all Cars and Trucks in California. The total number of Cars and Trucks was determined through California State Car registration data.

I then multiplied the total number of gallons saved by the number of pounds of CO_2 released per gallon (20 pounds of CO_2 released per gallon of gasoline, (Black 2005)) to determine the emissions savings. I then divided this savings by the current level of California's CO_2 emissions to determine the percent reduction of CO_2 that could be achieved through accurate tire pressure.

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[4] Discount rate choice is currently a hotly debated topic. Any discount rate from 1% to current market rates is acceptable (Zilberman, 2007). Higher discount rates lead to more conservative estimates because they lower the present value of future sums of money.

[5] Retail markups vary widely in the auto industry and 100% is towards the high end of the spectrum; I used this markup to arrive at a more conservative estimate.

The current level of CO_2 emissions was determined from the summary of the California GHG emission and sinks inventory.

If the cost of fitting a TPMS to one's car is outweighed by the benefits combined with a substantial reduction in GHG's that occurs from the reduction of fuel use, it may be wise policy to mandate the use of these devices. The fuel savings would negate any economic hardship imposed by mandating these devices. In addition this legislation would help reduce GHG emissions as well. If, however, the costs outweigh the benefits then it may not be a wise policy move to require them, though increases in fuel economy and reduction of GHG's could be enough to encourage voluntary tire pressure checking.

Results

Cost Benefit Analysis. Data from the Honda service center and Ed's Auto repair shop showed a near normal distribution for tire pressure deviations (Figure 1).

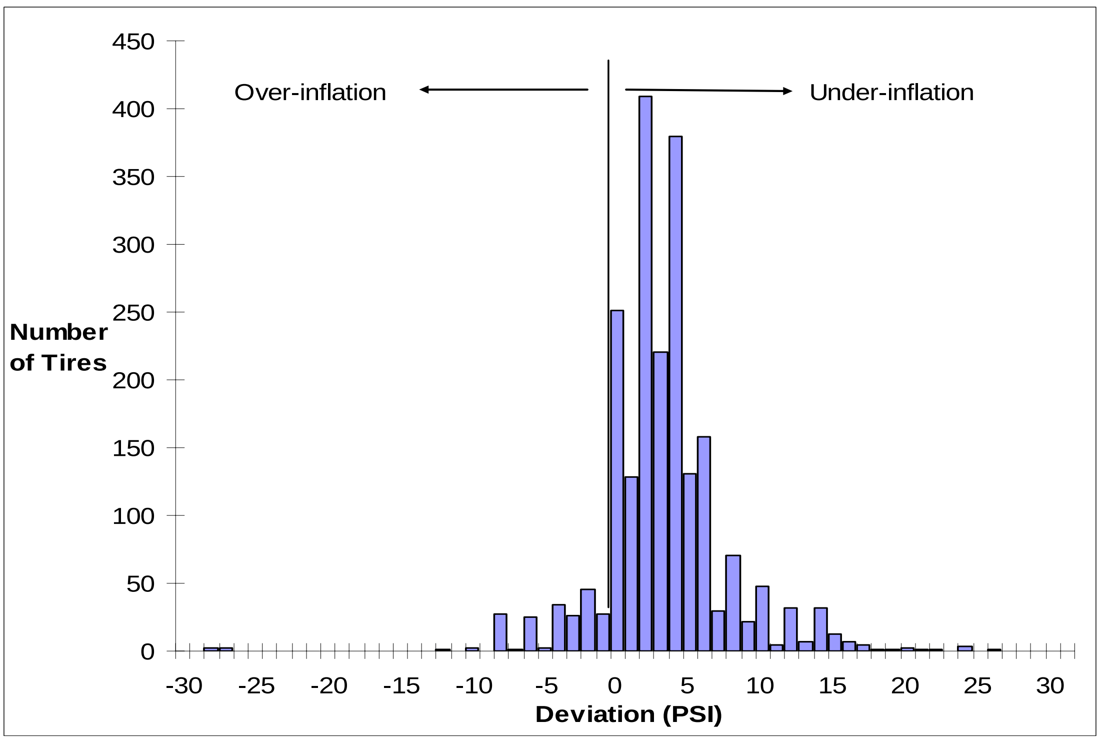

Figure 1: Tire Pressure Deviation Distribution

The data presented encompass deviations for all four tires, though the distribution of psi deviations for each tire is comparable. The bulk of data points (91%) indicate under-inflated tires (Figure 1).

All four tires showed, on average, a significant under-inflation ($n=536$ and $p<0.01$ in all four comparisons. A t-test compared actual inflation with ideal inflation). The average I used in the rest of my calculations is based on only the under-inflated tires because, as discussed in the methods section, over-inflated tires do not have the same relationship to rolling resistance and fuel economy as under-inflated tires.

Average tire under-inflation ranged from 3.78 ± 0.15 (mean ± SE) to 4.18 ± 0.16 psi (Table 1).

Table 1: Average Tire Pressure Deviation for each Tire

	Right Front (psi)	Right Back (psi)	Left Front (psi)	Left Rear (psi)
Average under-inflation of tires	3.94	4.18	3.91	3.78
Standard Error of the Average	0.15	0.16	0.15	0.15

I took the averages presented in Table 1 and applied the relationships between tire pressure under-inflation, rolling resistance and fuel economy that were presented in the methods section. These relationships resulted in a percent decrease in fuel economy due to under-inflated tires and both gallons and dollars saved per year (Table 2).

Table 2: Decrease in fuel economy, and savings in gallons and dollars per year for Car and Truck

		Car		Truck	
	% decrease in fuel economy	Gallons/year	$/year	Gallons/year	$/year
High*	4.4%	26.94	77.26	27.73	79.52
Average**	3.3%	19.97	57.28	20.56	58.96
Low***	2.2%	13.16	37.75	13.55	38.86

*High = 2% change in rolling resistance for a change of one psi
** Average = 1.5% change in rolling resistance for a change of one psi
*** Low = 1% change in rolling resistance for a change of one psi

The savings are broken down by type of vehicle in Table 2. The monetary savings of gasoline presented in Table 2 are based on a price of $2.87 per gallon, the average price of regular unleaded in California from February 2006-January 2007, according to the Automobile Club. It should be noted that savings will be higher for individuals who purchase higher grades of gasoline. The yearly monetary savings range from $38-$77 for Cars and $39-$80 for Trucks.

These values, though not overwhelmingly large on face value, must be looked at over time and in comparison to the cost of the TPMS.

The cost of a TPMS to a consumer would be a retail markup over the wholesale price of $69. The standard retail markup for the automobile industry is roughly 100%, so the final cost of a TPMS to a consumer would be $138. No present value needs to be computed because this cost would be incurred in the base year. The financial benefits associated with reduced fuel consumption are compared to this value. The benefits in each scenario are the present value of the benefits summed through the years from installation (Figure 2, 3). The present value calculations are based on a 5% discount rate.

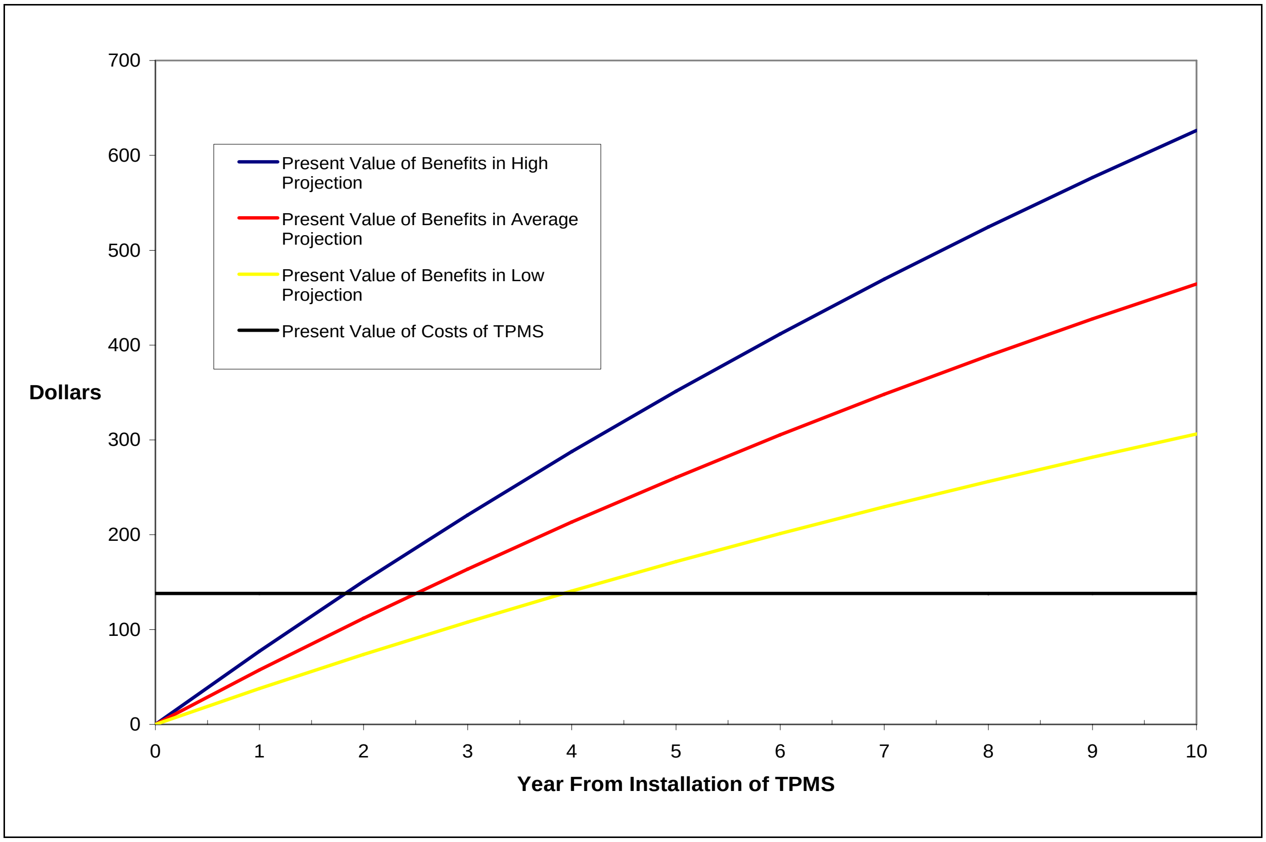

Figure 2: Cost/Benefits of TPMS in Cars, under 3 scenarios for rolling resistance and fuel economy relationships. Where the benefit line crosses the black line, costs = benefits from the view of the present.

In Cars, the present value of the benefits from installing TPMS in Cars exceeds the cost of the TPMS after a period of 2 to 4 years (Graph 2).

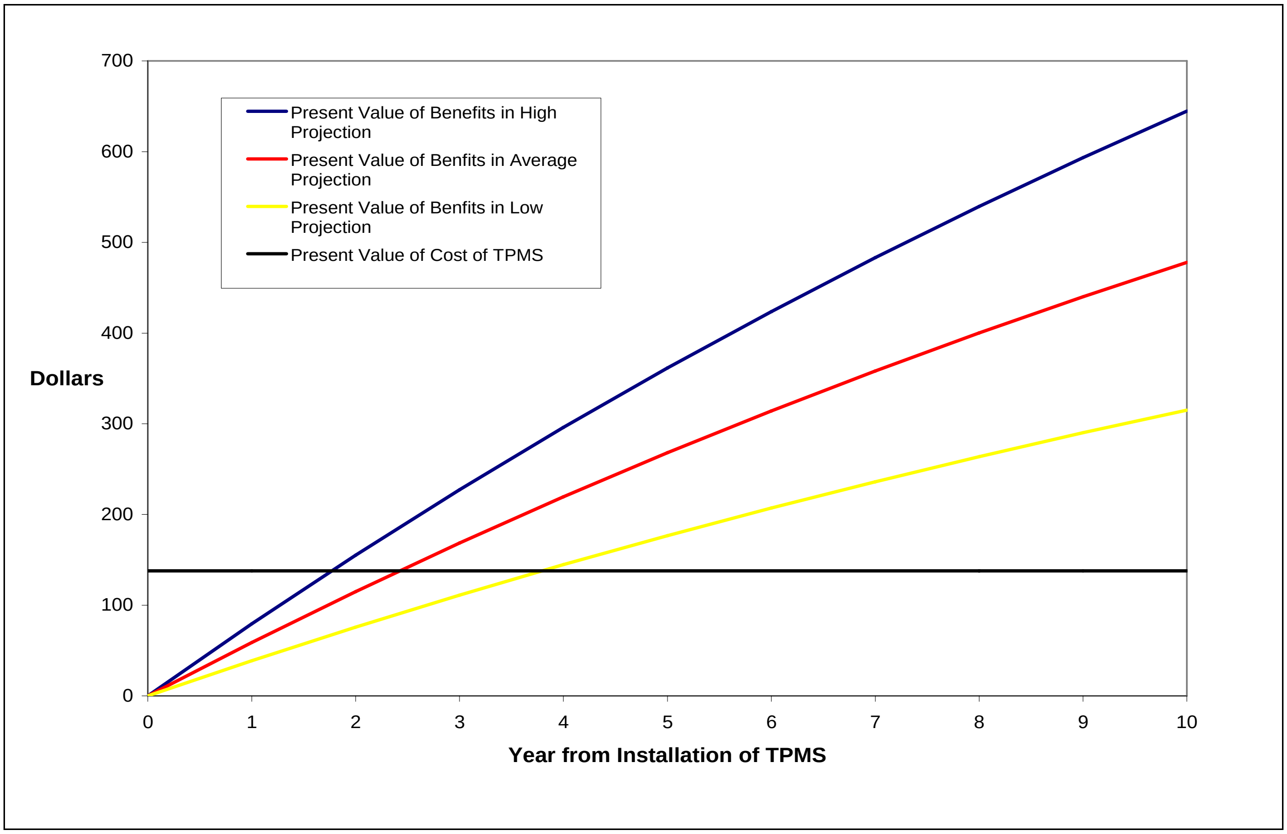

Figure 3: Cost/Benefits of TPMS in Trucks, under 3 scenarios for rolling resistance and fuel economy relationships. Where the benefit line crosses the black line, costs = benefits from the view of the present.

In Trucks, the present value of the benefits from installing TPMS also exceeds the cost of the TPMS after a period of 2 to 4 years (Graph 3).

Greenhouse Gas Reduction Gasoline savings were pooled for Cars and Trucks to examine emissions scenarios in each of the High, Average, and Low categories. The amount of CO_2 emission reduction by having accurate tire pressure is between .69% and 1.42% of total CO_2 emissions (Table 3).

Table 3: Gallons saved and GHG information

	High Scenario	Average Scenario	Low Scenario
% of Total CO_2 emissions Saved	1.42%	1.05%	0.69%

These percents, while not as large as I hypothesized, may still be important because they can yield net economic benefits within 2 to 4 years of installation of TPMS.

Discussion

The monetary benefit from reduced gasoline consumption is greater than the cost of installing a TPMS. In fact, the payback period is relatively short for both Cars and Trucks. In the

High scenario (a 2% change in rolling resistance for a change of 1 psi), one could expect full economic compensation within two years. In the Low scenario (a 1% change in rolling resistance for a change of 1 psi), one could expect full economic compensation within four years. The similarity in the payback period between Cars and Trucks was not expected. Looking more closely at the data, however, revealed that while trucks have considerably lower gas mileage, overall they encounter less driving annually, negating their poor mileage in terms of the net effect of TPMS.

My estimates might be too conservative for several reasons. Government reports on tire pressure deviation indicate that 27% of cars have at least one tire that is under-inflated by at least 8psi (National Highway Traffic Safety Administration 2001A). The data I collected from the Honda service center and Ed's Auto repair shop in Berkeley shows 19% of cars having at least one tire under-inflated by at least 8psi. If the 27% figure is more representative of cars in California, the average deviation of tires would be higher. This would mean that the fuel savings and greenhouse gas reductions that could be gained from accurate tire pressure would be higher than I estimated.

The difference in the percent of cars with tires under-inflated by 8psi or more may result from the fact that the climate in Berkeley tends to be more temperate than in other areas of the state. Temperature is a key factor in pressure, and more extreme temperatures could result in larger deviations. In general, my data were gathered from a small subset of the population of California that may not ideally represent the actual population. A more thorough study would have gathered data throughout the state. Since other research efforts indicate a higher level of under-inflation than my data indicates, it is likely that the average fuel savings is higher than my study indicates. This would only strengthen the argument that TPMS would be a worthwhile investment.

My data were heavily weighted toward Honda's, which is not representative of the State of California. If Honda's are more or less likely to have under-inflated tires, this could introduce bias, although I do not know what direction the potential bias lies in.

My results are based on several assumptions, such as if everyone installed a TPMS on their car, they would maintain accurate tire pressure. This is an unlikely assumption as many people might not take the time to accurately inflate their automobiles tires even if aware that they are under-inflated. This assumption is likely to cause my results to be lower than they would be otherwise. Another key assumption was a 5% discount rate for the present value of gasoline savings calculations, which may be a relatively high discount rate. Lower discount rates increase the present value of future monetary benefits. However, even with discount rates between 1-8%, the payback period is still within a range of 2 to 4 years. This indicates that the level of benefits is not highly sensitive to the discount rate, and a payback range of 2 to 4 years is likely to be accurate in the context of my study.

While my first hypothesis is supported, my second hypothesis was not upheld. My calculations show that due to accurate tire pressure, California could hope to see between a 1.42% and a 0.69% reduction in CO_2 emissions. This is notably lower than the 2.5% that I hypothesized. To achieve a 2.5% reduction, tire pressure deviation would have to be in the range of 6.7 psi/tire for the High scenario and 13.4 psi/tire for the low scenario. As discussed above there is evidence that I under-estimated tire pressure deviation. However, since government collected data shows that 27% of cars have at least one tire under-inflated by 8psi or more it is unlikely that the average tire pressure deviation is between 6.7-13.4 psi. Depending on the magnitude of tire pressure under-inflation in other areas of the state, the amount of CO_2 reduction could potentially be more than my calculated range, but not as high as a 2.5% reduction.

Despite the fact that my study shows a reduction in CO_2 of only 1.42% to 0.69%, it could still be a valid policy tool to require TPMS on existing cars. Policy makers have recognized the benefits of accurate tire pressure by requiring that TPMS's be built into new cars in the future. This decision was based on both fuel economy concerns and safety concerns. Safety concerns are another segment of the benefits derived from accurate tire pressure, but are outside the realm of this study.

In addition, it is unlikely that any one measure would achieve California's CO_2 reduction goal. The public is often wary of pollution reduction requirements, as they are often thought to coincide with a reduction in economic growth or profits. My study clearly illustrates that accurate tire inflation has a measurable impact on CO_2 emissions and provides economic benefits to consumers who plan on maintaining possession of their vehicle for more than 2 to 4 years. TPMS should be addressed in the discussion for CO_2 reducing strategies for California.

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Appendix A

	Right front		Left front		Right rear		Left rear	
Car Model	Actual	Ideal	Actual	Ideal	Actual	Ideal	Actual	Ideal

* All values are measured in psi

Appendix B

Formula	Variable Definitions
1) $TP_D = \sum (TP_I - TP_A)/N$	TP_D = Average Tire Pressure Deviation (psi) TP_I = Tire Pressure Ideal (psi) TP_A = Tire Pressure Actual (psi) N = number of tires being averaged
2) $RRC = TP_D * RR_1$	RRC = % change in Rolling Resistance RR_1 = 0.014 (Rolling Resistance factor 1).
3) $RRC = (TPI-24)*RR_1 + (TP_D - (TPI-24))*RR_2$	$RR_1 = 0.014$; $RR_2 = 0.02$ TPI = mode of ideal tire pressure
4) FC = RRC*(FF/.1)	FC = % change in fuel consumption FF = Fuel consumption Factor (.02 in High, .015 in Average, and .01 in Low.
5) $TFC = \sum FCt$	TFC = Total percent change in fuel consumption FCt = % change in fuel consumption for one tire.
6) MPGa = MPG*(1-TFC)	(*)MPG = miles per gallon MPGa = miles per gallon with under-inflated tires Values with a (*) next to them were found in the California's Department of Transportation's California Motor Vehicle Stock, Travel, and Fuel Forecast.
7) Gi = M / MPG	(*)M = average miles driven per year Gi = Gallons used in ideal case Values with a (*) next to them were found in the California's Department of Transportation's California Motor Vehicle Stock, Travel, and Fuel Forecast.
8) Ga = M / MPGa	Ga = Gallons used in under-inflated tires case
9) Gs = Ga-Gi	Gs = Gallons saved by having ideal tire pressure
10) Si = Gs*Pg	Si = savings for an individual driver in one year Pg = Price of a gallon of gasoline, $2.87
11) PVt = Si/((1+r)^t)	PVt = Present Value of Benefits in Year t r = discount rate t = year.

12) PVi = ∑PVt	PVi = Present Value of All Benefits from Present till year i.
13) CS = Gs*CF	CS = Pounds of CO_2 saved through having accurate tire pressure CF = Pounds of CO_2 released per gallon of gasoline burned
14) %CR = CS/TCE	%CR = percent of CO_2 reduction TCE = total California CO_2 emissions