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TECHNICAL PAPER

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LET'S TALK TRUCKING: TRUCK PERFORMANCE AND FUEL CONSUMPTION[1]

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Truck specifications (engine, transmission, driveline, rear axle, etc.) will affect performance and fuel consumption for the life of the truck. Therefore, it is important to understand the factors that affect performance and select components to optimize performance and fuel efficiency.

Truck performance is determined by power available or, in some cases, traction available. Power-limited performance assumes that tire-road friction is sufficient and that gradeability depends on how much engine power is available to overcome internal and external resisting forces.

Tractive effort is the drawbar pull available after drivetrain and engine accessory losses have been subtracted. The difference between the tractive effort available and the tractive effort required is the amount left over for acceleration or deceleration. According to SAE (2003) the formula for tractive effort is:

$$TE_{GN} = \frac{HP_N * 5252}{N} * \frac{E_G}{100} * R_G * \frac{2 * p * M}{5280}$$

where: TE_{GN} is the tractive effort in pounds available for each gear (G) and engine RPM (N), HP_N is the net engine power at "N" RPM, E_G is the powertrain efficiency in percent for each gear, R_G is the total reduction (rear axle ratio times the main transmission ratio), and M is the tire revolutions per mile at 45 mph.

The external forces acting on a truck include rolling resistance, air resistance, grade resistance, inertial resistance, and curve resistance (Wild, 1990). The tractive effort required to move the truck at a given speed is the sum of the external forces.

Rolling resistance is the force resisting wheel movement and is generally accepted to have static and dynamic components (Ljubic 1985). The tractive effort required to overcome rolling resistance (TE_R) can be expressed as:

$$TE_R = \frac{W * (RC_1 + RC_2 * V) * SC}{1000}$$

[1] This is the third in a series of five articles written from research conducted at Auburn University during 2004 on ways to improve the productivity, efficiency, safety and costs of the trucking operation associated with logging. For more information on this research study, please contact Tom Gallagher at tgallagher@auburn.edu . The research was funded by the Wood Supply Research Institute (WSRI). For more information on WSRI, contact Jim Fendig at fendig@bellsouth.net.

where: RC_1 is the static coefficient of rolling resistance, RC_2 is the dynamic coefficient of rolling resistance, V is vehicle speed (mph) and W is gross combination weight (lbs.) (SAE 2003). The coefficients are specific to tire pressure, tire size, tread design, and road surface conditions (Wild 1990). Since W will generally have only two values, maximum legal weight and empty weight, vehicle speed and road standard will have the most effect on rolling resistance.

The build-up of pressure from the impact of air on the blunt front faces of the tractor and the exposed portion of the trailer accounts for most of a unit's air drag. Suction at the rear end, skin friction as the air flows over the truck's surfaces, and parasitic losses from air flow over the wheels, axles, mirrors, etc. also add to air resistance. The power required to overcome aerodynamic drag increases rapidly at travel speeds over 30 mph. The tractive effort to overcome air resistance (TE_A) is:

$$TE_A = FA * V^2 * C_D * C_A * 0.0024$$

where: FA is the frontal area of the vehicle (ft^2) based on the height times the width and ignoring ground clearance, V is vehicle speed (mph), C_D is the air drag coefficient (0.97 for loaded trucks hauling tree-length material and 0.91 for unloaded trucks (Garner (1978)), and C_A is an air density correction for altitude (SAE 2003).

Gradeability is the maximum grade a truck-trailer combination can traverse without assistance. According to SAE (2003), the tractive effort in pounds to overcome a particular grade (TE_G) is:

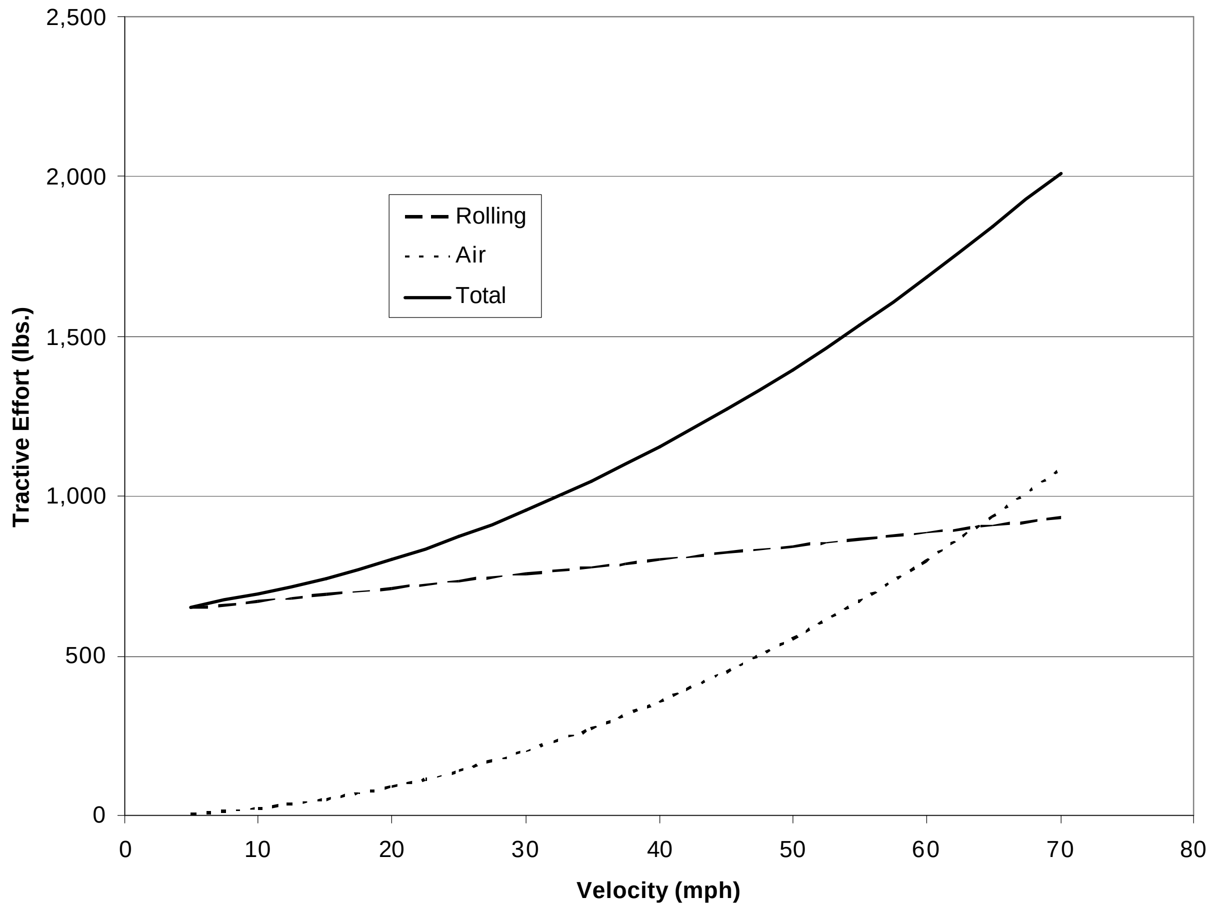
$$TE_G = W * \sin\left[\tan^{-1}\left(\frac{P}{100}\right)\right]$$

where: W is the total gross combination weight in pounds and P is the % grade.

The procedure recommended by SAE (2003) in Standard J2188, Commercial Truck and Bus SAE Recommended Procedure for Vehicle Performance Prediction and Charting, is to add the results of the tractive effort required to overcome rolling resistance, air resistance and grade and compare that to the tractive effort available. As an example, consider a truck with a 400 Hp engine with a drive-train efficiency of 0.93 operating at 1600 RPM with a rear axle ratio of 4, a transmission ratio of 0.74 (in the highest gear) and 11.00 x 22 tires (462 revolutions per mile at 45 mph). The resulting tractive effort from equation 1 would be 1987 pounds. To develop more tractive effort you would downshift to a lower gear to increase the total reduction.

Equations 2 and 3 can be used to calculate the tractive effort required to overcome rolling and air resistance. Figure 1 shows the tractive effort as a function of velocity for an 80,000 pound gross combination weight. The other factors are based on the tables included in SAE J2188 (2003). The Rolling constants for radial tires were 4.6 for RC_1 and 0.032 for RC_2. The road surface constant (RC) was 1.7 for asphalt in fair condition. Other factors were 96 ft^2 for a frontal area (FA) and 0.96 for the air drag coefficient (C_D).

Figure 1. *Tractive effort required to overcome rolling resistance and air resistance as a function of vehicle speed.*



Rolling resistance is weight and road surface dependent with some change as velocity increases. Air resistance varies with the velocity squared and is minimal at lower speeds, but increases significantly after 20 mph and can become as significant as rolling resistance. Based on the tractive effort available in the highest gear (1987 lbs.), the top speed for this truck on level ground would be 70 mph; however, the impact of grade must be added to the values in ***Figure 1***.

Figure 2: *Tractive effort related to grade.*

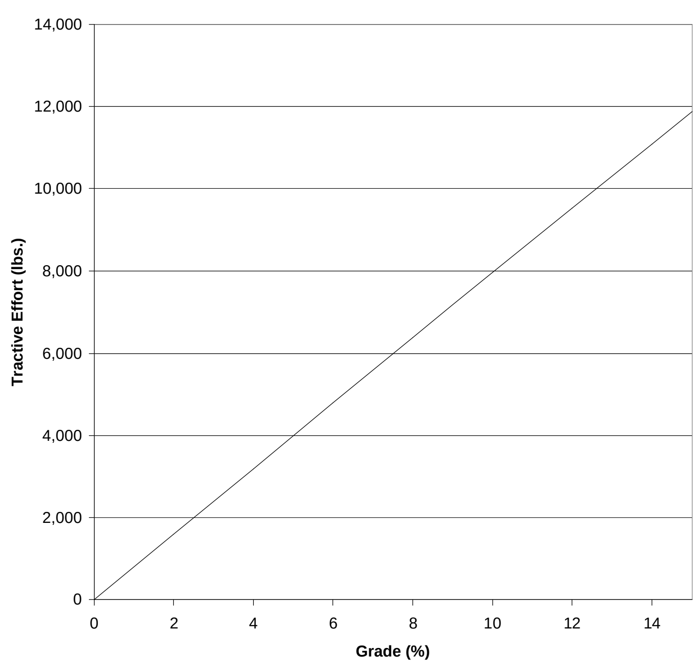


Figure 2 shows the effect of grade on tractive effort required. For the example, a 2% grade would almost double the tractive effort required (1600 lbs. to overcome a 2% grade

plus 1987 lbs. to maintain 70 mph on level ground). The driver would have to downshift to a gear with a 1.35 ratio and a correspondingly slower speed for the example given to produce the tractive effort required. The other alternative is to increase the horsepower; however, that is not as effective a choice. For the original 0.74 transmission ratio the engine would have to have 725 horsepower to generate 3600 pounds of tractive effort illustrating that changing gear ratio is more effective than increasing horsepower.

Curve resistance is similar to rolling resistance but is generated by the centripetal acceleration of a vehicle moving through a curve. Factors such as tire characteristics, axle spacing, steering geometry, road surface, and the articulation of the vehicle, all contribute to the additional drag force encountered in a curve.

Engine fuel efficiency varies with engine speed, and the most efficient speed is usually at mid-range for a given power output. Over-revving or lugging the engine is less fuel efficient than the mid-range. Operating at high RPM and power is also associated with higher wear and premature failure. Engine manufacturers typically publish charts showing the power, torque and fuel efficiencies as a function of RPM.

Road surface conditions have a significant effect on power requirements and fuel consumption. Ljubic (1985) reported a 24% increase in power requirements and an 18% increase in fuel consumption between an asphalt strip in poor condition and a stabilized, crushed gravel road for the test truck traveling at 39mph. The power requirement at the wheels increased by an additional 17% and fuel consumption by 30% for a non-stabilized, uncrushed gravel road compared to the stabilized, crushed gravel road.

Road surface conditions were also compared by McCormack (1990) for relatively level sections so that slope would not be a factor. He noted average fuel usage (loaded and empty) as high as 1.64 and 2.02 mpg at speeds less than 9 mph on unformed, sandy roads within a harvesting compartment. On the formed, sand roads that accessed the compartment, average speeds increased to 20 mph and average fuel usage was to 2.27 to 2.45 mpg. On gravel, main access roads, average speeds increased above 30 mph and fuel usage ranged from 3.53 to 4.60 mpg. On a paved, two-lane road average speed was around 50 mph and average fuel mileage ranged from 4.57 to 5.00 mph. He also noted higher fuel usage in urban as opposed to rural sections because of the additional stop/start occurrences. Urban sections also required lower speeds and increased braking.

Road speed has a critical impact on fuel consumption. Both air drag and rolling resistance increase with road speed. The test truck in Ljubic's (1985) report consumed 40% less fuel traveling loaded when speed was reduced from 45 mph to 34 mph on a gravel road and 33% less on an asphalt road. The unloaded truck consumed 34% less on gravel and 31% less on asphalt. McCormack (1990) explained that where higher travel speeds do not result in higher truck utilization (an additional trip per day) there appears to be significant economic losses associated with traveling too fast.

Engine size also affects fuel consumption. Ljubic (1985) compared a truck with a 300Hp engine to a truck with a 400Hp engine. At 34 mph on a gravel road with a GCW of 66 tons the 300Hp engine consumed 12.5% less fuel. The 300 Hp truck consumed 9.8% less fuel traveling 56 mph on an asphalt road. In addition to fuel consumption, increased power also requires more acquisition cost and rebuild cost.

Driver differences were also examined by McCormack (1990). The difference in average speed between the slowest and fastest drivers in a group of 5 was 7%, and the fuel usage difference was 8%. McCormack noted that the expected trend of increased fuel usage with higher speeds was evident, but that there were some differences not explained by average speed that he attributed to fuel efficient driving style.

Nader (1991) compared the fuel consumption for two drivers over the same route, but who responded differently to the grades and curves in the road. Driver A generally maintained an engine speed within the 1400 to 1600 rpm optimum, never exceeded 1800 rpm and maintained a fairly steady speed. Driver B averaged 1560 rpm, but generally strayed further from the optimum and exceeded 2000 rpm at several spots along the road. Driver B achieved higher accelerations, but because of his improper use of power he averaged a slower speed over the course. Driver B's excessive power consumption required a fuel consumption 11% higher than Driver A's. Nadar's recommendations were to maintain a steady speed; hold the engine speed near the optimum range; shift gears gradually during start-up; avoid using full power unless absolutely necessary; minimize braking time, with all due regard for driving safety; and avoid frequent gear changes.

Ljubic (1985) also compared a semi-trailer with dual tires to a semi-trailer with single wide tires. At 37 mph on an asphalt road the trailer with dual wheels required 12.25% more fuel to pull than the trailer with single wide tires. A contractor using single wide tires reported that power requirements were reduced by 13% and fuel consumption by 18%. The crews of this operation did caution that a suspension system which prevented damage to the second tire if the other on the same side went flat was necessary when using single wide tires.

McCormack (1990) found that running a truck without the trailer (bobtail) produced a 47% reduction in fuel use as compared to hauling an empty trailer (6.05 mpg with the empty trailer versus 8.90 mpg bobtail). Those savings were probably due to the reduced air resistance, rolling resistance and gross weight. He recommended a trailer parking arrangement that allowed bobtail running to and from the maintenance base.

As a final thought on fuel consumption, Mooney (2004) reminds us that fuel consumption and efficiency begins with proper maintenance. He states that dirty air filters, under-inflated tires, misaligned vehicles and leaky fuel lines increase trucking costs.

Trucking Simulators

Truck performance formulas can be used to predict instantaneous horsepower requirements, speed, and fuel consumption. However, to be useful the formulas need to be incorporated into a simulation program that can evaluate the entire route from the woods to the delivery point. The simulation program should be vehicle and road standard specific to be useful.

Truck manufacturers have developed programs to help customers determine the proper specifications for particular applications. Many of these programs are based on the Society of Automotive Engineers Standards. Cummins' Vehicle Mission Simulator (VMS) is one of the more commonly known of the truck manufacturer's programs. One concern with these programs is whether they represent the typical roads encountered when hauling forest products.

Otto 2000 developed by FERIC (Forest Engineering Research Institute of Canada) simulates the performance of haul vehicles, and estimates fuel consumption, average travel speeds, and trip times by modeling the characteristics of the driver, the truck, and the road. It can simulate trucking operations and the performance of current or potential vehicles on roads, and compare the effects of different component choices, driving styles, and road layouts on vehicle performance. http://www.feric.ca/en/ed/html/otto_2000.htm. FERIC has conducted extensive studies on transporting forest products and that experience has been incorporated into the development of Otto.

Payload

Trucking productivity is the amount of wood delivered per unit of time, e.g. tons per day. The objective is to make as many trips as possible with the maximum legal weight. Production, then, will depend on the amount of product per load which depends on the weight of the truck and trailer. Options that reduce truck and trailer weight will increase payload. A 2,000 pound reduction in empty weight at 3 trips per day and 230 days per year will increase production by about 4%.

McNeel (1990) compared conventional tractor-trailers hauling pulpwood and small sawlogs to lighter-weight tractor-trailer units. Tractor modifications included two 55-gallon aluminum fuel tanks instead of 75-gallon steel tanks, an aluminum cab protector, front bumper and wheels and rims. The tractor changes reduced the tare weight by 0.35 tons. Trailer modifications included the use of super-wide single tires, aluminum rims, fewer bolsters (3 instead of 4), lightweight landing gear and a 14-inch I-beam instead of the normal 16-inch I-beam for a weight reduction of 1.40 tons. The overall reduction in truck and trailer weight averaged 1.52 tons less, 13.83 tons versus 12.31 tons.

Using a fold-up, pole trailer can save weight, reduce trailer tire costs, and improve unloaded fuel efficiency. Although pole trailers are popular out West, they are only applicable where tree length material is long enough and/or large enough for a legal-weight load. In the East, sawlogs and material from thinnings usually require a double bunk trailer.

Recommendations

1) Reduce resistance to movement where possible to reduce tractive effort, and thus, fuel required. Use radial tires which have less rolling resistance than bias ply tires. Dry dirt roads require twice the power of paved roads, and as dirt roads become muddy or sandy the rolling resistance can double or triple; so, plan operations to leave wood near the county road to haul during wet periods and haul material over the longest woods road during dry weather. Maintain proper tire inflation pressures, especially for duals. Consider reducing driving speed. Select flatter routes when practical. Consider using super-wide singles instead of duals.

2) Make changes to improve fuel efficiency. Select the correct engine size, transmission and rear axle ratio for the conditions expected. The greater the power demanded the greater the fuel consumption, and gear reduction is more efficient at producing tractive effort than additional horsepower. Teach drivers fuel-efficient techniques, such as operating at the most efficient rpm, rather than the higher range. Since fuel usage is at the maximum during acceleration, pick routes that have fewer stop signs and traffic lights. Running "bobtail" uses about 40% less fuel than dragging an empty trailer.

3) When purchasing a new truck use a trucking simulator to determine the best combination of components.

For explanations of the bibliographical references, please consult the authors at tgallagher@auburn.edu.