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P3_7 Freight Train Efficiency

A. Phong , M. McNally, R. Pierce, T. Searle

Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH.

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Abstract
The Association of American Railroads announced in 2009 that 'freight trains in the U.S. averaged 480 ton-miles-per-gallon' [1]. This paper analyses the feasibility of the quoted value by calculating the fuel efficiency of a typical freight locomotive in use in North America. It is found that this is a valid claim and that the efficiency stated is not unreasonable.

Introduction

The locomotive to be investigated is from the GE Evolution Series. It is powered by a diesel engine which is connected to an electric generator that runs the electric motors; this is known as a diesel-electric transmission [2].

The quoted efficiency states that the average freight train can transport 480 short tons of cargo, by a distance of 1 mile, using 1 US gallon of fuel. Converting the values to SI units gives approximately 907kg of cargo, moved 773km, using 3790cm^3 of fuel. This can be simplified to 1kg of cargo, moved 185000km, using 1 litre of fuel.

Model

Assume that the train is travelling at a constant velocity and that the journey is sufficiently long so that the force required to accelerate and decelerate the train can be neglected. Equating the energy lost due to the force of drag (F_{drag}) and rolling friction (F_{rf}) to the energy obtainable from a litre of diesel ($E_{fuel\ per\ litre}$) gives,

$$\left(F_{drag} + F_{rf}\right) x = E_{fuel\ per\ litre}\ \varepsilon_e\ \varepsilon_t\ , \qquad (1)$$

where x is the distance travelled, ε_e is the efficiency of the engine and ε_t is the efficiency of the transmission. Drag force is defined as,

$$F_{drag} = \frac{1}{2} C_d A \rho_a v^2, \qquad (2)$$

where C_d is the drag coefficient, A is the frontal area, ρ_a is the density of air and v is the velocity. Rolling friction force is defined as,

$$F_{rf} = \mu_r\ F_n, \qquad (3)$$

where μ_r is the coefficient of rolling friction and F_n is the normal force ($F_n = mg$, where m is the mass of the locomotive and g is the acceleration due to gravity). By calculating the drag and friction forces per kg and rearranging Eqn. 1 for x, the distance that 1kg of cargo could be transported using 1 litre of fuel by this locomotive can be obtained.

Calculations

The following values are used:
$E_{fuel\ per\ litre} = 36\mathrm{MJ/litre}$ [3],
$\varepsilon_e \sim 42\%$ [4],
$\varepsilon_t \sim 85\%$ [5],
$C_d = 1.8$ [6] (assuming that passenger and freight trains are similar),

$A = 4.7\text{m} \times 3.12\text{m} = 14.7\text{m}^2$ [2] (assumed rectangular area for simplicity),
$\rho_a = 1.29 \text{ kg m}^{-3}$ [7],
$v = 31.4\text{ms}^{-1}$ [2],
$\mu_r = 0.002$ [8],
$m = 186000\text{kg}$ [2],
$g = 9.81 \text{ ms}^{-2}$.

From Eq. (2),

$$F_{drag} = 16800\text{N}.$$

Dividing this by the mass of the locomotive gives,

$$F_{drag}{}' = 0.0903\text{N/kg}.$$

Similarly from Eq. (3),

$$F_{rf} = 3650\text{N},$$
$$F_{rf}{}' = 0.0196\text{N/kg}.$$

Putting these values into Eq. (1) gives,

$$(0.1099\text{N/kg})\, x = 12.85\text{MJ/litre}$$

and hence

$$x = 117000\text{km kg/litre}.$$

Conclusion

It has been shown that the locomotive tested in this investigation can theoretically transport 1kg of cargo, a distance of 117000km, using 1 litre of fuel. For clarity, converting the calculated value into the units of the original quote gives 304 ton-miles-per-gallon. This is about 37% less efficient then the quoted value.

The drag force for a real world situation may be reduced when travelling at constant speed as the model uses a large and inefficient frontal surface area. In addition, actual freight trains are not usually running at maximum speed continuously like in the model and are more likely to maintain a slower speed to reduce drag. However, because freight trains usually carry very heavy loads, a lot of energy is needed to accelerate it at the start and decelerate it to stop, which will decrease its efficiency, especially if it needs to make other stops or change speed along its journey.

Considering the fact that the model used is very simple and many factors are neglected, the errors involved in the calculation will be large. The efficiency claimed may be reasonable but it is possible that the value is exaggerated. Further testing, using a more advanced model with a bigger sample of trains would give a more accurate and conclusive result.

References

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