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Vehicle Operating Costs: The Fuel Factor

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Vehicle Operating Costs: The Fuel Factor

Physics

At steady state, or near steady state:

$$\text{FE}\ [\text{mi/gal}] = \frac{\text{S}\ [\text{mi/hr}]}{\dot{\text{V}}_\text{f}\,[\text{gal/hr}]}$$

In terms of the mass consumption rate of the fuel:

$$\text{FE}\ [\text{mi/gal}] = \frac{\text{S}\ \rho_\text{f}}{\dot{\text{m}}_\text{f}}$$

Vehicle Operating Costs: The Fuel Factor

Engine Theory

The overall efficiency of an engine (sometimes called the "brake thermal efficiency") is defined via:

$$\eta_e = \frac{\text{energy sought}}{\text{energy bought}} = \frac{\text{bp [kJ/s]}}{\dot{m}_f\,[\text{kg/s}] \times \text{LHV}_p\,[\text{kJ/kg}]}$$

Rearranging yields:

$$\dot{m}_f = \frac{\text{bp}}{\eta_e \times \text{LHV}_p}$$

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More Physics

Our equation for fuel economy is now:

$$\text{FE [mi/gal]} = \eta_e \left[\frac{S}{bp} \right] (\rho_f \, \text{LHV}_p)$$

The term within square brackets is the inverse of a force. We must manipulate this term to obtain a force that is useful. The power delivered to the tire-road interface is related to the brake power output of the engine via:

$$bp \times \eta_{trans} \times \eta_{diff} = p_{T\text{-}R}$$

ACCOUNT FOR LOSSES
IN TRANSMISSION AND DIFFERENTIAL

Vehicle Operating Costs: The Fuel Factor

Effects of the Transmission

Thus, our equation for fuel economy is:

$$FE = \eta_e \left[\frac{S}{bp} \right] (\rho_f LHV_p) = \eta_e \eta_{trans} \eta_{diff} \left[\frac{S}{p_{T\text{-}R}} \right] (\rho_f LHV_p)$$

This version of the equation shows the importance of the transmission and the differential. Manual transmissions are more efficient than automatics, so they are much more common in Europe than the US. This also explains the recent development of "lock up torque converters" for automatic transmissions and one reason for the development of CVTs. Front wheel drive vehicles combine the tranny and diff into a single unit, the transaxle, so the product of these two efficiencies can be treated as a single efficiency for those vehicles.

Vehicle Operating Costs: The Fuel Factor

More Physics

Our equation for fuel economy was:

$$FE = \eta_e \left[\frac{S}{bp} \right] (\rho_f LHV_p) = \eta_e \eta_{trans} \eta_{diff} \left[\frac{S}{p_{T\text{-}R}} \right] (\rho_f LHV_p)$$

The term within square brackets is now the inverse of the force exerted by the tires on the road to propel the vehicle: the resistive force:

$$FE = \frac{\eta_e \{\eta_{trans} \eta_{diff}\} (\rho_f LHV_p)}{F_{res}}$$

Vehicle Operating Costs: The Fuel Factor

Road Load

The resistive force can be calculated from:

$$F_{res} = \frac{1}{2}\rho_{air} C_D A \left(S \pm U_x\right)^2 + \frac{1}{2}\rho_{air} C_D A U_y^2 + C_{RR} W_{tot} \pm W_{tot} \sin\theta$$

where the first term on the RHS is the aerodynamic drag force acting against the forward motion of the vehicle (U_x is the component of the wind in the direction of motion), the second term accounts for the crosswind component of the drag, the third term accounts for the frictional force between the tires and the road (this is referred to as "rolling resistance"), and the final term accounts for the grade.

Vehicle Operating Costs: The Fuel Factor

Road Load

On a level road with no wind, the resistive force is called the road load force:

$$F_{rl} = \frac{1}{2}\rho_{air} C_D A S^2 + C_{RR} W_{tot}$$

where it must be noted that the rolling resistance is a function of both vehicle weight and vehicle speed.

$$FE_{rl} = \frac{\eta_e \{\eta_{trans}\eta_{diff}\}(\rho_f LHV_p)}{F_{rl}}$$

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Effects of Vehicle Parameters

After substitution, the fuel economy equation becomes:

$$FE_{rl} = \frac{\eta_e \{\eta_{trans}\eta_{diff}\}(\rho_f LHV_p)}{(1/2)\rho_{air} A\ C_D S^2 + C_{RR} W_{tot}}$$

Any factor the increases the denominator (the road load force), decreases fuel economy (as long as this factor doesn't have the opposite effect on the overall engine efficiency). Thus, factors that decrease fuel economy include increased vehicle weight and cross-sectional area.

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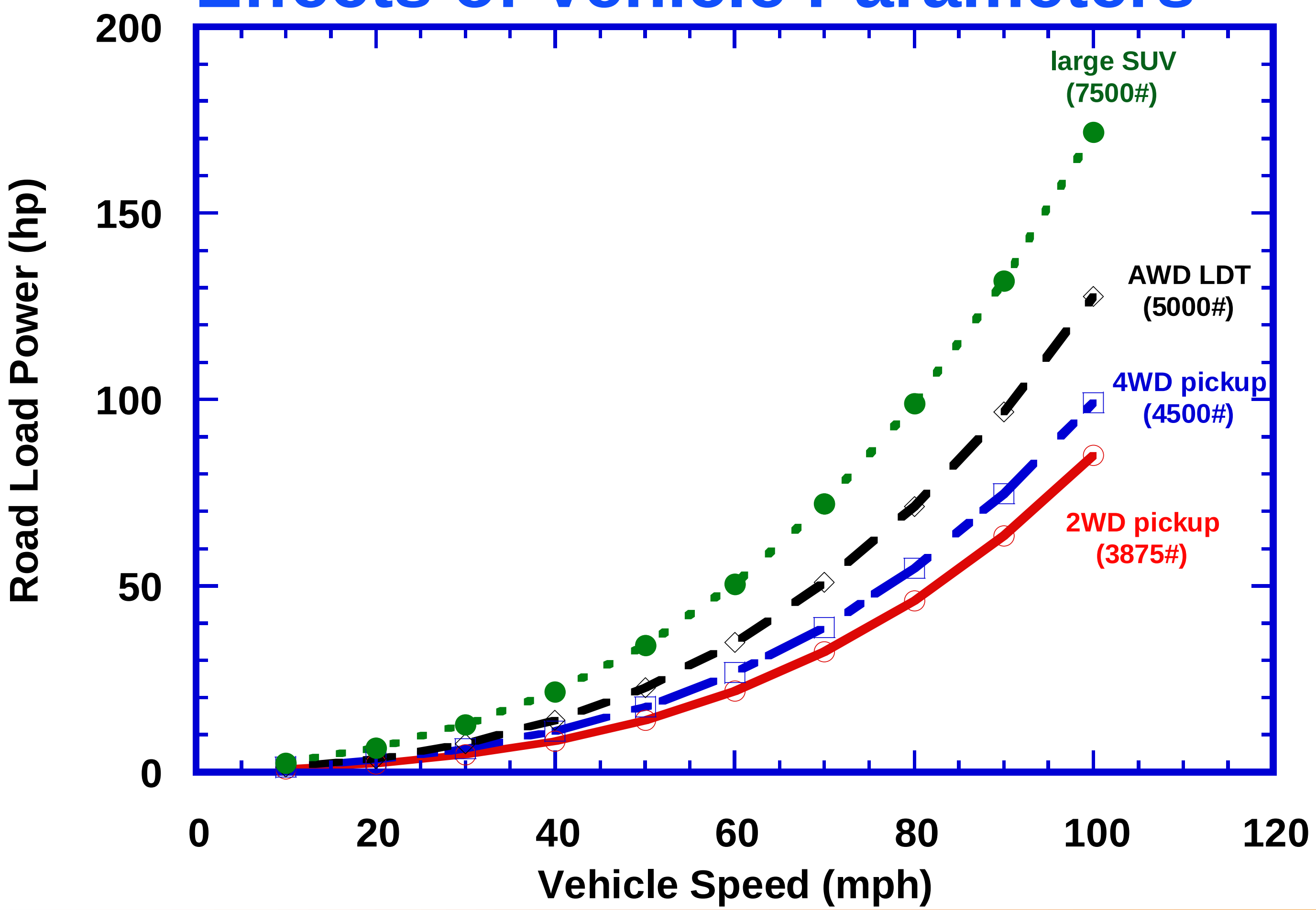
Effects of Vehicle Parameters



Vehicle Operating Costs: The Fuel Factor

Fuel Effects

Recall our equation for road load fuel economy:

$$FE_{rl} = \frac{\eta_e \{\eta_{trans}\eta_{diff}\}[\rho_f LHV_p]}{F_{rl}} = \frac{\eta_e \{\eta_{trans}\eta_{diff}\}\rho_{H2O}[sg_f LHV_p]}{F_{rl}}$$

The terms within the square brackets are properties of the fuel.

fuel	specific gravity [-]	LHV_p [MJ/kg]	FE* relative to gasoline
2D diesel	0.85	42.5	+14%
biodiesel (B100)	0.88	37.5	+4%
gasoline	0.747	42.6	-
E85	0.78	31.0	-24%

* Based solely on fuel property effects, but the diesel engine is also more efficient than the gasoline engine.

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Importance of the Engine

It can be shown that the overall efficiency of the engine is related to three fundamental efficiencies:

$$\eta_e = \eta_c \eta_{ti} \eta_m$$

The importance of the mechanical efficiency is why the auto manufacturers have gone to the expense of developing engines with components that have lower frictional and parasitic losses. Examples include: roller lifters, roller rockers, and electrically-driven (rather than belt-driven) power steering pumps and water pumps.

Vehicle Operating Costs: The Fuel Factor

Importance of the Engine

This equation also shows the reason that a diesel powered vehicle is much more fuel efficient than a comparable gasoline powered vehicle (2X rather than 1.14X):

$$FE_{rl} = \frac{[\eta_c \eta_{ti} \eta_m]\{\eta_{trans} \eta_{diff}\}(\rho_f LHV_p)}{(1/2)\rho_{air} C_D A S^2 + C_{RR} W_{tot}}$$

Specifically, the thermodynamic cycle that the diesel operates on is much more efficient than the cycle that a gasoline engine operates on (when the higher compression ratio of the diesel is accounted for in the comparison).

Vehicle Operating Costs: The Fuel Factor

Conclusions

For steady-state operation of a specific category of engine (e.g., light-duty spark ignition), the product of two fuel properties dominate the effects of the fuel on the fuel economy of the vehicle:

- **The physical density (usually tabulated in normalized form as the specific gravity)**
- **The chemical energy density (the constant pressure Lower Heating Value)**

$$\frac{FE_{E85}}{FE_{gasoline}} \approx \frac{[sg \cdot LHV_p]_{E85}}{[sg \cdot LHV_p]_{gasoline}}$$

Vehicle Operating Costs: The Fuel Factor

Conclusions

For <u>transient</u> operation of a specific category of engine (e.g., light-duty spark ignition), the effects of the fuel on the fuel economy are closely approximated by the same relationship.

$$\frac{FE_{E85}}{FE_{gasoline}} \approx \frac{[sg \cdot LHV_p]_{E85}}{[sg \cdot LHV_p]_{gasoline}}$$

Vehicle Operating Costs: The Fuel Factor

Conclusions

From this perspective (same engine, same vehicle, same payload, same tires), there is an inherent penalty that must be paid for the biofuels.

For "flex fuel vehicles", there is a 25-30% fuel economy penalty during operation on E85.

However, for diesel vehicles, operation on "B20" should produce a fuel economy penalty of only ~1.7% instead of ~8.7%, which is within the typical repeatability of fuel economy tests.

Vehicle Operating Costs: The Fuel Factor

Definitions

A	front cross-sectional area of vehicle [m^2]
bp	"brake" power output from the engine [kW]
C_D	aerodynamic drag coefficient [-]
C_{RR}	coefficient of rolling resistance [-]
FE	fuel economy [mpg, mi/gal]
FE_{rl}	fuel economy under road load conditions [mpg]
LHV_p	energy density of the fuel: the constant pressure Lower Heating Value [MJ/kg]
S	vehicle speed [mph or m/s]
sg_f	specific gravity of the fuel [-]
$\dot{m}_f$	fuel consumption rate by mass [kg/hr]
$\dot{V}_f$	fuel consumption rate by volume [gal/hr]

Vehicle Operating Costs: The Fuel Factor

Definitions

- U_x wind component along direction of vehicle motion [m/s]
- U_y wind component perpendicular to vehicle motion [m/s]
- W_{tot} total (loaded) weight of the vehicle [N or lb_f]
- ρ_f fuel density [kg/gal]
- ρ_{H2O} density of water at 25 ^{o}C [kg/gal]
- η_c combustion efficiency - efficiency of converting the chemical energy of the fuel to thermal energy [-]
- η_e overall engine efficiency [-]
- η_{diff} efficiency of the differential [-]

Vehicle Operating Costs: The Fuel Factor

Definitions

η_m mechanical efficiency of the engine – efficiency at overcoming frictional and parasitic losses [-]

η_{ti} indicated thermal efficiency - efficiency of the thermodynamic cycle on which the engine operates [-]

η_{trans} efficiency of the transmission [-]