A Review of Integrated Propulsion, Suspension and Guidance Passive Guideway Maglev Technologies

Jonathan Z. Bird
Laboratory for Electromechanical Energy Conversion and Control
Electrical and Computer Engineering Department, Portland State University, Portland, OR, USA
Email: jonathan.bird@ieee.org

Abstract— **This paper provides a review of integrated propulsion, suspension and guidance maglev technology that use fully passive guideway structures.**

***Keywords*— levitation, propulsion, linear motor, maglev**

I. Introduction

Maglev vehicles utilize magnetic fields in order to create suspension, propulsion and guidance forces without physical contact and thus speeds well in excess of 500 km/h are possible. Maglev can offer trip times that are competitive with air travel for only a fraction of the energy consumed by an aircraft [1]. The lack of frictional forces between the vehicle and the guideway, and maglev's low energy consumption compared to aircraft means that the operational costs, once the transportation system has been developed, should be low [2]. Furthermore, whereas aircraft rely solely on petroleum and consequently create a large amount of air pollutants, such as CO_2, NO_x, SO_xO, H_2SO_4 and soot [3] maglev's electric power can be derived from many renewable energy sources.

Recently there has been renewed interest in maglev vehicle technology because of the SpaceX Hyperloop proposal to use high-speed vehicles within partially evacuated tubes or tunnels [4]. By reducing air resistance, vehicle speeds up to 1,200km/h could be achievable [5-7]. Such speeds cannot be achieved using high-speed rail. Also, unlike high-speed rail, maglev vehicles have the ability to accelerate rapidly, climb steep grades, negotiate tight turns and operate in extremely adverse weather conditions [2]. Maglev vehicles enable lighter weight and smaller vehicles to be utilized and their inherently quiet operation eliminates the need for costly noise abatement in urban environments.

Despite maglev's attractive characteristics U.S. firms and Transit authorities have been reluctant to invest in this technology. Overseas high-speed rail has been extensively used rather than maglev. The reason for this is undoubtedly, in part, due to maglev's extremely high initial capital cost [8]. The author believes that there are three main causes for maglev's high cost: (1) a specialized elevated guideway needs to be constructed in order to house the vehicle suspension technology. (2) A linear synchronous motor for propulsion is invariably used, this turns the entire guideway into a motor. (3) A highly elaborate mechanical guideway directional switching mechanism is needed to change lanes. This is because maglev vehicles, unlike traditional rail, typically wrap around the guideway. Unless further transformational research is conducted to demonstrate that a radically lower cost maglev technology can be developed it is unlikely maglev will be taken up by future urban and intercity planners.

One potential method of significantly reducing guideway costs would be to integrate the propulsion, suspension and guidance forces into one motor and generate all the necessary forces using only one guideway surface. The design and control of such a motor is undoubtedly significantly more complex because all force requirements must be simultaneously met using one motor. Nevertheless, using such an approach appears to be the only foreseeable way that the guideway cost can become comparable to high-speed rail and interstate highway costs since rail and automobiles rely only one surface element.

Proponents often claim that the disadvantage of using a passive guideway is that a power source or power generator must be on the vehicle and/or a high-speed power transfer technique must be utilized. However, the rapid improvements in power electronic technology in recent decades has made inductive power transfer techniques a much more tenable solution [9-14]. Also a traditional high-speed rail pantograph system could be used at lower speeds especially if the maglev guideway can be integrated into existing rail networks.

Integrated passive guideway designs were extensively studied in the 1970's and early 80's [7, 15-46]. In this paper these less well-known technologies are reviewed, and an attempt is made to compare and critique the different techniques. An in-depth review of all maglev technologies can be found in [47]. This review is focused on past high-speed maglev vehicle designs.

I. Linear Induction motor Using Separate Electromagnetic Suspension and Guidance

The linear induction motor (LIM) is similar in many respects to its rotary counterpart. However, unlike the rotary induction motor, the secondary of the LIM is much shorter than the primary and this introduces new detrimental electromagnetic effects. The single-sided linear induction motor (SLIM), and double sided linear induction motor (DSLIM) typologies [48] are shown in Fig. 1.

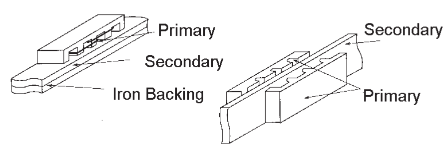

Fig. 1 Double and single sided LIM

The DSLIM iron or alloy secondary must be positioned vertically on the guideway with the short primary placed on the vehicle. Whilst the SLIM primary is positioned horizontally on the ground and usually has a thin copper or aluminum sheet on top of the back-iron to provide a low resistance current path. For a given weight, the DSLIM develops greater thrust than a SLIM [49], and unlike the SLIM the large attractive force between the primary and secondary members is cancelled out [49]. The German Transrapid 04 [40, 50, 51], shown in Fig. 2 used the DSLIM. The DSLIM has somewhat better electrical characteristics but the design of the guideway and track switching using a SLIM is far simpler.

Fig. 2 The German Transrapid 04, DSLIM driven maglev obtained a maximum speed of 253km/h in 1977 [40, 50, 51]

The SLIM can be designed to have either an axial or a transverse flux path, as illustrated in Fig 2. The transverse flux SLIM can be superior to the axial SLIM if the stack length is small compared with the pole-pitch because the transverse SLIM has a shorter magnetic path and this results in a lighter design with less back iron [52, 53]. However, when using a variable frequency supply the pole pitch can be made smaller than the stack length and therefore the use of a transverse flux SLIM for high-speed operation no longer has a significant advantage [45, 54]

The LIM air-gap flux is inductively created and therefore with an increased air-gap, the power factor becomes inevitably low [45]. Also, because the primary is short relative to the secondary, it is always coming into contact with new unmagnetized guideway regions resulting in a reduction in thrust force at high translational speeds. This effect gets increasingly worse when the relative translational speed exceeds the speed with which the electromagnetic field diffuses through the conductor of the secondary [54, 55].

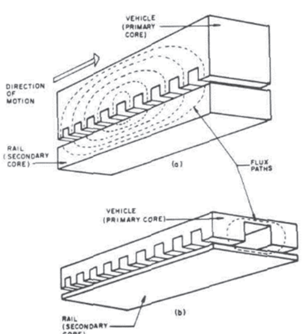

Fig. 2 Axial (a) and transverse flux SLIM (b), showing flux paths [56]

Fig. 3. Romag vehicle, 1972 [19]

For a given design speed, the end-effect can be reduced by using a higher frequency and a greater number of pole-pairs [54, 57, 58]. However, the number of poles that can fit onto the primary for a given design length, *L*, is limited by tooth saturation, and more importantly by the air-gap leakage [59]. For pole pitches much less than 200mm the air-gap leakage increases significantly, Nonaka recommended a pole-pitch no less than 300mm regardless of the design speed [59]. Therefore, the frequency to pole number ratio can only be increased so far before the primary length, *L*, of the LIM must be increased in order to operate at a good efficiency. This means that for high-speed applications, the LIM primary must be very long and unwieldy.

Problems with the end effect and low power factor have limited the use of the LIM to low-speed applications. Currently the Japanese HSST and Korean UTM use the LIM with electromagnetic suspension [60, 61].

Although electromagnetic suspension is highly efficient for low speed operation at high speed the iron guideway must be laminated in order to mitigate the induced eddy currents and drag forces. The use of laminated steel on the guideway will greatly add to the maglev guideway cost [62].

II. Single Sided Linear Induction Motor Using Iron Attraction

The SLIM creates a large attractive force between the primary and secondary. Therefore, this attractive force can be used to provide a vehicle with the magnetic suspension force [15-18]. Such a maglev vehicle was developed and showcased in 1972 by the Romag Corporation [15, 18, 19]. Fig. 3. shows that both an overhead and a ground vehicle configuration were developed. However, at higher speeds large induced currents in the track created by the SLIM result in the attractive force becoming significantly diminished, and at high enough speeds the normal force becomes a large repulsive force [63-65]. Therefore, this integrated method is not effective, or safe, for very high speed applications. Furthermore, since AC electromagnetic attraction produces only half the average suspension force per unit area compared to a DC electromagnet attraction [44] using a purely alternating current will result in poor suspension performance. In order to improve the suspension performance using this technique a DC current bias can be used to improve the attractive force, such a technique has been used more recently for low speed steel plate transportation [66-68].

III. Iron Cored Linear Synchronous Motor

The linear reluctance motor inherently creates a large attractive magnetic force; it was proposed by Ross that this attractive force could be used to create an integrated maglev motor [15-18], where the reluctance forces created by salient track poles could be used for propulsion while the iron's attraction could be used for suspension. However, the disadvantage of such a motor is that all the air-gap flux is provided by the AC magnetizing current flowing in the three-phase primary windings and this creates a low power factor. In order to improve on this design Levi proposed that a DC excitation on the primary be used to provide the magnetic suspension force and magnetization field, while an AC winding is used to synchronously interact with the salient pole guideway structure to create a propulsive force. This type of integrated maglev motor has been termed Iron Cored Linear Synchronous Motor (ICLSM) [21, 22]. A variety of different salient track structures have been proposed for the ICLSM, three such types, the homopolar, heteropolar, zig-zag ICLSM [20, 42, 45, 69] designs are illustrated in Fig. 4 – 6. It has also been suggested that magnets could provide the fixed field MMF excitation [23, 24].

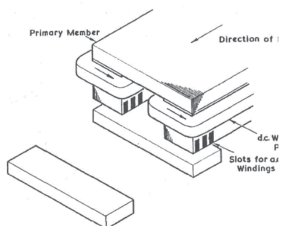

Fig. 4. Transverse flux segmented homopolar linear synchronous motor [20, 31, 45, 70]

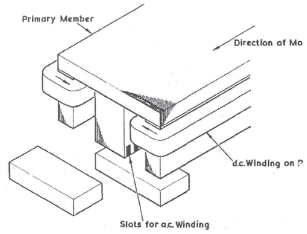

Fig. 5.Transverse flux heteropolar linear synchronous motor [20, 31, 45]

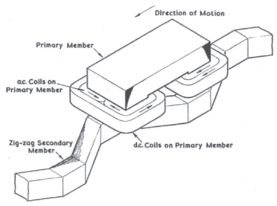

Fig. 6. Transverse flux zig-zag linear synchronous motor [20, 25, 46, 69]

Many past published designs used lumped parameter round rotor theory to predict the ICLSM performance. Therefore, there were often large discrepancies between the calculated and measured values particularly when the saturation, leakage effects and iron eddy current losses were neglected [26-28, 70]. Based on actual linear motor and rotary experimental test-rig results it has been reported that the ICLSM performance is approximately 70-85% of the values predicted by the round-rotor based calculations [29, 30]. A large scale low-speed ICLSM test vehicle on a 150m track was developed by Boldea in the mid 1980's in order to demonstrate the principle [71, 72].

The ICLSM was also considered for use in a Swiss underground high-speed transportation system, in which the vehicles traveled within partially evacuated tubes [7, 73, 74]. This homopolar track design with magnetic attractive guidance is illustrated in Fig. 7.

At high speeds induced eddy currents will create a significant magnetic drag force and power loss therefore a laminated guideway must be used for high-speed operation [7, 27, 31, 42, 45, 70]. As the ICLSM requires a high magnetization in the air-gap the track and vehicle stator iron must be very thick in order to prevent saturation. For the high speed designs, which require higher magnetization currents, over 2 times as much (laminated) track iron is required compared with an LIM [20, 43].

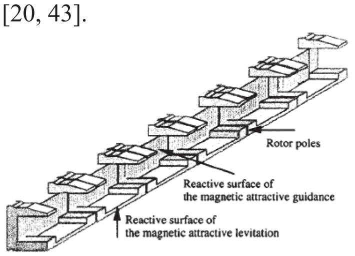

Fig. 7. Proposed Swissmetro homopolar linear synchronous motor guideway design [74]

IV. The Electromagnetic River

Eastham and Laithwaite proposed that if the SLIM was used without any track back-iron then the induced currents in the conductive, non-magnetic, track could create a large repulsive force between the primary and the conductive secondary, and this could allow the SLIM to create both the suspension and thrust forces simultaneously [32, 33]. An illustration of a prototype model vehicle using this method, which Laithwaite imaginatively termed an Electromagnetic River (ER), is shown in Fig 8. The primary is on the ground and the model vehicle has an aluminum secondary on its underside. Such a method of eddy current repulsion goes back to the first proposed maglev system by Bachelet in 1912 in which guideway solenoids were used to suspend a conductive 'vehicle' [40, 75]. Unfortunately, the suspension of a vehicle using the LIM's inductive repulsive forces, with a reasonable air-gap, requires a very large amount of reactive power. Therefore the ER motor must operate with an extremely low power factor [34-36, 76] In order to create a sufficient suspension-to-weight ratio water cooling of the windings would be essential [36] and, the primary would need to be very long (at least 8m) in order to accommodate enough poles to counteract the end-effects and provide sufficient thrust force at high speeds [59].

It has also been proposed that superconducting winding could be used in order to improve the suspension/weight ratio at a large air-gap [39, 77]. However, superconductors have losses when transmitting alternating current and these losses increase with the operating frequency and field density. At the high operating frequencies required by the ER the AC losses will become excessively large [78]. Also, the use of an even larger air-gap, will result in an even greater leakage flux, and make for an especially abysmal power factor [39].

The ER concept has never developed past the construction of small-scale models, where the track is active and the vehicle has a passive aluminum underside.

Fig. 8. Electromagnetic river demonstrator for maglev launch assist built at NASA's Marshall space flight center in Huntsville, Alabama [79]

V. Mechanical Rotation of Magnets

Rather than creating a traveling magnetic field using windings, it is also possible to create the traveling field by rotating magnets or superconducting magnets. The rotation of the magnets over a conductive non-magnetic surface, such as aluminum, will induce currents in the aluminum that can then create suspension and thrust forces like with the ER concept. However, as the air-gap field is provided by the magnet sources there will be no associated low power factor seen by the motor. Therefore, unlike with the LIM and ER increasing the air-gap will not require more reactive power. However, the rotation of the magnetic sources will introduce new mechanical losses and a motor will be required to rotate the magnets. With the use of rare-earth magnets or superconductors the combined system maybe designed to be relatively light weight. [38, 80-82]

This concept was first proposed by Davis and Borcherts [37]. They proposed rotating superconductors because using superconductors in a LIM configuration would create large AC losses [37, 38]. A radial and a helical superconducting magnet configuration were proposed [37, 38, 41, 65], as shown in Fig. 9 and Fig. 10.

As with the LIM the propulsion forces are dependent on the relative velocity of the rotor compared to the translational velocity and therefore a slip is always present [83]. Large braking forces result when the peripheral speed of the rotor is rotated slower than the vehicles traveling speed.

Although low or high-temperature superconductors may be used a significantly lower cost solution is achieved by using rare-earth Nd-Fe-B magnets [81]. Fujii and Ogawa first considered rotating axially placed rare-earth magnets [80, 84-87]. Two proposed methods for creating thrust and suspension force simultaneously using a tilt and an overlap type magnet wheel is shown in Fig. 11 and Fig. 12. The overlap type has better magnetic coupling to the guideway than the tilt type, but in order to create a large thrust a large portion of the rotor has to be rotated over air [85]. Greater guidance can be achieved by using an inclined guideway as shown in Fig. 13 [85]. However, such a guideway will make vehicle directional switching complex and the guidance force is at the permanent expense of a reduced suspension force. Only results for standstill operations of these two topologies have been published.

A Nd-Fe-B Halbach rotor configuration was considered by Bird as shown in Fig. 14 [47, 81, 88, 89]. Using the illustrated split-sheet topology creates some re-centering lateral forces [47]. However, the re-centering forces do not scale well and result in a significant reduction in the lift and thrust. Although the magnetic coupling between the guideway and magnetic rotor is poor this electrodynamic wheel typology has the potential to enable a completely flat guideway structure to be utilized, such a typology could therefore potentially be as low cost as high-speed rail.

VI. Conclusion

A review of less studied passive integrated suspension, propulsion and guidance technologies has been presented. A discussion of the advantages and disadvantages of each technology was highlighted. The ICLSM and the use of mechanical rotational magnets, such as the electrodynamic wheel appear to offer the best means of attaining similar cost-performance to the prevailing high-speed linear synchronous motor designs with separate electromagnetic or electrodynamic suspension. The use of a radial magnet electrodynamic wheel topology offers the tantalizing possibility of reducing the guideway costs to a similar level as incurred by high-speed rail. However, significant control challenges must be overcome before this technology can be implemented in a full-size vehicle.

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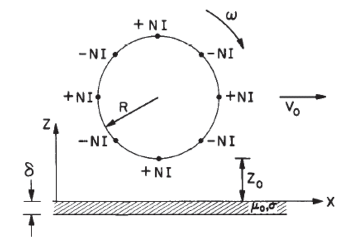

Fig. 9. Radial superconducting rotor configuration [38]

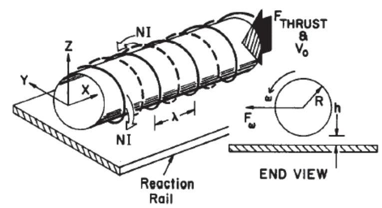

Fig. 10. Helical superconducting rotor configuration [37]

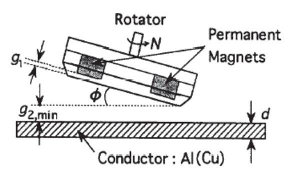

Fig. 11 Tilt type magnet wheel [86]

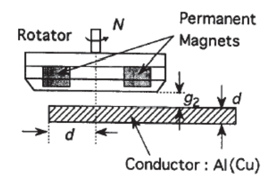

Fig. 12 Partial overlap type magnet wheel [86]

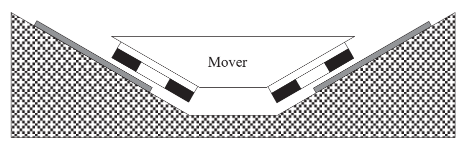

Fig. 13 Magnet wheel with guidance [85]

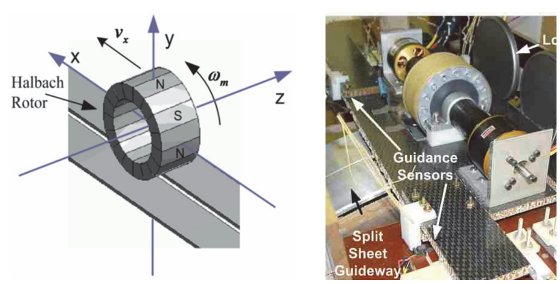

Fig. 14 An electrodynamic wheel over a split–sheet guidway [47, 88, 89]

References

[1] H. J. Lever, "Technical Assessment of Maglev System Concepts, Final Report by the Government Maglev System Assessment Team," CRREL-SR-98-12, US Army, CRREL, Oct. 1998.

[2] R. Hoopengardner and D. Keever, "FTA Low-Speed Urban Maglev Research Program – Lessons Learned," FTA-DC-26-7260.2009.01, Fed. Transit Admin., Washington, DCMarch, 2009.

[3] *Intergovernmental Panel on Climate Change (IPCC), "Aviation and the Global Atmosphere"*. Cambridge University Press, 1999, p.^pp. Pages.

[4] P. E. Ross, "Hyperloop: No pressure," *IEEE Spectrum*, vol. 53, no. 1, pp. 51-54, Jan. 2016.

[5] K. Decker, J. Chin, A. Peng, C. Summers, G. Nguyen, A. Oberlander, *et al.*, "Conceptual Feasibility Study of the Hyperloop Vehicle for Next-Generation Transport," presented at the American Institute of Aeronautics and Astronautics, Reston, VA, USA, 2017.

[6] C. L. Taylor, D. J. Hyde, and L. C. Barr, "Hyperloop Commerical Feasibility Analysis", US Department of Transportation, DOT-VNTSC-NASA-16-01, July 2016.
[7] A. Casset, M. Rosenmayr, N. Macabrey, and M. Jufer, "Swissmetro and transrapid comparison of the electromechanical components and the power supply in a specified vacuum tunnel environment," in *16th International Conference on Magnetically Levitated Systems and Linear Drives*, Rio de Janeiro, pp. 119-129,2000.
[8] E. Pfanner, "Japan Pitches Its High-Speed Train With an Offer to Finance " *New York Times*, Nov. 19 2013.
[9] C. S. Wang, G. A. Covic, and O. H. Stielau, "General stability criterions for zero phase angle controlled loosely coupled inductive power transfer systems," in *The 27th Annual Conference of the IEEE Industrial Electronics Society*, Colorado, USA, pp. 1049-1054,2001.
[10] K. W. Klontz, D. M. Divan, D. W. Novotny, and R. D. Lorenz, "Contactless power delivery system for mining applications," *IEEE Transactions on Industry Applications*, vol. 31, no. 1, pp. 27-35, 1995.
[11] G. A. J. Elliott, J. Boys, and A. W. Green, "Magnetically coupled systems for power transfer to electric vehicles," in *International Conference on Power Electronics and Drive Systems*, Singapore, pp. 797-801,1995.
[12] C. H. Stephan, J. M. Miller, and L. C. Davis, "A program for individual sustainable mobility," in *Global Powertrain Congress*, Ann Arbor, MI,Sept.,2003.
[13] B.-M. Song, R. Kratz, and S. Gurol, "Contactless inductive power pickup system for maglev applications," in *Industry Applications Conference*, pp. 1586 - 1591,2002.
[14] O. H. Stielau and G. A. Covic, "Design of loosely coupled inductive power transfer systems," in *Power System Technology*, pp. 85-90,2000.
[15] J. A. Ross, " ROMAG transportation system," *Proceedings of the IEEE*, vol. 61, no. 5, pp. 617-620, May 1973.
[16] B. V. Jayawant, "Electromagnetic suspension and levitation," *IEE Proceedings Part A*, vol. 129, no. 8, pp. 549-580, Nov 1982.
[17] T. Morizane, N. Kimura, and K. Taniguchi, "Simultaneous control of propulsion and levitation of linear induction motor in a novel maglev system," in *Power Electronics and Motion Control Conference*, Beijing, China, pp. 127-131,2000.
[18] R. G. Gilliland and G. W. Pearson, "Integrated Magnetic Propulsion and Suspension Hover Test Report," U.S. Department of Transportation, Seattle, WA UMTA/WA/06/0014-85/2, March 1985.
[19] R. G. Rule and R. G. Gilliland, "Combined magnetic levitation and propulsion: the mag-transit concept," *IEEE Transactions on Vehicular Technology*, vol. 29, no. 1, pp. 41-49, Feb. 1980.
[20] E. J. F., B. M. J., and R. D., "A comparison of some propulsion methods for magnetically-levitated vehicles," in *Maglev Transport Now and for the Future*, Solihull England, pp. 111-118,1984.
[21] E. Levi, "Linear synchronous motors for high-speed ground transportation," *IEEE Transactions on Magnetics*, vol. 9, no. 3, pp. 242-248, Sept. 1973.
[22] E. Levi, "Preliminary Design Studies on Iron Cored Synchronously Operated Linear Motors," Department of Transport, DOT-FRA 76-005, 1976.
[23] D. H. Kang and H. Weh, "Design of an integrated propulsion, guidance and levitation system by magnetically excited transverse flux linear motor (TFM-LM)," *IEEE Transactions on Energy Conversion*, vol. 19, no. 3, pp. 477-484, Sept 2004.
[24] R. G. Gilliland and G. W. Pearson, "A linear synchronous unipolar motor for integrated magnetic propulsion and suspension," in *International Conference on Maglev & Linear Drives*, Vancouver, Canada, pp. 149-155,1986.
[25] G. W. McLean, "Review of recent progress in linear motors," *IEE Proceedings Part B*, vol. 135, no. 6, pp. 380-416, Nov. 1988.
[26] I. Boldea and S. A. Nasar, "Linaer synchronous homopolar motor (LSHM) - a design procedure for propulsion and levitation system," *Electric Machines and Electromechanics*, vol. 4, no. pp. 125-135, 1979.
[27] I. Boldea and S. A. Nasar, "Field winding drag and normal forces of linear synchronous homopolar motors," *Electric Machines and Electromechanics*, no. 2, pp. 253-268, 1978.
[28] D. L. Atherton, "Design and Control Studies of a Linear Synchronous Motor for Urban Transit Application," *IEEE Transactions on Magnetics*, vol. 18, no. 6, pp. 1847-1855, Nov. 1982.
[29] T. R. Haller and W. R. Mischler, "A comparison of linear induction and linear synchronous motors for high speed ground transportation," *IEEE Transactions on Magnetics*, vol. 14, no. 5, pp. 924-926, Sept. 1978.
[30] G. B. Kliman, "Linear electric motors," in *Industry Applications Annual Conference*, pp. 256-261, Cincinnati, Sept. 28-Oct. 3, 1980.
[31] J. F. Eastham, M. J. Balchin, and P. C. Coles, "Full-scale testing of a high speed linear synchronous motor and calculation of end-effects," *IEEE Transactions on Magnetics*, vol. 24, no. 6, pp. 2892-2894, 1988.
[32] J. F. Eastham and E. R. Laithwaite, "Linear induction motors as 'electromagnetic rivers'," *Proceedings of the IEE*, vol. 121, no. 10, pp. 1099-1108, Oct. 1974.
[33] J. F. Eastham and S. Williamson, "Experiments on the lateral stabilistaion and levitation of linear induction motors," *IEEE Transactions on Magnetics*, vol. 10, no. 3, pp. 470-473, Sept. 1974.
[34] J. F. Eastham and D. Rodger, "The performance of induction levitators," *IEEE Transactions on Magnetics*, vol. 20, no. 5, pp. 1684-1686, Sept. 1984.
[35] B. V. Jayawant, *Electromagnetic Levitation and Suspension Techniques*. London: Edward Arnold, 1981.
[36] R. M. Katz, A. R. Eastham, G. E. Dawson, D. A. Atherson, and C. L. Schwalm, "Integrated magnetic suspension and propulsion of guided ground transportation vehicles with a SLIM," *IEEE transactions on Magnetics*, vol. 15, no. 6, pp. 1437-1439, 1979.
[37] L. C. Davis and R. H. Borcherts, "Superconducting paddle wheels, screws, and other propulsion units for high-speed ground transportation," *Journal of Applied Physics*, vol. 44, no. 7, pp. 3294-3299, July 1973.
[38] R. H. Borcherts and L. C. Davis, "The superconducting paddlewheel as an integrated propulsion levitation machine for high speed ground transportation," *Electric Machines and Electromechanics*, vol. 3, no. pp. 341-355, Apr-June 1979.
[39] K. Chirgwin, "Linear electric motor propulsion systems," in *Transport Without Wheels*, E. R. Laithwaite, Ed., ed London: Elek Books Ltd, 1977, pp. 37-59.
[40] E. R. Laithwaite, *A History of Linear Electric Motors*. London: Macmillan, 1987.
[41] Philco-Ford, "Department of Transportation, Conceptual Design and Analysis of the Tracked Magnetically Levitated Vehicle Technology Program (TMLV) - Repulse Scheme Volume 1 - Technical Studies," Department of Transport, Springfield, VA DOT-FR-40024 (Task I), Feb. 1975.
[42] G. R. Slemon, "An experimental study of a homopolar linear synchronous motor," *Electric Machines and Electromechanics*, vol. 4, no. pp. 59-70, 1979.
[43] T. A. Nondahl, "Design studies for single-sided linear electric motors: homopolar synchronous and induction," *Electric Machines and Electromechanics*, vol. 5, no. pp. 1-14, 1980.
[44] T. M. Barrows, "Comparison of combined versus separate lift/propulsion systems," *IEEE Transactions on vehicular technology*, vol. 29, no. 1, pp. 71-80, Feb. 1980.
[45] J. F. Eastham, M. J. Balchin, P. C. Coles, and D. Rodger, "Comparison of short primary linear machines for high speed maglev vehicles," *IEEE Transactions on Magnetics*, vol. 23, no. 5, pp. 2338-2343, 1987.
[46] G. W. McLean, "Combined lift and thrust for maglev vehicles using the zig-zag synchronous motor," in *Maglev Transportation Now and for the Future*, Solihull, England, pp. 87-93,1984.
[47] J. Bird, "An investigation into the use of electrodynamic wheels for high-speed ground transportation," Ph.D. Thesis, Electrical and Computer Engineering, University of Wisconsin-Madison, Madison,WI, 2007.
[48] E. R. Laithwaite, "Application of linear induction motors to high-speed transport system," *Proceedings of the IEE*, vol. 116, no. 5, pp. 713-724, 1969.
[49] S. A. Nasar and L. D. Cid, "Propulsion and levitation forces in a single-sided linear induction motor for high-speed ground transportation," *Proceedings of the IEEE*, vol. 61, no. 5, pp. 638-644, May 1973.
[50] W. W. Dickhart, "Status of transrapid maglev," *Electro International*, no. pp. 613-617, April 16-18 1991.
[51] K. Glatzel, G. Khurdok, and D. Rogg, "The development of the magnetically suspended transportation system in the Federal Republic of Germany," *IEEE Transactions on Vehicular Technology*, vol. 29, no. 1, 1980.
[52] E. R. Laithwaite, J. F. Eastham, and H. R. Bolton, "Linear motors with transvers flux," *Proceedings of the IEE*, vol. 118, no. 12, pp. 1761-1767, Dec. 1971.

[53] J. F. Eastham and E. R. Laithwaite, "Linear-motor topology," *Proceedings of the IEE*, vol. 120, no. 3, pp. 337-344, March 1973.
[54] S. Yamamura, *Theory of Linear Induction Motors*: University of Tokyo Press, 1979.
[55] T. A. Lipo and T. A. Nodahl, "Pole-by-pole d-q model of a linear induction machine," *IEEE Transactions on Power Apparatus and Systems*, vol. 98, no. 2, pp. 629-639, March/April 1979.
[56] R. D. Thornton, "Magnetic levitation and propulsion, 1975," *IEEE Transactions on Magnetics*, vol. 11, no. 4, pp. 981-995, Jul. 1975.
[57] M. Iwamoto, E. Ohno, T. Itoh, and Y. Shinryo, "End-effect of high-speed linear induction motor," *IEEE Transactions on Industry Applications*, vol. 9, no. 6, pp. 632-638, 1973.
[58] M. Iwamoto and S. Yamamura, "End effect of high-speed linear induction motors," *Electrical Engineering in Japan*, vol. 92, no. 3, pp. 94-101, June 1972.
[59] S. Nonaka and T. Higuchi, "Design strategies of single-sided linear induction motors for propulsion of vehicles," in *Inter. Conf. on Maglev and Linear Drives*, Las Vegas, USA, pp. 1-5,1987.
[60] D. Y. Park, B. C. Shin, and H. Han, "Korea's urban maglev program," *Proc. IEEE,* , vol. 97, no. 11, pp. 1886-1891, Nov. 2009.
[61] Y. Yasuda, M. Fujino, M. Tanaka, and S. Ishimoto, "The first HSST maglev commercial train in Japan," presented at the Proc. 18th intern. conf. magn. lev. systems and linear drives (MAGLEV 2004), Shanghai, China, 2004.
[62] R. H. Borcherts and L. C. Davis, "Lift and drag forces for the attractive electromagnetic suspension systems," *IEEE Transactions on Magnetics*, vol. 10, no. 3, pp. 425-428, 1974.
[63] G. H. Bohn and G. Steinmetz, "The electromagnetic levitation and guidance technology of the 'transrapid' test facility Emsland," *IEEE Trans. Magn.*, vol. 20, no. 5, pp. 1666-1671, Sept. 1984.
[64] I. Boldea and S. A. Nasar, *Linear Motion Electrical Machines*. New York: Wiley, 1976.
[65] I. Boldea and S. A. Nasar, *Linear Motion Electromagnetic Systems*: John Wiley & Sons, 1985.
[66] H. Hayashiya, H. Ohsaki, and E. Masada, "A combined lift and propulsion system of a steel plate by transverse flux linear induction motors," *IEEE Transactions on Magnetics*, vol. 35, no. 5, pp. 4019-4021, September 1999.
[67] C. T. Liu and S. Y. Yao, "Electromagnetic field and force analyses of a noncontacting conveyance system for steel mill application," *IEEE Transactions on Magnetics*, vol. 38, no. 5, pp. 3318-3320, Sept 2002.
[68] Y. Nozaki, J. Baba, K. Shutoh, and E. Masada, "Improvement of transverse flux linear induction motors performances with third order harmonics current injection," *IEEE Transactions on Applied Superconductivity*, vol. 14, no. 2, pp. 1846-1849, June 2004.
[69] S. M. Al-Kasimi and A. O. BaQubas, "The inductance analysis of the trapezoidally railed linearsynchronous motor as compared to the Zig-Zag version for Maglev applications," *Power Electronics Specialists Conference, 1992*, vol. 2, no. 29, pp. 1447-1450 June 1992.
[70] M. J. Balchin, J. F. Eastham, and P. C. Coles, "Effects of pole flux distribution in a homopolar linear synchronous machine," *J. Appl. Phys.*, vol. 75, no. 10, pp. 6987-6989, May 1994.
[71] I. Boldea, A. Trica, G. Papusoiu, and S. A. Nasar, "Field tests on a maglev with passive guideway linear inductor motor transportation system," *IEEE Transactions on Vehicular Technology*, vol. 37, no. 4, pp. 213-219, 1988.
[72] I. Boldea, "Magnibus - the Romanian linear inductor (synchronous) motor (passive guideway) maglev," in *Maglev Transport Now and for the Future*, Solihull, England, pp. 149-154,1984.
[73] A. Cassat and C. Espanet, "Swismetro combined propulsion with levitation and guidance," in *18th International Conference on Magnetically Levitated Systems and Linear Drives*, Shanghai, China, pp. 747-758,2004.
[74] A. Cassat and M. Jufer, "MAGLEV projects technology aspects and choices," *IEEE Transactions on Applied Superconductivity*, vol. 12, no. 1, pp. 915-925, March 2002.
[75] E. Bachelet, "Foucault and eddy currents put to service," *The Engineer*, no. pp. 420-421, Oct. 18, 1912.
[76] A. R. Eastham, G. E. Dawson, R. Ong, and L. W. Coathup, "The design and operation of the homopolar linear synchronous motor for linear drive and for integrated suspension/propulsion applications," in *Maglev Transport Now and for the Future*, Solihull, England, pp. 95-104,1984.
[77] S. B. Kuznetsov, "Combined system of levitation, propulsion and guidance for maglev vehicles using high-temperature superconducting magnetic potential well," *IEEE Transactions on Applied Superconductivity*, vol. 5, no. 2, pp. 614-617, June 1995.
[78] R. J. Kaye, W. R. Chambers, J. F. Dempsey, R. C. Dykhuizen, J. B. Keller, G. A. Mann*, et al.*, "SERAPHIM Urban Maglev Propulsion Design," Sandia National Laboratories, Albuquerque, NM FTA-DC-26-7098-02.1, 2002.
[79] W. A. Jacobs, "Magnetic launch assist - NASA's vision for the future," *IEEE Transactions on Magnetics*, vol. 37, no. 1, pp. 55-57, 2001.
[80] N. Fujii, M. Chida, and K. Ogawa, "Three dimensional force of magnet wheel with revolving permanent magnets," *IEEE Transactions on Magnetics*, vol. 33, no. 5, pp. 4221-4223, 1997.
[81] J. Bird and T. A. Lipo, "An electrodynamic wheel: an integrated propulsion and levitation machine," in *Electric Machines and Drives Conference*, pp. 1410-1416,June,2003.
[82] J. Bird and T. A. Lipo, "A preliminary investigation of an electrodynamic wheel for simultaneously creating levitation and propulsion," in *18th International Conference on Magnetically Levitated Systems and Linear Drives*, Shanghai, China, pp. 316-325,2004.
[83] J. Bird and T. A. Lipo, "Characteristics of an electrodynamic wheel using a 2-D steady-state model," *IEEE Trans. Magn.*, vol. 43, no. pp. 3395-3405, Aug. 2007.
[84] D. Ogawa, Y. Horiuchi, and N. Fujii, "Calculation of electromagnetic forces for magnet wheels," *IEEE Transactions on Magnetics*, vol. 33, no. 2, pp. 2069-2072, March 1997.
[85] N. Fujii, G. Hayashi, and Y. Sakamoto, "Characteristics of magnetic lift, propulsion and guidance by using magnet wheels with rotating permanent magnets," in *Industrial Applications Conference* Rome, Italy, pp. 257-262,Oct.,2000.
[86] N. Fujii, K. Naotsuka, K. Ogawa, and T. Matsumoto, "Basic characteristics of magnet wheels with rotating permanent magnets," in *Industry Applications Conference*, pp. 203-209,1994.
[87] N. Fujii, O. Ogawa, and T. Matsumoto, "Revolving magnet wheels with permanent magnets," *Electrical Engineering in Japan*, vol. 116, no. 1, pp. 106-117, 1996.
[88] J. Bird and T. A. Lipo, "Modeling the 3-D rotational and translational motion of a Halbach rotor above a split-sheet guideway," *IEEE Trans. Magn.*, vol. 45, no. 9, pp. 3233-3242, Sept. 2009.
[89] J. Bird and T. A. Lipo, "A 3D steady-state magnetic charge finite element model of an electrodynamic wheel," *IEEE Trans. Magn.*, vol. 44, no. 2, pp. 253-265, Feb. 2008.