

A1_2 Breaking Bad Physics

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Abstract

In the TV series Breaking Bad the protagonist's use an electromagnet in a truck causing the vehicle to tip over. This article investigates the likelihood of this occurring and finds that it's unlikely to happen because the electromagnet would need more coils per unit length than would be allowed by its size.

Introduction

In one of the episodes of the TV series Breaking Bad the protagonists need to erase some sensitive information on a laptop in a police evidence room. They decide to do this by parking in a truck outside and then use a scrapyard electromagnet to wipe the hard drive. All does not go to plan and they end up tipping over the truck, the feasibility of which we will investigate.

Theory

The electromagnet is powered by 21 12-volt car batteries connected in series with another 21 12-volt batteries. This gives a total voltage of 252V, and a total internal resistance of

$$R_{TI} = \left(\frac{1}{21R_I} + \frac{1}{21R_I} \right)^{-1} = 10.5R_I, \quad (1)$$

where R_I is the internal resistance of the battery. Because the batteries are likely old, we will take the Cold Cranking Amps to be 360A [1]. This gives an internal resistance of 0.033Ω, which we will round up to 0.04Ω due to corrosion. This results in $R_{TI} = 0.42\Omega$.

The total resistance is given by R_{TI} plus the resistance from the wire, R_W , where

$$R_W = \rho L/A = 5.4 \times 10^{-9} L/a^2, \quad (2)$$

with the resistivity $\rho=1.7 \times 10^{-8} \Omega\text{m}$ for copper [2] and where L is the length of wire, a is the radius, and the cross-sectional area $A = \pi a^2$.

The magnetic field on the axis of a solenoid with an iron core is given by [3]

$$B_z = \frac{1}{2} \mu n I \left(\frac{z-z_1}{\sqrt{(z-z_1)^2+a^2}} - \frac{z-z_2}{\sqrt{(z-z_2)^2+a^2}} \right), \quad (3)$$

where n is the number of coils per unit length, I is the current, a is the radius of the solenoid, z is the solenoid's axis, z_1 and z_2 the ends of the solenoid with $z_1 < z_2$, and μ is the permeability which is approximately $200\mu_0$ for a solenoid

with an iron core [4]. The dimensions of the electromagnet are approximately 1m in diameter and 0.2m in length, and the truck is parked approximately 4m from the inside of the evidence room's wall. Therefore $a=0.5\text{m}$ and we can set $z=4\text{m}$, $z_2=0.1\text{m}$ and $z_1=-0.1\text{m}$. This means that at the wall Eq.(3) becomes

$$B_z = 9.60 \times 10^{-8} n I. \quad (4)$$

In order to find the magnetic field at different points on the wall the solenoid will be treated like an electric dipole [5]. This gives the magnetic field components parallel and perpendicular to the dipole's axis (the z axis) by

$$B_z = C(3 \cos^2 \theta - 1)/r^3, \quad (5)$$

$$\text{and } B_{\perp} = 3C \cos \theta \sin \theta / r^3, \quad (6)$$

with r being the distance from the centre of the dipole to the position of interest and ϑ being the angle between r and the z -axis.

Using Eq.(4) and Eq.(5) with $\vartheta=0^\circ$ and $r=4\text{m}$:

$$C = 3.07 \times 10^{-6} n I. \quad (7)$$

In the TV show several metal objects in the evidence room were attracted to the wall and stuck there, so we will treat the electromagnet as acting on a circular sheet of metal 4m from the electromagnet's centre with a radius of 1m. The force exerted by two magnetised surfaces is approximately [6]

$$F = B^2 A / 2\mu_0. \quad (8)$$

In our problem B varies with position and the direction of the force will depend on $\hat{\mathbf{b}}$, so we will modify it by taking the z component of the force for an infinitesimal area, and integrate over the whole surface:

$$F_z = \int_A \frac{B^2}{2\mu_0} \hat{\mathbf{b}} \cdot \hat{\mathbf{z}} dA = \int_A \frac{B B_z}{2\mu_0} dA, \quad (9)$$

where

$$B = \sqrt{B_z^2 + B_{\perp}^2} = C(3 \cos^2 \theta + 1)^{0.5} / r^3.$$

This gives the force exerted on the wall and therefore the force exerted on the truck. If we use R as the distance from the centre of the wall to the point of interest and ϕ as the angular position around the z-axis, this leads to $r^2 = R^2 + z^2$ and $dA = R dR d\phi = 2\pi R dR$. Therefore

$$F_z = \frac{\pi C^2}{\mu_0} \int_0^1 D(R) R dR,$$

with

$$D(R)R \approx \frac{4R}{(R^2 + z^2)^3} - \frac{15R^3}{2(R^2 + z^2)^4}$$

via series expansion of $D(R)R$ around $\vartheta=0$, and then using the small angle approximation $\vartheta \approx \sin\vartheta = R/r$. Therefore, upon integration,

$$F_z = \frac{\pi C^2}{\mu_0} \left[-\frac{1}{(R^2 + z^2)^2} + \frac{5(3R^2 + z^2)}{8(R^2 + z^2)^3} \right]_{R=0}^{R=1} \\ = 9.96 \times 10^{-9} n^2 I^2, \quad (10)$$

using Eq.(7) and $z=4\text{m}$.

The dimensions of the truck are approximately that of a 10' U-haul box truck which weighs 2600kg and has a width of 1.8m [7]. The truck is also weighed down by 42 10kg car batteries and 2 people, which brings the weight of the truck to 3150kg. If we treat the electromagnet as a cylinder with the density of iron, its weight will be approximately 1250kg. The centre of the electromagnet is 0.8m from the centre of the truck, so the centre of mass is 0.23m towards the edge of the truck, and therefore $d=0.67\text{m}$ from the edge. The total mass of the system is $m=4400\text{kg}$ and the vertical height to the centre of mass is approximately $h=1.2\text{m}$.

Therefore, the torque due to the electromagnet is $\tau_1 = Fh$, and the torque due to the weight is $\tau_2 = -mgd$. By setting the net torque to zero and rearranging, this leads to a minimum force from the electromagnet of

$$F_{min} = mgd/h = 24100 \text{ Newtons}. \quad (11)$$

Equating Eq.(10) and Eq.(11) we get

$$nI = 1.56 \times 10^6. \quad (12)$$

Using Eq.(1), Eq.(2), Eq.(12), and $I=V/R$,

$$n = 6170(R_{TI} + R_W) = 2590 + \frac{3.3 \times 10^{-5} L}{a^2}.$$

Therefore, the minimum number of coil layers radially is

$$N_L = 2an = 5200a + 6.7 \times 10^{-5} L/a.$$

Assuming the iron core takes up half the radius of the electromagnet, the coils are on average 0.375m from the centre so the length of wire is

approximately

$$L = 2\pi(0.375)N_L N_z = 0.235N_L/a,$$

where N_z is the number of layers axially ($N_z = \text{solenoid length/wire diameter}$). Therefore

$$N_L = \frac{5200a^3}{a^2 - 1.6 \times 10^{-5}}.$$

The maximum possible number of layers radially due to the size of the electromagnet is

$$N_{Lmax} = 0.25/2a.$$

We can solve for a by setting $N_L < N_{Lmax}$, but this has no real solution, so therefore it's impossible for the electromagnet to pull the truck over at this distance.

Conclusion

The main simplification used that could make it possible is from the increase in the magnetic field due to the iron core, but the exact relationship is complicated and not linear. However, most of the simplifications would decrease the likelihood of the truck tipping over, such as imperfect packing and insulation of the wires was ignored in the solenoid, and a continuous metal sheet wouldn't be formed on the other side of the wall. There's also a current of 200+ Amps going through the wires, so the temperature would rapidly rise, decreasing the field strength due to increased resistance, and possibly melting the insulation and connections. Therefore, by our approximations, the truck wouldn't have tipped over because N_L would need to be greater than N_{Lmax} .

References

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