

Linear Encoder with Energy-Harvesting Multi-Turn Technology



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This document contains a description of technologies that are the subject of pending patent applications.

Abstract

Absolute linear encoders typically require external power, batteries, or complex multi-track sensing to retain position over long travel lengths. While Wiegand-based energy harvesting has become a proven and widely adopted solution for battery- and gear-free absolute rotary encoders, its application to linear systems has remained impractical due to magnetic field constraints.

This paper presents a practical method for enabling reliable Wiegand pulse generation in linear encoders by employing a standard magnetic strip. By introducing a dedicated magnetic field collection and deflection structure, the charging and triggering conditions required by the Wiegand wire are met across its full length. This approach extends established energy-harvesting multi-turn (EHMT) technology from rotary to linear applications, enabling a compact, battery-free absolute linear encoder built from standard components.

Introduction

After the introduction of Wiegand wire (or pulse-wire) technology for position measurement and energy harvesting to power counter logic, this concept was licensed and adopted by numerous companies for use in rotary encoders. Although the original intellectual property disclosed the possibility of applying the same principle to linear encoders, that technology has not been successfully implemented in practice until now.

One reason is that the magnetic conditions required for reliable pulse generation in a Wiegand wire are much harder to achieve in linear applications than in rotary ones. To understand this limitation, it is necessary to briefly explain the underlying physical principle of the Wiegand wire.

The material used for Wiegand wires, typically Vicalloy, is mechanically treated so that two distinct magnetic regions are formed. One region exhibits soft magnetic behavior, while the other region exhibits hard magnetic behavior. When an external magnetic field is applied, both regions align with the field. When the external field is removed, the hard magnetic region attempts to force the soft magnetic region back into its original orientation. However, due to the magnetostrictive properties of the material, the magnetic field generated internally is not strong enough to complete this reversal. As a result, the wire remains in a metastable state. The soft magnetic core switches abruptly only when an external magnetic field of opposite polarity is applied. This switching event generates a voltage pulse in the surrounding coil.

This behavior is well documented in scientific literature and will not be repeated here in detail. However, many descriptions do not clearly emphasize that the switching process behaves like a domino effect. The switching process requires both sufficient time and well-defined magnetic field conditions to propagate along the wire.

Two Critical Parameters: Charging and Triggering Thresholds

The magnetic field strength required to charge the wire and the magnetic field strength required to trigger the pulse are critical parameters in ensuring the successful initiation and propagation of the switching process.

1. **The Charging Condition:** The first condition stems from the requirement for a small wire diameter; the Wiegand effect is only sustained in thin-gauge ferromagnetic wires. The harvested energy originates from the switching of the soft magnetic region, which represents only a small portion of the wire. Therefore, the available energy is limited, and sufficient output is only achieved if as much of the wire as possible is brought into the metastable charged state.

This requirement can be summarized as follows: To be properly charged, every segment of the wire must be subjected to a longitudinal magnetic field that exceeds a specific threshold amplitude.

It is possible to overcharge the wire. If the magnetic field exceeds a certain intensity, the pulse energy begins to decrease. This decrease occurs because the boundary between the hard and soft magnetic regions is not sharply defined; a stronger external field shifts this boundary in favor of the hard magnetic region, reducing the volume of the soft magnetic region. In extreme cases, this behavior can reduce the pulse energy to zero, although such conditions are rarely encountered in practical applications.

2. **The Triggering Condition:** The second condition concerns the initiation and propagation of the pulse. When the external magnetic field reaches the trigger threshold, the soft magnetic region undergoes a sudden polarity reversal. This switching propagates along the wire as the Bloch wall moves through the magnetic domains.

For this process to complete successfully, the external magnetic field must remain sufficiently strong and homogeneous along the entire wire for the duration of the switching event. If the field varies too much or the intensity drops below the required level, the switching process can stall. This results in incomplete or weak pulses with insufficient energy to power the counter logic.

The triggering condition can be summarized as follows: When the trigger threshold is reached at any point along the wire, the entire length of the wire must be immersed in a defined magnetic field for the duration of the switching process. In all cases, the external magnetic field refers to the field component aligned with the wire axis.

Limitations of Linear Applications

Rotary applications easily meet these conditions using a few high-strength magnets, such as NdFeB, AlNiCo, or SmCo. For rotary encoders, only one or two magnets are required to count rotations, regardless of the encoder diameter. Even when additional magnets are used to increase resolution for larger diameters, the total number remains minimal.

This approach is not feasible for linear encoders. As the measurement length increases, the number of required magnets increases proportionally. In typical applications such as elevators, where measurement lengths can easily reach 50 meters, the scale becomes a challenge. If a 0.1 mm resolution is required using the same magnetic field strength for fine resolution, a magnet would be needed approximately every 2 cm. This would result in a total of 2500 magnets. Beyond the mechanical effort of mounting such a large array, the material cost alone makes this approach impractical.

As a result, modern linear magnetic encoders typically use flexible magnetic strips with alternating polarity. However, due to the linear arrangement of the magnetic poles and the relatively low magnetic field strength, Wiegand wires cannot be used directly with these standard magnetic strips.

A new Broadcom® innovation addresses this limitation by featuring a Wiegand-based counter that integrates with standard magnetic strips to enable a fully absolute linear encoder. The primary engineering challenge was to develop a method for collecting and shaping the magnetic field to achieve the following objectives:

- Ensure sufficient field strength to effectively charge the Wiegand wire.
- Establish trigger conditions that satisfy the performance requirements previously described.

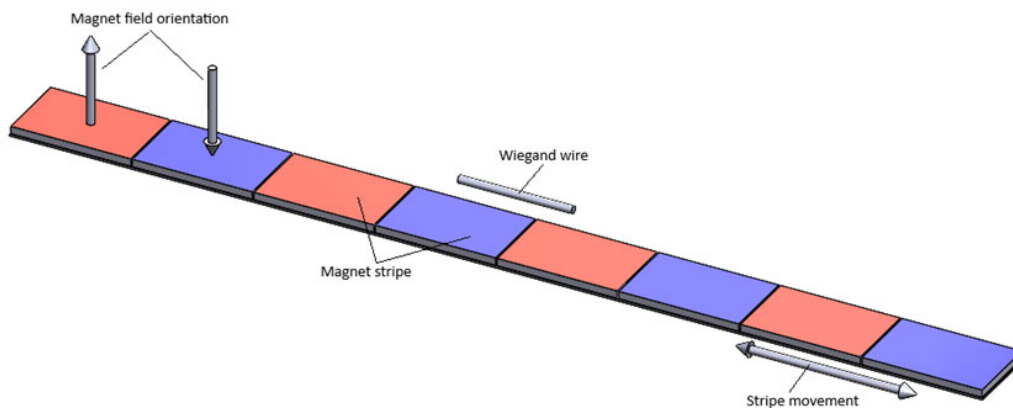
Development and Wire Orientation Analysis

From a theoretical perspective, there are three basic ways to orient the Wiegand wire relative to the magnetic strip: longitudinal, orthogonal, and vertical.

Longitudinal Orientation

In the longitudinal configuration, the wire axis is aligned with the direction of motion. At certain positions, opposite magnetic poles are located near each end of the wire, providing the necessary field for charging. However, as the sensor moves, a position occurs where a magnetic pole is centered directly beneath the wire, flanked by opposite poles at both ends. In this state, the magnetic field along the wire axis reverses direction at the center point, preventing the formation of a homogeneous field and failing to trigger the Wiegand effect.

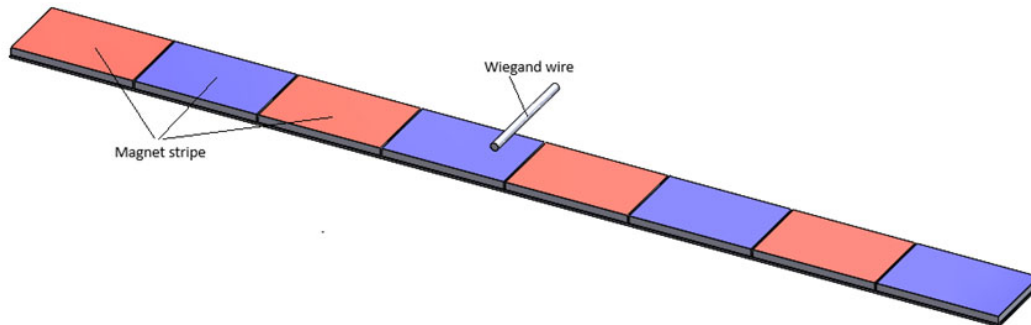
Figure 1: Wiegand Wire Longitudinal Orientation



Orthogonal Orientation

In the orthogonal orientation, the wire axis is perpendicular to the direction of motion. Because the magnetic field component along the wire's longitudinal axis is negligible or nonexistent, the magnetic domains cannot be oriented to charge the wire, making reliable pulse generation impossible. A double magnetic stripe with shifted magnetic zones might solve this; however, it would also increase the system footprint and overall costs, especially for longer measurement distances.

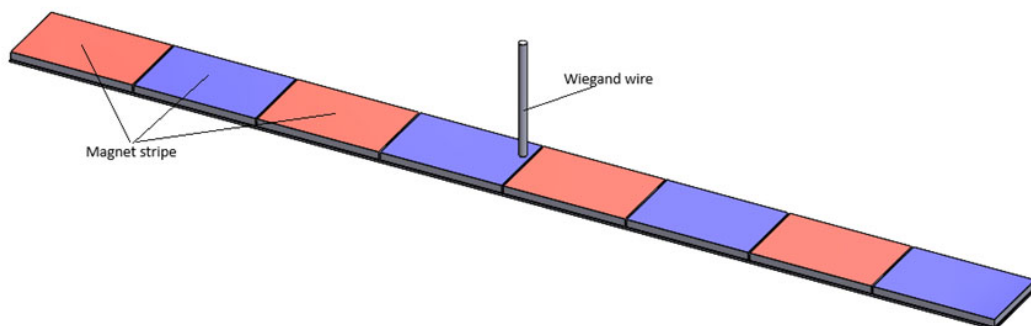
Figure 2: Wiegand Wire Orthogonal Orientation



Vertical Orientation

In the vertical orientation, the magnetic field component along the wire axis changes polarity during motion. However, because one end of the wire is significantly farther from the magnetic strip than the other, the field strength remains insufficient to trigger the wire. And at the required trigger position, the magnetic flux is concentrated near the strip and weakens rapidly toward the opposite end, resulting in an inhomogeneous field distribution that cannot reliably flip the magnetic domains.

Figure 3: Wiegand Wire Vertical Orientation



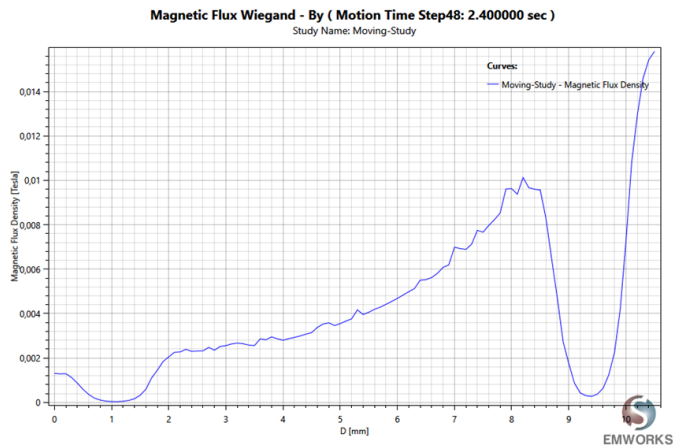
Standard magnetic strips are magnetized vertically, following the Wiegand wire orientation shown in Figure 3, producing a surface field of only 0.3 mT. The pitch (length of the single magnets) is highly variable and changes from less than 1 mm to more than 20 mm.

It is evident that without additional elements, the Wiegand wire cannot function properly in any of the orientations previously discussed. This limitation was confirmed by both simulation and by measurement on a prototype. In every orientation, the field strength remains insufficient unless additional elements are used to collect and channel the magnetic flux. But the vertical orientation is the nearest to match the conditions; therefore, it was used for further developments.

To better illustrate the previously mentioned limitations, we have used simulation results, which were subsequently validated through empirical measurements.

1. Without ferromagnetic collectors, the field at the central position for the vertical arrangement,—the region of optimal field distribution—appears as shown in the following figure. The active region of the Wiegand wire is 6.4 mm long and situated between 1.8 mm to 8.4 mm.

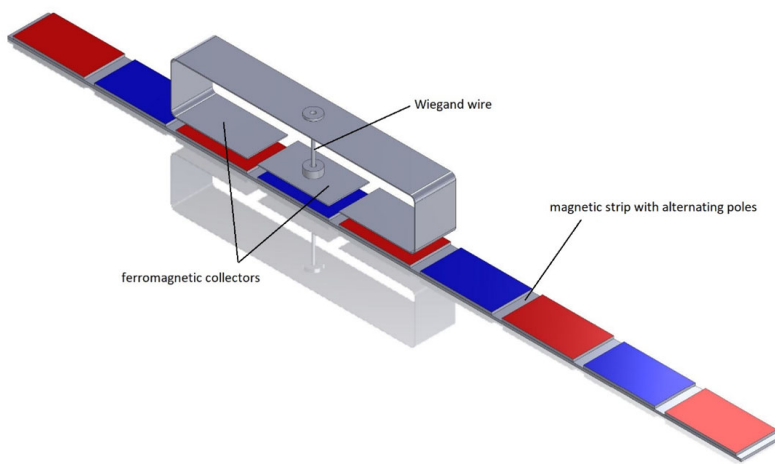
Figure 4: Amplitude of the Charging Field Component along the Wiegand Wire Axis (No Ferromagnetic Elements)



At the end of the wire nearest the magnet strip, the field amplitude reaches 10 mT; however, the other ends of the wire receive only slightly more than 2 mT. Measurement data indicates that a minimum field of approximately 6 mT is required for reliable charging. Consequently, the magnetic field fails to sufficiently trigger the wire, resulting in either a total absence of pulses or inconsistent, low-amplitude signals.

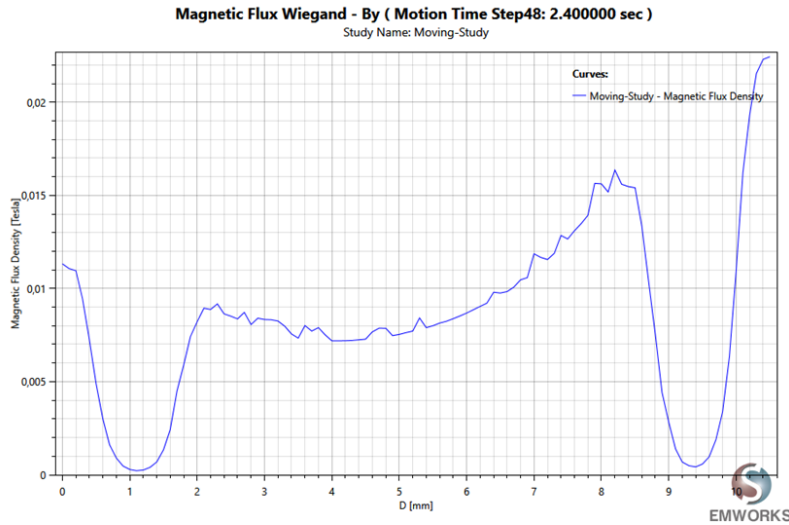
2. Ferromagnetic elements are now added, as shown in the following image.

Figure 5: Added Ferromagnetic Elements



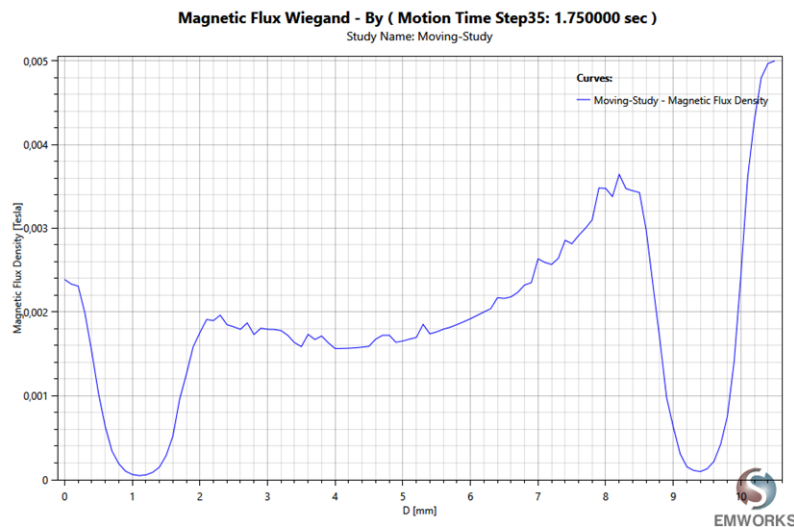
The integration of these ferromagnetic collectors optimizes the field distribution along the Wiegand wire, as illustrated in the following image.

Figure 6: Amplitude of the Charging Field Component in Wiegand Wire Axis (With Ferromagnetic Collectors as Shown in Figure 5)



Now, the axial field along the wire (extending from 2 mm to 8.5 mm) consistently exceeds 7 mT. Still, the distribution is somewhat non-homogeneous. The segment of the Wiegand wire closest to the magnet stripe is charged with 16 mT, the ends with 9 mT, and the central region is only 7 mT. Although this distribution satisfies the basic activation requirements, a critical challenge remains at the trigger position. As illustrated in the following simulation, the field geometry at the moment of switching presents a much more complex scenario.

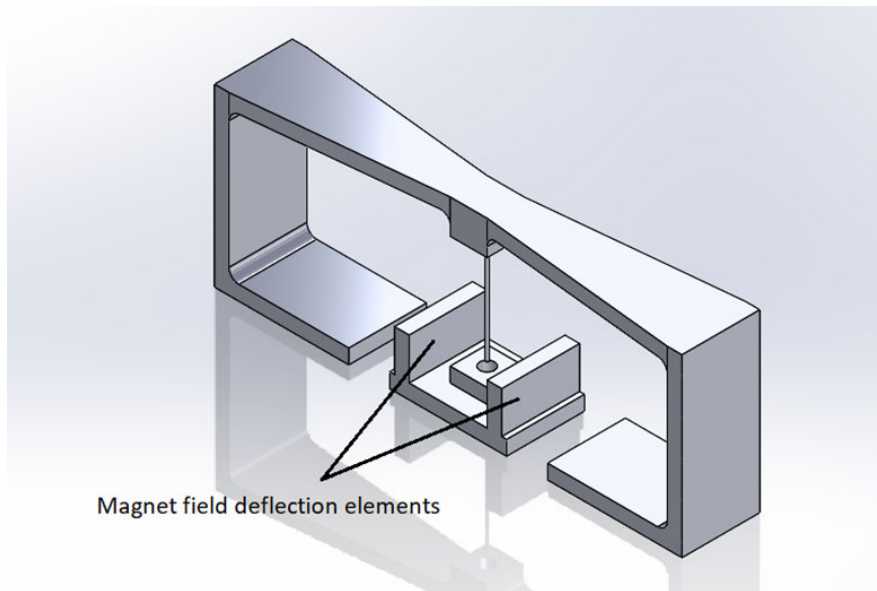
Figure 7: Amplitude of the Trigger Field Component in Wiegand Wire Axis (With Ferromagnetic Collectors as Shown in Figure 5)



When the field intensity near the magnetic strip reaches the 3 mT threshold (identified as the average trigger field amplitude), the flux density across the remainder of the wire drops significantly—ranging between 1.5 mT and 2 mT. This gradient is insufficient to guarantee constant and smooth propagation of the Bloch wall. Consequently, the magnetic reversal is often incomplete or fails to propagate, leading to induced pulses in the pickup coil that are highly inconsistent and lack the energy required for reliable operation.

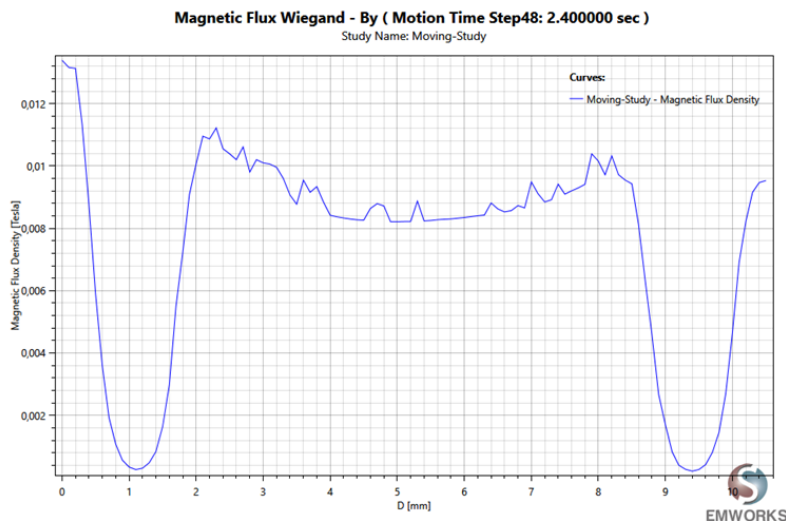
- Broadcom solved the problem of the inhomogeneous magnetic field by integrating specialized deflection elements into the central ferromagnetic collector, as shown in the following image.

Figure 8: Ferromagnetic Collector with Specialized Deflection Elements



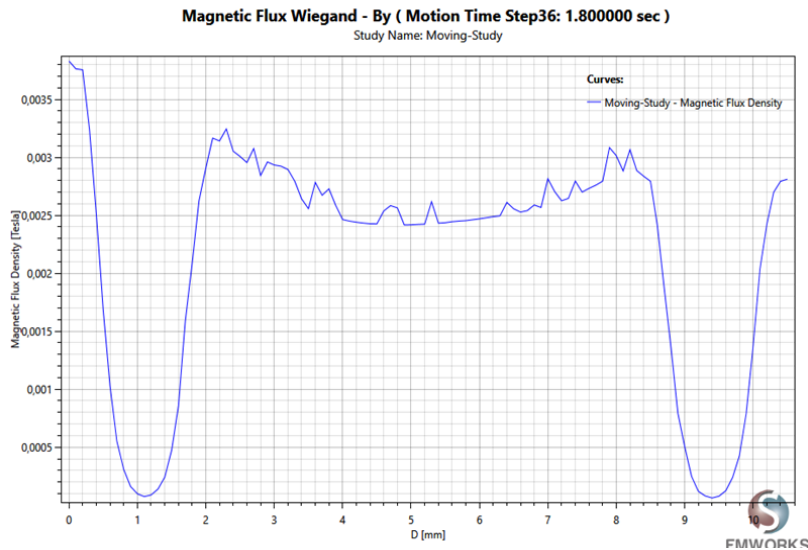
By using these deflection elements, the magnet field is prevented from coupling directly from the magnets to the lower part of the wire. This redirection of the flux results in the optimized field distribution at the charging position, as shown in the following image.

**Figure 9: Amplitude of the Charging Field Component in Wiegand Wire Axis
(With Ferromagnetic Collectors and Deflection Elements as Shown in [Figure 8](#))**



The maximum amplitude is reduced from 16 mT to 11 mT, which is more than sufficient for the full alignment of the magnetic domains within the wire. Concurrently, the minimum field amplitude has been increased to over 8 mT (up from 7 mT). More importantly, the magnetic field distribution at the critical trigger position is transformed, as illustrated in the following image.

Figure 10: Amplitude of the Trigger Field Component in Wiegand Wire Axis
(With Ferromagnetic Collectors and Deflection Elements as Shown in [Figure 8](#))



As shown in the preceding figure, the magnetic field distribution has achieved the necessary homogeneity to ensure a stable and reproducible pulse. This uniform flux density allows the Bloch wall to propagate without interruption, resulting in consistent energy output across all sensing cycles.

Conclusion

By implementing the flux-shaping architecture described in this paper, the Wiegand principle—traditionally reserved for rotary energy-harvesting multi-turn (EHMT) encoders—can now be effectively applied to linear systems. This breakthrough enables the use of cost-effective, standard magnetic strips to achieve high-resolution, absolute linear encoding without the need for external power or backup batteries.

Using a magnetic strip pitch of 16 mm in conjunction with a 39-bit counter, the maximum measurable length is approximately 8.8 million kilometers, which far exceeds the requirements of any terrestrial application.

The measured tolerance for the distance between the magnetic strip and the read head is 1 to 3 mm and can be further improved by adjusting the strip pitch or magnetic layer thickness.

The same combination of magnetic strip and Wiegand counter can also be used for rotary applications with large diameters or for systems that combine linear and circular motion paths.

The ASIC used in this system is already a standard component for rotary encoders, supporting high-speed interpolation between magnetic poles. A prototype achieved a resolution of less than **0.01 mm** with an absolute accuracy of approximately 1 mm. The maximum operating speed—constrained by the ASIC processing limits and the 16 mm strip pitch—is approximately **8 m/s** (28.8 km/h).

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