# Permanent Magnetic Braking System


**Xuan Duong, Mechanical Engineering**

Mentor: Dr. Carlos Castro Candelas

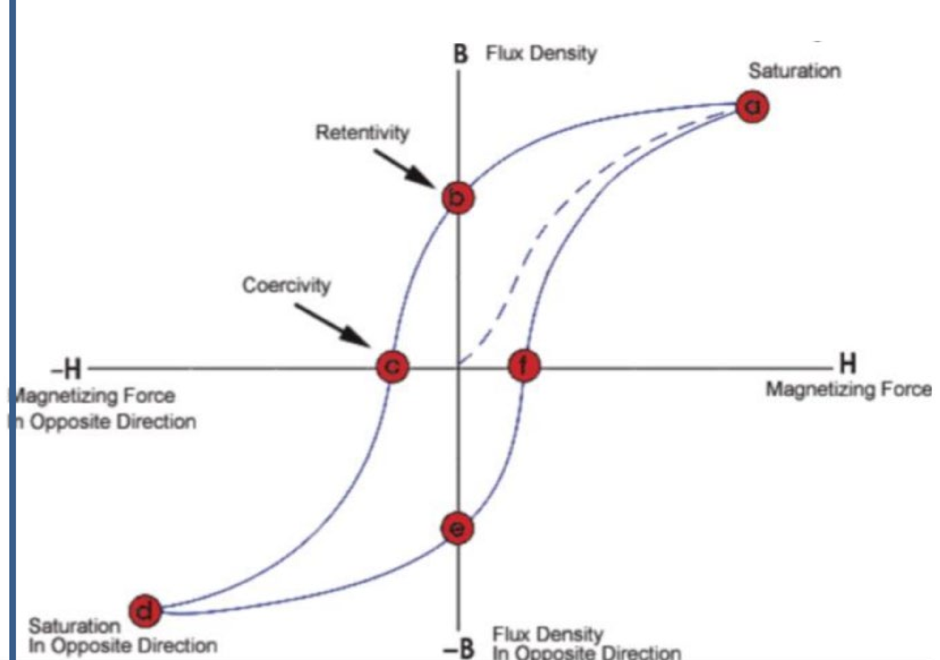
Kellogg Honors College Capstone Project

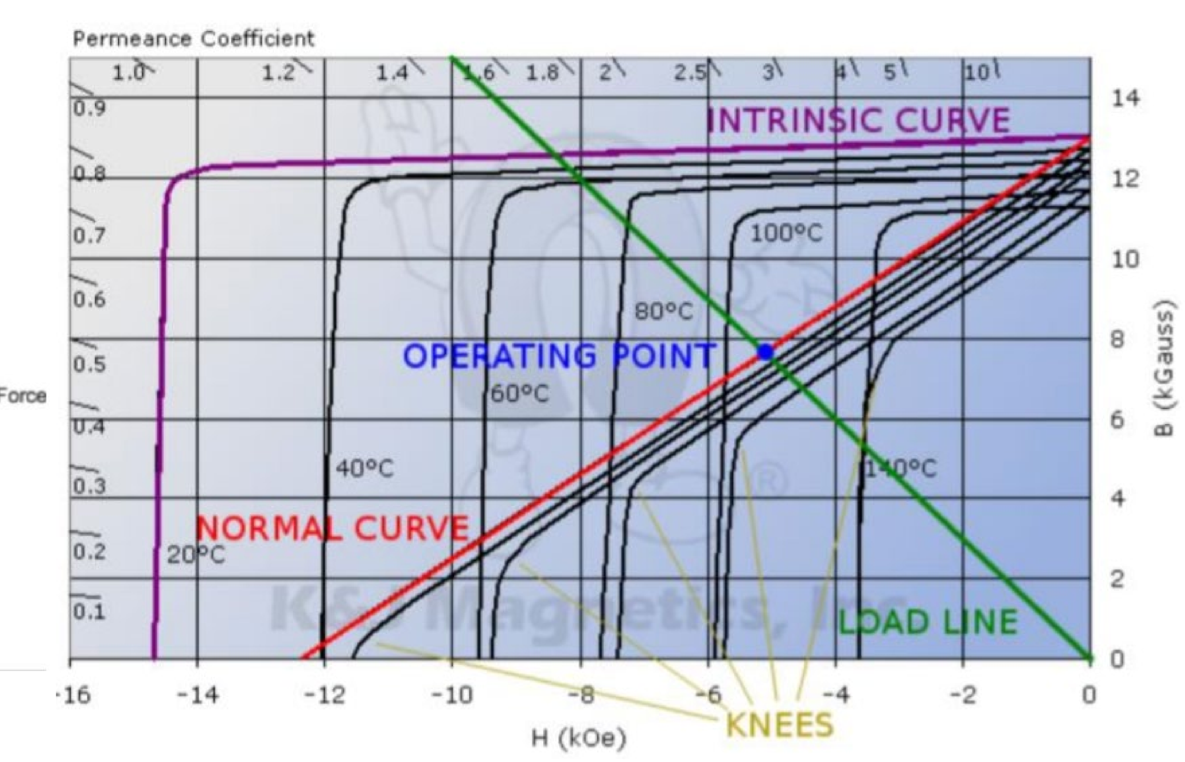

## I. Background

To understand how permanent magnetic braking works, it is important to first understand how electromagnetic field is created. Eddy Current—the electrical current that is created when there is a change in magnetic field in the conductor . The Eddy current is normal to the magnetic field lines which acts as a solenoid itself. As a result, according to Lenz's law of electromagnetic induction, the Eddy current produces its own magnetic field that flows in an opposite direction as the initial magnetic field that created it. Hence, the moving object, can be magnets or the conductor, moves slower dues to the magnetic drag force.

## II. Material Selection

To find a proper material, a few factors are considered. With magnetic braking, heating also one of the issues especially with permanent magnets. It can only operate until a certain temperature and then it will thermally deform which result in lessening the magnetic field strength. To make sure that it does not happen, the operating point and temperature of the magnets need to be known. To do that, demagnetization curve or BH curve is used. It is a curve that describe the thermal properties and quality of the magnet. The BH curve is the second quadrant of the hysteresis loop, a graphical way to describe how a conductor becomes magnetized.




## III. Braking Force

The magnetic drag force acts as the braking force that is now commonly used in many industrial processes. The braking force is calculated using an equation from a study of Tamkang University, Taiwan . The force is based on the ohm's law and Lorentz force— a force that exerts on the particle by electric and magnetic field .

$$F_d = \alpha \cdot \sigma \cdot \delta \cdot B_o^2 \cdot A \cdot V$$

Where: $\alpha = shape\ factor$

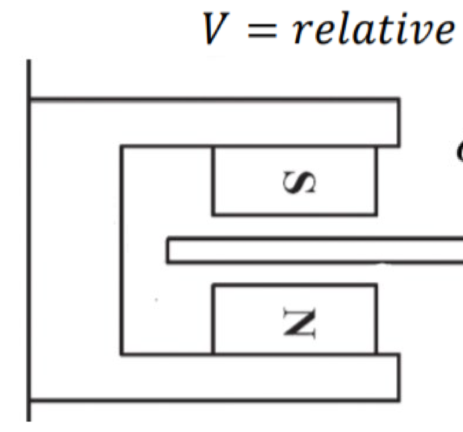
$\sigma = conductivity\ of\ metal$

$\delta = the\ thickness\ of\ the\ metal$

$B_o = field\ strength\ in\ the\ gap\ between\ two\ magnets$

$A = area\ of\ the\ reaction$

$V = relative\ velocity\ between\ magnets\ and\ conductor$




$$\alpha := 1 - \frac{1}{2 \cdot \pi}\left(4 \cdot \operatorname{atan}\left(\frac{L}{w}\right) + \frac{L}{w} \cdot \ln\left(1 + \frac{w^2}{L^2}\right) - \frac{w}{L} \cdot \ln\left(1 + \frac{L^2}{w^2}\right)\right)$$

The conductor in this case is 6061-T6 Aluminum rail that is roughly one mile long. According to Notre Dame University[2], the conductivity of the metal is:

| Material | Conductivity | | Resistivity | Reference |
|---|---|---|---|---|
| | (% IACS) | (Siemens/m) | (Ohm-m) | (See Endnotes) |
| 6061-T4 | 37.60 - 40.50 | 2.265E+07 | 4.415E-08 | NDT Mag |
| 6061-T4 | 40.00 | | 4.300E-08 | ALASM |
| 6061-T6 and -T9 | 40.00 - 44.80 | 2.459E+07 | 4.066E-08 | NDT Mag |
| 6061-T6 | 43.00 | | 4.000E-08 | ALASM |

## IV. Cancellation Force

The cancellation force is a force that is created by the solenoid. Instead of using the solenoid to brake, the electromagnetic coil is used to counteract the permanent magnetic field so that the pod can move forward. The cancellation force is also calculated using the Lorentz force. However, the cancellation force is derived from the kinetic energy of the magnetic flux density:

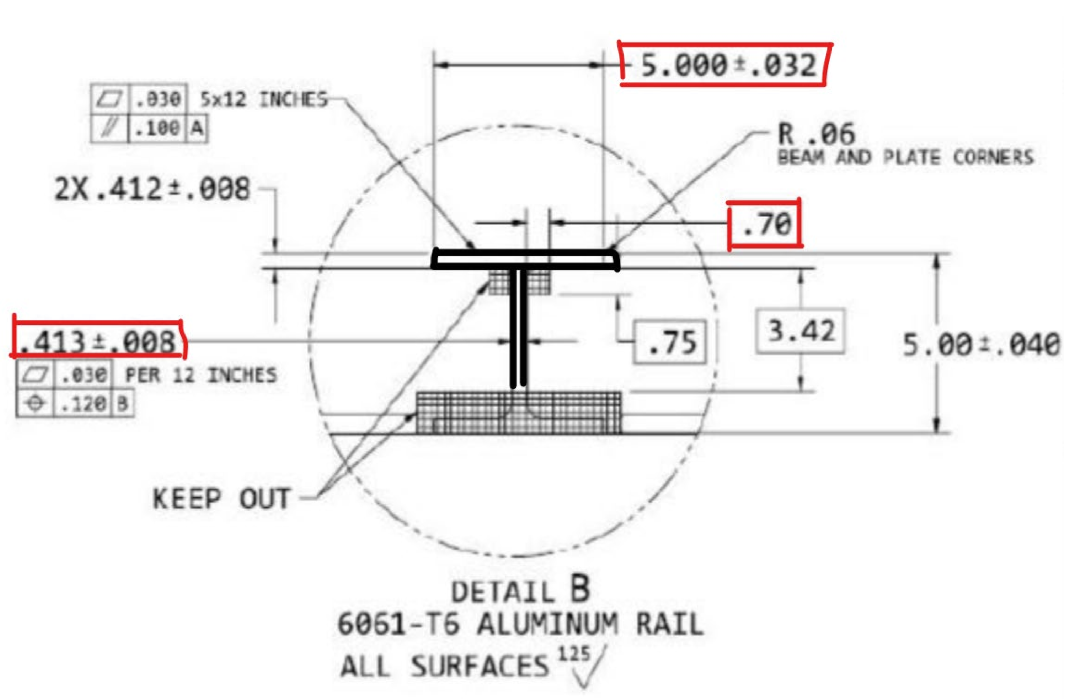
$$KE = \frac{1}{2} m V^2$$

$$L = \frac{\mu N^2 A}{I}$$

Where:

N = the number of turns of the coil

$\mu$ = permeability that depends on whether the conductor is inside the coil or before it going through the coil




$$F := \frac{(N \cdot I)^2 \cdot \mu_o \cdot A}{2 \cdot L_{gap}^2}$$

The size is determined using the dimensions of the rail that provided from SpaceX.

The nominal width of the magnet must below:

$$w = \frac{5}{2} - \frac{0.413}{2} - 0.7 = 1.5935\ in$$

## V. Disadvantages and Advantages

Since SpaceX requires the pod to have fail-safe system—the system must have ability to brake without electricity, permanent magnetic braking is ideal because it solely uses Eddy currents to brake, and no power is needed. There are also a few disadvantages of permanent magnetic that needs to be taken into consideration. One of the problems is that the magnets can lose magnetic strength over time if the temperature is hot to the point that it passes the critical limit that the magnet can handle. Other drawback would be heavy weight, high attraction force, and expensive rare earth magnets. The advantages are no friction hence no damage on the rail, simple design and concepts, and suitable with the pod's dimension.

## VI. Conclusion

With calculations and trade studies, the magnetic braking system is not as expensive as it was predicted. Hence, the magnetic braking seems to be very economical for the hyperloop team to look into. Other factors are not included in this paper that can be important if magnetic braking system is selected to be on the pod.

## VII. References


1. Collins, Danielle. "Electromagnetism: Faraday's Law, Ampere's Law, Lenz' Law, & Lorentz Force." *Motion Control Tips*, 13 Aug. 2017, www.motioncontroltips.com/four-laws-of-electromagnetism-you-should-know/.
2. *Conductivity and Resistivity Values for Aluminum & Alloys*. https://www.nde-ed.org/GeneralResources/MaterialProperties/ET/Conductivity_Al.pdf
3. Eitel, Lisa. "Ogura Explains How Permanent-Magnet Brake Work with New Animation." *Motion Control Tips*, 8 Oct. 2018, www.motioncontroltips.com/ogura-explains-how-permanent-magnet-brake-work-with-new-animation/.
4. "Electromagnet, Electromagnetic Coil and Permeability." *Basic Electronics Tutorials*, 9 Feb. 2018, www.electronics-tutorials.ws/electromagnetism/electromagnets.html.
5. Gregersen, Erik, et al. "Magnetic Permeability." *Encyclopædia Britannica*, Encyclopædia Britannica, Inc., 6 May 2020, www.britannica.com/science/magnetic-permeability.
6. Hribar, Jure. 2008, *Magnetic Braking*.
7. http://mafija.fmf.uni-lj.si/seminar/files/2007_2008/1-BRAKING_MAGNETIC.pdf
8. *K&J Magnetics - Demagnetization Curves*, www.kjmagnetics.com/bhcurves.asp.
9. KJMagneticsProducts. "Calculating Eddy Currents." *YouTube*, YouTube, 3 Sept. 2019, www.youtube.com/watch?v=5WwoccFfxb8.
10. Ma, Der-Ming, and Jaw-Kuen Shiau. 2010, *The Design of Eddy-Current Magnet Brakes*.
12. Richmond, Michael. *Solenoids and Magnetic Fields*, spiff.rit.edu/classes/phys313/lectures/sol/sol_f01_long.html.