LINEAR MACHINE POWER REQUIREMENTS AND SYSTEM COMPARISONS

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ABSTRACT

The revenue vehicle designs of the two German Maglev groups are analysed and the complex power requirements at the trackside substation calculated. The two systems are the Electromagnetic System (EMS) with either linear induction motor (LIM) or long stator motor propulsion, and the Electrodynamic System (EDS) with linear synchronous motor (LSM) propulsion. The operational conditions considered were 400 and 500 km/h velocities either at steady state cruise or with a grade or headwind additional loading. It is found that the LSM of the EDS system is the most suitable form of propulsion for these operating conditions, the long stator motor for the EMS having apparently reasonable characteristics at 400 km/h, but becoming degraded at 500 km/h, and the LIM's studied being unsuited to the high speed range. These results highlight the necessity to compare not only the active power supplied to a vehicle, but also the complex power at wayside substations to be able to indicate the overall efficiencies and power factors of the competing systems.

The German, the Canadian and the Philco-Ford EDS designs are also compared by weight make-up and specific energy intensity. These results show that the advantage gained from a lightweight aircraft-type construction, coupled with the relatively longer body, is lost in the German design because of the extra dead weight of the wheel sets required for running on conventional duo-rail with the resultant heavier body structure. The respective machine power factors are included in the intensity calculations to link in reactive power storage.

INTRODUCTION

Several countries are engaged in research and development projects which employ magnetic levitation (Maglev) and linear motor or air-fan propulsion as component parts of high speed (up to 500 km/h) guided ground transport vehicles. The various systems can be divided into two major categories, the electrodynamic system (EDS) and the electromagnetic system (EMS). The main difference is that the former employ "repulsive" levitation and cryogenic magnets, and the latter "attractive" levitation and conventional iron-cored magnets. The state-of-the-art for both types of Maglev is such that system comparisons are being made between full-sized revenue-earning vehicle designs on specific routes. Because of the complexity and profusion of parameters involved it is customary to choose a few specific parameters for detailed comparison which will hopefully embody the major characteristics and performance of a system. Two parameters frequently chosen are the power-to-weight ratio of the levitation and guidance system (kW/tonne) and the specific energy intensity, (kWh/passenger-km). However, to make meaningful comparisons, the way in which other factors may dominate the choice of these and other primary parameters must be clarified.

THE GERMAN SYSTEM

The analysis and design details of the German Maglev revenue vehicles are given in the 1977 Status-seminar[1] and the basic characteristics are repeated in Table I. The vehicles are made up from two sections, the EDS design speed being 500 km/h and the EMS 400 km/h. Two propulsion schemes are considered for the EMS vehicle, i.e. the double-sided linear induction motor (LIM), and the long stator motor which also incorporates a lift function in the suspension system.

TABLE I. Characteristics of German Vehicles.

System	EDS	EMS	
Stator configuration	long	short	long
Speed, km/h	500	400	
Mass, tonnes	135	170	165
Length, m.	56	64	
No. sections	2	2	
No. passengers	200	240	
Payload, tonnes	20	24	
Height, m.	4.2	4.2	4.0
Width, m.	3.5	4.2	
Aerodynamic coefficient, m^2	3.94	4.75	
Substation spacing, km.	15	12	

A preliminary system comparison has been made of the three alternatives[2], concluding that none of the systems was sufficiently developed to allow a clear choice to be made. Although this comparison showed the power requirement at the substation, it only included the real power for the main magnetic and aerodynamic drag. Although this represents all the losses for the EDS for a given motor efficiency, no mention was made of the EMS cooling momentum drag, the short stator d.c. line loss and the long stator track iron and distribution loss, all of which appear downline from the substation. Furthermore, since the speeds of operation were also different the aerodynamic drag power would introduce a further discrepancy, e.g. an increase of speed from 400 to 500 km/h would result in a doubling of the aerodynamic dragpower. A study was performed to establish the exact power requirements of the different systems, including power factor and motor efficiency values enabling estimates of substation complex power to be made[3]. When the speed is extrapolated to 500 km/h for the EMS vehicles an additional double-sided motor is required for the short stator vehicle, and the weight is increased by 20% to 205 tonnes. The long stator design at 500 km/h requires an increase in gross weight of 10%, to 180 tonnes[1]. Operation of the EDS at the lower speed of 400 km/h should not be too far from an optimized design.

In considering the values of power factor and efficiency to use in establishing terminal conditions at the substation for the EMS vehicles, it was obvious that there were few published test results or even design figures for multi-megawatt high speed motors. Reference 4 suggests calculated efficiencies of 0.6 and 0.78 and associated power factors of 0.5 and 0.65 respectively as the first and second stage of development, and calculations have been made using both these sets of values. The breakdown of active power (Fig. 1) was:-

(1) Aerodynamic drag
(2) Magnetic drag from lift and guidance
(3) On-board system power (excluding any on-board batteries or generators).
(4) Remaining steady-state drag, viz. cooling air inlet drag.
(5) Steady-state losses due to motor inefficiency.
(6) Residual acceleration, viz. extra power to accelerate against headwinds, gradients, etc.
(7) Losses from residual acceleration.

The value of 0.013g residual acceleration was taken for the EDS in common with other values used in (1) for the EMS analysis. The systems both claim propulsion capacity for 3.5% gradients at cruise speeds. The steady-state or cruise power for the EDS is the sum of blocks 1, 2 and 5 in Fig. 1 which are the only system losses. The EMS cruise power is given by the sum of blocks 1 to 5. It must be noted that the figures used for the EMS long stator should be treated with some scepticism, if only for the reason that no largescale experimental performance characteristics have yet been reported. It is

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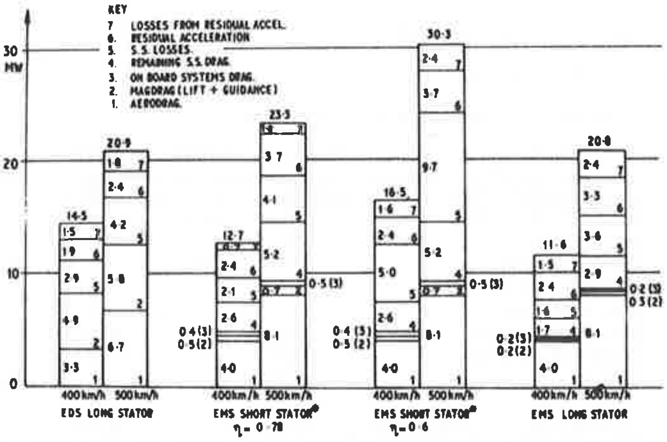

Fig. 1. Total active power of systems (MW).
Note: D.C. distribution and pickup loss not included.

apparent that, in terms of real power consumed, the long stator EMS and the EDS are both roughly equivalent when loaded at 500 km/h. The low efficiency LIM (short stator) EMS uses roughly 45% and the high efficiency LIM/EMS 11% more active power. If an estimate is also made of the D.C. line loss for the LIM, before current pickup, of 15%, the modified EMS/LIM figures are 70% and 31% respectively.

The values shown here could not have been deduced from the suspension lift-to-drag ratios or specific powers. For example the EDS 500 km/h magnetic lift-to-drag ratio of 32 (equivalent to 36 kW/tonne) is modified by aerodynamic drag so that cruise lift-to-drag becomes 15 (92 kW/tonne). Similarly, the EDS short stator magnetic specific power of 3 kW/tonne at 400 km/h (equivalent to magnetic lift-to-drag ratio of 370) is modified by the addition of aerodynamic and cooling drag to a steady-state value of 44 kW/tonne (lift-to-drag ratio of 25). The choice of a suspension subsystem with high magnetic lift-to-drag ratio does not ensure an overall high ratio because of the aerodynamic and other system losses.

TABLE II. Apparent efficiency (powerfactor - efficiency product) of the German Vehicles

	400 km/h		500 km/h	
	steady state	loaded	steady state	loaded
EDS	0.67	0.62	0.66	0.60
EMS, long stator	0.57	0.46	0.44	0.36
EMS, short stator, high efficiency	0.51	0.51	0.51	0.51
EMS, short stator, low efficiency	0.30	0.30	0.30	0.30

The change in efficiency and power factor of the three systems as loading and speed vary is indicated in Table II. The EDS system looses 7% in going from unloaded 400 km/h to loaded 500 km/h operation. A similar transition for the EMS long stator motor results in a 21% loss representing a conservative estimate as it ignores non-linearities in the iron-cored system. The short stator values were held constant as the design called for a doubling up of the motors to give sufficient thrust at the higher speed; each motor remained at much the same output, but would be operating at different slip.

The power factor of a system enables the complex power to be evaluated from a substation active power. Reactive power flow in a machine-power network is stored in the leakage inductances of the system and air gap of the machine, and as such does no useful work. However reactive power represents a power demand that has to be catered for both in plant rating and energy cost. An iron-cored structure such as a LIM or the EMS long stator motor must have a much lower power factor than a linear synchronous motor (LSM) of the same mechanical power output, since airgap magnetization is provided by superconductors requiring no input reactive power, and the armature leakage inductance is small since the track winding is air-cored. These points are born out by Figure 2, which shows the complex substation power as an ordinate against the active power for each of the four operating conditions of the systems. The success of the electrodynamic system in requiring small amounts of reactive power to provide propulsion throughout the speed and loading variation considered is apparent. The size of the ordinate, i.e. the complex power, therefore demonstrates the relative merits of the overall systems, at the substation. Despite the rough equivalence of active power used, the EMS long stator requires 38% more than the EDS base, and the high efficiency short stator 51% more. Including a line loss the LIM value rises to a 78% increase. If the lower efficiency short stator EMS is considered, then the figures become increases of 156% and 202% on the EDS 100% base.

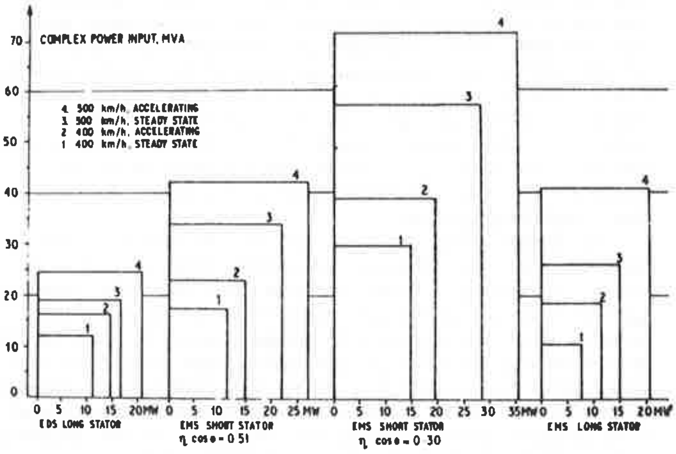

Fig. 2. Total complex and active power of systems.

From this data a power requirement comparison can be made between the three German Maglev vehicles operating under similar conditions. The comparisons cannot be strictly rigorous, since the EMS and EDS vehicles are primarily designed for different baseline operation. However, the spread of system total complex power, at the trackside substations, (Figure 2) is indicative of the type of system performance to be expected for identical service conditions. Several factors have emerged from the analysis:-

(i) The EDS has good system performance at both 500 and 400 km/h in terms of energy conversion and power consumption, and has scope for increases in power factor and efficiency, depending on economic costs of power and capital equipment.

(ii) The short stator induction machines for the EMS are quite unsuitable for high speed (500 km/h) operation, and are probably also unsuited to 400 km/h operation, primarily because of their high reactive power consumption and hence excessive overall power requirement. For example at 500 km/h the high and low-efficiency LIM's respectively required 1.8 and 3 times as much complex power as an EDS/LSM, and at 400 km/h, 1.4 and 2.4 times as much.

(iii) The long stator motor EMS appears to need marginally less power than the EDS at 400 km/h (90%), but when loaded, or at the higher speed of 500 km/h, this slight advantage is lost. Another consideration is that this machine concept has only been tested at low speed, so high-speed operating characteristics must only be regarded as tentative.

(iv) Using specific power, lift-to-drag ratio or specific energy intensity to assess system performance only indicates the active power supplied to make up thrust and losses (if included) in the system. Low power factors in the LIM systems means trackside and transmission components as well as utility energy supply costing must be in terms of total complex power used by a system. The MVA as well as the MW requirements of a system must be obtained in relation to a common guideway route together with similar baseline specifications before reasonable comparisons can be made.

MAGLEV VEHICLE WEIGHT BREAKDOWN

Another area for comparison of vehicle data is that of weight breakdown and for this study two additional single section EDS systems are included with the German vehicle data presented in Figure 3, i.e. the Philco-Ford[5] and the Canadian[6,7] conceptual vehicle designs (see Table III). Two options are included for Philco-Ford, the baseline 80-passenger vehicle, and the 140-passenger vehicle.

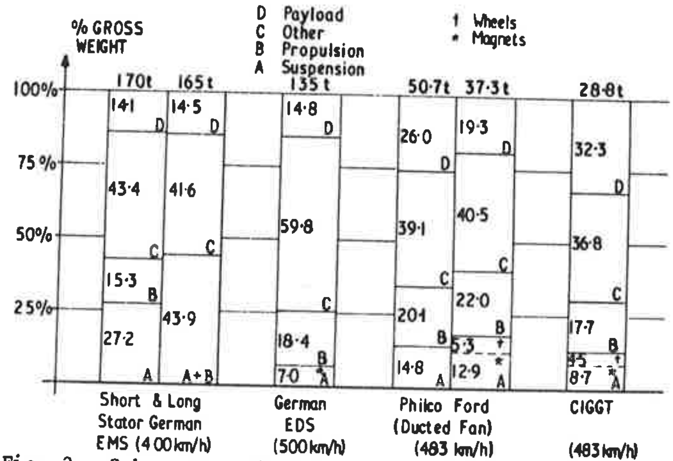

Fig. 3. Subsystem weight breakdown (% Gross).

TABLE III. Characteristics of conceptual EDS Vehicles.

System	Philco-Ford		CIGGT
Propulsion	Ducted Fan		LSM
Speed, km/h	483		483(6) 480(7)
Mass, tonnes	37.3	50.7	28.8
Length, m.	33.67	42.9	36.5
No. passengers	80	140	100
Payload, tonnes	7.2	13.2	9.3
Height, m	3.454		3.20
Width, m	2.94	3.454	3.20
Aerodynamic coefficient, m^2	1.80	2.20	2.42(6) 2.58(7)

Figure 4 shows the weight information scaled in tonnes for the six vehicles. The overall weight per seat of the German EDS vehicle compared to CIGGT and the 140 seat Philco-Ford designs is approximately double. This is largely because of the weight penalty of the heavy duo-rail compatible wheelsets opposed to lightweight aircraft-type wheels of the other EDS designs. The EMS figures for weight-per-seat demonstrate the large amount of power-conditioning and mechanical hardware in the subsystems, which is also borne out by the payload variations from 14.1% (EMS) to 32.3% (CIGGT).

SPECIFIC ENERGY INTENSITY

The specific energy intensity(ψ) of a transport system evaluates the amount of prime energy required per passenger, per kilometer of travel. Within the calculation, the substation convertor efficiency, generation and transmission efficiency, and load factor for the vehicles are included[7]. In obtaining values for (ψ) for non-electrical systems the heating value of the fuel and the journey stage length need to be known[5]. The values of specific energy intensity (including power factor) for the six vehicle designs considered is shown in Table IV.

The Philco-Ford values are low because of the low aerodynamic coefficients chosen together with the high magnetic lift-todrag ratio obtained with a 2.54cm thick aluminium reaction rail. In comparing the CIGGT value with the German EDS, the large vehicle weight of the

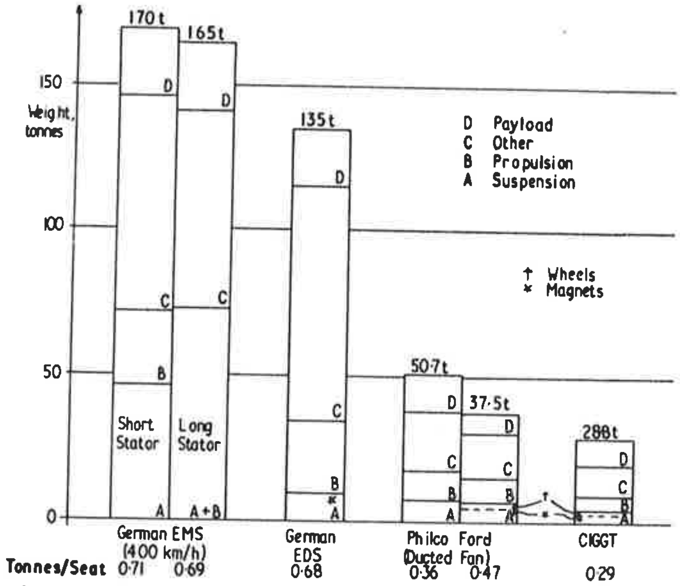

Fig. 4. Subsystem weight breakdown.

TABLE IV. Specific Energy Intensity.

System	EMS Short stator		EMS Long stator	EDS	Philco-Ford 140 pass.	Philco-Ford 80 pass	CIGGT
speed	500		500	500	483	483	480
	high η	low η					
ψ	6.51	11.2	5.1	4.45	2.75	3.63	3.72

latter has completely offset the advantage obtained by increasing the vehicle length as shown by the Philco-Ford difference between short and long vehicles. This decrease in ψ occurs since passenger number increases more rapidly than drag on the extended vehicle.

CONCLUSIONS

The study evaluates and compares total substation power required by the German revenue vehicle designs. The evidence suggests that the linear induction motor does not appear to be a good choice for a propulsion subsystem at 500 km/h or indeed at 400 km/h. The long stator motor(EMS) is likewise degraded when loaded at 400 km/h or run at 500 km/h. The EDS/LSM on the other hand appears to have the most promise for the required operating speed range of 400-500 km/h.

When compared with other EDS designs the German system is shown to be limited by its excessive dead weight as a consequence of the requirement for conventional duo-rail compatibility.

In evaluating any system it has been shown that it is necessary to completely identify the energy make-up rather than specify particular parameters such as lift-to drag ratio or specific power intensity in isolation.

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