TIRES, TECHNOLOGY AND ENERGY CONSUMPTION

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Overview of Presentation

- Components of overall vehicle energy use and relationship to thermodynamic laws
- Tire contribution to energy use on different speed cycles and its measurement
- Effects of tire properties, design and operation on vehicle fuel economy
- Trade-off of RRC with other tire properties

First and Second Law Efficiency

- Conversion of fuel energy to heat and work involve both Carnot cycle limitations, and real world frictional and pressure losses.
- At a maximum temperature of 1000 C, the Carnot cycle efficiency is about 76 percent.
- Theoretical Otto (gasoline) cycle efficiency is about 45% at 10:1 compression ratio based on “first law” efficiency.

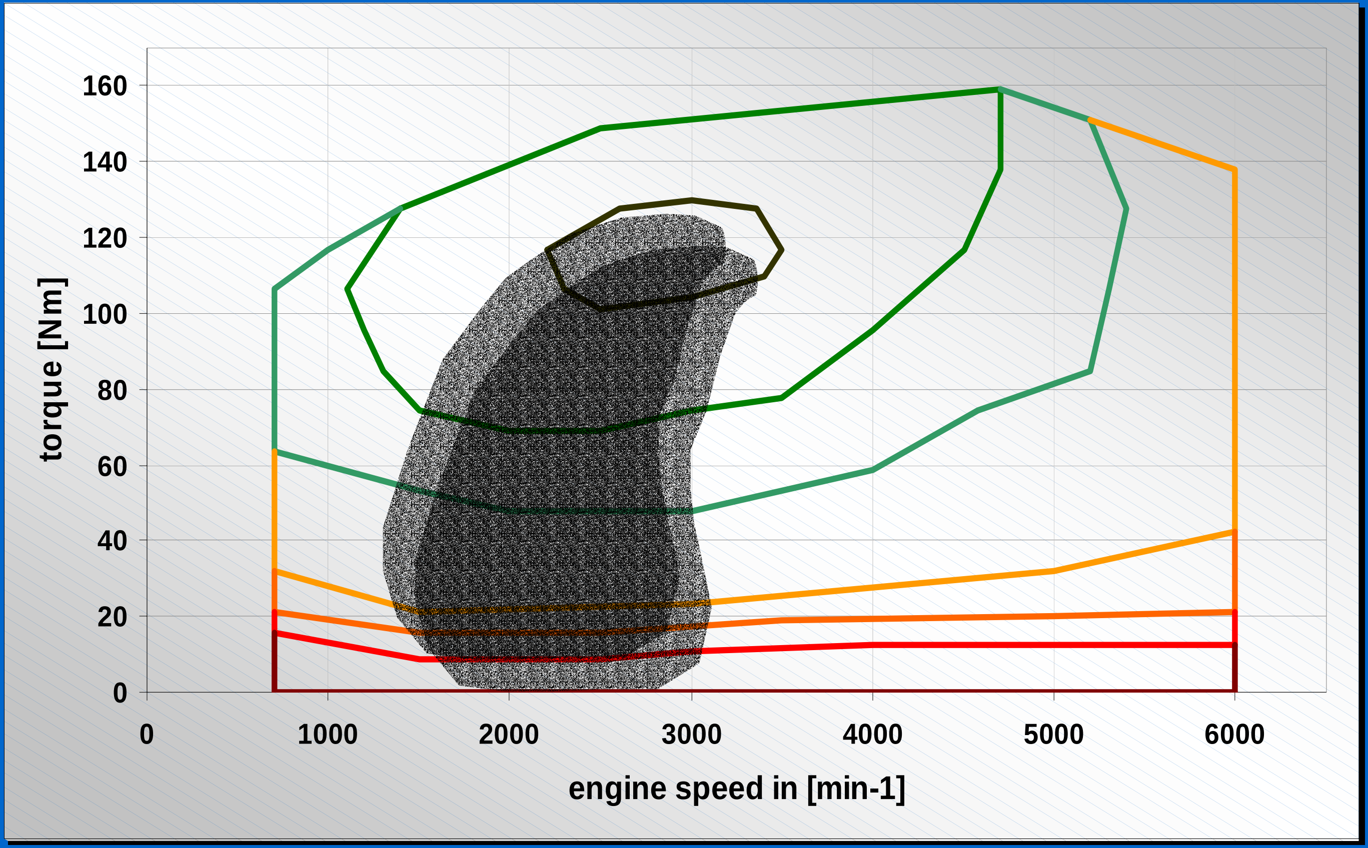
Actual Engine Efficiency

- Peak first law efficiency of modern gasoline engines (spark ignited) is in the 34 to 36% range while light-duty diesel engines are in the 40 to 42% range.
- Peak efficiency realized only in a small portion of operating map, and actual efficiencies during typical driving are much lower than the peak value.

Energy Demand for Driving

- External forces to be overcome include:
  - Inertia force proportional to weight *acceleration
  - Tire rolling resistance proportional to velocity
  - Aerodynamic drag proportional to square of velocity
  - Engine power requirement must overcome external forces plus transmission loss and driveline loss, as well as accessory loads
  - Total fuel consumed must also account for fuel used when idling and braking.

Engine BSFC Map



Calculated Example-Midsize Car

- Since the velocity- time profile is specified for the Federal Test Procedure, the tractive energy requirements can be numerically computed as functions of weight, drag co-efficient and tire RR co-efficient.
- Complete fuel consumption calculation requires knowledge of transmission efficiency, accessory power and engine fuel consumption map as a function of engine speed and load.

Tractive Energy Required

- Energy Use

	City Cycle	Highway Cycle	Composite cycle
Rolling Resistance	27.7%	35.2%	30.35%
Aerodynamic Drag	18.0	50.4%	29.43%
Inertia Force	54.3%	14.4%	40.22%

Fuel Consumption Analysis

	City Cycle	Highway Cycle	Composite Cycle
Tractive Energy	57.5%	80.5%	65.5%
Accessory Energy	10.0%	6.0%	8.7%
Idle + Braking Consumption	15.0%	2.0%	10.4%
Transmission + Driveline Loss	17.5%	11.5%	15.4%

Derivation of FC Sensitivity

- On the composite cycle, tires account for 30.35% of tractive energy. Tractive Energy accounts for 65.5% of fuel consumed. Hence, tire portion of energy consumed is 0.3035*0.655 = 19.89%
- Note that typical engine efficiency on the composite cycle is only about 22 to 23%. Hence, tires account for about 4.5% of fuel energy on first law basis, but this is not a useful measure for the issue of fuel conservation.

Relationship between RR and FE

- The 2 % change in composite FE per 10% change in RR assumes no other changes.
- However, a load reduction makes the engine less efficient, so that theoretically, the reduction should be about 1.5 to 1.7% , and about 1.1-1.2% in the city and 2.0-2.2% on the highway.
- The calculations do not account for all of the tire effects and their contribution to overall energy use, as well as non-linear and interactive effects.

Larger Picture of Tire Effects

- The tires have a mass that contribute to inertia force with rotational inertia added.
- Rotating tires are a major contributor to total aerodynamic drag force.
- The tire RR co-efficient is itself a function of vehicle related, ambient, and load conditions not covered by the RR test.
- These issues are examined briefly.

Mass and Drag Effect

- Typically a set of 4 car tires weighs 65 to 75lbs, and the rotational and translational inertia are equivalent to about 5% of vehicle inertia. A 10% reduction in tire weight increases FE by 0.25%
- Rotating tire drag can be 20 to 25% of total vehicle aerodynamic drag. Increasing the width of the tire, and changing the tread, or the rim and wheel can change tire drag by 3 to 6%. This can change FE by 0.1 to 0.3%.

Effect of Design Parameters

- RR varies linearly with load and inversely with square root of inflation pressure. There is an interactive effect where RR is less sensitive to inflation pressure at lighter load.
- For a given application and a constant tire technology, tire RR is inversely proportional to radius and aspect ratio but increases with increasing width (about 5% per 20mm). Effect of diameter is quite dominant.

Effect of Tire Mounting and Ambient Conditions

- Position has an effect on RR
  - toe-in creates additional side force, increasing RR by 1% per 0.15deg per wheel
  - slip angle has large effect (next slide)
  - camber and road curvature also have some effects but these are small
- Both ambient and tire temperature have a significant effect on RR. For example, from -20C to +20C, RR can be reduced by 50%.

Effect of Slip Angle on RR

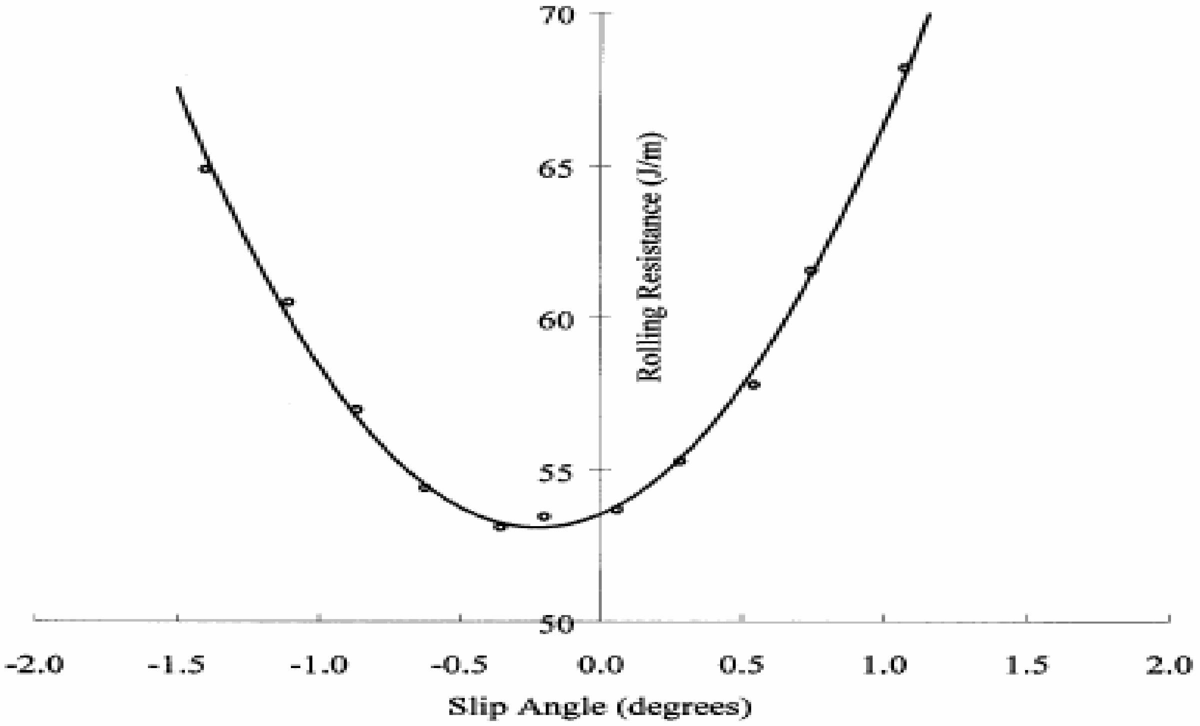


Figure 7. Rolling resistance as a slip angle for a FR78-14 passenger car tire at 5.7 kN, 195 kPa, and 80 kph (reproduced with permission from [17])

Effect of Driving Conditions

- RR increases with speed in a non-linear fashion. Current J2452 procedure fits a V+ V**2 curve, but dependence is small at speeds < 60mph. Beyond critical speed (usually over 80 mph) standing waves develop and RR increases rapidly.
- RR is also a function of the torque transmitted or absorbed. Beyond a specific torque, tires either spin (acceleration) or skid (braking), leading to huge increases in RR as shown in chart.

RR versus Tire Torque

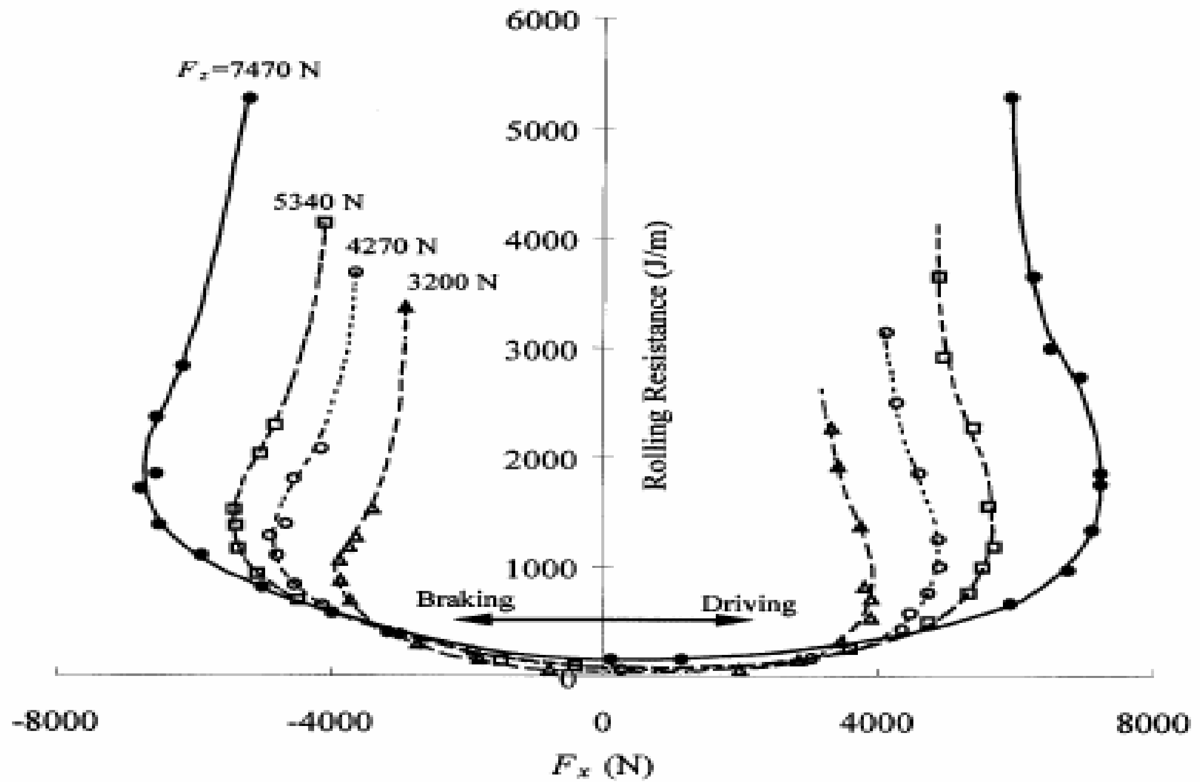


Figure 6. Rolling resistance as a function of longitudinal force (driving/braking torque) for various vertical loads for a 6.45S14 passenger car tire at zero slip angle (reproduced with permission from [16])

Measurement of RR and FE

- RR now measured using SAE J2452 is an improvement over older J1269 procedure but provides no insight into other effects. RR is measured during stepwise coast-down but not while transmitting power.
- Vehicle mounting effects and ambient effects (mainly temperature) could further alter on-road RR but it is not clear if this affects relative ranking between tires.

Estimation of FE Effect

- The EPA dyno test simulates total energy use by matching the coast down time on the road to the dyno coast down. RR under powered condition is likely a little different and accuracy of simulation under transient conditions not well understood.
- Main issue with real world FTP testing is the test-to-test variability, requiring multiple tests to ensure that differences as small as 1 or 0.5 percent is quantified with statistical confidence.

Estimation of FE Effect

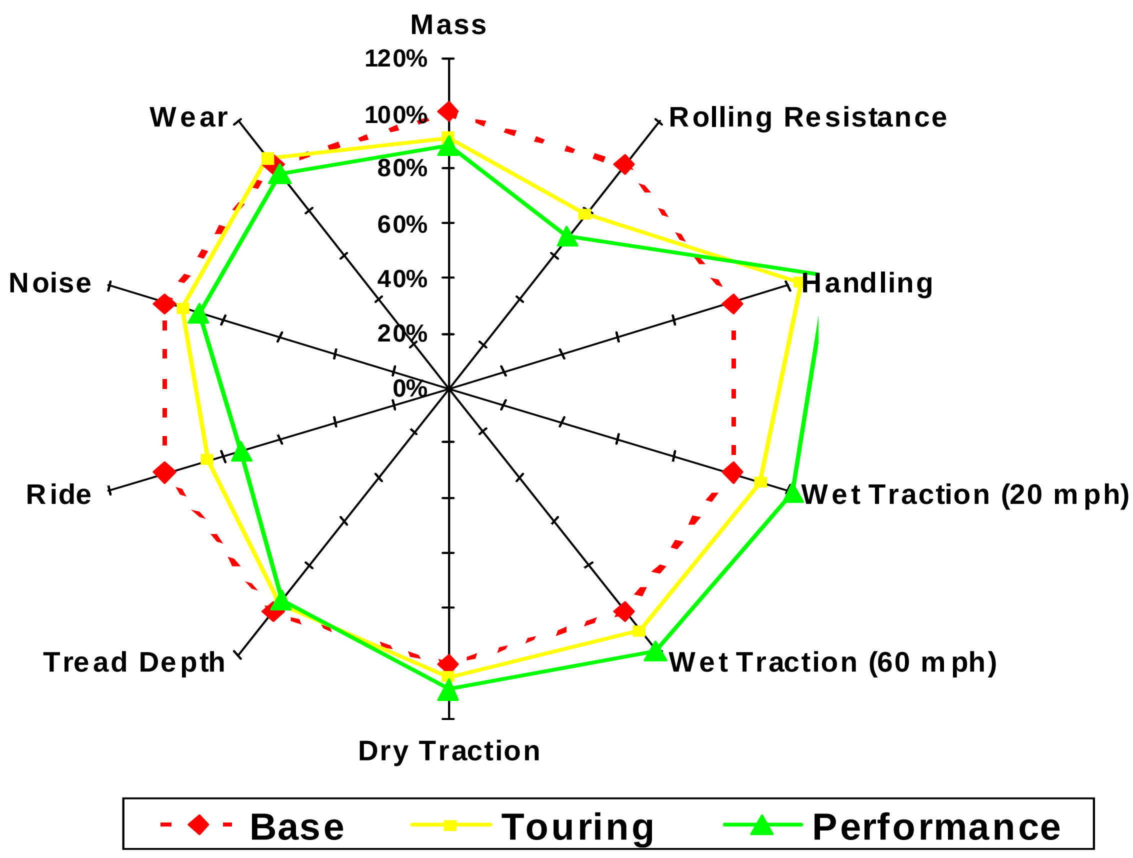
- California is looking at using a vehicle simulation model to estimate FE effects. However, the simulation models have simplistic representation of tire RR (e.g. no tire rotating inertia, temperature based change in RR, etc.) and are not accurate.
- Rules of thumb approach may be best for use by wide range of consumers. Development of rules of thumb by vehicle category or type (e.g. small car, pickup truck, SUV) is required.

Tire RRC Trade-off

- Auto-manufacturers emphasize that tire properties trade-off is a function of tire technology, and trade-off for a new tire should be evaluated at given technology level.
- Over time, it is possible to improve all properties simultaneously with technology improvements. Hence comparisons of tires at different technology levels will show no consistent trade-off pattern.
- New silica tires have lower RRC tradeoff with other desired properties than older designs.

GMNA Product Development

PERFORMANCE TRADE-OFFS BY TIRE TYPE



Estimates of Trade-off

- Recently, much more new data on RRC of tires in the market has been obtained.
- Data must be subjected to sophisticated regression analysis due to inter-relationship between tire properties.
- Preliminary analysis indicates modest relationship between RRC and tire wear, strong relationship with high speed rating

Fuel Efficient Replacement Tires

- Lack of after-market tire rolling resistance data requires “educated estimate” of benefit.
- About half of all consumers replace tires with the same brand, while others use a different (lower cost?) brand. However, impact on rolling resistance is not completely clear
- Significant shift to high performance tires occurring in the market may be making rolling resistance worse and decreasing average life.

Comments on Labeling

- All auto-manufacturers said that they were unsure of value to consumer of RRC information due to complexity of tradeoff with other properties.
- OEM spec tire provides best balance of properties according to them.
- Factoring in tire price and life may yield different consumer preferences- maybe higher RRC?
- Some technologies (double and triple tread) not shown to OEM due to cost?