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TIRE OPERATIONAL AND SUSTAINABILITY TRADEOFFS

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16. Abstract

This report forecasts likely changes in passenger car and light truck fuel economy through 2025 as a result of projected tire evolution with respect to aspect ratio and design inflation pressure. Tire-material evolution over the last decade is expected to continue. Tire aspect ratios from 55 to 85 are examined, along with cold inflation pressures from 35 to 50 psi. The forecast fuel economy change is the primary factor considered in evaluating tire sustainability. The secondary factor considered is the change in raw material usage, which affects tire weight. The changes are predicted for the five vehicle powerplants now in use: gasoline, diesel, hybrid, plug-in hybrid, and battery electric. Vehicles from class A to class E plus pickup trucks are analyzed. This is done with consideration of expected changes in vehicle weight. Tire sizes that are likely to be used, as the vehicles change, are estimated.

It is possible that operational tradeoffs may preclude tire changes that are desirable in terms of sustainability. To this end, probable ride and handling effects along the different possible tire-evolution paths are assessed. Aspects of ride that are considered are harshness, modal frequencies, and in-vehicle noise. Cornering in the ordinary driving range, stopping, and the limits of cornering are examined as aspects of handling. Effects on wet and on snowy surfaces are considered as well as behavior on dry surfaces.

The conclusion reached is that the best tire technical path to follow from now until 2025 is to use higher-aspect-ratio tires operating at higher-cold-inflation pressures, provided that any negatives in ride and handling can be overcome in vehicle design. Styling questions are not considered in the report, but it is noted that these could be an important problem, since the tires on the technically desirable path will not have the appearance that customers have been accustomed to.

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passenger tires, light truck tires, rolling resistance, tire weight, aspect ratio, inflation pressure, cornering properties, braking, harshness, uniformity, in-vehicle noise, fuel economy, gasoline powered, diesel, hybrid, plug-in hybrid, electric vehicles

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Contents

Introduction

One of the current, major national goals is to sharply reduce energy consumption for personal transportation, in order to reduce greenhouse emissions (primarily carbon dioxide) and increase security of energy supply. Specifically, for passenger cars and light trucks, the new Corporate Average Fuel Economy (CAFE) standard calls for an average of 54.5 mpg by 2025, as opposed to the 27.5 mpg that was applicable until 2010 [1].[1, 2]

Tires, which make highway transportation feasible [4], are an important contributor to vehicle energy consumption primarily because of the hysteretic properties of the viscoelastic materials, which form all the tire structure, except for the reinforcing cords. Viscoelastic materials generate heat as the tire is deformed in rolling. At the same time that energy loss is occurring, the tires are generating all vehicle control forces and providing crucial vibration absorption. Both of these vital characteristics also depend on the viscoelastic properties of the tire materials. In addition, tires must simultaneously provide structural safety in very challenging conditions. The design problem is a complex engineering tradeoff in terms of materials properties and structural design.

The choices that must be made by original equipment (OE) vehicle designers in response to the mandated fuel consumption reductions will force adoption of revised designs by tire manufacturers.

Purpose

The purpose of this report is to forecast likely future changes in fuel consumption and certain operational capability when following several technically feasible tire-design path changes. The predicted tire changes for light vehicles, passenger car (PC) and light truck (LT), are intended to help vehicle designers meet the mandated fuel-consumption improvements from now until 2025, while retaining proper vehicle operational characteristics.

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[1] Numbers in square brackets are references listed in the References section.

[2] The 54.5mpg is a value derived on the basis of the traditional EPA test using unadjusted combined mileage. “The combined ‘real world’ or sticker result customer’s will see on a vehicle’s window sticker will be about 20% lower – 45.4 mpg for cars and 32.1 mpg for light trucks under 8500GVW, for a projected car/light truck fleet average of 40 mpg.” [2] Comparable information for larger vehicles is contained in Reference 3.

Projected Vehicle and Tire Evolution

Vehicle evolution at the OE level, to meet the mandated CO_2 emissions goals while retaining operational practicality and rationally containing costs, will drive changes in tire design. In turn the tire-design changes will feed back into the vehicle-design process determining what vehicle-design changes are indeed practical. Because there is no way to simulate the precise feedback process that will occur, the report will present highly likely final vehicle characteristics based on the literature and engineering judgment. These projected final vehicle properties will be the starting point for the discussion of tire operational capability and fuel consumption, which is the purpose of this report.

Though the basic underlying goals are expressed in terms grams of CO_2 per mile (light vehicles) or grams per load-ton per 100 miles (medium and heavy vehicles), this report is expressed in the more common terms of fuel amount, distance, and weight. Also, in many cases (because it is more mathematically sensible) the discussion is phrased in terms of fuel consumption in gallons per mile rather than in fuel economy terms, miles per gallon. Figure 1 shows the relationship of mpg to gpm.

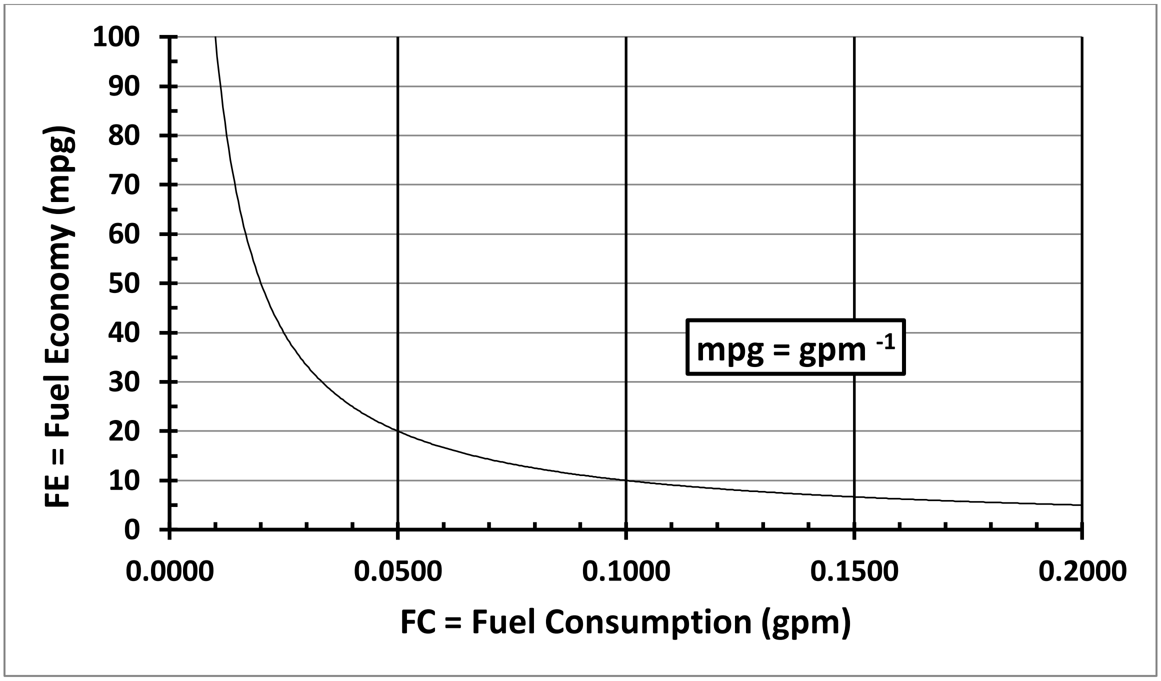

Figure 1. Fuel economy vs. fuel consumption.

Projected Light Vehicle Evolution Through 2025[3]

The mandated increases in unadjusted combined fuel economy that will drive light-vehicle evolution take the form shown in Figures 2 and 3.[4] These are year-specific curves formed of three line segments based on the vehicle footprint [1], which is the average vehicle track multiplied by the wheelbase expressed in square feet. Table 1 shows the 2013 and 2025 unadjusted segment values with their window-sticker equivalents. For clarity, mandated fuel economy evolution for average A, B, C, D, and E class passenger cars, defined in Table 2, is shown in Figure 2.

Typical standard-cab full-sized pickup trucks are shown in Figure 3. The truck examples are averages of data for Dodge Ram 1500, Ford F-150, and Toyota Tundra pickups with appropriate engine, driver train, and bed sizes to produce the plotted examples.

Table 1
Fuel economy break points.

Year	Passenger Car			Light Truck		
	Footprint (ft^2)	Unadjusted mpg	Sticker mpg	Footprint (ft^2)	Unadjusted mpg	Sticker mpg
2013	41	37	28	41	31	24
	56	28.5	22	66	22.5	17
2025	41	61	43	41	50	37
	56	46	34	74	30	23

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[3] This report treats the current 2025 CAFE goals for passenger cars and light trucks as a certainty. The mandated 2018 review may alter the 2025 goals considerably, but it is not feasible to consider this question at this time, since the review will use the experience from now until 2018 in arriving at an answer.

[4] The large footprint breakpoint for light trucks is set to evolve over time in such a fashion as to inhibit introduction of trucks made larger to get around the fuel-economy mandate.

Table 2
Car sizes[5].

European Segments (Classes)	American Colloquial	Volumes (ft^3)	Example Average Footprint[6] (ft^2)	Vehicles Used to Compute an Average Class Footprint
A	Minicompact	$V < 85$	31.04	Scion=iQ
				Smart For TWO
				Fiat 500
B	Subcompact	$85 \leq V \leq 100$	39.42	Ford Fiesta
				Mini Cooper Coupe
				Toyota Yaris
C	Compact	$100 \leq V \leq 110$	44.27	Chevy Cruze
				Ford Focus
				VW Jetta
D	Midsize	$110 \leq V \leq 120$	47.64	Chevy Malibu
				Ford Fusion
				Honda Accord
E	Full-size	$120 \leq V$	48.98	Chevy Impala
				Ford Taurus
				Toyota Avalon

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[5] These are some of the possible descriptions and tabulations. The correlation of the different descriptions is not absolutely rigorous, so others may define these somewhat differently.
[6] These were the ones used for each class in plotting Figure 2 based on the average for the example vehicles in each class.

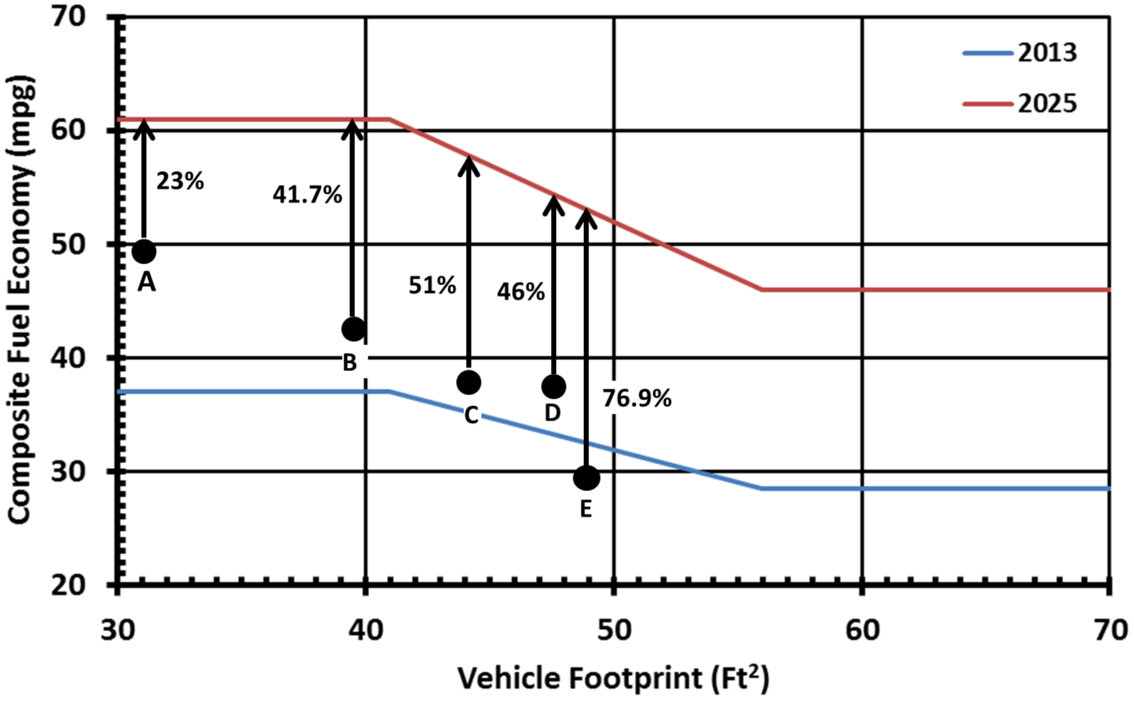

Figure 2. Mandated passenger car fuel economy: vehicle class examples.

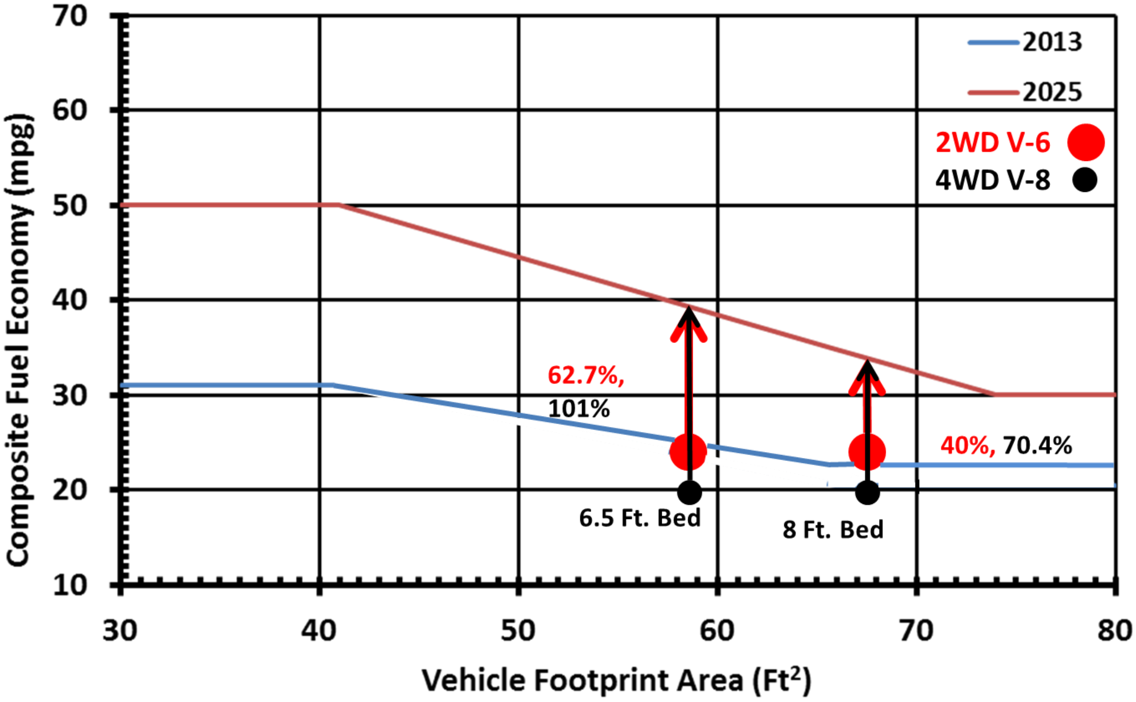

Figure 3. Mandated light truck fuel economy: full-sized standard cab examples.

While achieving the mandated fuel economies, it is expected that light vehicles will evolve such that the following will be true.[7]

1. Vehicle weight will be sharply reduced perhaps by as much as 30 percent dependent on vehicle class. Carbon fiber composites would be ideal from a weight reduction standpoint, however, questions of recyclability and cost may inhibit their broad use.
2. Vehicle-interior volume within a vehicle class will remain fundamentally the same for reasons of passenger room (people do not downsize well) and maintenance of load carrying capacity.
    a. Crash safety requirements, which will become more stringent, will also inhibit overall vehicle size reductions as there is a need for crush space to control occupant accelerations during a crash.
    b. For passenger vehicles there could be a size/weight conflict with respect to fuel economy when aerodynamics is considered. It is difficult to do good aerodynamics for something as boxy as a Class A or B vehicle.
3. Powerplants for vehicles (engines, motors, energy storage, and regenerative braking systems) will evolve to emphasize thermodynamic efficiency.

2013 Fuel Consumption vs. EPA Test Weight

As a start, it is necessary to look at probable fuel consumption as a function of EPA vehicle test weigh (curb weight plus 300 pounds) for the types of propulsion systems expected to be in use in 2025.[8] Schuring [5] observed that EPA combined fuel economy is a hyperbolic function of vehicle test weight with a good fit. Therefore, it seemed reasonable to expect that expressing vehicle fuel consumption as a function of EPA test vehicle weight should lead to a first-order linear approximation. Indeed it does, as will be shown by examples for gasoline-fueled passenger cars (PCs), light trucks (LTs), diesel PCs, hybrid PCs (HEVs), plug-in hybrid PCs (PHEVs), and electric PCs (EVs), based on data gleaned from EPA information [6] and curb weight data publically available from OEM sales brochures. Finally, all the powerplants are compared.

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[7] Autonomous vehicles are not considered because there is no obvious way to consider their potential effect. Also, it is not certain that they will be part of the vehicle population unless liability law is specifically revised to consider them.

[8] In this comparison thermodynamic evolution of the individual propulsion systems is not projected.

In some cases certain assumptions, such as the theoretical (0, 0) point inherent in the chosen model, had to be invoked due to sparse data. (0, 0) was treated as a data point, but the intercepts were not forced through (0, 0).

Gasoline Passenger Cars and Light Trucks

Gasoline-fueled cars and light trucks have comprised almost all of the US light-vehicle fleet for many years. Separate analysis of EPA and sales-brochure data for PCs and LTs yielded almost identical response models, as a function test weight. Noting this, PC and LT data were combined to form Figure 4.

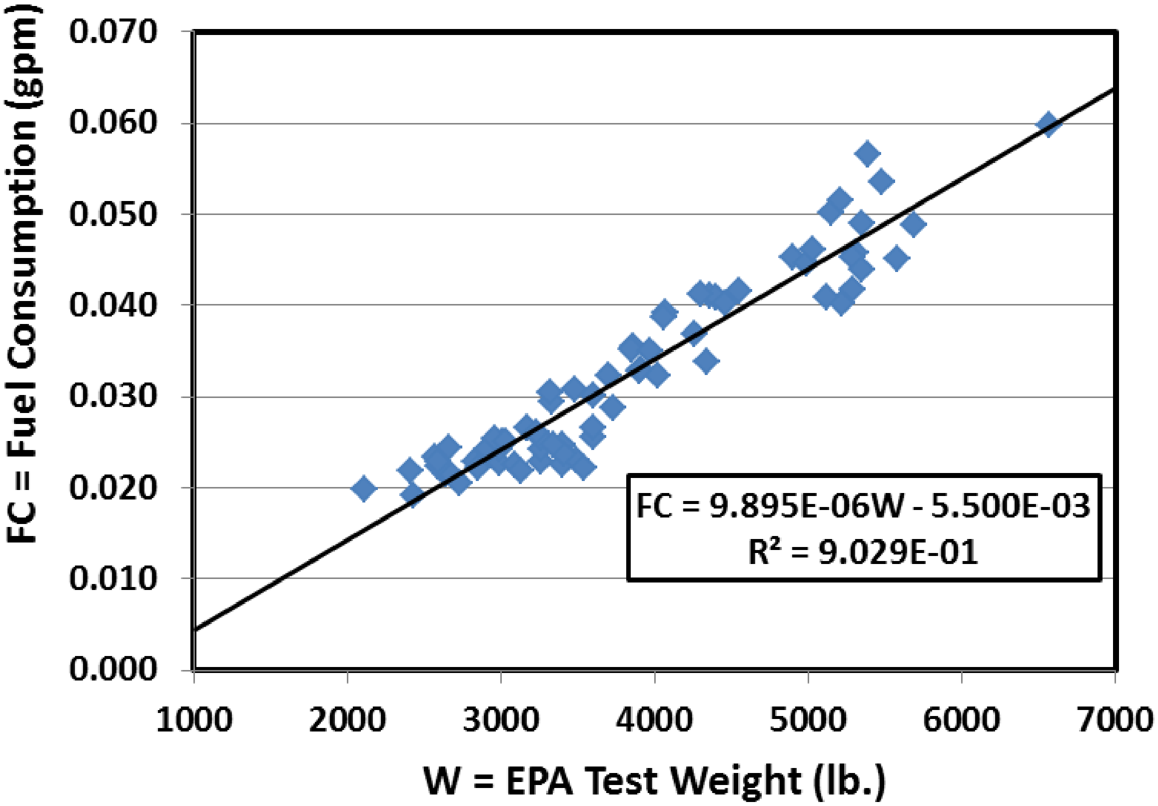

Figure 4. Unadjusted combined fuel consumption for gasoline fueled vehicles.

In the case of gasoline-fueled vehicles assuming the validity of the theoretical point (0, 0) leads to FC = $9.6531X10^{-6}W – 4.5078X10^{-3}$; $R^2 = 0.91$—a reasonably good comparison to the fit in Figure 4.

Diesel Passenger Cars

The EPA data, which are relatively sparse, contain only data from passenger cars and certain SUVs that are heavy enough to be considered light trucks. However, given the weight range covered in the data and the fact that the gasoline and diesel vehicles are essentially the same except for engine type, the data shown in Figure 5 will be assumed to be applicable to both passenger cars and light trucks.

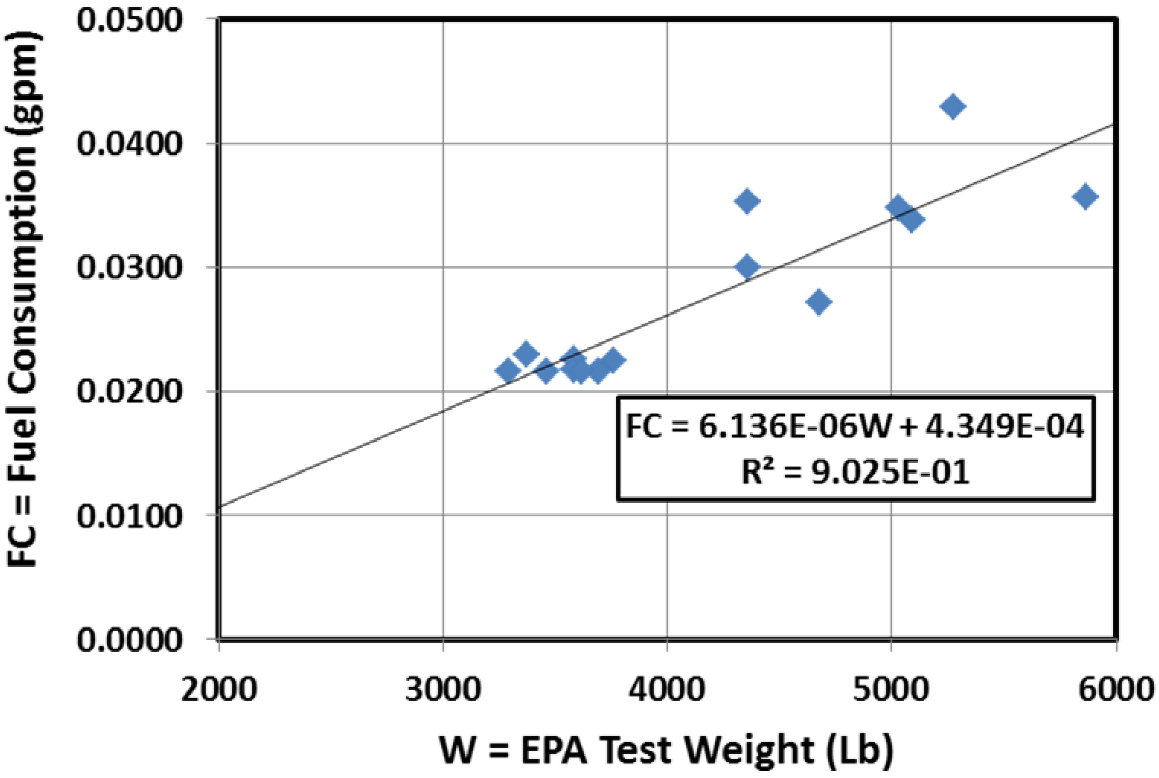

Figure 5. Unadjusted combined fuel consumption for diesel vehicles.

In the case of diesel-fueled vehicles assuming the validity of the theoretical point (0, 0) leads to FC = $7.0028\text{X}10^{-6}$W – $1.5912\text{X}10^{-3}$; R^2 = 0.89—again a reasonable comparison to the fit in Figure 5.

Comparison of Figures 4 and 5 shows the expected fuel economy advantage for the diesel with respect to the gasoline-fueled vehicle. Approximately, a 10.5 percent difference should be expected just based on the energy content difference between a gallon of diesel fuel and a gallon of gasoline, if the engines were of equal thermodynamic performance. Other effects arise because of the better thermodynamic efficiency of the diesel. The diesel becomes more advantageous with respect to fuel economy as vehicle weight increases.

Electric Vehicle (EV)

The EPA data are sparse and almost all for PCs. Therefore, in producing Figure 6 the theoretical point (0, 0) was considered to be a valid part of the data set. The result shows that electric vehicles are certainly quite efficient when measured in equivalent gallon-per-mile electrical terms (gpm_e) using a wall-to-wheel viewpoint. The wall-to-wheel viewpoint says that what we care about is operation of the EV measured in terms of the power applied to it at the charging station and not in powerplant CO_2 emission terms. EPA took this view because the CO_2 behavior is so different for solar, wind, hydro, nuclear, or coal that it cannot be made sensible at this time. Over time fossil-fuel generating stations will cease to exist in any case, so this is a long-view measure of EV fuel economy.

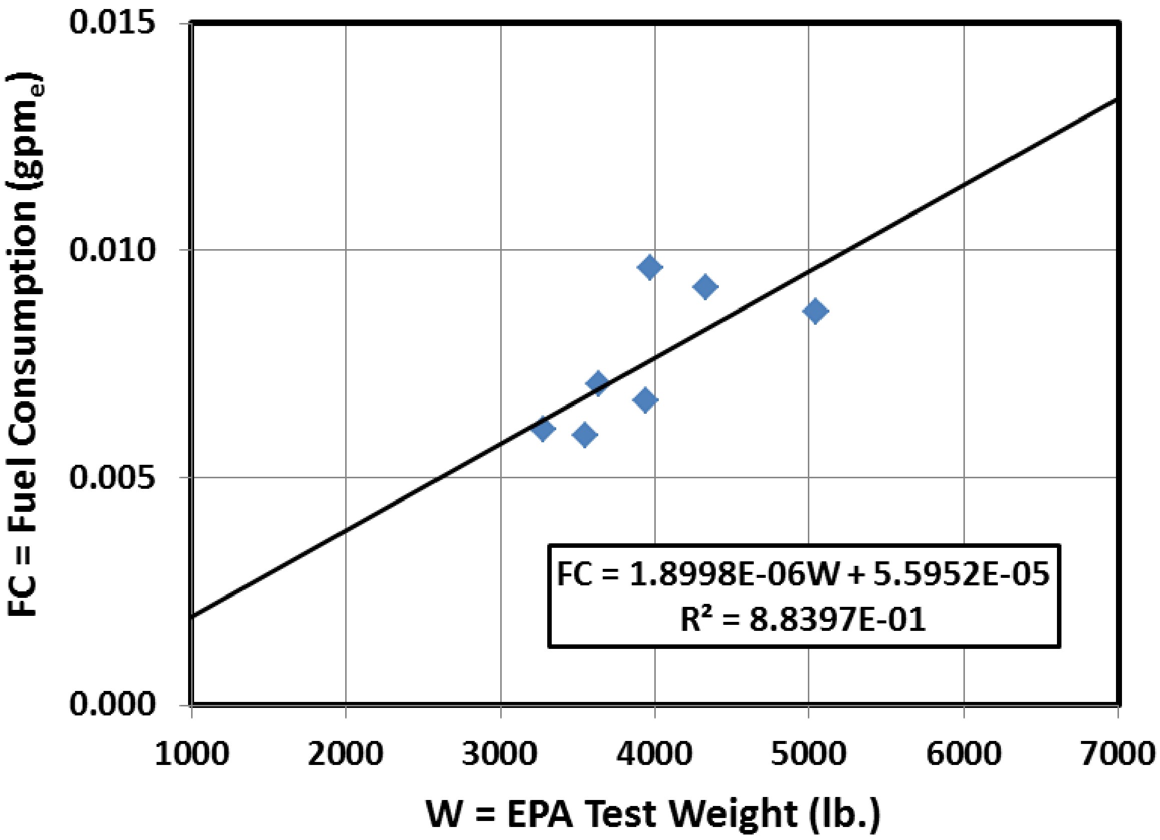

Figure 6. Unadjusted combined fuel consumption for electric vehicles.

Hybrid Vehicle (HEV)

The data are sparse and variable at a given weight with the different hybrid systems in use. A decision was made to characterize HEV behavior on the basis of the collection of vehicles produced by Toyota and to consider the theoretical point (0, 0) a valid part of the data set. Figure 7 is the result.

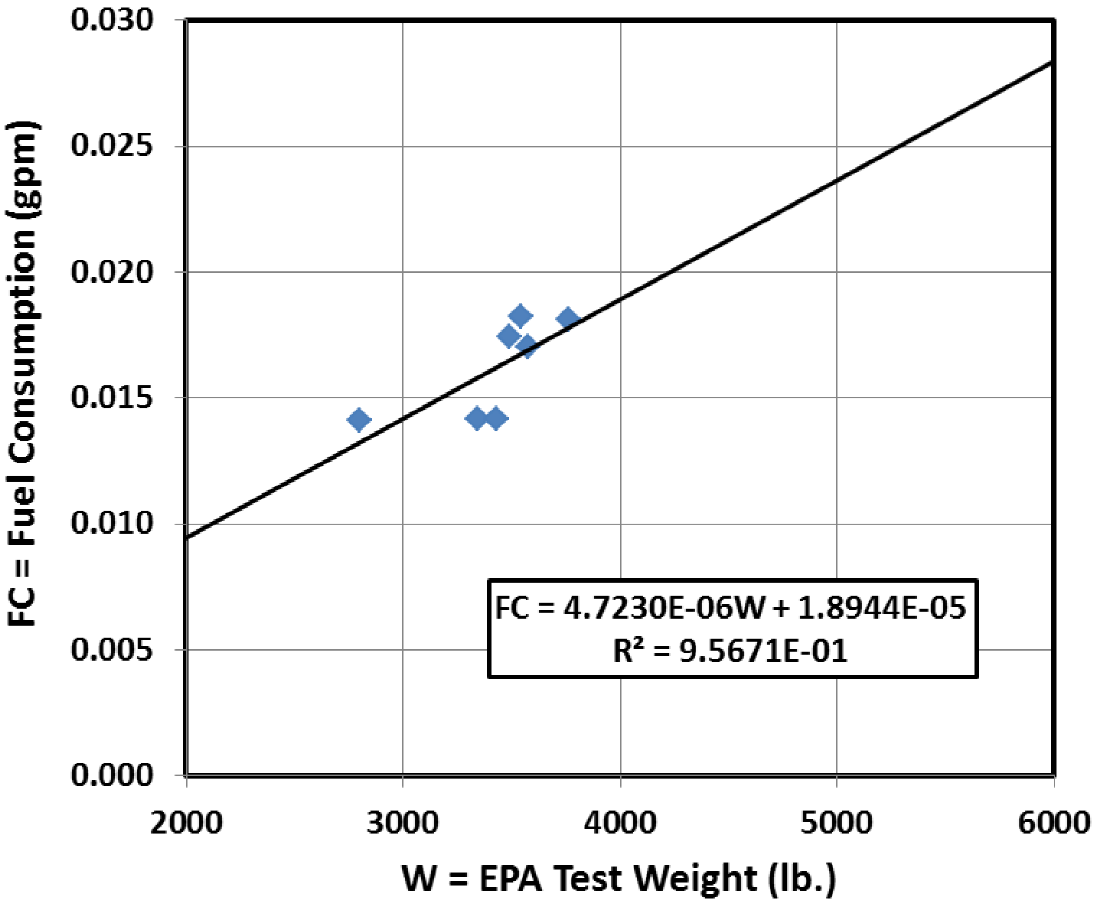

Figure 7. Unadjusted combined fuel consumption for hybrid vehicles.

Plug-in Hybrid Vehicle (PHEV)

Again the data [7] are sparse. The combined fuel consumption in Figure 8 was computed from the sticker data applicable to the cars considered. The theoretical point (0, 0) was considered a valid part of the data set.

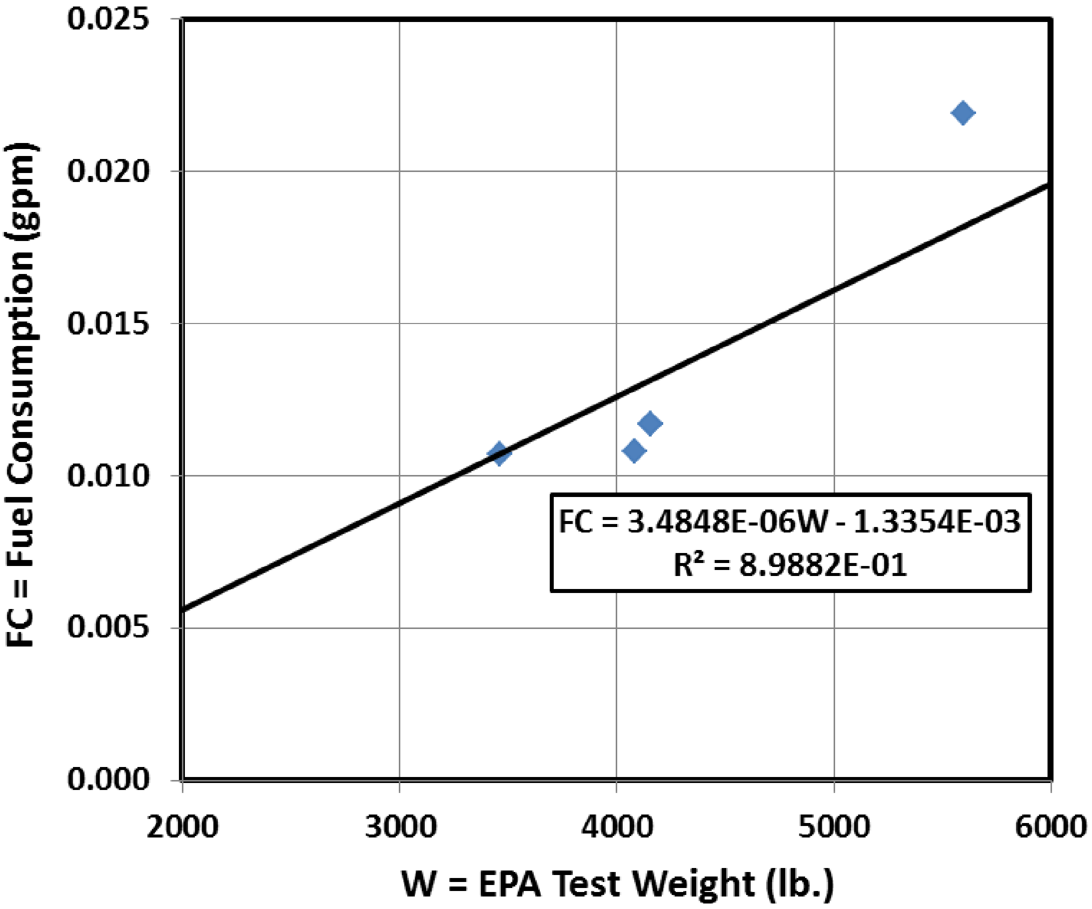

Figure 8. Unadjusted combined fuel consumption for plug-in hybrid vehicles.

The Five Powerplants Compared

The fuel consumption versus weight curves for the five powerplants presented in Figures 4 through 8 have been plotted in a common graphic, Figure 9. The relative thermodynamic efficiency of the difference systems is obvious. Vehicle use of more electric propulsion is better wall-to-wheel neglecting anything but vehicle fuel consumption. Comparative CO_2 emissions mine or well-to-wheel, different fueling infrastructures and the comparative range/refueling or recharging convenience issues are not dealt with in this report. Figure 10 expresses the powerplant comparison in fuel-economy terms.

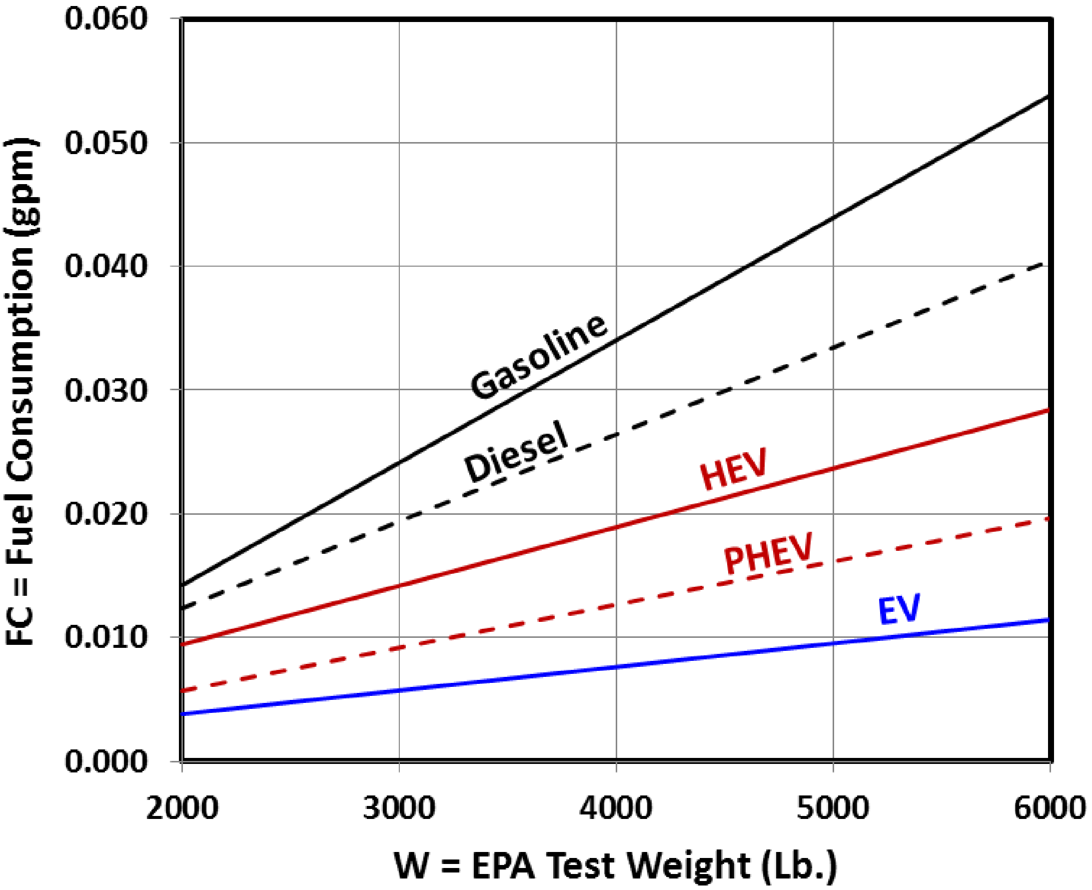

Figure 9. Fuel consumption vs. test weight for the five propulsion systems.

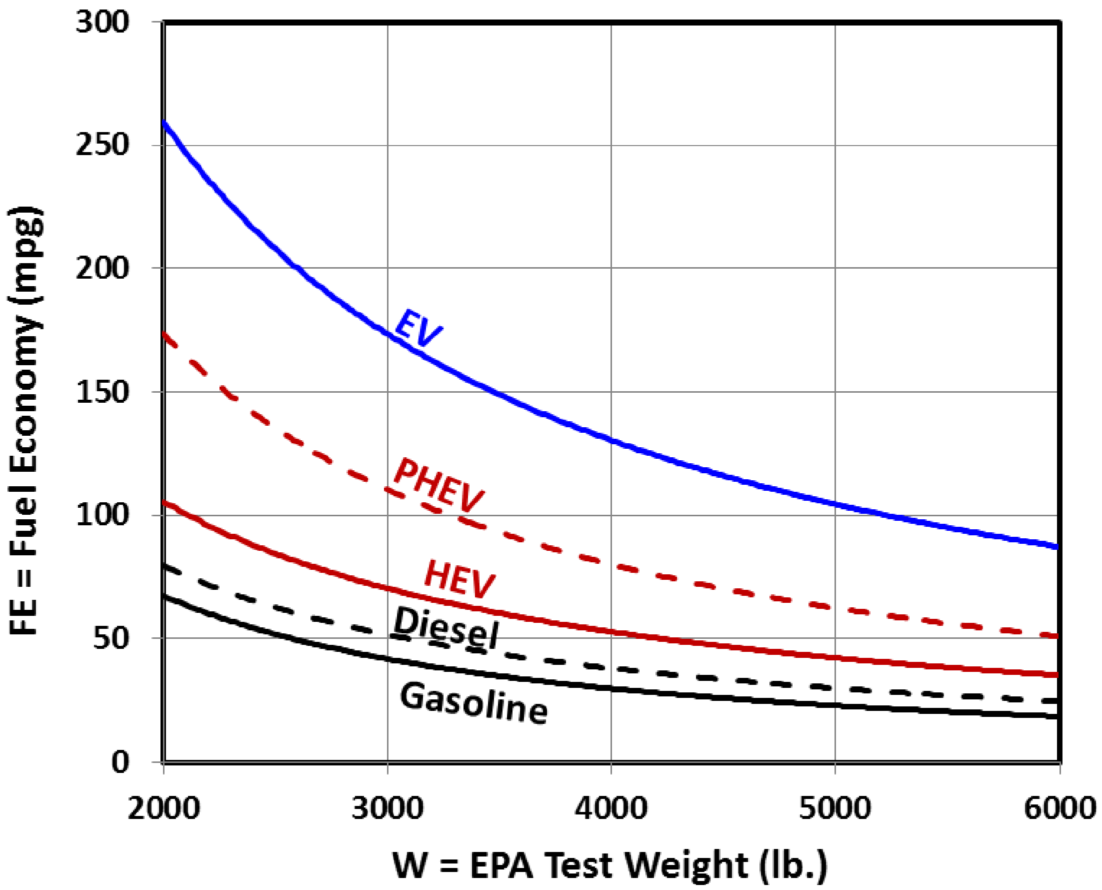

Figure 10. Fuel economy vs. test weight for the five propulsion systems.

The Effect of Rolling Resistance on Fuel Consumption

The previous section gives a first approximation to light vehicle fuel consumption based on 2013 vehicles, as a function of EPA test weight for each of the five powerplants expected to be in common use from now through 2025. The relative curb weights of vehicles with each type of powerplant are given in Table 3. The effect of altered tire rolling resistance in each case is estimated by analyzing the vehicle energy sinks based on the relevant fuel consumption estimates from the previous section.

Table 3

Relative vehicle curb weights as a function of powerplant type.

Powerplant	Curb Weight/Curb Weight Gasoline
Gasoline	1.00
Diesel	1.00
HEV	1.16
PHEV	1.32
EV	1.23

The basis point for what follows is a hypothetical C Class sedan whose fuel economy is computed from the curve in Figure 4 and which happens to have a curb weight equal to that of a Chevrolet Cruze. It is assumed that limited energy-usage information for current gasoline-fueled vehicles can be expanded to consideration of other power plants based on assumptions that will be noted as the analyses are performed.

Table 4 is the energy allocation for the Chevrolet Cruze derived from published data [8]. Applying the analysis in Table 5, the total energy consumed by each sink can be computed. Then, if the relative size of the sinks is modified, the effective sensitivity to variation in a given parameter like rolling resistance can be examined. The relative behavior (percentage wise) is reasonably accurate with respect to the real world, but the absolute behavior (mpg, etc.) is inaccurate because the basic energy per distance input is derived from unadjusted combined EPA mileage. The energy to travel a mile is understated about 20 percent by the unadjusted combined EPA mileage. This could cause confusion when data derived from a real world scaled test are mixed with the data used herein. The example in the next paragraph illustrates what could happen.

The 2013 Cruze Auto 6-Spd 1.4L unadjusted, combined mileage is 40.4 mpg, while the combined mileage sticker shows 30 mpg. The calculations in Table 5 yield the same percent of energy usage due to rolling resistance for either measure of combined fuel economy. If the energy computed to be lost due to rolling resistance in each mile is restated in force times distance terms and then divided by the vehicle test weight times the length of a mile, the result is the effective rolling resistance coefficient. Doing this for the unadjusted combined mileage yields $C_R = 0.0056$. Doing it for sticker combined mileage yields 0.0075, a much more realistic number. This is an example of why the caution in the last paragraph is important.

Table 4
Chevrolet Cruze fuel energy use breakdown.

Loss Type	Symbol	For Cruze
Electrical Loads Independent of Power Plant	E_1	1.1%
Engine Mechanical Loss (pumping, etc.)	E_2	14.1%
Driveline and Chassis	E_3	0.8%
Transmission and Final Drive	E_4	6.8%
Tire Rolling Resistance	E_5	4.6%
Aerodynamic Drag	E_6	6.5%
Kinetic Energy Dissipated During Braking	E_7	4.2%
Other Loss (Thermal, Heat, for Combustion Engine)	E_{OL}	62.0%

Table 5
Allocation of energy usage.[9]

Measure	Variable or Formula
EPA Test Weight (lb.)	W
EPA Composite Fuel Economy (mpg)	FE_C
Specific Energy in Fuel[10] (Btu/g)	E_G
Energy Used Per Mile (Btu/m)	$E_m = E_G/FE_C$
DEFINED MECHANICAL LOSSES	
Electrical Loads Independent of Power Plant	E_1
Engine Mechanical Loss (pumping, etc.)	E_2
Driveline and Chassis	E_3
Transmission and Final Drive	E_4
Tire Rolling Resistance	E_5
Aerodynamic Drag	E_6
Kinetic Energy Dissipated During Braking	E_7
Sum of Defined Mechanical Losses	$E_S = E_1+E_2+E_3+\ldots+E_7$
OTHER LOSS[11]	
Other Loss (Thermal for Combustion Engine)	$E_{OL}= E_m-E_S$
EFFECT OF REDUCING ROLLING RESISTANCE	
Percent Reduction in Rolling Resistance	ΔE_5
Reduced Tire Rolling Resistance	$E_{5R}=E_5(100- \Delta E_5)/100$
Reduced Sum of Defined Mechanical Losses	$E_{SR}=E_1+E_2+\ldots+E_{5R}+E_6+E_7$
Reduced Other Loss	$E_{OLR}=E_{OL}(E_{SR}/E_S)$
Reduced Energy Used Per Mile	$E_{mR}=E_{SR}+E_{OLR}$
Predicted Reduced Rolling Resist. Composite Fuel Economy (mpg)	$FE_{CP}=E_G/E_{mR}$
Predicted Increase in EPA Composite Fuel Economy (%)	$\Delta FE_C=100(FE_{CP}/FE_C)$

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[9] The percentages shown in Figure 11 were restated in terms of energy in the fuel or from the electric outlet, whichever is appropriate.

[10] This is equivalent to that in a gallon of gasoline, 114000 Btu, in all cases in this report except for the diesel, where 129500 Btu is appropriate.

[11] Other loss is all energy use per mile not accounted for by the defined mechanical losses.

Carrying out the calculations in Table 5 using the data applicable to the hypothetical C Class sedan predicts a 1.21 percent increase in fuel economy for a 10 percent reduction in rolling resistance. This is in reasonable agreement with the D-Class 4-cylinder results obtained by four recognized fuel economy modelers [9]. Therefore, the Table 5 computation is applied with the assumptions noted in Table 6 to estimate the rolling resistance effect on fuel economy.

Applying the method in Table 5 to C-class vehicles with curb weights scaled to that of the 3100 pound gasoline vehicle, with each vehicle's weight adjusted to its EPA test weight and then invoking a full slate of rolling resistance reductions down to a hypothetical zero rolling resistance, yields equations of the form of Equation 1, which allow prediction of approximate fuel consumption as a function of rolling resistance and vehicle weight (mass) for 2013 model vehicles. Note that Equation 1 is an elaborated version of the equations, which appear in Figures 4 through 8.

$$FC = (C_1\Delta_5^2 + C_2\Delta_5 + C_3)\,W + C_4 \qquad (1)$$

Where: W = EPA Test Weight (lbs.)

Δ_5 is the fraction of the original rolling resistance remaining[12]

Table 6 summarizes the assumptions used in applying the computation outlined in Table 5 to each powerplant type. Table 7 contains all the resultant constants that appear in the relevant versions of Equation 1 applicable to each powerplant. These versions of Equation 1 are used in estimating probable energy savings as a result of reduced rolling resistance and weight during the rest of the discussion of light vehicles.

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[12] Δ_5 is computed from Equation 2.

Table 6

Assumptions used in applying the Table 5 calculation for each powerplant type.

Powerplant	Assumptions
Gasoline	• Mechanical loss percentages as in Table 4.
Diesel	• EPA test weight equal to that of the gasoline-fueled car. • Mechanical losses identical to those in the gasoline-fueled car.
EV	• EPA test weight = gasoline-fueled car curb weight X EV weight factor in Table 3 + 300 lb. • Engine mechanical loss (pumping, etc.) = 0 • Transmission and Drive Line losses = ½ those in gasoline car for reasons of simplicity. • Rolling resistance = (EPA test weight EV/EPA test weight gasoline) X (gasoline powered rolling resistance). • Kinetic energy dissipation = 0.75 (EPA test weight EV/EPA test weight gasoline) X (gasoline-fueled kinetic energy dissipation)[13].
HEV	• EPA test weight = gasoline-fueled car curb weight X HEV weight factor in Table 3 + 300 lb. • Engine mechanical loss (pumping, etc.) = 0.89 of gasoline case based on the absence of IC engine operation in standby, stopped in traffic, etc. • Transmission and Drive Line losses assumed identical to Gasoline case. • Rolling resistance = (EPA test weight HEV/EPA test weight gasoline) X (gasoline-fueled rolling resistance). • Kinetic energy dissipation = 0.75 (EPA test weight HEV/EPA test weight gasoline) X (gasoline-fueled kinetic energy dissipation).
PHEV – 38[14]	• EPA test weight = gasoline-fueled car curb weight X PHEV weight factor in Table 3 + 300 lb. • Engine mechanical loss (pumping, etc.) = 0 during electrical operation and identical to that in the HEV in other operation. • Transmission and Drive Line losses assumed identical to EV in electrical operation and same as HEV otherwise. • Kinetic energy dissipation = 0.75 (EPA test weight PHEV/EPA test weight Gasoline) X (gasoline powered kinetic energy dissipation).

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[13] This is an assumption of 25 percent energy recovery by regenerative braking. The limitation is the permissible battery charging rate. Addition of an ultra-capacitor would allow this to be much more effective.

[14] 38 is the number of full electrical miles assumed.

Table 7
Equation 1 fitted constants for all five powerplants.

Powerplant	C_1	C_2	C_3	C_4
Gasoline	$-8.0845X10^{-10}$	$9.9454X10^{-7}$	$8.9020X10^{-6}$	$-5.5000X10^{-3}$
Diesel	$-6.1181X10^{-10}$	$7.5263X10^{-7}$	$5.3846X10^{-6}$	$4.3490X10^{-4}$
EV	$6.2096X10^{-9}$	$4.9287X10^{-7}$	$1.4008X10^{-6}$	$5.5952X10^{-5}$
HEV	$4.5331X10^{-10}$	$6.7654X10^{-7}$	$4.0468X10^{-6}$	$1.8944X10^{-5}$
PHEV	$1.0800X10^{-10}$	$7.0822X10^{-7}$	$2.7762X10^{-6}$	$-1.3354X10^{-3}$

Four Paths to Adapt Tires for Service in 2025

At the start of the discussion of light-vehicle evolution, the first design point was that there will be a sharp reduction in vehicle weight between now and 2025. The reduction will be at least 15 percent. Ford has this as a CEO-established goal for 2018 light trucks, so 15 percent is certainly at the bottom of the potential 2025 range for light vehicles. The author believes that 30 percent may be possible based on personal experience with aircraft, provided cost can be constrained.

Four general paths for adapting tires to these much lighter vehicles are explored. Tires deigned on these paths will reduce rolling resistance by different relative amounts, but the most optimal tires for rolling resistance may not be feasible because of operational constraints, as perceived by automotive OEMs, or tire-structural limitations that may exist due to deviations from current tire-design practice. On all four paths some rolling resistance reduction will come from evolution in tire materials and tire-mass reduction driven by improved structural design and manufacturing precision.

The tires on all adaptation paths will be smaller in load capacity and can be lighter, because of vehicle mass (weight) reduction. As Walter [10] observed in 1983, there are two fundamental branches on the path to lower rolling resistance: low aspect ratio and high aspect ratio. He was starting from an environment in which the common tire aspect ratios were 70 or 75. For reasons of styling and higher cornering stiffness, which feels better subjectively to drivers in turning, the low-aspect-ratio path has been followed since 1983. The high-aspect-ratio path offers less harsh ride and better wet-road traction (as will be discussed later), but less crisp handling as well as not having visual similarity to racing tires.

Each branch can be pursued at about current inflation pressures or at higher inflation pressures (perhaps as much as 50 psi for passenger cars in the author's view). The question will be one of balance between lower rolling resistance and various operational properties plus tire- design tradeoffs.

Table 8 lists four potential evolution paths for passenger car and light truck tires. In all cases the intent is to keep the tire diameters reasonably related to current diameters. Larger diameters would allow some additional reduction in rolling resistance, but at a space penalty and with certain ride consequences.

Table 8
Paths to tires adapted for service in 2025.

Path	Aspect Ratio	Inflation
1	Low (current) Under 60	Current
2		Increased
3	High (80 or more)	Current
4		Increased

The significant design tradeoff is with respect to higher inflation pressure. This is illustrated by considering a P185/55R15 as an example. At this time, once 36 psi is reached the rated load capacity of passenger tires does not increase further, though higher inflations are considered. Another possibility would be passenger tires designed to a revised standard allowing for load to continue to increase along the trend line from 26 to 36 psi until 50 psi is reached. In this report it was decided to follow the possible revised path of allowing load to increase to 50 psi. Table 9 is a comparison of the two trend assumptions for the P185/55R15 example. Note that following the chosen trend path, which leads outside current passenger tire practice, may not lead to a desirable structural solution.

In any case, Paths 1 and 3 in Table 8 only involve introduction of new sizes at current inflation pressures and so do not encounter potential structural risk.

Table 9
Load vs. inflation for a P185/55R15 current and linear with inflation.

Inflation (psi)	26	29	32	35	38	41	44	47	50
T&RA (lb.) [15]	805	871	948	1014	1047	1047	1047	1047	1047
Linear (lb.)[16]	805	871	948	1014	1086	1156	1226	1297	1367

Estimated Fuel Economy Effect of Following the Four Paths

The estimated fuel economy effects of following the four paths of tire evolution are evaluated for the hypothetical average passenger car for each class shown in Figure 2 and for the average light trucks shown in Figure 3. The Figure 2 and 3 hypothetical average vehicles are defined in Table 2 and the associated discussion.

The estimated fuel-economy effects are computed for all five powerplants in the case of passenger cars, but only for gasoline, diesel, and HEV in the case of light trucks.[17] Vehicle structural weight is assumed to be reduced by 15, 20, 25, and 30 percent for purposes of illustration. The difference between curb weight and gross vehicle weight is assumed to be unchanged in each case, and the future tires are sized to provide the same relative load reserve as that found in a given vehicle class at this time, when the tire pressure monitoring system (TPMS) would issue a low-pressure warning. But, there is no way to say which of the assumed states, if any, will truly be the one that will exist in 2025. Note that powerplant improvements are not considered in this analysis, which is based on 2013 data.

Estimated Fraction of 2013 Rolling Resistance Remaining in 2025

The first step in the fuel-economy-estimation process is estimation of the fraction of the 2013 rolling resistance, Δ_5, remaining in 2025 when following each of the four paths. Table 10 lists the items affecting each path. Application of Equation 2 produces Δ_5, which is required input for applying Equation 1 to compute the effect of each path on rolling resistance.

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[15] These loads are from the Tire and Rim Association Year Book [15]

[16] These loads are those that result from extending the loading trend up to 36 psi in [15] linearly to 50 psi.

[17] The requirements for operation off-the-road away from recharging facilities and the potentially large energy consumption on soft terrain, hauling, and plowing make PHEV and EV light trucks look undesirable with current technology.

Tire size (load-carrying capacity) at a given aspect ratio should affect rolling resistance coefficient, but the effect of tire size on rolling resistance coefficient is not accounted for in this study due to an absence of data on the effect. However, the effect of tire size is noted in Table 10 in case information allowing its inclusion becomes available later. As tire size is reduced, tire weight will fall, which will decrease raw-material needs so long as wear mileage remains essentially constant. Based on Walter's work [10], it is assumed that the aspect-ratio effect is inherently included in the passenger car study.[18] The aspect-ratio effect is not inherent in the light-truck study, so the results for light trucks should be better in the change from 70 to 85 aspect ratio than what appears in this study. The assumption that $\Delta_{AR} = \Delta_{SI} = 0$ in the Equation 2 reflects the limitations just discussed.

Table 10
Factors affecting rolling-resistance coefficient on each tire-evolution path.

Path	Δ_{ME}, Material Evolution	Δ_{AR}, Aspect Ratio Change[19]	Δ_{P}, Inflation Change	Δ_{SI}, Tire Size Effect[20]
1	✓			✓?
2	✓		✓	✓?
3	✓	✓?		✓?
4	✓	✓?	✓	✓?

$$\Delta_5 = (1-\Delta_{ME}) \bullet (1-\Delta_{P}) \bullet (1-\Delta_{AR}) \bullet (1-\Delta_{SI}) \qquad (2)$$

Where: $\Delta_{ME} = (CRR_{ME13} - CRR_{ME25}) / CRR_{ME13}$

$\Delta_{P} = (CRR_{35} - CRR_{50}) / CRR_{35}$

$\Delta_{AR} = 0$ in the absence of data defining its value.

$\Delta_{SI} = 0$ in the absence of data defining its value.

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[18] The example aspect ratios in this study are symmetrical with respect to 70 aspect ratio and should be about equal in their rolling-resistance coefficients [10].

[19] Presence of the question mark indicates insufficient information to account for the aspect-ratio effect on rolling resistance.

[20] Presence of the question mark indicates insufficient information to account for the tire-size effect on rolling resistance.

Figure 11 shows the expected evolution of CRR due to tire-material refinement. The slope is based on data in TRB SR 286 [9]. The basis for the intercept is the OE tire data between one and two sigma below the mean of all OE data in RMA COMMENTS TO DOCKET NHTSA-2008-0121 dated AUGUST 21, 2009 [11]. The intercept choice is based on the concept that good OE tires in the RMA data are the logical precursors of common practice in the future. Accepting the projected evolution in Figure 11 leads to $\Delta_{ME} = 0.154$ for the period from 2013 to 2025.

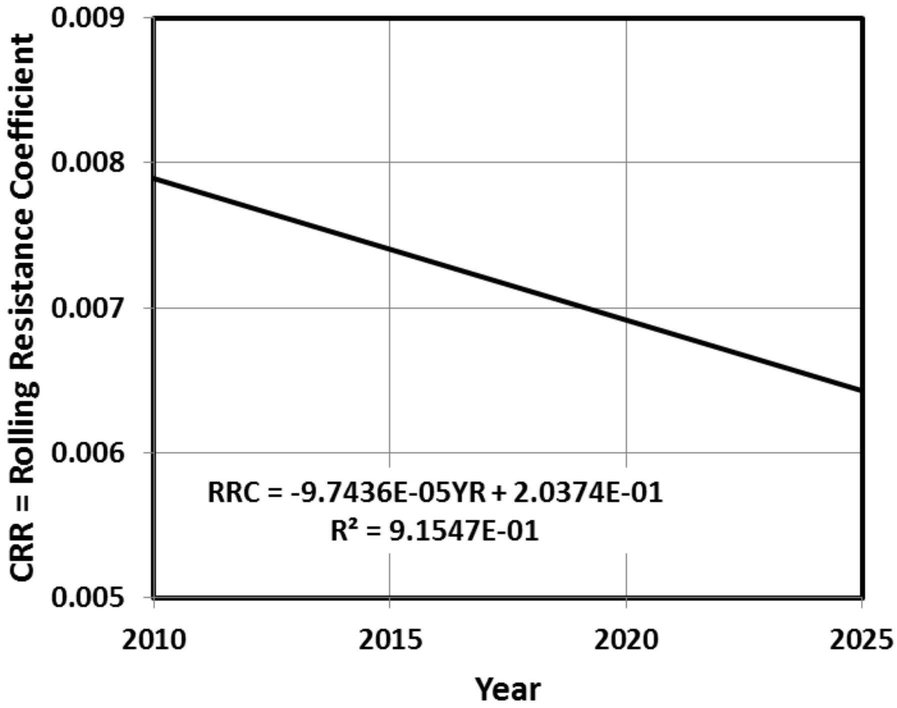

Figure 11. Projected rolling-resistance-coefficient evolution for light-vehicle tires.

Figure 12 shows the effect of inflation pressure on CRR. It was derived from material in LaClair [12]. The LaClair data lead to $\Delta_P = 0.129$ in a change from 35 psi cold inflation to 50 psi cold inflation.[21]

Applying Equation 2 with the values just discussed produces Δ_5 values, the fraction of the 2013 rolling resistance expected to remain in 2025. These are tabulated in Table 11 and are substituted in Equation 1 to estimate the fuel consumption on each tire-evolution

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[21] The operational inflation is assumed to be the cold inflation plus 2.9 psi (20kPa).

path for the five powerplant types and the vehicle classes mentioned earlier. This is done in the next section.

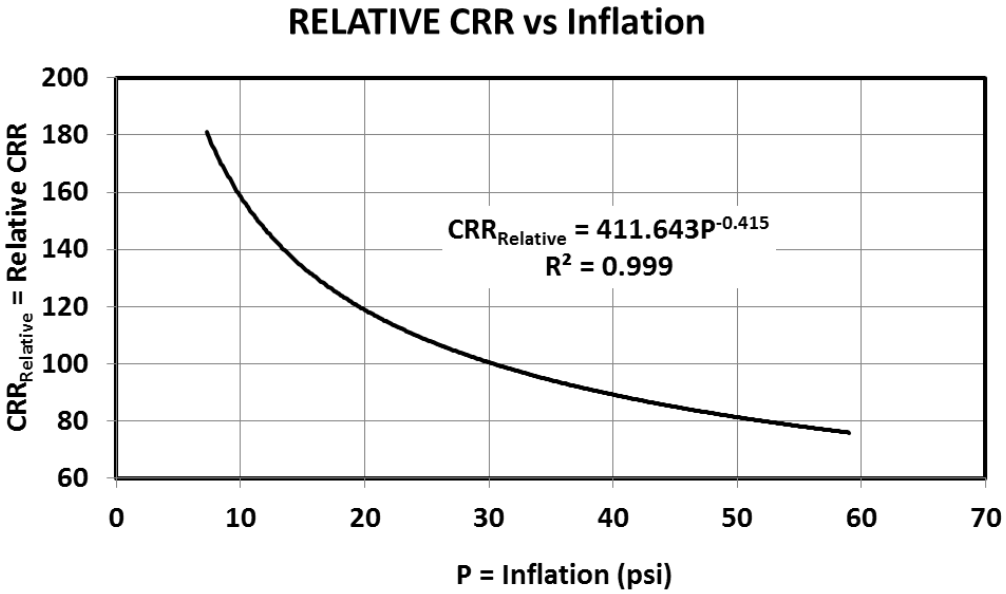

Figure 12. Rolling-resistance coefficient for light-vehicle tires versus inflation pressure.

Table 11
Fraction of 2013 rolling resistance expected to remain in 2025.

Tire Evolution Path	Δ_5, Remaining CRR Fraction
1	0.846
2	0.737
3	0.846
4	0.737

In the absence of information allowing use of values other than zero for Δ_{AR} and $\Delta_{SI,}$ the potential advantages of Paths 3 and 4 will be decided in terms of tire weight and operational factors, as Path 1 and Path 3 should yield essentially the same CRR result as should Path 2 and Path 4. This discussion will follow the next section.

Estimated Change in Fuel Economy on Each Path

The section on projected light-vehicle evolution through 2025 examined evolution over the next 12 years in terms of five passenger-car classes, a standard two-wheel drive (2WD) full-sized pickup truck, and a standard four-wheel drive (4WD) full-sized pickup truck. The vehicle used in each case was based on an average of three popular vehicles within the given class. These are specified in Table 2 and the discussion in the projected light-vehicle-evolution section. Using Equation 1 the fuel consumption of the vehicles whose EPA test weights are shown in Table 12 was computed for tires with current rolling-resistance values and then with rolling-resistance values based on Paths 1 and 2. Next, the change in fuel usage due to following the different, potential, tire-evolution paths was computed using Equation 3 for a 15,000 mile driving year. The results of Equation 3 are based on EPA unadjusted combined fuel economy, which has been used to this point, as noted at the start of the section on projected light-vehicle evolution through 2025. In a practical economic sense, customer savings through improved fuel economy will depend on real-world fuel usage, so the Equation 3 results are modified in Equation 4 to approximate window-sticker values based on the example vehicles evaluated in this report. The fuel savings based on assuming the that window-sticker-based consumption figures are accurate are then priced by assuming that the effective price of a gallon of gasoline will follow the projection in Figure 13, which is based on Energy Information Administration data [13] using Equation 5. The effective fuel-consumption-change results are shown in Tables 13 and 14 based on Equation 3. Finally, dollar savings for driving four years at 15,000 miles a year for the life of the tires are shown in Tables 15 and 16. They assume that a 60,000 mile tire life is and will be the effective norm. If the reader disagrees with the assumptions just made, he or she can readily adjust the results to fit a different estimated mileage by appropriate multiplication of the results presented in this report. Also, rolling resistance falls as a tire wears. No attempt is made to adjust for this. Some readers may want to make this adjustment to the results herein.

$$\Delta_{GAL/YR} = 15000(FC_{CUR} - FC_{IMP}) \quad (3)$$

Where: $\Delta_{GAL/YR}$ = Reduced fuel consumption due to improved tires

FC_{CUR} = fuel consumption using current technology tires (gpm)

FC_{IMP} = fuel consumption using improved technology tires (gpm)

$$\Delta_{GALC/YR} = F \bullet \Delta_{GAL/YR} \quad (4)$$

Where: $\Delta_{GALC/YR}$ = reduced fuel consumption at consumer level due to improved tires

F = factor used to modify unadjusted combined fuel consumption to adjusted[22]

$$D_{SAV} = 4\, P_{GAL} \bullet \Delta_{GALC/YR} \quad (5)$$

Where: D_{SAV} = dollar savings in driving 60,000 miles with improved tires

P_{GAL} = projected price of gasoline in 2025

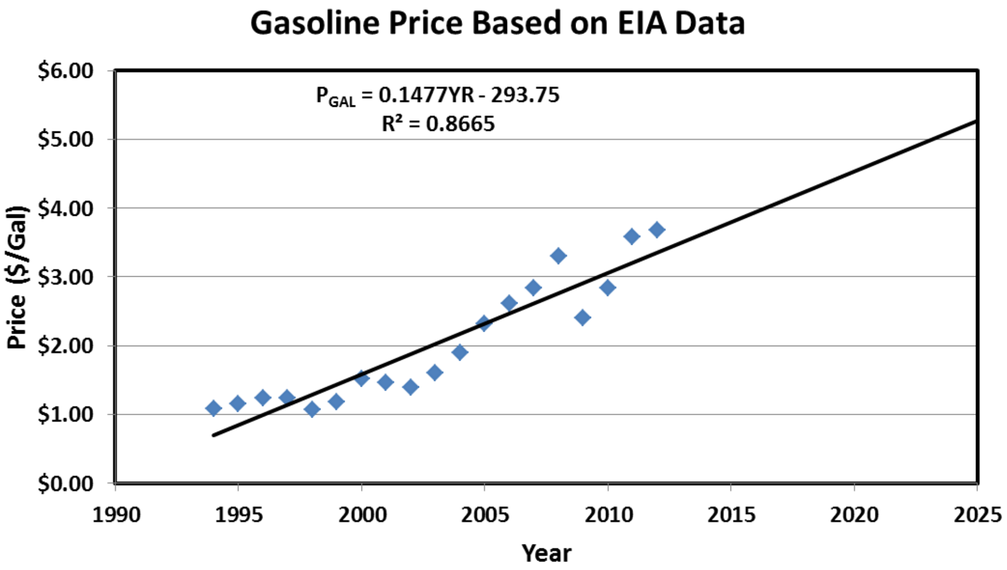

Figure 13. Fuel-cost projection using EIA data ($5.35/gallon mid-2025).[23]

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[22] F = 1.24 based on a linear fit of combined window-sticker fuel-consumption data [6] versus EPA combined, unadjusted, fuel-consumption data for the vehicles used to plot Figures 4-8 considered as a group. R^2 for the combined window-sticker fuel-consumption versus EPA combined, unadjusted fuel consumption is 0.99.

[23] The linear gasoline-price estimation has only limited certainty given the volatility of energy prices.

Table 12
EPA fuel-economy test weights for the example vehicles.

Vehicle Type or Class	Powerplant	EPA Fuel Economy Test Weights (lbs.)				
		% Curb Weight Reduction from Current Weight				
		0	15	20	25	30
A	Gasoline	2399	2084	1979	1875	1770
	Diesel	2399	2084	1979	1875	1770
	HEV	2735	2420	2315	2210	2105
	PHEV	3071	2756	2651	2546	2441
	EV	2882	2567	2462	2357	2252
B	Gasoline	2702	2342	2222	2102	1982
	Diesel	2702	2342	2222	2102	1982
	HEV	3087	2726	2606	2486	2366
	PHEV	3471	3111	2991	2870	2750
	EV	3255	2895	2774	2654	2534
C	Gasoline	3326	2872	2721	2570	2418
	Diesel	3326	2872	2721	2570	2418
	HEV	3810	3356	3205	3054	2902
	PHEV	4294	3840	3689	3538	3387
	EV	4022	3568	3417	3265	3114
D	Gasoline	3557	3069	2906	2743	2580
	Diesel	3557	3069	2906	2743	2580
	HEV	4079	3590	3427	3264	3101
	PHEV	4600	4111	3948	3785	3622
	EV	4307	3818	3655	3492	3329
E	Gasoline	3898	3359	3179	2999	2819
	Diesel	3898	3359	3179	2999	2819
	HEV	4474	3934	3754	3574	3395
	PHEV	5050	4510	4330	4150	3970
	EV	4726	4186	4006	3826	3646
2WD Pickup[24]	Gasoline	5085	4367	4128	3889	3649
	Diesel	5085	4367	4128	3889	3649
	HEV	5850	5133	4893	4654	4415
4WD Pickup[24]	Gasoline	5439	4668	4411	4155	3898
	Diesel	5439	4668	4411	4155	3898
	HEV	6262	5491	5234	4977	4720

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[24] PHEV and EV trucks are ignored because extra battery weight beyond that in a HEV is dead load in a work situation (e.g. hauling, towing, and snow plowing). Field recharging is not now practical. Delivery vans for urban and suburban use would be a different case. Also, the weights of 6.5 and 8 foot pickups are close enough together that only 8 foot is considered here.

Table 13
Fuel savings in driving 15,000 miles per year on path 1 or 3 tires.

Vehicle Type or Class	Powerplant	Yearly Fuel Savings Using Path 1 or 3 Tires in Gallons				
		% Curb Weight Reduction from Current Weight				
		0	15	20	25	30
A	Gasoline	5.5	4.8	4.5	4.3	4.1
	Diesel	4.2	3.6	3.4	3.3	3.1
	HEV	4.3	3.8	3.6	3.5	3.3
	PHEV	5.0	4.5	4.3	4.2	4.0
	EV	3.4	3.0	2.9	2.7	2.6
B	Gasoline	6.2	5.4	5.1	4.8	4.5
	Diesel	4.7	4.1	3.9	3.6	3.4
	HEV	4.8	4.3	4.1	3.9	3.7
	PHEV	5.7	5.1	4.9	4.7	4.5
	EV	3.8	3.4	3.2	3.1	3.0
C	Gasoline	7.6	6.6	6.2	5.9	5.5
	Diesel	5.8	5.0	4.7	4.5	4.2
	HEV	6.0	5.3	5.0	4.8	4.5
	PHEV	7.0	6.3	6.0	5.8	5.5
	EV	4.7	4.2	4.0	3.8	3.6
D	Gasoline	8.2	7.0	6.7	6.3	5.9
	Diesel	6.2	5.3	5.0	4.8	4.5
	HEV	6.4	5.6	5.4	5.1	4.9
	PHEV	7.5	6.7	6.5	6.2	5.9
	EV	5.0	4.4	4.3	4.1	3.9
E	Gasoline	8.9	7.7	7.3	6.9	6.5
	Diesel	6.8	5.8	5.5	5.2	4.9
	HEV	7.0	6.2	5.9	5.6	5.3
	PHEV	8.3	7.4	7.1	6.8	6.5
	EV	5.5	4.9	4.7	4.5	4.2
2WD Pickup	Gasoline	11.7	10.0	9.5	8.9	8.4
	Diesel	8.8	7.6	7.2	6.8	6.3
	HEV	9.2	8.0	7.7	7.3	6.9
4WD Pickup	Gasoline	12.5	10.7	10.1	9.5	8.9
	Diesel	9.4	8.1	7.7	7.2	6.8
	HEV	9.8	8.6	8.2	7.8	7.4

Table 14
Fuel savings in driving 15,000 miles per year on path 2 or 4 tires.

Vehicle Type or Class	Powerplant	Yearly Fuel Savings Using Path 2 or 4 Tires in Gallons				
		% Curb Weight Reduction from Current Weight				
		0	15	20	25	30
A	Gasoline	9.4	8.2	7.8	7.3	6.9
	Diesel	7.1	6.2	5.9	5.6	5.2
	HEV	7.3	6.5	6.2	5.9	5.6
	PHEV	8.6	7.7	7.4	7.1	6.8
	EV	5.7	5.1	4.9	4.7	4.5
B	Gasoline	10.6	9.2	8.7	8.2	7.8
	Diesel	8.0	6.9	6.6	6.2	5.9
	HEV	8.2	7.3	7.0	6.6	6.3
	PHEV	9.7	8.7	8.4	8.0	7.7
	EV	6.5	5.8	5.5	5.3	5.0
C	Gasoline	13.0	11.3	10.7	10.1	9.5
	Diesel	9.9	8.5	8.1	7.6	7.2
	HEV	10.2	9.0	8.6	8.2	7.8
	PHEV	12.0	10.7	10.3	9.9	9.5
	EV	8.0	7.1	6.8	6.5	6.2
D	Gasoline	13.9	12.0	11.4	10.7	10.1
	Diesel	10.5	9.1	8.6	8.1	7.6
	HEV	10.9	9.6	9.2	8.7	8.3
	PHEV	12.9	11.5	11.0	10.6	10.1
	EV	8.6	7.6	7.3	6.9	6.6
E	Gasoline	15.3	13.2	12.5	11.7	11.0
	Diesel	11.6	10.0	9.4	8.9	8.4
	HEV	12.0	10.5	10.0	9.6	9.1
	PHEV	14.1	12.6	12.1	11.6	11.1
	EV	9.4	8.3	8.0	7.6	7.2
2WD Pickup	Gasoline	19.9	17.1	16.2	15.2	14.3
	Diesel	15.1	12.9	12.2	11.5	10.8
	HEV	15.6	13.7	13.1	12.4	11.8
4WD Pickup	Gasoline	21.3	18.3	17.3	16.3	15.3
	Diesel	16.1	13.8	13.1	12.3	11.6
	HEV	16.7	14.7	14.0	13.3	12.6

Table 15
Projected fuel-cost savings in driving 60,000 miles on path 1 or 3 tires.

Vehicle Type or Class	Powerplant	Tire Life Cost Savings Using Path 1 or 3 Tires in Dollars				
		% Curb Weight Reduction from Current Weight				
		0	15	20	25	30
A	Gasoline	$146	$127	$120	$114	$108
	Diesel	$110	$96	$91	$86	$81
	HEV	$114	$100	$96	$92	$87
	PHEV	$133	$120	$115	$111	$106
	EV	$89	$79	$76	$73	$70
B	Gasoline	$164	$142	$135	$128	$121
	Diesel	$124	$108	$102	$97	$91
	HEV	$128	$113	$108	$103	$98
	PHEV	$151	$135	$130	$125	$119
	EV	$101	$89	$86	$82	$78
C	Gasoline	$202	$175	$166	$156	$147
	Diesel	$153	$132	$125	$118	$111
	HEV	$158	$139	$133	$127	$120
	PHEV	$186	$167	$160	$154	$147
	EV	$124	$110	$106	$101	$96
D	Gasoline	$216	$187	$177	$167	$157
	Diesel	$164	$141	$134	$126	$119
	HEV	$169	$149	$142	$135	$129
	PHEV	$200	$178	$171	$164	$157
	EV	$133	$118	$113	$108	$103
E	Gasoline	$237	$204	$193	$182	$172
	Diesel	$179	$155	$146	$138	$130
	HEV	$186	$163	$156	$148	$141
	PHEV	$219	$196	$188	$180	$172
	EV	$146	$129	$124	$118	$113
2WD Pickup	Gasoline	$309	$266	$251	$237	$222
	Diesel	$234	$201	$190	$179	$168
	HEV	$243	$213	$203	$193	$183
4WD Pickup	Gasoline	$331	$284	$268	$253	$237
	Diesel	$250	$215	$203	$191	$179
	HEV	$260	$228	$217	$207	$196

Table 16
Projected fuel-cost savings in driving 60,000 miles on path 2 or 4 tires.

Vehicle Type or Class	Powerplant	Tire Life Cost Savings Using Path 2 or 4 Tires in Dollars				
		% Curb Weight Reduction from Current Weight				
		0	15	20	25	30
A	Gasoline	$181	$157	$149	$141	$133
	Diesel	$137	$119	$113	$107	$101
	HEV	$141	$124	$119	$114	$108
	PHEV	$165	$148	$143	$137	$131
	EV	$110	$98	$94	$90	$86
B	Gasoline	$204	$177	$168	$158	$149
	Diesel	$154	$134	$127	$120	$113
	HEV	$159	$140	$134	$128	$122
	PHEV	$187	$167	$161	$154	$148
	EV	$125	$111	$106	$102	$97
C	Gasoline	$251	$217	$205	$194	$182
	Diesel	$190	$164	$155	$147	$138
	HEV	$196	$173	$165	$157	$149
	PHEV	$231	$207	$198	$190	$182
	EV	$154	$137	$131	$125	$119
D	Gasoline	$268	$231	$219	$207	$195
	Diesel	$203	$175	$166	$157	$147
	HEV	$210	$185	$176	$168	$160
	PHEV	$247	$221	$212	$204	$195
	EV	$165	$146	$140	$134	$128
E	Gasoline	$294	$253	$240	$226	$213
	Diesel	$222	$192	$181	$171	$161
	HEV	$230	$202	$193	$184	$175
	PHEV	$272	$243	$233	$223	$214
	EV	$181	$160	$153	$147	$140
2WD Pickup	Gasoline	$383	$329	$311	$293	$275
	Diesel	$290	$249	$236	$222	$208
	HEV	$301	$264	$252	$239	$227
4WD Pickup	Gasoline	$410	$352	$333	$313	$294
	Diesel	$310	$266	$252	$237	$222
	HEV	$322	$282	$269	$256	$243

Within the assumptions made, the projected rolling-resistance savings for vehicle owners are expected to be significant. Comparing the results in Tables 13 and 14 or Tables 15 and 16, the projected effect of inflation on fuel consumption is equal to 71 percent of that which will be due to materials evolution alone. Thus, increased inflation pressure should be used in 2025, provided ride factors, tire structural problems, or a potential reduction in vehicle-structural-fatigue life do not preclude its use.

Tire Sizes and Mass Reductions on the Four Tire-Adaptation Paths

Tire-size changes and associated mass reductions between now and 2025 are other important contributors to tire sustainability besides rolling-resistance improvements. Vehicle weight and direct material usage in tire manufacturing are both reduced.

To evaluate tire size and mass reduction, it was necessary to choose appropriate tire sizes for each vehicle that were assumed to be typical of a given passenger-car class and full-sized light trucks. The tire sizes were chosen to insure safe carrying of one-fourth of the projected vehicle gross vehicle weight rating (GVWR) at the tire-pressure-monitoring-system tripping pressure appropriate for 35 psi cold inflation (tripping pressure equal 26 psi) and 50 psi cold inflation (tripping pressure equal 38 psi). The existing tire sizes on the vehicles used to define the class-typical example vehicle were used as reference points. Plainly, this produces significant reserve load at the recommended tire-inflation pressure, which is advantageous with respect to tire safety.

The tire sizes were defined by applying a spreadsheet which the Tire and Rim Association was kind enough to lend in support of this project [14]. Obviously, many of the tire sizes that resulted are not now commercial. Those that did not appear in the 2012 TRA Year Book [15] are viewed as new sizes herein and appear in blue ink in the tables. The Path 1 tire sizes, which are the same sizes that would exist using current tire technology, are shown in Table 17.

Path 2 tire sizes were chosen according to the same rationale as used for Path 1, tires with the proviso that the basic rim diameters were kept the same for each example vehicle as on Path 1. The Path 2 sizes are shown in Table 18.

Table 17

Path 1 tire sizes. (Entries in blue are new sizes.)

Vehicle Type or Class	Powerplant	Tire Size				
		% Curb Weight Reduction from Expected 2013 Vehicle Weight				
		0	15	20	25	30
A	Gasoline	P185/55R15	P175/55R15	P165/55R15	P165/55R15	P165/55R15
	Diesel	P185/55R15	P175/55R15	P165/55R15	P165/55R15	P165/55R15
	HEV	P185/55R15	P185/55R15	P175/55R15	P175/55R15	P175/55R15
	PHEV	P195/55R15	P185/55R15	P185/55R15	P185/55R15	P185/55R15
	EV	P195/55R15	P185/55R15	P185/55R15	P175/55R15	P175/55R15
B	Gasoline	P195/55R15	P185/55R15	P175/55R15	P175/55R15	P175/55R15
	Diesel	P195/55R15	P185/55R15	P175/55R15	P175/55R15	P175/55R15
	HEV	P195/55R15	P195/55R15	P185/55R15	P185/55R15	P185/55R15
	PHEV	P205/55R15	P195/55R15	P195/55R15	P195/55R15	P195/55R15
	EV	P205/55R15	P195/55R15	P195/55R15	P195/55R15	P185/55R15
C	Gasoline	P195/55R16	P195/55R16	P195/55R16	P185/55R16	P185/55R16
	Diesel	P195/55R16	P195/55R16	P195/55R16	P185/55R16	P185/55R16
	HEV	P215/55R16	P195/55R16	P195/55R16	P195/55R16	P195/55R16
	PHEV	P225/55R16	P215/55R16	P205/55R16	P205/55R16	P195/55R16
	EV	P215/55R16	P205/55R16	P195/55R16	P195/55R16	P195/55R16
D	Gasoline	P205/55R16	P195/55R16	P195/55R16	P195/55R16	P185/55R16
	Diesel	P205/55R16	P195/55R16	P195/55R16	P195/55R16	P185/55R16
	HEV	P215/55R16	P205/55R16	P205/55R16	P195/55R16	P195/55R16
	PHEV	P235/55R16	P215/55R16	P215/55R16	P215/55R16	P205/55R16
	EV	P225/55R16	P215/55R16	P205/55R16	P205/55R16	P195/55R16
E	Gasoline	P215/55R17	P195/55R17	P195/55R17	P195/55R17	P195/55R17
	Diesel	P215/55R17	P195/55R17	P195/55R17	P195/55R17	P195/55R17
	HEV	P225/55R17	P215/55R17	P205/55R17	P205/55R17	P205/55R17
	PHEV	P235/55R17	P225/55R17	P215/55R17	P215/55R17	P215/55R17
	EV	P225/55R17	P215/55R17	P215/55R17	P205/55R17	P205/55R17
2WD Pickup	Gasoline	P245/70R17	P235/70R17	P215/70R17	P215/70R17	P215/70R17
	Diesel	P245/70R17	P235/70R17	P215/70R17	P215/70R17	P215/70R17
	HEV	P245/70R17	P235/70R17	P235/70R17	P235/70R17	P235/70R17
4WD Pickup	Gasoline	P245/70R17	P235/70R17	P235/70R17	P215/70R17	P215/70R17
	Diesel	P245/70R17	P235/70R17	P235/70R17	P215/70R17	P215/70R17
	HEV	P245/70R17	P235/70R17	P235/70R17	P235/70R17	P235/70R17

Table 18
Path 2 tire sizes. (Entries in blue are new sizes.)

Vehicle Type or Class	Powerplant	Tire Size				
		% Curb Weight Reduction from Expected 2013 Vehicle Weight				
		0	15	20	25	30
A	Gasoline	P155/55R15	P145/55R15	P135/55R15	P135/55R15	P135/55R15
	Diesel	P155/55R15	P145/55R15	P135/55R15	P135/55R15	P135/55R15
	HEV	P165/55R15	P155/55R15	P145/55R15	P145/55R15	P145/55R15
	PHEV	P165/55R15	P165/55R15	P155/55R15	P155/55R15	P155/55R15
	EV	P165/55R15	P165/55R15	P155/55R15	P145/55R15	P145/55R15
B	Gasoline	P165/55R15	P155/55R15	P155/55R15	P145/55R15	P145/55R15
	Diesel	P165/55R15	P155/55R15	P155/55R15	P145/55R15	P145/55R15
	HEV	P175/55R15	P165/55R15	P165/55R15	P155/55R15	P155/55R15
	PHEV	P185/55R15	P175/55R15	P175/55R15	P165/55R15	P165/55R15
	EV	P185/55R15	P165/55R15	P165/55R17	P165/55R17	P155/55R15
C	Gasoline	P175/55R16	P165/55R16	P165/55R16	P155/55R16	P155/55R16
	Diesel	P175/55R16	P165/55R16	P165/55R16	P155/55R16	P155/55R16
	HEV	P185/55R16	P175/55R16	P175/55R16	P175/55R16	P165/55R16
	PHEV	P205/55R16	P195/55R16	P185/55R16	P185/55R16	P175/55R16
	EV	P195/55R16	P185/55R16	P175/55R16	P175/55R16	P175/55R16
D	Gasoline	P185/55R16	P165/55R16	P165/55R16	P165/55R16	P155/55R16
	Diesel	P185/55R16	P165/55R16	P165/55R16	P165/55R16	P155/55R16
	HEV	P195/55R16	P185/55R16	P175/55R16	P175/55R16	P175/55R16
	PHEV	P205/55R16	P195/55R16	P195/55R16	P185/55R16	P185/55R16
	EV	P205/55R16	P185/55R16	P185/55R16	P185/55R16	P175/55R16
E	Gasoline	P185/55R17	P175/55R17	P165/55R17	P165/55R17	P155/55R17
	Diesel	P185/55R17	P175/55R17	P165/55R17	P165/55R17	P155/55R17
	HEV	P195/55R17	P185/55R17	P185/55R17	P185/55R17	P175/55R17
	PHEV	P215/55R17	P205/55R17	P195/55R17	P195/55R17	P185/55R17
	EV	P205/55R17	P195/55R17	P185/55R17	P185/55R17	P185/55R17
2WD Pickup	Gasoline	P205/70R17	P185/70R17	P185/70R17	P175/70R17	P175/70R17
	Diesel	P205/70R17	P185/70R17	P185/70R17	P175/70R17	P175/70R17
	HEV	P225/70R17	P205/70R17	P205/70R17	P205/70R17	P195/70R17
4WD Pickup	Gasoline	P205/70R17	P185/70R17	P185/70R17	P175/70R17	P175/70R17
	Diesel	P205/70R17	P185/70R17	P185/70R17	P175/70R17	P175/70R17
	HEV	P225/70R17	P205/70R17	P205/70R17	P205/70R17	P295/70R17

The change from Paths 1 and 2 to Paths 3 and 4 is drastic. There was a need to ascertain how choices inherent in each path affected tire mass and then use this information as feedback to the choice process. There is no accepted set of equations describing tire weight in terms of nominal rim diameter, aspect ratio, and section width. The situation is complex and is in detail tire-company dependent, so the author derived a rough approximate estimation of tire mass based on the following reasoning.

1. Passenger-tire weights available from a tire-company website are usable data to derive an approximation so long there is data for an adequate number of rim diameters, aspect ratios, and section widths to allow computation of relations such as weight as a function of section width at a given aspect ratio and rim diameter within specific tire lines.
2. The tire-line mileage warranty of tires whose data is used must exceed 60,000 miles to fit with the other assumptions in this report.
3. Tire weights go to zero as section width goes to zero.

The results are Equation 6 and a set of values of $f(AR, R_D)$ for specific nominal rim widths and aspect ratios listed in Table 19.

$$W_T = f(AR, R_D) \bullet S_W \qquad (6)$$

Where: W_T = tire weight (lb.)

AR = aspect ratio

R_D = nominal rim diameter (in.)

S_W = section width (mm)

$f(AR, R_D)$ = weight slope function

Table 19
Weight-slope function values.

AR	R_D	$f(AR, R_D)$
55	15	0.0815
	16	0.0934
	17	0.1053
	18	0.1172
70	17	0.1493
	18	0.1697
	19	0.1901
85	14	0.1051
	15	0.1345
	16	0.1638
	17	0.1932
	19	0.2519

After consideration of various possibilities that satisfied the load requirements noted at the beginning of this section, the author decided to use 14-inch nominal-rim-diameter tires for all the passenger cars on Paths 3 and 4. Tires with 15- and 16-inch rim diameters were used for the light trucks. The results are Tables 20 and 21.

Table 20
Path 3 tire sizes. (Entries in blue are new sizes.)

Vehicle Type or Class	Powerplant	Tire Size				
		% Curb Weight Reduction from Expected 2013 Vehicle Weight				
		0	15	20	25	30
A	Gasoline	P145/85R14	P135/85R14	P135/85R14	P125/85R14	P125/85R14
	Diesel	P145/85R14	P135/85R14	P135/85R14	P125/85R14	P125/85R14
	HEV	P155/85R14	P145/85R14	P145/85R14	P135/85R14	P135/85R14
	PHEV	P155/85R15	P155/85R15	P155/85R15	P145/85R14	P145/85R14
	EV	P155/85R14	P145/85R14	P145/85R14	P145/85R14	P135/85R14
B	Gasoline	P155/85R14	P145/85R14	P145/85R14	P145/85R14	P135/85R14
	Diesel	P155/85R14	P145/85R14	P145/85R14	P145/85R14	P135/85R14
	HEV	P165/85R14	P155/85R14	P155/85R14	P155/85R14	P145/85R14
	PHEV	P175/85R14	P165/85R14	P165/85R14	P165/85R14	P155/85R14
	EV	P175/85R14	P165/85R14	P155/85R14	P155/85R14	P155/85R14
C	Gasoline	P175/85R14	P165/85R14	P155/85R14	P155/85R14	P155/85R14
	Diesel	P175/85R14	P165/85R14	P155/85R14	P155/85R14	P155/85R14
	HEV	P185/85R14	P175/85R14	P165/85R14	P165/85R14	P165/85R14
	PHEV	P195/85R14	P185/85R14	P185/85R14	P175/85R14	P175/85R14
	EV	P185/85R14	P175/85R14	P175/85R14	P175/85R14	P165/85R14
D	Gasoline	P175/85R14	P165/85R14	P165/85R14	P155/85R14	P155/85R14
	Diesel	P175/85R14	P165/85R14	P165/85R14	P155/85R14	P155/85R14
	HEV	P185/85R14	P175/85R14	P175/85R14	P175/85R14	P165/85R14
	PHEV	P195/85R14	P185/85R14	P185/85R14	P185/85R14	P175/85R14
	EV	P195/85R14	P185/85R14	P185/85R14	P175/85R14	P175/85R14
E	Gasoline	P185/85R14	P175/85R14	P165/85R14	P165/85R14	P165/85R14
	Diesel	P185/85R14	P175/85R14	P165/85R14	P165/85R14	P165/85R14
	HEV	P195/85R14	P185/85R14	P185/85R14	P175/85R14	P175/85R14
	PHEV	P205/85R14	P195/85R14	P195/85R14	P185/85R14	P185/85R14
	EV	P205/85R14	P195/85R14	P185/85R14	P185/85R14	P185/85R14
2WD Pickup	Gasoline	P215/85R16	P215/85R16	P195/85R16	P195/85R16	P195/85R16
	Diesel	P215/85R16	P215/85R16	P195/85R16	P195/85R16	P195/85R16
	HEV	P235/85R15	P225/85R15	P225/85R15	P215/85R15	P215/85R15
4WD Pickup	Gasoline	P215/85R16	P215/85R16	P195/85R16	P195/85R16	P195/85R16
	Diesel	P215/85R16	P215/85R16	P195/85R16	P195/85R16	P195/85R16
	HEV	P235/85R15	P225/85R15	P225/85R15	P215/85R15	P215/85R15

Table 21
Path 4 tire sizes. (Entries in blue are new sizes.)

Vehicle Type or Class	Powerplant	Tire Size				
		% Curb Weight Reduction from Expected 2013 Vehicle Weight				
		0	15	20	25	30
A	Gasoline	P125/85R14	P115/85R14	P115/85R14	P115/85R14	P105/85R14
	Diesel	P125/85R14	P115/85R14	P115/85R14	P115/85R14	P105/85R14
	HEV	P135/85R14	P125/85R14	P125/85R14	P115/85R14	P115/85R14
	PHEV	P135/85R14	P135/85R14	P135/85R14	P125/85R14	P125/85R14
	EV	P135/85R14	P125/85R14	P125/85R14	P125/85R14	P125/85R14
B	Gasoline	P135/85R14	P125/85R14	P125/85R14	P125/85R14	P115/85R14
	Diesel	P135/85R14	P125/85R14	P125/85R14	P125/85R14	P115/85R14
	HEV	P145/85R14	P135/85R14	P135/85R14	P135/85R14	P125/85R14
	PHEV	P155/85R14	P145/85R14	P145/85R14	P135/85R14	P135/85R14
	EV	P145/85R14	P135/85R14	P135/85R14	P135/85R14	P135/85R14
C	Gasoline	P145/85R14	P135/85R14	P135/85R14	P135/85R14	P125/85R14
	Diesel	P145/85R14	P135/85R14	P135/85R14	P135/85R14	P125/85R14
	HEV	P155/85R14	P155/85R14	P145/85R14	P145/85R14	P135/85R14
	PHEV	P165/85R14	P155/85R14	P155/85R14	P155/85R14	P155/85R14
	EV	P165/85R14	P155/85R14	P155/85R14	P145/85R14	P145/85R14
D	Gasoline	P155/85R14	P145/85R14	P135/85R14	P135/85R14	P135/85R14
	Diesel	P155/85R14	P145/85R14	P135/85R14	P135/85R14	P135/85R14
	HEV	P165/85R14	P155/85R14	P155/85R14	P145/85R14	P145/85R14
	PHEV	P175/85R14	P165/85R14	P155/85R14	P155/85R14	P155/85R14
	EV	P165/85R14	P155/85R14	P155/85R14	P155/85R14	P145/85R14
E	Gasoline	P155/85R14	P155/85R14	P145/85R14	P145/85R14	P135/85R14
	Diesel	P155/85R14	P155/85R14	P145/85R14	P145/85R14	P135/85R14
	HEV	P165/85R14	P155/85R14	P155/85R14	P155/85R14	P155/85R14
	PHEV	P185/85R14	P175/85R14	P165/85R14	P165/85R14	P165/85R14
	EV	P175/85R14	P165/85R14	P165/85R14	P155/85R14	P155/85R14
2WD Pickup	Gasoline	P185/85R16	P175/85R16	P175/85R16	P165/85R16	P165/85R16
	Diesel	P185/85R16	P175/85R16	P175/85R16	P165/85R16	P165/85R16
	HEV	P205/85R16	P195/85R16	P185/85R16	P185/85R16	P185/85R16
4WD Pickup	Gasoline	P185/85R16	P175/85R16	P175/85R16	P165/85R16	P165/85R16
	Diesel	P185/85R16	P175/85R16	P175/85R16	P165/85R16	P165/85R16
	HEV	P205/85R16	P195/85R16	P185/85R16	P185/85R16	P185/85R16

Based on the Path 1 tire sizes noted in Table 17, Equation 6 was applied using the appropriate weight slope function values from Table 19 yielding projected tire weights for all tire sizes noted in Table 17. Next, the projected tire weight in each cell was subtracted from the current tire, zero percent curb-weight-reduction case. This yielded the projected tire-material-weight savings for four tires on a vehicle, which are summarized in Table 22.[25] These inherent savings associated with tire resizing, as vehicle-weight reduction occurs, are significant.[26]

Carrying out the tire-weight computations for the tires listed in Tables 18, 20, and 21, which are applicable to Paths 2, 3, and 4, yields tire-material-weight summaries for each path. Subtracting the material-weight summary for each path from the Path 1 case shows the potential material savings when following each path compared to Path 1 sizing. These results appear in Tables 23, 24, and 25.

As shown in Table 24, Path 3, which is an 85-aspect-ratio-equivalent to Path 1 at the current, recommended, cold-inflation pressure of 35 psi, would yield results dependent on the vehicle class and powerplant. Sometimes on an individual case basis Path 3 would be better than Path 1 and sometimes worse in terms of material usage. On average, assuming all cases are of equal importance, Path 3 would yield slightly larger material savings (2.4 pounds per vehicle). Path 2, a higher pressure (50 psi) version of Path 1 with current aspect ratios and rim diameters, significantly reduces tire-material usage in all cases with respect to Path 1 as illustrated by the results in Table 23. The average result for all cases is 15.3 pounds of tire materials saved per vehicle.

Path 4 is the higher-pressure version of Path 3. If the Path 4 material savings shown in Table 25 are compared with the Path 2 material savings, the results are a mix with regard to which path is better in individual cases. The average result is about a pound more material saving for Path 4 than Path 2.

The overall material-savings predictions indicate that the higher pressure paths would be better assuming other unforeseen problems, such as structural problems, do not govern the results. The precise choice of path will depend on other factors besides material savings. It is the author’s opinion that a mixed path aimed at optimizing each

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[25] The question of what to do about the spare tire or its equivalent is ignored in this analysis.

[26] One pound over a million vehicles would save 500 tons of tire material. Given the number of vehicles produced and in use, it is obvious that the real savings would be in the thousands of tons each year.

vehicle independently (Path 2 for vehicle number 1, Path 4 for vehicle number 3, etc.) should not be chosen, as it would greatly increase the number of tire products, which is already too large.

Table 22

Tire-material savings per vehicle as vehicle weight is reduced.

Vehicle Type or Class	Powerplant	Estimated Tire Material Saving on Vehicle (lb.)				
		% Curb Weight Reduction from Current Weight				
		0	15	20	25	30
A	Gasoline	0.0	3.3	6.5	6.5	6.5
	Diesel	0.0	3.3	6.5	6.5	6.5
	HEV	0.0	0.0	3.3	3.3	3.3
	PHEV	0.0	3.3	3.3	3.3	3.3
	EV	0.0	3.3	3.3	6.5	6.5
B	Gasoline	0.0	3.3	6.5	6.5	6.5
	Diesel	0.0	3.3	6.5	6.5	6.5
	HEV	0.0	0.0	3.3	3.3	3.3
	PHEV	0.0	3.3	3.3	3.3	3.3
	EV	0.0	3.3	3.3	3.3	6.5
C	Gasoline	0.0	0.0	0.0	3.7	3.7
	Diesel	0.0	0.0	0.0	3.7	3.7
	HEV	0.0	7.5	7.5	7.5	7.5
	PHEV	0.0	3.7	7.5	7.5	11.2
	EV	0.0	3.7	7.5	7.5	7.5
D	Gasoline	0.0	3.7	3.7	3.7	7.5
	Diesel	0.0	3.7	3.7	3.7	7.5
	HEV	0.0	3.7	3.7	7.5	7.5
	PHEV	0.0	7.5	7.5	7.5	11.2
	EV	0.0	3.7	7.5	7.5	11.2
E	Gasoline	0.0	8.4	8.4	8.4	8.4
	Diesel	0.0	8.4	8.4	8.4	8.4
	HEV	0.0	4.2	8.4	8.4	8.4
	PHEV	0.0	4.2	8.4	8.4	8.4
	EV	0.0	4.2	4.2	8.4	8.4
2WD Pickup	Gasoline	0.0	6.0	17.9	17.9	17.9
	Diesel	0.0	6.0	17.9	17.9	17.9
	HEV	0.0	6.0	6.0	6.0	6.0
4WD Pickup	Gasoline	0.0	6.0	6.0	17.9	17.9
	Diesel	0.0	6.0	6.0	17.9	17.9
	HEV	0.0	6.0	6.0	6.0	6.0

Table 23

Tire-material savings per vehicle for path 2 compared with path 1.

Vehicle Type or Class	Powerplant	Path 2 Tire Material Saving per Vehicle Compared to Path 1 (lb.)				
		% Curb Weight Reduction from Current Weight				
		0	15	20	25	30
A	Gasoline	9.8	9.8	9.8	9.8	9.8
	Diesel	9.8	9.8	9.8	9.8	9.8
	HEV	6.5	9.8	9.8	9.8	9.8
	PHEV	9.8	6.5	9.8	9.8	9.8
	EV	9.8	6.5	9.8	9.8	9.8
B	Gasoline	9.8	9.8	6.5	9.8	9.8
	Diesel	9.8	9.8	6.5	9.8	9.8
	HEV	6.5	9.8	6.5	9.8	9.8
	PHEV	6.5	6.5	6.5	9.8	9.8
	EV	6.5	9.8	9.8	9.8	9.8
C	Gasoline	7.5	11.2	11.2	11.2	11.2
	Diesel	7.5	11.2	11.2	11.2	11.2
	HEV	11.2	7.5	7.5	7.5	11.2
	PHEV	7.5	7.5	7.5	7.5	7.5
	EV	7.5	7.5	7.5	7.5	7.5
D	Gasoline	7.5	11.2	11.2	11.2	11.2
	Diesel	7.5	11.2	11.2	11.2	11.2
	HEV	7.5	7.5	11.2	7.5	7.5
	PHEV	11.2	7.5	7.5	11.2	7.5
	EV	7.5	11.2	7.5	7.5	7.5
E	Gasoline	12.6	8.4	12.6	12.6	16.8
	Diesel	12.6	8.4	12.6	12.6	16.8
	HEV	12.6	12.6	8.4	8.4	12.6
	PHEV	8.4	8.4	8.4	8.4	12.6
	EV	8.4	8.4	12.6	8.4	8.4
2WD Pickup	Gasoline	32.9	31.4	19.4	21.6	21.6
	Diesel	32.9	31.4	19.4	21.6	21.6
	HEV	28.5	26.9	26.9	26.9	29.1
4WD Pickup	Gasoline	32.9	31.4	31.4	21.6	21.6
	Diesel	32.9	31.4	31.4	21.6	21.6
	HEV	28.5	26.9	26.9	26.9	29.1

Table 24
Tire material-savings per vehicle for path 3 compared with path 1.

Vehicle Type or Class	Powerplant	Path 3 Tire Material Saving per Vehicle Compared to Path 1 (lb.)				
		% Curb Weight Reduction from Current Weight				
		0	15	20	25	30
A	Gasoline	-0.6	0.3	-3.0	1.2	1.2
	Diesel	-0.6	0.3	-3.0	1.2	1.2
	HEV	-4.9	-0.6	-3.9	0.3	0.3
	PHEV	-1.6	-4.9	-4.9	-0.6	-0.6
	EV	-1.6	-0.6	-0.6	-3.9	0.3
B	Gasoline	-1.6	-0.6	-3.9	-3.9	0.3
	Diesel	-1.6	-0.6	-3.9	-3.9	0.3
	HEV	-5.8	-1.6	-4.9	-4.9	-0.6
	PHEV	-6.7	-5.8	-5.8	-5.8	-1.6
	EV	-6.7	-5.8	-1.6	-1.6	-4.9
C	Gasoline	-0.7	3.5	7.7	4.0	4.0
	Diesel	-0.7	3.5	7.7	4.0	4.0
	HEV	2.6	-0.7	3.5	3.5	3.5
	PHEV	2.1	2.6	-1.2	3.0	-0.7
	EV	2.6	3.0	-0.7	-0.7	3.5
D	Gasoline	3.0	3.5	3.5	7.7	4.0
	Diesel	3.0	3.5	3.5	7.7	4.0
	HEV	2.6	3.0	3.0	-0.7	3.5
	PHEV	5.8	2.6	2.6	2.6	3.0
	EV	2.1	2.6	-1.2	3.0	-0.7
E	Gasoline	12.8	8.6	12.8	12.8	12.8
	Diesel	12.8	8.6	12.8	12.8	12.8
	HEV	12.8	12.8	8.6	12.8	12.8
	PHEV	12.8	12.8	8.6	12.8	12.8
	EV	8.6	8.6	12.8	8.6	8.6
2WD Pickup	Gasoline	5.4	-0.5	0.6	0.6	0.6
	Diesel	5.4	-0.5	0.6	0.6	0.6
	HEV	-7.7	-7.1	-7.1	-0.5	-0.5
4WD Pickup	Gasoline	5.4	-0.5	12.6	0.6	0.6
	Diesel	5.4	-0.5	12.6	0.6	0.6
	HEV	-7.7	-7.1	-7.1	-0.5	-0.5

Table 25
Tire-material savings per vehicle for path 4 compared with path 1.

Vehicle Type or Class	Powerplant	Path 4 Tire Material Saving per Vehicle Compared to Path 1 (lb.)				
		% Curb Weight Reduction from Current Weight				
		0	15	20	25	30
A	Gasoline	7.8	8.7	5.4	5.4	9.6
	Diesel	7.8	8.7	5.4	5.4	9.6
	HEV	3.6	7.8	4.5	8.7	8.7
	PHEV	6.8	3.6	3.6	7.8	7.8
	EV	6.8	7.8	7.8	4.5	4.5
B	Gasoline	6.8	7.8	4.5	4.5	8.7
	Diesel	6.8	7.8	4.5	4.5	8.7
	HEV	2.6	6.8	3.6	3.6	7.8
	PHEV	1.7	2.6	2.6	6.8	6.8
	EV	5.9	6.8	6.8	6.8	3.6
C	Gasoline	11.9	16.1	16.1	12.4	16.6
	Diesel	11.9	16.1	16.1	12.4	16.6
	HEV	15.2	7.7	11.9	11.9	16.1
	PHEV	14.7	15.2	11.4	11.4	7.7
	EV	11.0	11.4	7.7	11.9	11.9
D	Gasoline	11.4	11.9	16.1	16.1	12.4
	Diesel	11.4	7.7	16.1	16.1	12.4
	HEV	11.0	11.4	11.4	11.9	11.9
	PHEV	14.2	11.0	15.2	15.2	11.4
	EV	14.7	15.2	11.4	11.4	11.9
E	Gasoline	25.4	17.0	21.2	21.2	25.4
	Diesel	25.4	17.0	21.2	21.2	25.4
	HEV	25.4	25.4	21.2	21.2	21.2
	PHEV	21.2	21.2	21.2	21.2	21.2
	EV	21.2	21.2	21.2	21.2	21.2
2WD Pickup	Gasoline	25.1	25.7	13.7	20.3	20.3
	Diesel	25.1	25.7	13.7	20.3	20.3
	HEV	12.0	12.6	19.1	19.1	19.1
4WD Pickup	Gasoline	25.1	25.7	25.7	20.3	20.3
	Diesel	25.1	25.7	25.7	20.3	20.3
	HEV	12.0	12.6	19.1	19.1	19.1

Operational Tradeoffs

There are many factors, which influence the practical use of tires. These lead to operational tradeoffs. [27] This portion of the report is a brief and somewhat simplified look at tire properties affecting operational tradeoffs with respect to ride plus vehicle handling and control. It focuses on tire evolution along the four tire design paths previously postulated to potentially aid sustainability. There are many other complex tradeoffs, which could be considered, but were outside the scope of this report. Indeed, the complexity of the situation inhibits allowance for vehicle design interactions so the report focuses on tire characteristics with the intention of providing conceptual information to tire and vehicle-design engineers.

Ride

In this section five tire characteristics affecting tactile vibration, what passengers feel, and structure borne (in-the-car) noise, most of what passengers hear in a closed car, are considered. Airborne, environmental, noise, what is heard along the roadside, is not considered.

The tire characteristics that will be discussed contribute to what passengers feel and hear. They are: spring rate, damping, modal behavior, enveloping, and uniformity. Spring rate, damping, and modal behavior determine what the tire does with the excitations that come from interaction with road-surface irregularities, which are termed harshness, or from the tire/wheel/hub system's own irregularities, which are termed uniformity problems.

The tire has multiple spring rates dependent on the deformation to which it is subjected. Herein, the discussion will largely concentrate on vertical (or radial) spring rate. For detailed information on other tire spring rates please see Pottinger et al [16].

Vertical spring rate is often measured for a non-rolling tire based on the slope of a load-deflection curve. This is not the tire-usage condition. It is better to determine the

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[27] For example, roads become contaminated with water, mud, sand, snow, etc., forcing tread patterns to be a tire- design feature. Design of a proper tread pattern requires engineering consideration of operational tradeoffs between and among tire performance factors such as wear evenness, cornering force, tire/pavement interaction noise, tread groove cracking, and so forth. This is a small sample from the complex world of tire operational tradeoffs.

radial spring rate for the tire rolling at operating speed. It is data for the loaded rolling case that are used from this point onward. Among many other items, Pottinger, Marshall, Lawther, and Thrasher [17] discuss the various methods of determining tire radial spring rate and show the correctness of the decision to use loaded rolling data.

Four factors affecting radial spring rate dominate, as vehicle mass reduction occurs and changes are made to follow the four different paths for tire evolution discussed in this report. The factors are: inflation-pressure change, change in aspect ratio, load change, and tire size reduction.

Inflation pressure change is an inherent factor in a change from Path 1 to Path 2 or from Path 3 to Path 4. Figure 14 [18] shows that radial spring rate increases linearly as inflation increases. Consequently, the 1 to 2 and 3 to 4 path changes will lead to about a 40 percent increase in radial stiffness with significant ride consequences, if all else affecting tire stiffness is equal.

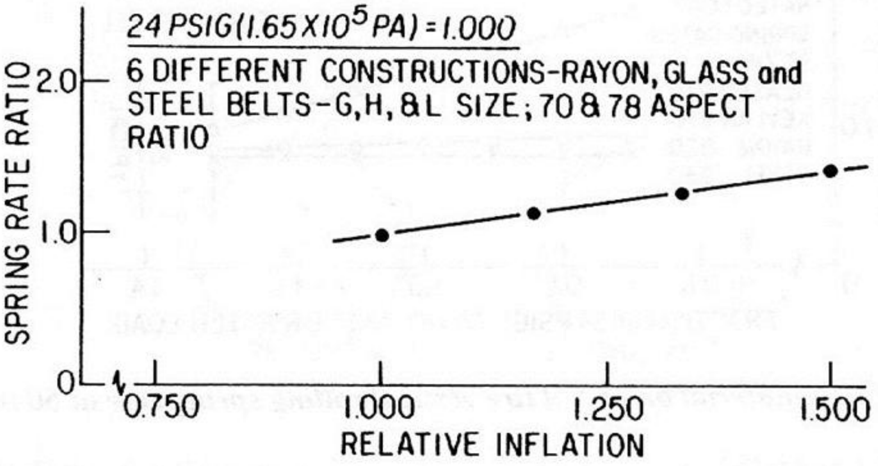

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Figure 14. Relative spring rate as a function of inflation pressure. [18]

Tire radial stiffness is a function of aspect ratio, if load capacity and inflation pressure are held constant. Figure 15 based on extrapolation of data originally used to draw Figure 10 in Reference 18 indicates that the step from 55 to 85 aspect ratio, Path 1 to Path 3 or Path 2 to Path 4, should lead to a 25 percent reduction in vertical spring rate for tires of the same load capacity, if all else is equal.

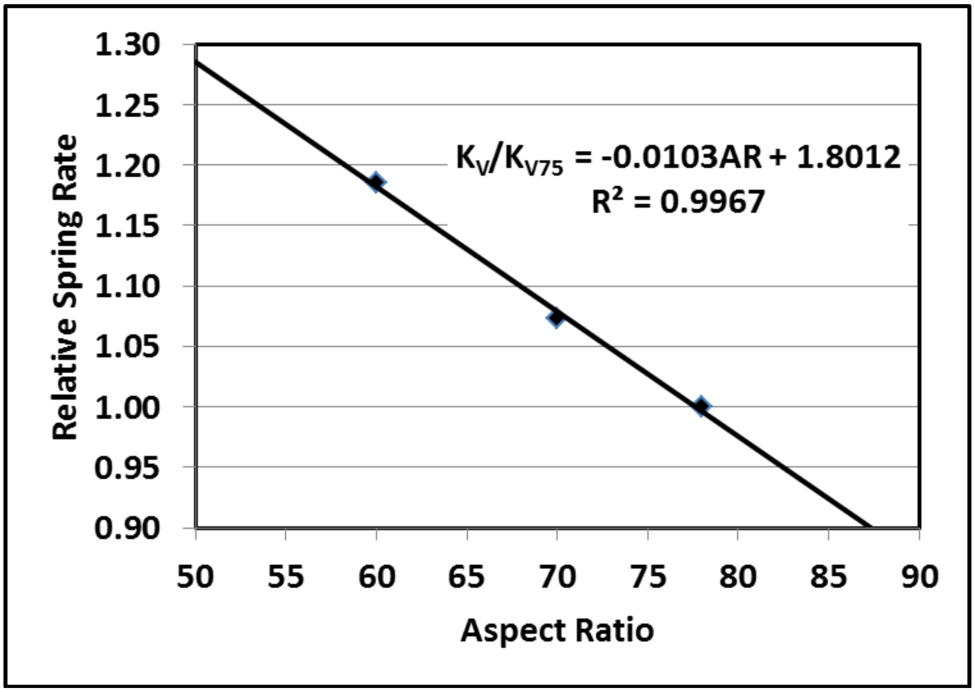

Figure 15. Relative spring rate as a function of aspect ratio.

Load change and tire size reduction are mixed together. At a given load, if tire size is reduced, tire radial stiffness will decline. Tire-size reduction is inherent in the vehicle-weight reduction process. It is worth noting that load change in a given tire size absent other changes, has little effect on tire radial spring rate (Figure 16) [18] .

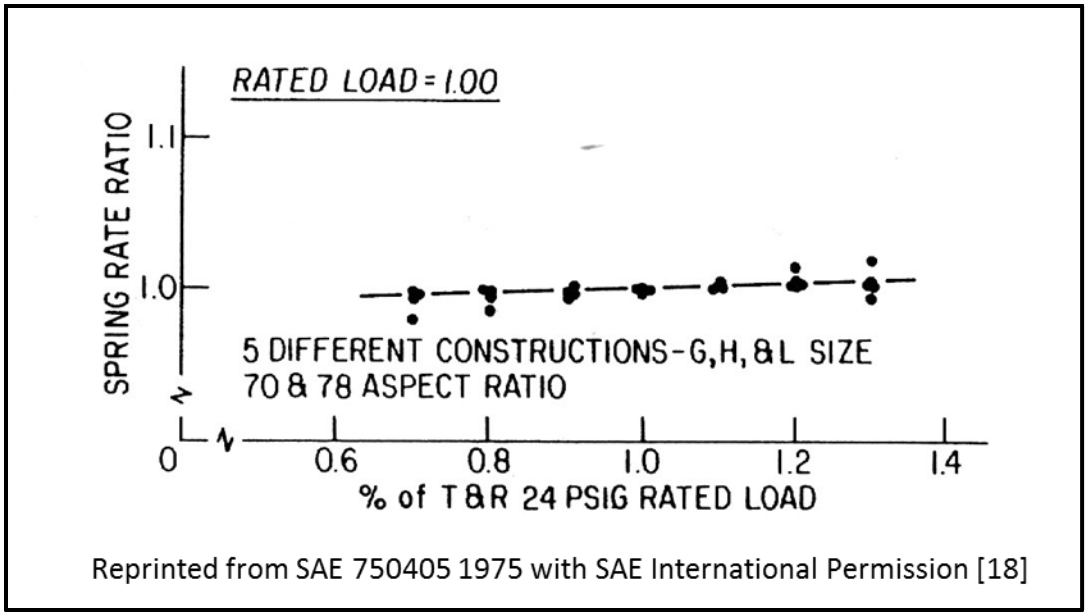

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Figure 16. Relative spring rate as a function of fraction of rated load [18].

As indicated in Figure 17 [17], tire vertical damping is strongly dependent on the tire being in a rolling state. The values for the rolling tire are a small fraction of critical damping. However, the tire damping is not unimportant. As excitation frequency moves up through the frequency spectrum into the area where tire modal behavior is critical, the tire damping becomes the damping in vehicle suspensions [19].

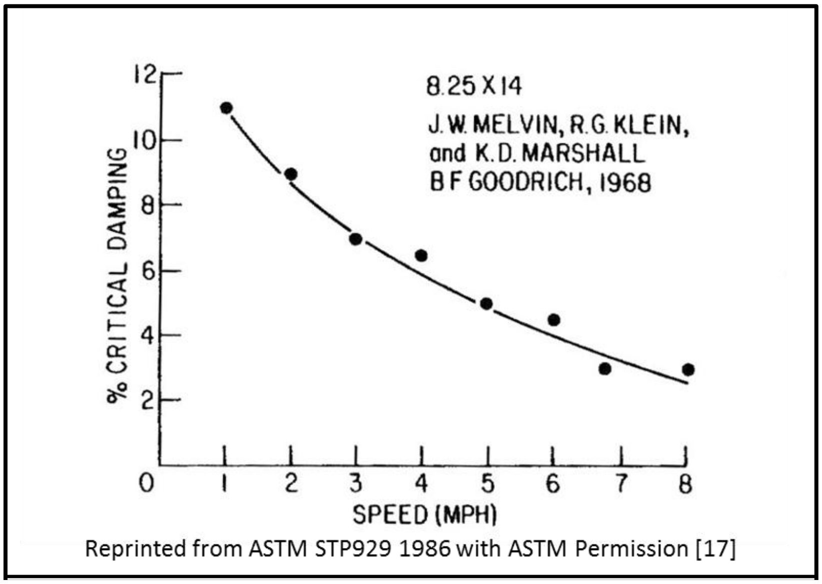

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Figure 17. Tire damping. [17]

The tire's vibration modes, particularly the fundamental modes related to vertical and longitudinal oscillations of the wheel hub for a loaded tire, are dominant factors in vibration and noise-transmission performance from the standpoint of ride and in-the-car noise. The modal frequencies vary with tire size, construction details, and inflation pressure, but the mode shapes are invariant. The first radial natural frequency is important for in-the-car noise transmission from the road, as noted in the 1960s and 1970s by Phillips [20] and Chiesa et al. [21] Phillips also observed that torsional resonances are important to in-the-car noise below 60 Hz. In the same era, Barson and Dodd [22] noted that torsional resonances are crucial to vibration transmissibility. As tires become smaller with all else being the same, the natural frequencies tend to rise. Natural frequencies also rise as inflation pressure increases.

A tire's shell characteristics are important not just in terms of its modes, but also in terms of its interaction with road-surface irregularities through a process called enveloping. As the wavelength of road profile variations becomes less than the length of the tire footprint[28], the tire drapes over the pavement irregularities like tar strips, seams, and step offs between pavement slabs altering the spindle force history.

In 1952, Julien and Paulsen [23] showed that the encounter of a tire with a short bump wider than the tread, for example a tar strip, produces spindle forces with the character shown in Figure 18 [17]. They made four significant observations.

1. If all other variables are fixed, the magnitude of vertical force is linearly dependent on inflation pressure.
2. High tire deflections produce lower vertical forces and slightly higher longitudinal forces.
3. The tire's response to an upward road-elevation change is not exactly the same as its response to a downward change.
4. Tire-response amplitude is not linearly dependent on obstacle size.

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[28] For road wavelengths longer than the footprint, the tire can be viewed as a point follower transmitting the force developed as a consequence of its stiffness and the change in road elevation.

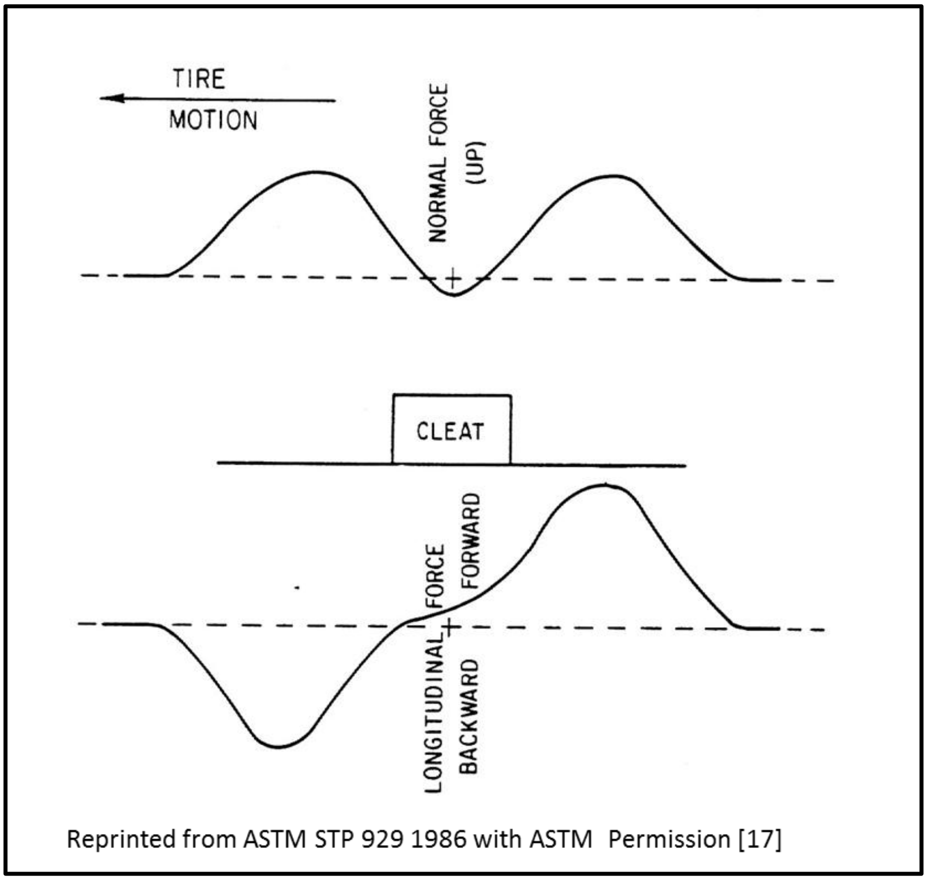

Figure 18. Low speed cleat impact force signatures. [17]

A number of other investigators have looked at the problem adding dynamics, which appear in highway speed impact data such as that shown in Figure 19 [18]. Barone [24] observed that:

1. The principal vibration frequencies were independent of the size and form of the object enveloped.
2. The tire behaves as a linear constant-parameter system having a ring-down frequency independent of excitation amplitude.
3. Almost all response is first-mode response for the particular sense of vibration occurring, normal or longitudinal.

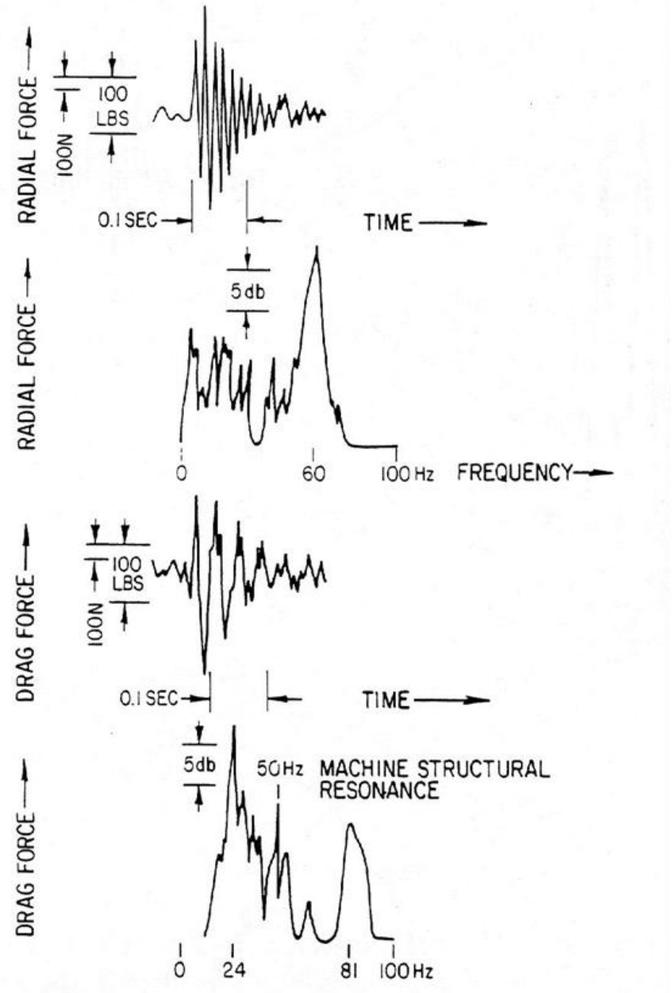

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Figure 19. Typical maximum axle-force responses for a tire over a cleat. [18]

Julien and Paulsen [23] in their very early experiments noted that about 75 percent of the enveloping effect was pneumatic. What they were changing by varying inflation pressure was the tire stiffness. The only helpful design measure substantiated in the literature outside of using a high tire aspect ratio, as on Paths 3 and 4, is to keep the tire-tread band out-of-plane bending stiffness as low as possible [18, 25].

Considering what has been discussed, it is now possible to infer the comparative harshness effects of following the four tire-evolution paths. The change in inflation pressure from Path 1 to Path 2 or Path 3 to Path 4 is going to increase ride harshness by as much as 40 percent due the change in envelopment characteristics, if there are no other changes made. The aspect-ratio change from Path 1 to Path 3 or Path 2 to Path 4 will lead to about a 25 percent decrease in harshness due to reduced force input magnitudes during envelopment. Additionally, there are changes in modal natural frequencies.

Clearly, from a harshness standpoint, if the decision is to stick with current cold inflation pressures Path 3, high aspect ratio is better than sticking with current aspect ratios, Path 1. Ride will be improved because harshness will be reduced. Table 13 shows the equivalent fuel savings on either path. Table 24 shows the tire material savings for Path 3 compare with Path 1. If all the situations represented in Table 24 are considered equally probable, on average Path 3 saves about 2.4 pounds of tire material per vehicle. However, choosing Path 3 will use more material in certain specific design situations, as shown in Table 24.

If the decision is to go to higher inflation pressure because of the appreciably greater fuel savings indicated by comparing Table 14 to Table 13, there are two possible approaches: go from Path 1 to Path 2 or go from Path 1 to Path 4. Path 1 to Path 2 involves a probably significant increase in harshness due to a 40 percent increase in forces generated in enveloping combined with average Path 2 saving of 15.3 pounds of tire material per vehicle. Path 1 to Path 4 involves a probable increase in harshness of 15 percent due to increased forces generated in enveloping due to the increase in both aspect ratio and inflation pressure. The combined average Path 4 saving of 16.2 pounds of tire material per vehicle is slightly better than that on Path 2. Plainly, Path 4 is better than Path 2 in a ride sense and about equal in fuel and tire material consumption.

Increases in tire modal frequencies are likely in net on any of the four paths. Tires will become smaller. The higher relative sidewalls in higher aspect ratio tires, Paths 3 and 4 will tend to reduce the size effect on modal natural frequencies. Higher inflation pressure inherent on Paths 2 or 4 will increase modal frequencies. The net effect of all this will probably be positive for vibration transmission so long as the frequency matching of vehicles and tires does not become closer, because human vibration sensitivity tends to be reduced as frequencies rise above 6 Hz [17]. However, impact boom and road roar coming from interaction with road irregularities may become worse as the ear is more sensitive to higher frequencies [17].

The reduction in tire damping inherent in lower loss materials could become a negative factor.

A few remarks about uniformity[29], and the resultant tire self-excited ride vibration are appropriate. Pottinger [26] provides a succinct review of the subject, particularly of those excitations which can be corrected: imbalance and first harmonic tire-force excitation. Higher harmonic forces can only be kept in bounds by careful tire manufacturing. There is no way to correct higher harmonic forces once the tire is cured.

The discussion of imbalance and first harmonic tire-force excitation ignores problems due to poorly machined hubs, and wheels with off-center or over-sized pilot holes, neither of which should exist today.

Imbalance can be corrected by appropriately placed weights. For well-made tires and wheels, imbalance is easily corrected using current equipment and should not be a worse problem with the projected tire modifications.

First harmonic tire-force excitation, both radial and fore-aft, may prove to be a worse problem than it is today. The source is tire/wheel-assembly radial runout. The force generated in the radial direction is proportional to the tire stiffness, which will increase if either Path 2 or 4 is followed. The force generated in the fore-aft direction depends on the angular acceleration occurring due to rolling-radius variation around the tire. Significant reductions in tire and wheel runouts beyond their current state may prove difficult. The best correction is match mounting of the wheel low point and tire high point so as to render the assembly's rolling radius as constant as possible. It is possible to introduce an eccentric collar into the system that can essentially eliminate tire first harmonic excitation [26]. This has not had to be done to date, but it exists as a potential solution should the problem worsen.

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[29] This is really variation of the tire/wheel/hub assembly from perfection.

Handling and Control

Several tire factors or properties that fundamentally affect vehicle handling and control are examined. The probable change in these factors along each of the four paths is used as another factor in choosing among the paths. No attempt is made to model individual vehicle responses as the individual tire force-and-moment properties and chassis parameters descriptive of the various classes of vehicles considered in this report are not available now and are not expected to be available before 2025. The discussion assumes a dry road unless a specific contaminant like water, snow, or ice is mentioned.

It is assumed that the reader is familiar with the terminology in SAE J2047 [27] and the Historical SAE Tire Coordinate System described therein.[30] They are applied in this section.

The starting place for handling-and-control studies is the low-slip-angle regime where almost all driving takes place. This was recognized by General Motors in the late 1960s and formalized in papers by Nordeen [29, 30] and in the General Motors Tire Performance Criteria (TPC) Specification System [31]. The original TPC system characterized a tire's handling properties in terms of cornering coefficient (CC), aligning torque coefficient (ATC), load sensitivity (h(1°)), and load transfer sensitivity (g(4°)) using data acquired from -6° to +6° at normal forces of 160% of rated load or less. Indeed, almost no driving (except emergency maneuvers) involves slip angles magnitudes beyond 1.3 to 1.4 degrees, as indicated in Figure 20 [31], which was derived based on data in reference 32.

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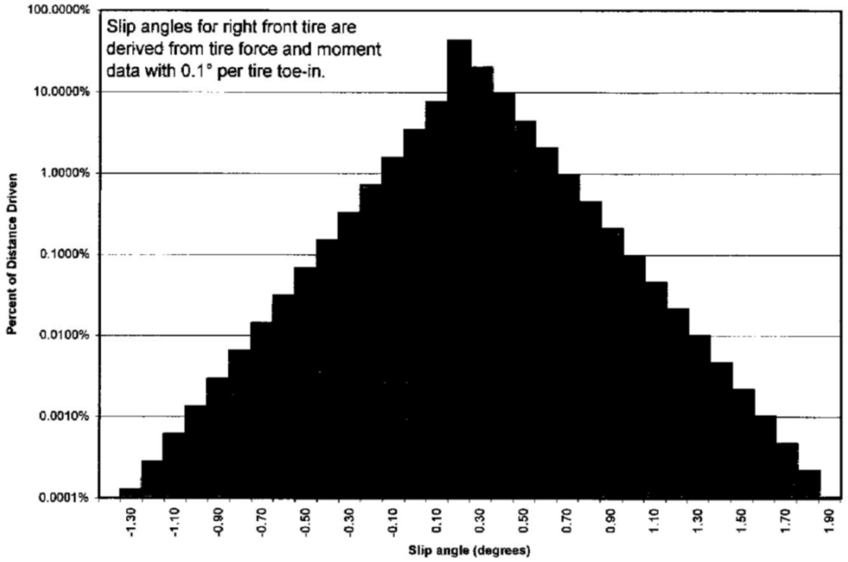
[30] In SAE J670 [28], the Historic System is referred to as the Superseded Tire Axis System, but it remains in use.



(Reprinted from Tire Science and Technology, Vol. 27, No. 3, 1999 with Tire Society Permission) [31]

Figure 20. Example tire force histogram. [31]

Nordeen [30] states that a 4% percent change in lateral-acceleration capability is subjectively detectable by chassis engineers with higher being better. The principle tire influence on lateral acceleration at low lateral-acceleration levels is CC. ATC is a secondary influence primarily because of its effect on steer due to linkage flexibility. Schroder and Chung [33], who were primarily concerned with lateral transient response, reached the same conclusion. Both CC and ATC can be projected for each of the four tire-evolution paths, so they will be used in evaluating the probable handling and control comparison of the paths.

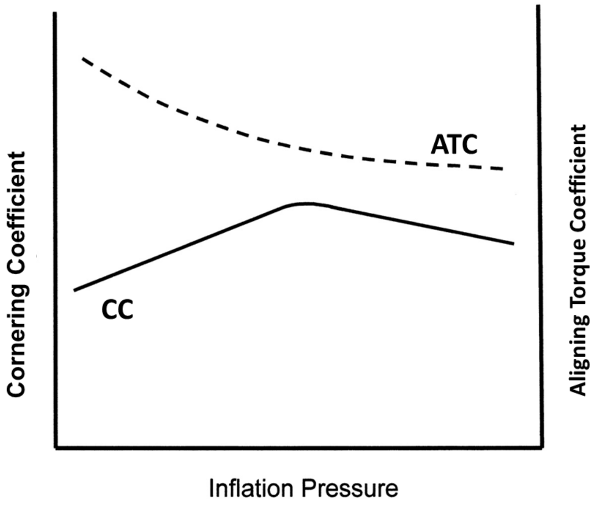
The load effects, h(1°) and g(4°), cannot be projected, so they will be ignored in comparing the paths.

Tire-relaxation length is a moderate contributor to low lateral-acceleration transient response [33]. A precise comparison is not possible, but generally tires with stiffer sidewalls and lower aspect ratio will have a shorter relaxation length contributing to better transient response.

Based on Walter's work [10], CC and ATC are related to aspect ratio, as indicated in Table 26. The effect of inflation pressure on CC and ATC is as shown in Figure 21. Unfortunately, the parameters for the curves are not available in the literature. My personal experience has revealed that the CC peak for 75 series LT tires occurs around 40 psi. The effect of tire size is that CC is larger for smaller tires of the same aspect ratio at the same percentage of tire rated load. This also could not be considered because of a lack of data in the literature.

Table 26
Cornering coefficient and aligning torque coefficient vs. aspect ratio.

Aspect Ratio	Relative Magnitudes	
	CC	ATC
55	1.00	1.00
70	0.97	1.15
85	0.88	1.39



Reprinted from Chapter 8 of The Pneumatic Tire, NHTSA ,2005 [34]

Figure 21. Cornering coefficient and aligning torque coefficient vs. inflation pressure. [34]

Assuming that durometer values will remain about the same between now and 2025 and that the composite stiffnesses of the radial tire belts will remain comparable to current practice, cornering and aligning torque coefficient will change along each path of tire evolution as indicated in Table 27. The resulting effect on driver perception of handling when cornering in typical driving will generally be as follows. Cornering on Path 1 tires will seem similar to current cornering, as will on-center behavior. Cornering on Path 2 tires will not be very different from the current perception, except that on-center feel will not seem as strong due to the reduction in ATC with increased inflation. The precise Path 2 cornering result will depend on the location of the peak in the cornering coefficient versus inflation-pressure curve depicted diagrammatically in Figure 21. On Path 3 cornering will not seem as responsive due to the reduction in CC with increased aspect ratio; however, on-center feel will seem much stronger due to the associated increase in ATC. Path 4 cornering will be much like Path 3 cornering with reduced on-center feel due to an inflation pressure induced reduction in ATC.

Table 27
Change in cornering coefficient and aligning torque coefficient on each path.

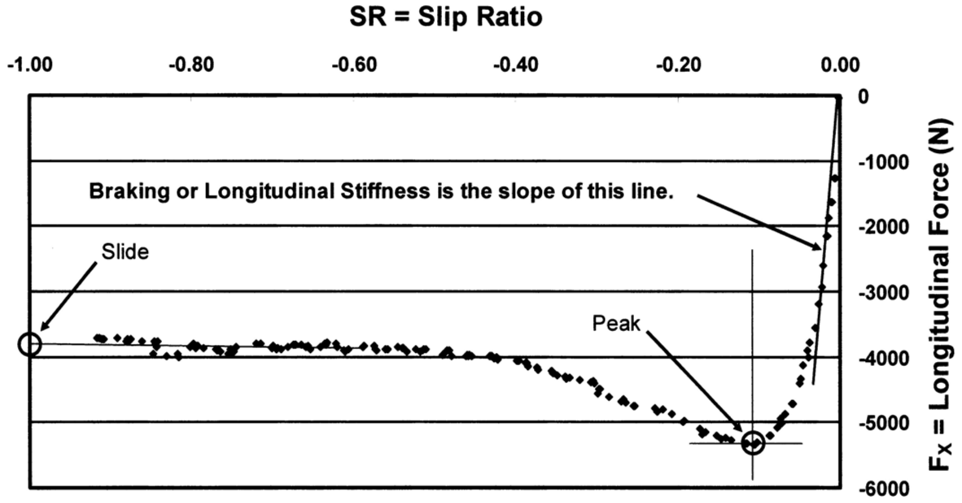
Path	2025 Compared to 2013 Levels	
	CC	ATC
1	Similar	Similar
2	Similar to Slightly Higher Than Path 1	Lower
3	Significantly Lower	Significantly Higher
4	Similar to Slightly Higher Than Path 3	Lower Than Path 3

The ability of the tire to generate frictional force through interaction with the pavement, often erroneously called grip, has been recognized as a crucial characteristic since the beginning of the tire and automotive industries. This is the fundamental limit on the ability to corner, stop, or accelerate. The effective friction coefficient can be characterized in all three modes of operation. Though the results are not identical in all operational modes, braking results provide an adequate magnitude approximation for frictional force capabilities from the standpoint of this report. They will be discussed and then friction will be brought into the cornering discussion extended to higher lateral accelerations. Obviously, many situations in real life involve combined braking or accelerating and cornering, but these are not touched in this report due to the complexity of combined mode operation. [35, 36, 37]

Figure 22 is an example of data from a straight-line braking test on a dry surface. Two pieces of data are particularly significant: peak and slide forces or friction coefficients. The peak characterizes the maximum frictional force that the tire can develop on the test surface. Slide characterizes the frictional force developed when the tire is operating like a hockey puck just sliding across the road surface. Near-slide directional control is not possible. If the tire is operating below or near the peak, directional control is still possible. For this reason antilock braking was developed.

The braking stiffness, which parallels changes in tire ride stiffness on the four paths, influences the dynamics of antilock systems. It is important in the tuning of antilock systems, but its effect will not be discussed in this report,

From the standpoint of this report, what will be the likely effect on the relative peak and slide values of following each of the four paths, starting with dry surface operation?



Reprinted from Chapter 8 of The Pneumatic Tire, NHTSA, 2005. [34]

Figure 22. Example dry surface braking test data. [34]

On Path 1, tire-friction properties in 2025 will be very like current properties unless the tread-compound frictional properties are reduced in the process of producing the rolling-resistance reduction represented in Figure 11. Safety concerns are such that a reduction in tread-compound friction properties is unlikely, but given the need to reduce rolling resistance, an increase in tread-compound friction is also unlikely. Thus, the probable compromise will leave tread-compound friction in 2025 about where it is now coupled with a further reduction in rolling-loss characteristics after a lot of development.

Given the approximately constant Path 1 compound frictional properties just hypothesized, the effect of following Path 2 will be a significant reduction in both peak and slide friction on a dry road. This is a result of the increase in the average normal pressure in the tire footprint, which is represented in Figure 23.[31] The result will be an increase in stopping distance and a reduction in available maximum lateral acceleration.

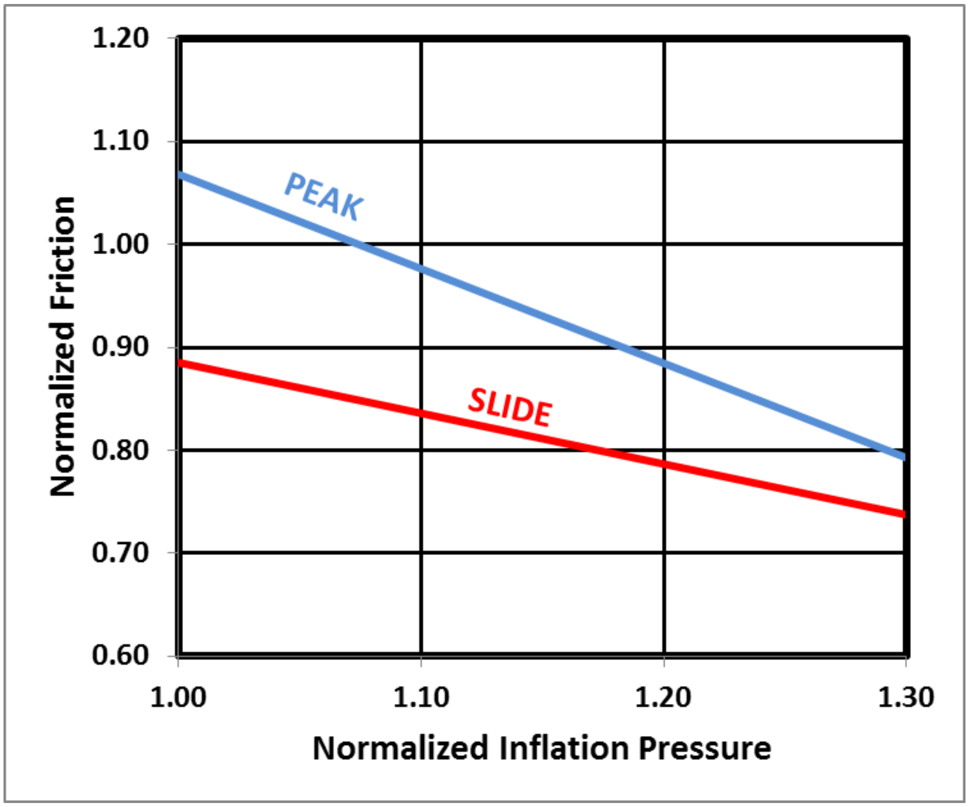


Figure 23. Effect of increased inflation pressure on peak and slide.

On a dry road, Path 3 will lead to peak-and-slide results very similar to those on Path 1. Path 4 behavior relative to Path 3 behavior will be comparable to the relative behavior on Path 2 with respect to Path 1.

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[31] The effect parallels the common situation in which the effective operational friction of Truck-Bus-Radial tires is considerably less than that of PC tires.

The consequences of the changes in peak and slide are summarized in Table 28.

Table 28
Peak and slide on the paths and consequent vehicle control changes.

Path	μ2025 Relative to μ2013		Possible Lateral Acceleration	Stopping Distance
	Peak	Slide		
1	≈	≈	≈	≈
2	<	<	<	>
3	≈	≈	≈	≈
4	<	<	<	>

Earlier in this section, Schroder and Chung's [33] observation that relaxation length has only a small effect on transient response at low slip angles was noted. Schuring [38] observed that there is an effect at high slip angle, as lateral force reaches the limits noted in Table 28. The effect is a phase delay that would affect emergency maneuvers, but would be undetectable to ordinary drivers, so its effect is not considered in this report.

Following the four different tire-evolution paths between now and 2025 will lead to modified tire frictional characteristics on wet or snowy roads.

People often think of the changes on wet surfaces in terms of hydroplaning, an absolute loss of traction on a wet surface due to a water film completely separating the tire from the road, but real life is usually different. Hydroplaning happens, but far more common is a reduction in or modification of the tire contact area with the road, which alters the frictional- generated control forces enough to cause a change in vehicle dynamics sufficient to lead to driver loss of control.[32] This change comes from the buildup of pressure in the water film that exists as a tire operates across a wet road. Figure 24 shows the normal, vertical, pressure distribution existing in the contact of a rolling P195/70R14 tire at rated load. The precise normal stress distribution of different tires varies in detail [39], but the basic distributions are enough alike that the interactions with a wet surface are characteristically similar. As Grogger and Weiss [40] show in

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[32] The actual situation is an interaction of the road texture, tread pattern, drainage, water depth, and tire geometry, but the focus here is on the four paths, which are functions of tire geometry and inflation pressure.

Figure 25, buildup in pressure as the tire rolls into the water film forces part of the tire out of contact. Even if the part of the tire footprint still in contact is in perfect dry contact with the road, the result is going to be reduced and different forces. Hydroplaning theory [41] indicates that the contact area will be most modified at lower inflation pressures and when tire-footprint aspect ratios (width/length) are larger. Thus, the wet traction effect of following the four paths assuming unchanged tread compound friction will be as follows.

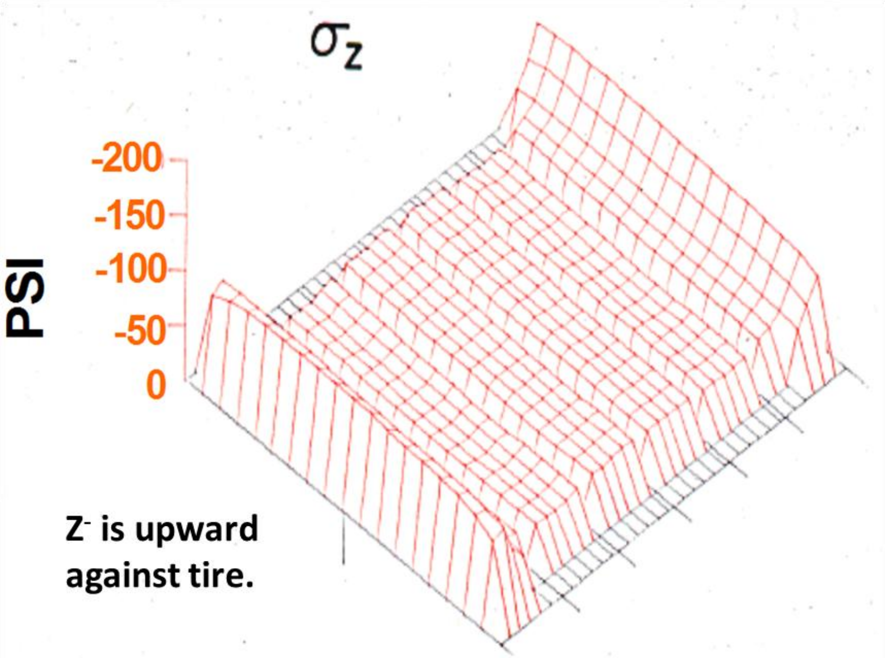
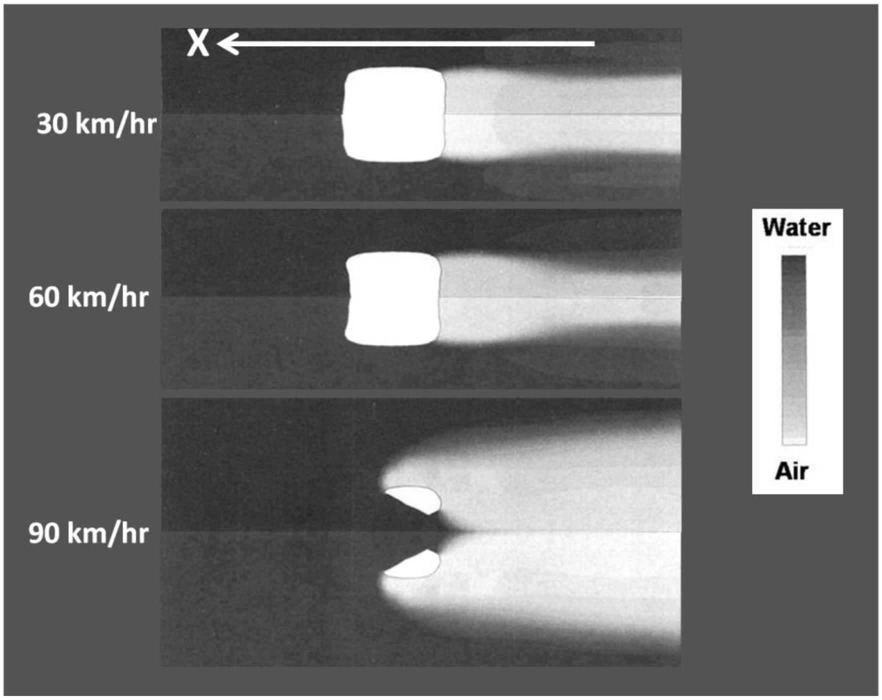


Figure 24. Example of tire normal stress.



From a Figure in *Tire Science and Technology*, Vol. 25, No. 4, 1997 with Tire Society Permission [40]

Figure 25. Smooth tire change in contact with speed on a wet surface.

Path 4 will show the smallest change in force generation when changing from a dry road to a wet road, as it benefits from both an inherently lower footprint aspect ratio and a higher inflation pressure. Paths 2 and 3 will not show as small a change in passing from a dry to wet road as should be seen on Path 4. This is due to the fact Path 2 shows only an increase in inflation pressure and Path 3 shows only a better footprint aspect ratio instead of having both effects as is true for Path 4. Path 1 will show the largest change as it has neither of the advantageous features.

Assuming that the groove void volumes of the tires on the four path are essentially equal and the relative fraction of the void laid out transversely and circumferentially is the same, the snow traction will be best with the larger footprints associated with the lower inflations inherent on Paths 1 and 3. Given that the footprints on Path 3 are also longer—a desirable feature in snow—the paths should lineup in this order from best to worst in snow traction terms: Path 3, Path 1, Path 4, Path 2.

Synopsis

The vehicle-fuel-consumption effect for possible tire evolution from now until 2025 has been projected along with changes in raw material-consumption in tires, as measures of tire sustainability. Likely effects on operational performance have been examined simultaneously. This was done because it is not possible to look at the sustainability impact of potential design changes without considering tradeoffs in performance affecting normal tire usage. To this end, likely effects on ride, and handling and control have been projected. Other operational- performance characteristics, such as wear and high-speed performance, have been assumed to be maintained but were not explicitly considered in this analysis.

Expected light-vehicle, passenger-car, and light-truck evolution in response to the fuel economy mandates for 2025 is the starting point. Practical considerations in terms of passenger space and cargo volume plus crash safety militate against drastically smaller vehicles. However, analysis of EPA combined fuel economy for existing vehicles immediately illustrated the value of reducing vehicle test weight to increase fuel economy. In a practical sense, gross vehicle weight drives tire sizing, once a decision is made as to tire aspect ratio and rim diameter.

An examination of the practical design space for variants to current tire-design practice that will improve fuel economy through reduced rolling resistance without untenable operational property changes led to a space defined by continuing improvements to tire materials, aspect ratios from 55 to 85, and reasonable increases to tire-inflation pressures, perhaps to 50 psi. The final decision was to explore four paths. Path 1 is 55 aspect ratio, 35 psi cold inflation, and evolving materials. Path 2 is 55 aspect ratio, 50 psi cold inflation, and evolving materials. Path 3 is 85 aspect ratio, 35 psi cold inflation, and evolving materials. Path 4 is 85 aspect ratio, 50 psi cold inflation, and evolving materials. In each case, the effect of vehicle-weight reduction was considered with respect to tire sizing and tire-weight savings.

The analysis of the effect of tire rolling resistance on fuel economy, as a function of EPA vehicle test weight for vehicle classes A through E plus pickups, was performed for the five types of vehicle powerplants now in service: gasoline, diesel, hybrid, plug-in hybrid, and electric. The analysis was carried out for test weights from current to test weights reduced by 30 percent.

The comparison of the 2013 fuel economies for the five powerplants shown in Figure 10 makes it obvious that use of electric propulsion has fuel-economy advantages, which will grow as electric use grows as a percentage of total driving. Unfortunately, in CO_2 terms, the exact advantage is uncertain for plug-in hybrids and electric vehicles due to the emissions associated with the generation of the electricity used to charge the vehicle batteries.[33] Another important aspect of vehicles with some electrical propulsion is that they have higher curb weights than comparable gasoline or diesel vehicles, as noted in Table 3.

The next step was to estimate the change in 2013 rolling resistance that will occur by 2025 when following each path. The results, summarized in Table 11, indicate similar reductions from projected materials evolution and potentially feasible inflation-pressure increases. It is likely that there is an aspect-ratio effect and a size effect that will be associated with the change in tire size as vehicles become lighter. Unfortunately, there is not adequate information to define these two effects.

The expected change in fuel consumption for the example vehicles with various levels of assumed EPA test-weight evolution are summarized on the four tire-evolution paths in Tables 13 and 14. The EPA unadjusted fuel-economy results quantify the significant fuel savings and improvement in tire sustainability that will occur on any of the paths. They indicate that the change from 35 to 50 psi cold inflation pressure inherent on Paths 2 and 4 is equivalent to three quarters of what can be achieved through the expected materials research and development from now until 2025. Adjusting the mileage to approximate consumer usage based on the relation between sticker and unadjusted fuel economy results produced an estimate of the economic savings for consumers over a 60,000-mile tire life. The savings are significant according to results presented in Tables 15 and 16. Interestingly, the results are probably conservative because the reduction of rolling resistance with tire wear is not considered.

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[33] In reality, zero emission vehicles do not exist. Today, they are just a way of shifting emissions between locations.

Reduction in the amount of materials required to manufacture tires is another significant sustainability factor. Tires were sized for the example vehicles along the four paths yielding Tables 17 through 21. The tire-material weight savings are noted in Tables 22 through 25. The savings simply due to the vehicle-weight-reduction effect on required tire sizes are significant. Interestingly, it is apparent that Paths 2 and 4, which involve an increase in cold inflation pressure, would yield the greatest tire-weight reductions. It is also interesting that the 85-aspect-ratio tires appear to offer slightly lower tire weights given the assumptions stated in this report.

Overall, it appears that tires with higher cold-inflation pressures offer better sustainability than tires designed based on current cold-inflation pressures. The question is whether or not there are potential operational tradeoffs that would preclude their use. Tire-property tradeoffs that affect ride and vehicle control were briefly examined.

From a ride standpoint, aspect ratio, tire size, inflation pressure, and tire-material damping all have effects on tactile and noise inputs to drivers and passengers. The decision to employ higher inflation pressures to improve sustainability will definitely increase the magnitude of force inputs to the vehicle rendering harshness worse, as the tire envelopes road-surface irregularities. This effect will be less severe at higher aspect ratios. Thus, Path 4 would be better than Path 2. Correspondingly, Path 3 tires should yield a smoother ride than Path 1 tires. The reduction of tire size combined with higher inflation pressure will push modal frequencies higher, which should aid ride tuning to reduce tactile annoyance, but may make tuning to reduce in-cabin noises like boom and road roar more difficult. The reduction in tire damping inherent in improved sustainability will be a negative for tire transmissibility characteristics. Given the higher spring rate of tires at higher inflations, first harmonic uniformity (which induces vehicle shake) may worsen, requiring implementation of something like the eccentric collar to prevent ride problems.

Assuming the same tread-material properties for tires on the four paths, the frictional properties of the tires will depend on how the tires on a given path use the tread-compound characteristics in a particular vehicle-acceleration situation. The difference in use will depend on the tire aspect ratio and inflation pressure. On a dry road, the stopping distance for Path 2 and 4 tires will be greater than for Path 1 and 3 tires due to their higher average contact pressure. Correspondingly, the maximum possible lateral acceleration will be lower for Path 2 and Path 4 tires than on Path 1 and 3 tires. For ordinary drivers, the effect on stopping distance will be far more significant than the limitation on lateral acceleration. Drivers are sensitive to the cornering-coefficient level of tires, which affects the feeling of control in ordinary driving. The inflation pressure on the different paths is very near the point where the cornering coefficient reaches a maximum, so inflation pressure is not going to be the determinant of cornering feel. However, aspect ratio will be a determinant with Path 3 tires feeling less well controlled than Path 1 tires and Path 4 tires feeling less well controlled than Path 2 tires. Under dry conditions, so long as the pressure-level rise associated effect on stopping distance is not too large, it is probable that the Path 2 tire will be preferable.

Assuming that the highest friction level on wet or snowy pavement coupled with the least abrupt change when going from dry to wet is the objective, Path 4 would lead to the most satisfactory tires for an ordinary motorist.

In conclusion, so long as the negatives noted in ride and handling can be ameliorated in vehicle design, the best probable technical path is higher-aspect-ratio tires at a higher cold-inflation pressure. The greatest difficulty might be with tire appearance that may make the technical path more difficult to follow. Customers believe that the more tires look like racing tires the better they are for his or her vehicle. This matter is not addressed in this report.

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