The PRT Project
Phase 1 Design & Engineering

Linear Induction Motors (LIMs)
PRT Propulsion System

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LIMs and PRT

1 Executive Summary

Linear induction motors are simple, reliable, non-contact prime movers ideally suited to long travel applications. Since drive and braking are independent of wheel friction they have been seen for many years as the ideal solution for transport applications.

Various designs of LIM powered transport have been devised but only one - the Senate Subway system in Washington DC, using Force Engineering's LIMs - has yet proved commercially successful. This new project presents an opportunity to review all design options from first principles for all aspects of drive and control.

There are many ways of implementing LIM drives and this discussion begins with an explanation of the LIM and the various possibilities. Arguments are presented outlining the pros and cons of each choice. It is concluded that a simple horizontal LIM drive with motors fixed to the track is the preferred choice.

This is encouraging because it concurs with similar successful applications of LIMs to luggage transportation. Whilst these do not have safety as a top priority they do embody many of the operating principles that need to be employed in a safe and practical PRT scheme.

The resulting scheme is an intelligent powered track layout with an unintelligent passive vehicle. The track is consequently expensive but the vehicles are simpler, more reliable, and cheaper. This was very much as originally envisaged.

Elsewhere in our reports it is shown that the LIM, despite its apparently poor electrical efficiency, results in a system which is very efficient in terms of energy usage. The LIM only uses power when needed.

The aim should now be to prove all the essential system components on a representative test track at the earliest opportunity.

Force Engineering is confident this system can be built economically and efficiently.

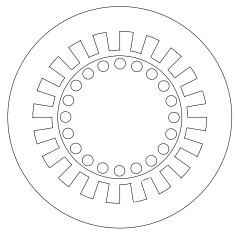
2 Introduction to Linear Induction Motors (LIMs)

A LIM is basically a rotating squirrel cage induction motor opened out flat. Instead of producing rotary torque from a cylindrical machine it produces linear force from a flat one. The technology is not new but merely designed in a different form. Only the shape and the way motion is produced have changed. There are no moving parts; operation is silent; maintenance is minimal; the motor is extremely rugged; control and installation are simple.

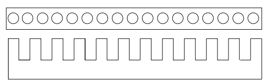
LIM output power depends on size and thermal rating. Operating speeds vary from nothing to many metros per second and are determined by both design features and supply frequency. Speed is easily controlled, whilst starting, stopping, and reversing are also straightforward.

The LIM is a well proven technology ideally suited to PRT application. Motion is independent of wheel friction making the LIM ideal in adverse environments. Either LIM or reaction plate can be fixed whilst the other part moves. Environmental protection can be provided with a non-magnetic stainless steel enclosure.

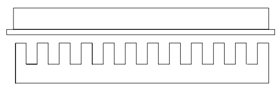
2.1 How Does a LIM Work?



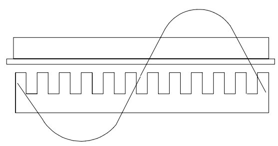
take a conventional squirrel cage
induction motor ……



open it out flat .….



smooth the rotor bars
into a conductor sheet …...



apply AC power
….... and you have a LIM

As the drawings show the LIM is essentially a circular motor opened out flat. The wound stator, which is the part usually known as the LIM, consists of a conventional 3 phase winding in a laminated iron core. When energised from a 3 phase AC supply a travelling magnetic field is produced which sweeps across the flat motor face. Direction is reversed simply by swapping two incoming supply phases.

The ‘reaction plate’ is the equivalent of the rotor. This is usually a flat conductor sheet of aluminium or copper, backed by steel. Currents induced in the reaction plate by the stator’s travelling field create a secondary magnetic field. It is the reaction of these two fields which produces the linear thrust.

2.2 The Choice of LIMs for PRT

Double Sided Vertical Reaction Plate, or Single Sided Horizontal Arrangement?

The LIMs can be arranged in either vertical or horizontal arrangement and there is a choice of double or single sided orientation. From considerations of track and switch mechanical design it becomes obvious that a single sided horizontal motor offers the best practical solution.

Then there is the choice as to whether the LIM stators are fixed or whether they move, with the opposite for the reaction plate. A correct decision depends on details of each application and in the case of PRT many factors have influence e.g. length and speed of travel, power source, control requirements, duty cycle and cooling, weight and space considerations.

2.3 In-Track or On-Board LIMs?

Intelligent Vehicles with On-Board LIMs:

Pros:
- Good speed/position control
- Offers good LIM braking
- Passive track
- Fewest LIMs

Cons:
- Power supply to vehicle
- LIM & controller weight penalty
- LIM cooling required
- Full length reaction plate

Passive Vehicles with In-Track LIMs:

Pros:
- LIMs & power supply fixed
- Minimum vehicle weight
- Low duty cycle – no LIM cooling
- Extra LIMs at inclines etc
- Short reaction plates
- IPT possibilities

Cons:
- Inferior speed/position control
- More LIMs & controllers needed
- Vehicle position sensing necessary
- Inferior LIM braking

These arguments are reasoned as follows;

2.3.1 LIM Size & Weight

Making some initial assumptions about the vehicle performance a LIM approx. 160-180kgs would be required to provide the necessary thrust. Together with a controller this would add 200-250 kgs to the vehicle. Since the aim is a lightweight and efficient vehicle this weight is prohibitive. Space will also be at a premium so eliminating the volume required for LIMs and control packages is a valuable gain. Obviously weight and volume are not important for an in-track drive.

2.3.2 Drive Redundancy

An on-board drive would be divided into two independent parts to allow for redundancy. In the event of a single drive failure the vehicle could still function although with degraded performance.

With in-track LIMs, redundancy is automatically implied since the vehicle would pass over one failed LIM to the next, albeit at a reduced performance.

2.3.3 Worst Case Loads

An on-board LIM must have sufficient drive capability to meet the worst-case demands. So if there is a steep gradient or strong headwind at only one point on the track the on-board LIM must be designed to cope with this, however rarely this capability may be required.

But with in-track motors this situation is more easily solved since more LIMs can be added at more demanding locations or more powerful LIMs fitted at some points.

2.3.4 Vehicle Control

Optimum control is only possible when the vehicle is under power at all times. This is most easily achieved with an on-board LIM. However, if in-track LIMs are spaced no more than one car length apart then the vehicle is also under control at all times. Obviously many more in-track LIMs are require than if on-board LIMs were fitted.

2.3.5 Duty Cycle Rating

In-track LIMs are only energised when a vehicle reaction plate is covering them, so they are in practice turned off more than on. This means the motor can be short term rated allowing a smaller, lighter and less expensive design to be used.

On-board LIMs have to be rated for continuous operation which requires the installation of external cooling systems such as fan blown heatsinks or recirculating water coolers.

The duty cycle rating of a LIM is fixed by its internal winding losses. If natural heat loss is not sufficient to keep it below its maximum operating temperature (150C) then passive heatsinks can be added, or fans can be added for forced air cooling.

2.3.6 Reliability

From a reliability viewpoint the simplest concept is to locate the LIMs in-track. If LIMs are fixed on-board then any failure of even a single LIM might disrupt the whole system. But failure of an in-track LIM would simply means the vehicle ‘coasts’ until it reaches the next LIM, where control is resumed.

2.3.7 Reaction Plates

The reaction plate is a simple construction of sheet steel faced with sheet copper or aluminium. This can be protected environmentally in any conventional manner.

For on-board LIMs the reaction plate must span the full length of the track. This is not an inconsiderable engineering challenge.

With in-track LIMs a short reaction plate is mounted on the vehicle. In order to retain vehicle control the length of this plate determines the spacing of the in-track LIMs. Reaction plate assemblies are relatively light and inexpensive.

2.3.8 Power Supply

The power supply to in-track LIMs is simply a hard wired cable. This connects a standard 3 phase industrial supply (400v 50Hz or 480v 60Hz) to the LIM/controller at a convenient terminal box. There are no moving parts and nothing to maintain.

Power supply to a moving vehicle is much more problematic. The choice lies between conventional sliding contacts, overhead pantograph, live rails, wheel driven generators, or Inductive Power Transfer (IPT). Most of these suffer some disadvantage, so any choice for on-board power is a compromise between power required and maintenance costs.

IPT at useful power levels is not currently available commercially but could be developed using the in-track LIMs to generate power on-board the vehicle. This requires separate study and a development program.

2.3.9 Emergency Braking

LIMs can be used as brakes as well as drives but emergency braking poses heavy demands on the system design whether the LIM is on-board or in-track. And it can only work if power is guaranteed to be available at all times. For braking the LIM would have to be larger than required for normal drive and the current required for full braking would be high. All inverters would also be larger than otherwise required. If all vehicles had to brake synchronously the electrical demand on the system power supply could be a problem. From consideration of these issues the conclusion was therefore quickly reached that mechanical brakes would be preferable for emergency stop situations. LIMs can still provide trim braking and emergency brake assistance if necessary.

2.3.10 Safety Issues

LIMs are totally passive. They do not generate audible or electric noise. Electric and magnetic fields are localised and only present when the motor is energised and neither is significant. There is very little stray magnetic field and this need be no concern for operational issues.

Control system failure is probably the main safety concern and this must be taken care of by careful software/hardware design.

2.3.11 Maintenance

Depending on local Health and Safety restrictions it is possible that a damaged or failed LIM could be removed and replaced from below the guideway without serious interruption of operations. The LIM controller would be mounted remotely and could probably be replaced without major disruption.

2.3.12 Control System Simplification

With in-track LIMs the necessary communication between guideway and vehicle is minimised resulting in a safer and more reliable operation. Signal communication between the LIMs and control equipment can be via fibre optic cables which are insensitive to electromagnetic interference, however caused.

2.3.13 Environment

For outdoor application LIMs can be sealed in stainless steel enclosures for complete weather protection. Waste heat from both LIM and reaction plate will eliminate snow and ice problems, though considerable care must be taken to dispose of any resulting water. This must be done for personnel safety reasons and also to eliminate any corrosive effects on structural components.

From these fundamental issues it was concluded that in-track LIMs were the preferred solution for the PRT system.

2.4 Vehicle Speed Control

2.4.1 Speed Measurement

The LIM stator winding has no awareness of the position or speed of the reaction plate. Hence vehicle speed, position, and travel direction must be determined from feedback devices monitoring the vehicle performance.

On-board wheel driven tachometers are possible, with signal transmission back to the ground via radio or similar. In-track proximity sensors can be used with a 'bar code' or other grid mounted on the vehicle to provide a signal hard wired to the local controller.

2.4.2 LIM Power Control

The advent of mass produced and reliable inverter drives for rotary motor applications provided the cost breakthrough in LIM control. However, it has been found that conventional control algorithms used for rotary motor control are not optimum for LIMs. With a LIM the voltage and frequency should be controlled independently. Many standard inverter drives use a 'fixed' voltage-to-frequency ratio and are therefore not suited to LIM drives.

With a LIM the drive frequency is used to vary synchronous speed and 'slip' to ensure the LIM is operating at minimum current consumption at all times. Drive voltage is used to control thrust and hence actual speed.

2.4.3 Control Inverters

Force Engineering's preferred supplier for inverter drives is currently Control Techniques. Force and CT have worked closely on many LIM applications with good commercial success. As a result there is a close understanding between Force's designers and CT's application team. However, Force is open to any other potential supplier who might offer cost effective drives in high volumes.

Sensor feedback signals can either be fed directly to an intelligent drive or, after being processed by plc/pc can be fed to a non-intelligent or 'dumb' inverter. The choice depends on numbers of drives and complexity of the system.

LIMs operate with power factors in the range 0.5 to 0.7 but the low p.f. is automatically corrected by the inverter, which draws current at 0.98 p.f. from the supply.

LIMs do not generate EMC interference, providing that a clean power source is used and that screened cables are used. A 'clean source' is an inverter with sinewave output filters. These are commonly available.

2.5 Station Area Drives

The LIM drives within the station areas may take several forms. Accelerating from rest we need maximum thrust at low speed, moving toward the merge point where the vehicle must be travelling at the same speed as the main line. This can be achieved optimally by having more than one LIM designs as accelerators. Inverter amps and therefore cost can thus be minimised.

2.5.1 Permanent Magnet Braking

Permanent magnet brakes are totally passive and failsafe. They are not controllable, other than by increasing the airgap by physical movement (as used in roller coasters). Their operating lifetime is practically unlimited, providing they are correctly manufactured and protected against corrosion etc. Stainless steel covers can be used as with LIMs.

A permanent magnet brake works on the eddy current principle, in a similar way to a LIM. However, eddy currents are only induced when there is relative motion, which means a permanent magnet brake is not effective at very slow speeds and cannot bring a vehicle to an exact halt. They cannot be used as parking brakes.

The objective is to ensure that a fully loaded car will stop at, or before, the station. This means that a lightly loaded car would stop well before the station, requiring that LIMs will also be needed (between the brakes) to ensure all cars are driven under control to their final station position.

2.6 On Board Power – IPT/Wheel Generators

It should be technically feasible to induce power from in-track LIMs to a wound rotor on board the vehicle – i.e. Inductive Power Transfer. This topic requires further research and development and could not be made available in time for the test track implementation.

But power can be generated on board the vehicle from wheel driven alternators. This energy has to be derived from the vehicle’s motion and hence adds to the effective friction or drag. Required LIM thrust is increased by this factor.

2.7 Headwinds

Drag due to headwinds is by far the largest component of force required to drive the vehicle. Sine all installed equipment has to be rated in terms of maximum force this is directly reflected in equipment costs. Hence a careful decision has to be made between maintaining operational performance in high winds, which may only occur infrequently, versus capital cost of the installed drives.

2.8 Vehicle Platooning

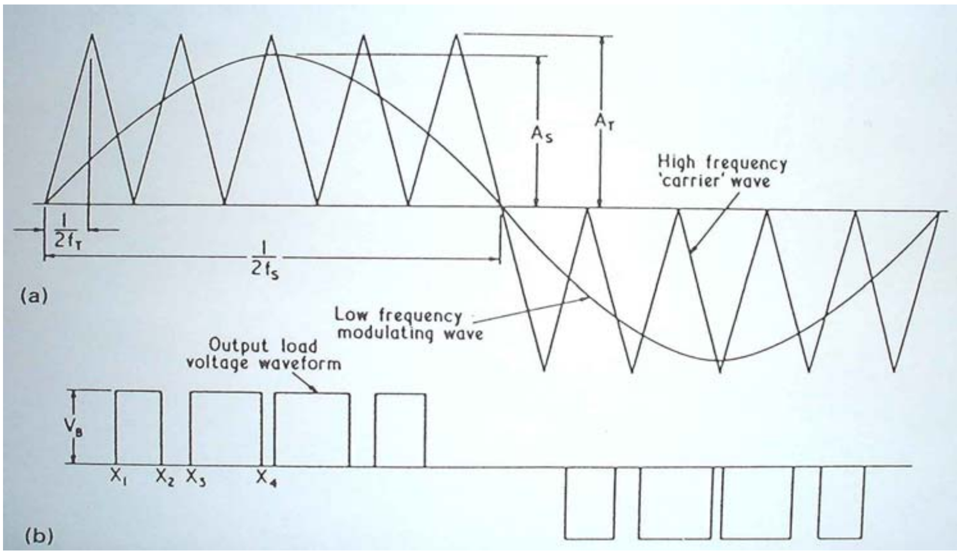
It has been accepted that adjacent LIMs within a certain zone could be fed from separate inverters in a 'leap-frog' manner. This would reduce the overall inverter cost but requires a switching device on the output of the inverter which may not be readily available commercially.

But if inverters can be purchased economically in large volumes the ideal solution is to power each LIM from its own inverter. This allows complete freedom of operation, including vehicle platooning when desirable.

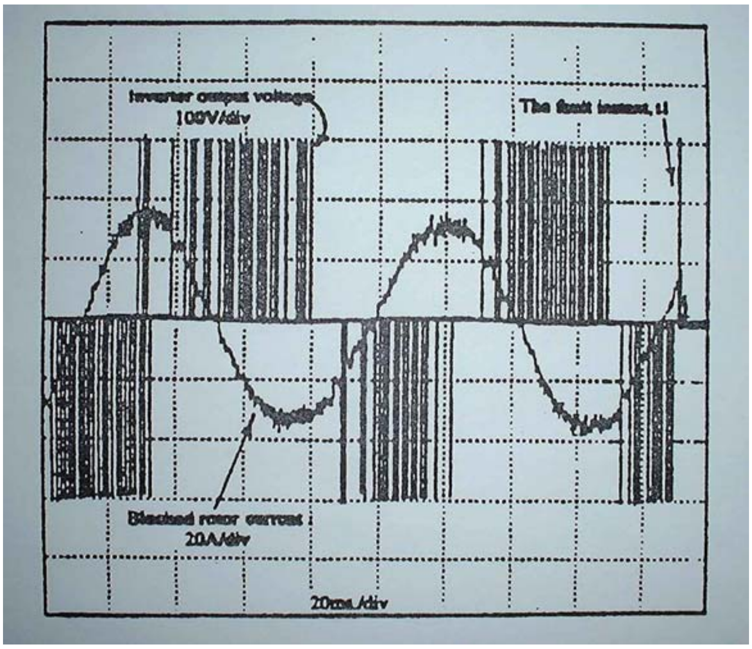
3 Basic Principles of Inverter Drives

Inverters convert the fixed frequency utility supply to another frequency chosen by the user. They are commonly employed as 'electronic gearboxes' so that fixed speed induction motors can be used as variable speed drives.

The inverter works by rectifying the fixed-frequency fixed-voltage ac supply to dc energy. This energy is 'stored' in a high voltage 'link' capacitor (similar to a battery) which also acts as an input/output buffer. The inverter converts this dc energy to a variable frequency, variable voltage ac output. It uses semiconductors to switch dc in small pulses of varying time span, in order to 'fabricate' an ac signal. This is called PWM (Pulse Width Modulation).



The most common semiconductors used are IGBTs (Insulated Gate BiPolar Transistors) which switch on and off at a rate between 3kHz and 12kHz. PWM waveforms result in a motor current as near to the ideal sinewave as possible - although the voltage waveform is far from sinusoidal.



The inverter's output voltage can be the same or less than the input voltage, but not higher. Because the dc link capacitor can only draw 'real' power from the supply an inverter's input power factor is almost unity. Input voltage with a 50Hz 3 phase supply is usually 400v (Europe) but 480v with 60Hz (USA). The same power requires less amps at the higher voltage.

3.1 Reversing Travel Direction

In a 3 phase inverter the 'phase separation' between the 3 output phases is maintained at 120 'electrical degrees', but the phase 'rotation' – i.e. forward or backward – can be changed at any time by altering the switching sequences. So the inverter can reverse a motor very quickly. Internal protection circuits prevent damage to the inverter and motor load.

Since the IGBTs are designed to switch very frequently (3-12kHz) the effects of turning the motor on and off are insignificant. Hence energising the LIMs as a car passes every few seconds will have no effect on the operating lifetime of the inverter.

However, an inverter must not be left running without an output load. So it is not possible to switch from one motor to another without first turning off the output. This does not mean the inverter is 'powered down', only that the output voltage is temporarily removed.

3.2 Transistors and Thyristors

Before IGBTs were available most early inverters were based on thyristor technology. Thyristor inverters are no longer fashionable but would be more useful in our application because a thyristor has a high current overload capability. An IGBT cannot be overloaded whereas a thyristor can carry 500-600% rated current for a brief, but useful, period. The difference is a function of semiconductor physics and internal device heating.

3.3 LIM Switching

A linear induction motor is designed for very frequent stop/starts. Most rotary induction motors have an initial switch on transient current around 500-600% full load current. This limits the number of effective starts per hour. But the relatively large airgap of the linear motor means the switching transient is much less significant. Since the LIM is designed for short term operation, frequent switching of LIMs does not present a problem.

Also, regular on/off switching does not shorten the LIM's expected life although the motor insulation system has to be carefully designed for long term operation with inverters. Force is aware of LIMs that have been in regular commercial use for more than 25 years.

3.4 Inverter Speed Control

For 'intelligent control' Force supplies a modified Control Techniques UNIDrive configured for LIM operation with a UD70 pre-programmed control module. Where external processing power is available the simpler and cheaper Commander can be utilised.

Consider the problem of 2 adjacent vehicles. For a speed of 10 m/s and a headway of 2 sec the car separation is 20m. Assuming a speed holding of ± 1%

Maximum speed	= 10.1 m/s	– say this is the following car	
Minimum speed	= 9.9 m/s	– say this is the leading car	
Closing speed	= 0.2 m/s	– following car catches up leading car	
Time to touch	= 20m/0.2m/s	= 100 seconds	≈ 1.67 minutes

Even at 12.5m/s and 3 sec headway the time to touch is still only 2.4 minutes. This is obviously unacceptable, especially as a speed holding of ± 1% may not be achievable. Hence a control system based on the speed control alone is not viable for this application.

A position control system is required to maintain a controlled gap between adjacent cars. This requires a series of position sensors, a position demand signal, a closed loop position amplifier and a power drive stage for each car.

With in-track LIMs the power drive stage must be located in-track. To reduce data transfer between car and fixed equipment the best location for the position amplifier, the position demand signal and the position sensor is also in-track. The power drive stage is an inverter. If the inverter has enough spare inputs and processing power, and is sufficiently programmable, it is possible to make the inverter perform the major part of the remaining tasks. This requires a complex and probably more expensive inverter than one that would only be capable of providing the power drive stage. But this complex inverter would not require any additional controller.

Each LIM must be fed from an inverter, but a correctly sized or correctly switched inverter may power more than one LIM. Each motor must only be powered when covered by a vehicle.

If the system is configured so that an inverter can power more than one motor, it must be arranged so that it cannot drive motors that are thrusting different cars. As each car can be slightly out of position, we must ensure that at least one LIM behind the car is powered from an inverter assigned to drive this car.

Switching the outputs of active inverters is not recommended by manufacturers (see notes below). The switching of inactive inverters is possible with a conventional mechanical contactor, but unknown with a solid state contactor. However, mechanical contactors are unacceptable because of their limited life. This means that any switching of the inverter output must use a solid state contactor, and this might have to be a very special device. Quoted inverter output 'enable' and 'disable' times are sufficient to allow the output to be disabled between switching (160ms available if two inverters per group used). For this application the inverter outputs would have to be switched at a rate of once every 2-3 seconds. The position sensor needs to be capable of determining direction of motion in order to detect a vehicle rolling backwards. Appropriate action can then be taken.

3.5 Extract from Control Techniques Unidrive Inverter Manual

Output Contactor

If the cable between the drive and the motor is to be interrupted by a contactor or circuit breaker, ensure that the drive is disabled before the contactor or circuit breaker is opened or closed. Severe arcing may occur if this circuit is interrupted with the motor running at high current and low speed.

A (mechanical) contactor is sometimes required to be fitted between the drive and motor for safety isolation purposes. The recommended motor contactor is the AC3 type.

Switching of an output contactor should only occur when the output of the drive is disabled. Opening or closing of the contactor with the drive enabled will lead to:

1. OI.AC trips (which cannot be reset for 10 seconds)
2. High levels of RFI noise emission
3. Increased contactor wear and tear

Drive Enable input:

Sample period	Enable function PWM switching frequency dependent 5.5ms for 3, 6, & 12kHz 7.4ms for 4.5 & 9kHz Disable or trip function 1ms

From Control Techniques Application Department:

Product support engineers have no experience of switching inverter output with a solid state device. They are concerned whether a solid state device can allow for the very high frequency switching of an inverter output.

In more general terms, when using a conventional contactor, the contacts must be closed whenever the drive is enabled. This is typically done with an auxiliary contact on the contactor, in series with the drive enable input, which is late-make, early-break.

3.6 Permanent Magnet Eddy Current Brakes

Permanent magnet eddy current brakes can be used to slow down the vehicle after leaving the switch in an entirely fail safe manner without using external power. The kinetic energy of the moving car is dissipated as heat in the reaction plate.

3.6.1 Brake Specification:

Reaction plate:

Thickness	4 mm
Resistivity	1.8 x 10^{-8} ohm-m (copper)
Clearance gap	5 mm
Length	3 m
Width Conductor	300 mm
Width Backiron	150 to 200 mm

Mass to be decelerated:

Without passengers	600 kg
With passengers	1050 kg
Entry velocity to brake section	10 m/s
Braking distance	25 m
Max. deceleration horizontal	0.2 g (1.96 m/s/s)
Pitch of brake units fit between LIMs	2 to 2.5 m approx.
Pitch of LIMs	3 m approx.

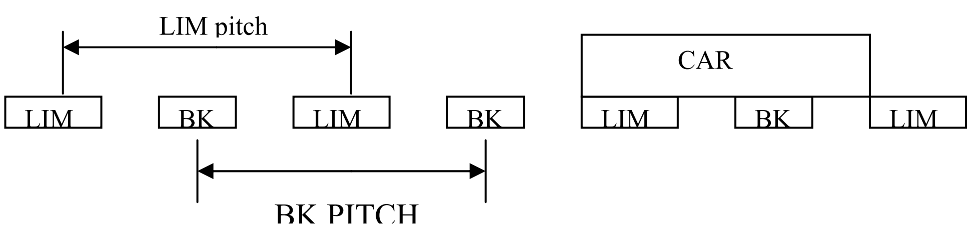


Fig 1

It may also be necessary to maintain a constant velocity down an incline if the power fails. Incline might be 1:50 or 1:20

Max. Deceleration Incline 0.2 g (1.96 m/s/s)

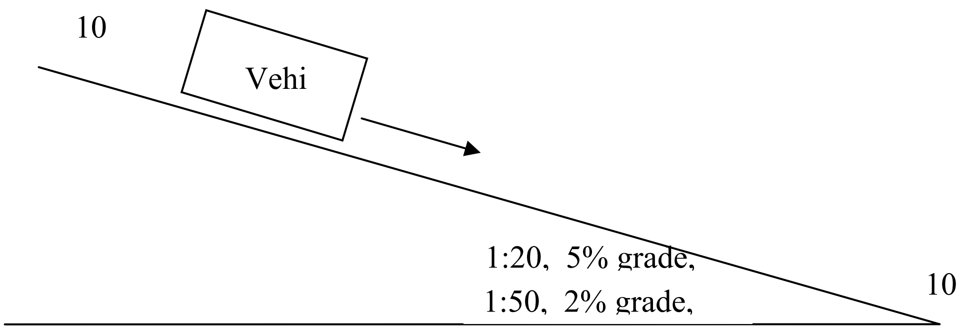


Fig 2

3.6.2 Average Braking Force on Horizontal

From the above values we can check the braking distance:

V^2 = U^2 +2 a S and S = (-10)^2 / (2 x -1.96) = 25.5 m

Average braking force = 1050 x 1.96 = 2058 N. This assumes friction is initially ignored.

It may not be possible to maintain a constant braking force, because of following;

1) The shape of the brake force/speed characteristic, see typical curve in Fig 3
2) The spacing of the motors and brakes, see Fig 1

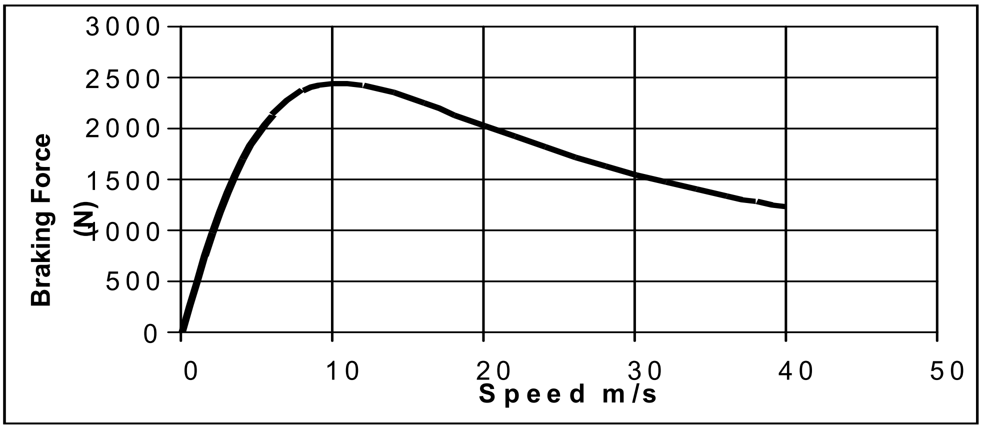


Fig 3

By using four different brake designs with different force/speed characteristics it is possible to reduce the vehicle speed from 10 m/s to approx. 1.6 m/s in 28 m of travel. See Figs 4 and 5. It may be possible to improve this performance with further study.

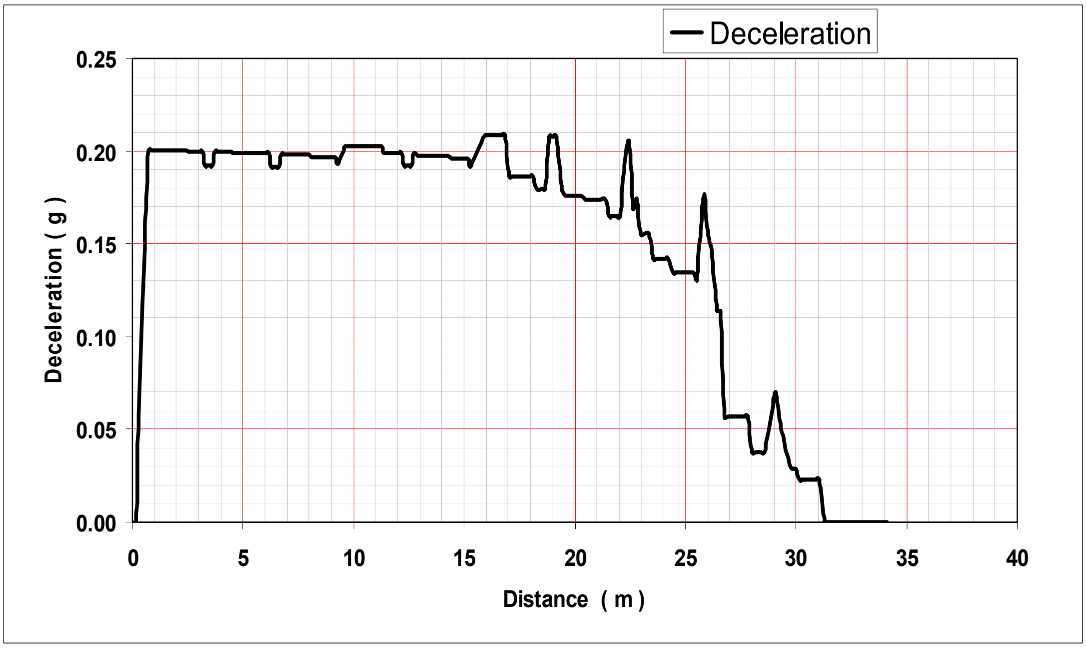


Fig 4

Fig 5

Ten brake units as shown in Fig 6 will be required to achieve the performance shown in Figs 4 and 5. Typical size of each brake unit is 67 wide x 518 long x 38 mm thick. Weight per brake unit approximately 13 kg.

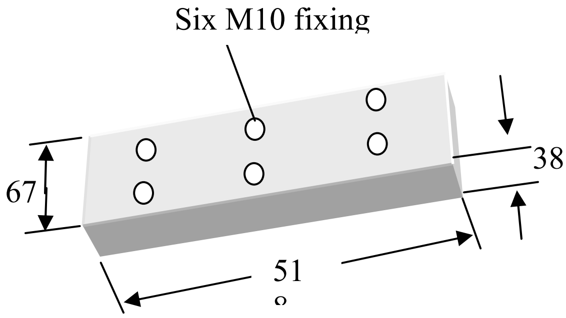


Fig 6

Budget Price: One off magnet brake unit £ 800 each

3.6.3 Average Braking Force on Incline

For a 2% gradient (1:50)
force due to incline = m x g x sin θ = 1050 x 9.81 x sin 1.15 = 206 N

To maintain the velocity at 10 m/s a braking force of approximately 206 N will have to be applied to the vehicle, if friction is initially ignored.

If friction is 2% (approx. 206 N) and included then brakes should not be required.

But if the slope has a 5% gradient (1:20) then a braking force of [(1050 x 9.81 x sin 2.86) – 206] = 308 N will be required.

The velocity down the slope can be limited to approximately 10 m/s if one brake unit as shown in Fig 7 is fitted every 5 m along the incline. Typical size of each brake unit is 67 wide x 174 long x 38 mm thick, weight per brake unit approximately 5 kg.

Budget Price: One off magnet brake unit £ 350 each

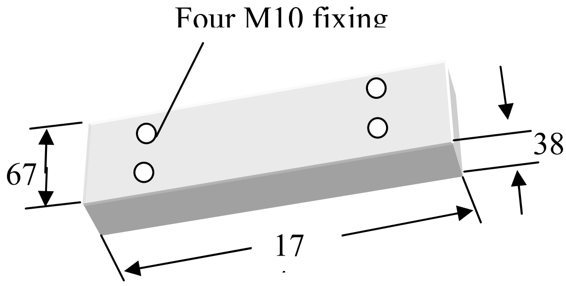


Fig 7

The speed variation as the vehicle rolls down the incline is shown in Fig 8.

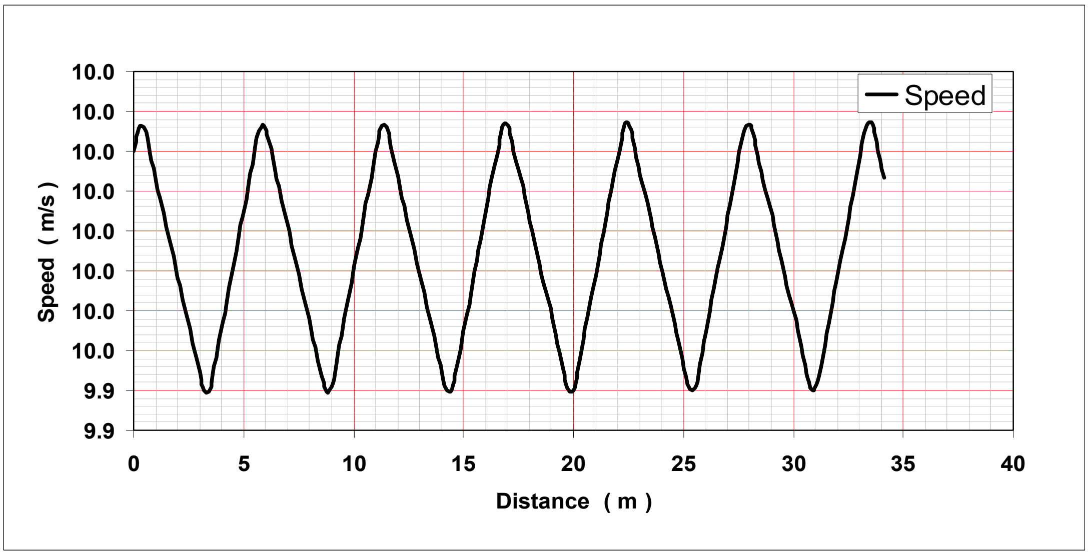


Fig 8

Braking Conclusions:

Permanent magnet eddy current brakes are a reliable and fail safe way to control vehicle speed, both decelerating into the station areas and on a long decline.

3.7 Operation of LIMs with Inverters

3.7.1 Cruise LIMs

Using max LIM current of 60amps and a 'group' of 8 LIMs in all cases.
All prices based on 1,000 per year quantities.

Option 1 1 Dumb Inverter per LIM

Inverter & filter	=	£1,500	require 8	=	£ 12,000
Group controller	=	?	require 1	=	?
			Total	=	£ 12,000 + Group Controller

Option 2 2 Dumb Inverters per Group

Inverter & filter	=	£1,500	require 2	=	£ 3,000
Output filter	≈	£250	require 2	≈	£500
SSC	≈	£100	require 8	≈	£800 (component cost)
Group controller	=?		require 1	=	?
			Total	=	£ 4,300 + Group Controller

Note: This system loses flexibility since the group of LIMs can only work as one block.

The technique of switching inverter output by solid state contactors is not approved by the inverter manufacture and will require further investigation.

Option 3 1 Smart/Intelligent Inverter per LIM

Inverter & filter	=	£2,000	require 8	=	£ 16,000
			Total	=	£ 16,000 + Group Controller

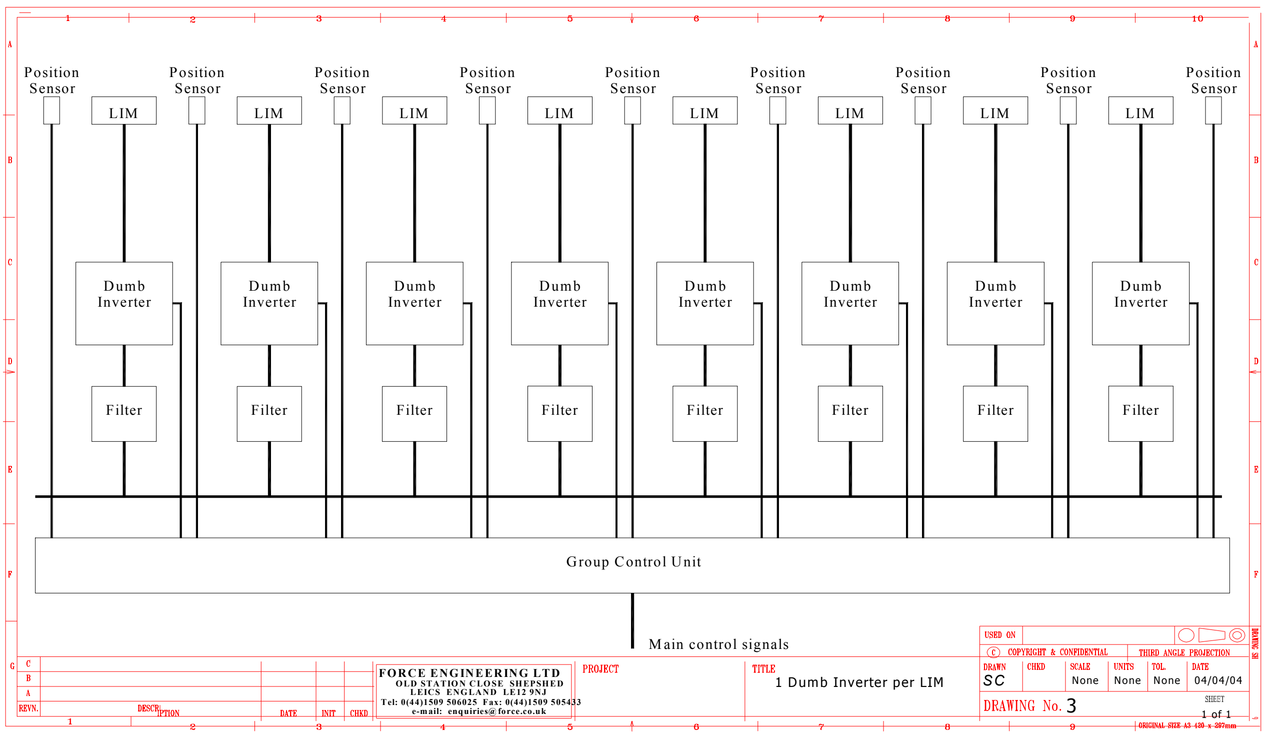
Note: The viability of interface between inverter and position sensor needs to be investigated. The number of items connected to the main control bus is larger than before. Data flow between the inverters in a group also increases the demands on the control buss.

Option 4 2 Smart Inverters per Group

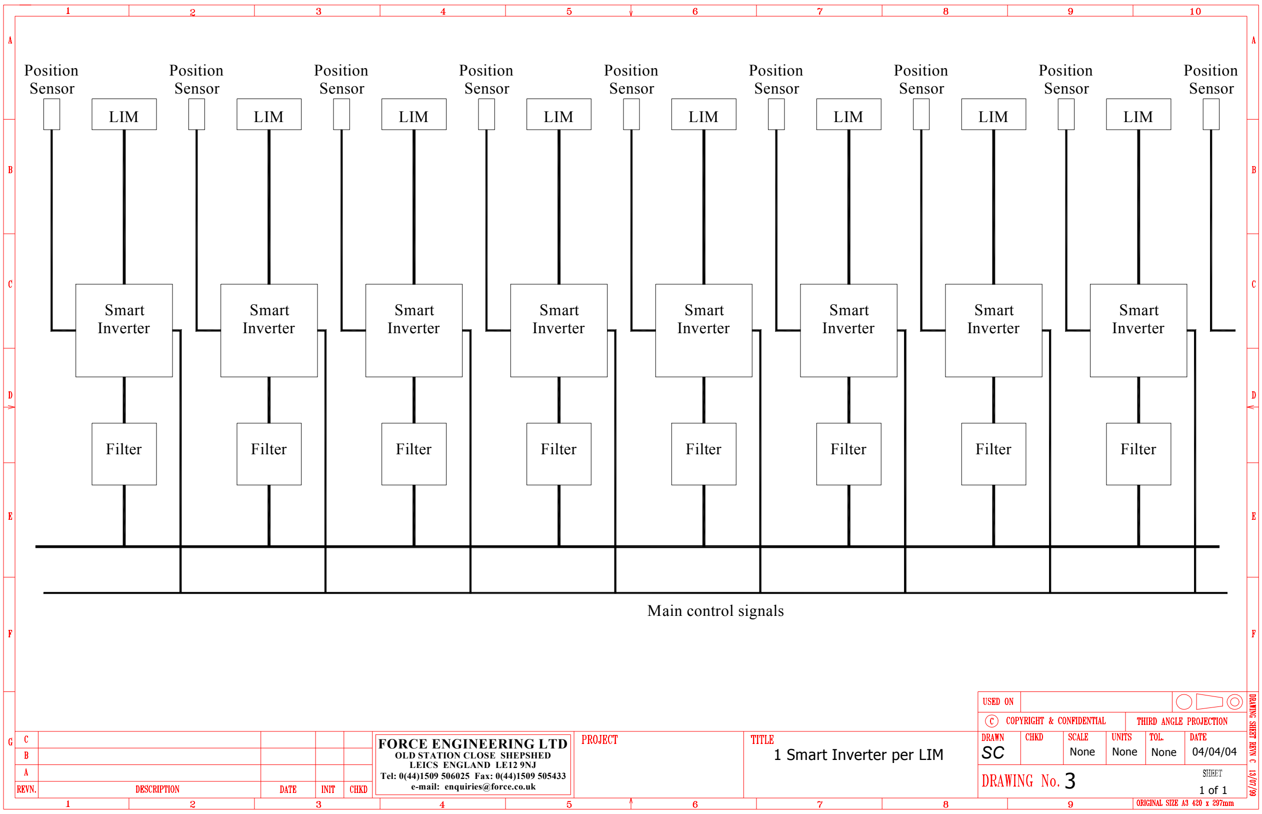
This option is not viable because the inverters do not have sufficient inputs to accept the signals from 8 position sensors, nor enough outputs to switch the SSCs. A group controller would still be required. Thus cost would be higher than option 2 but would have no advantages.

4 Accelerator LIMs

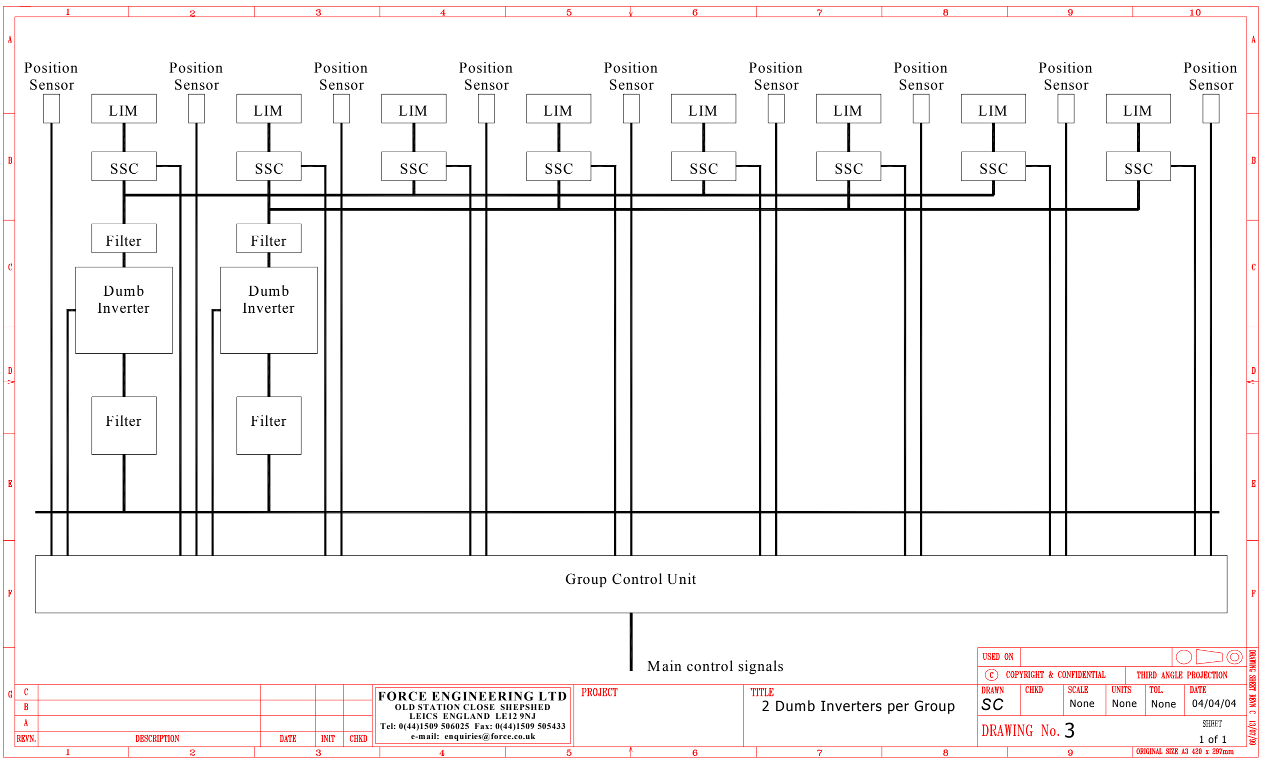
Similar results apply although a larger 70amp drive is needed.



1 'Dumb' Inverter per LIM



2 'Dumb' Inverters per Group



1 'Smart' Inverter per LIM

Practical LIM Designs:

4.1 Drive Specification

1. Station area – accelerate 1050kg at 0.25m/s/s from rest to 12.5m/s at merge.
2. 12.5m/s high speed loop – little or no acceleration capability.
3. Decelerate from 10 or 12.5m/s at switch to rest at station.

4.2 Station Accelerator

In order to minimise inverter current (and hence cost) we will ideally need 2 designs of accelerator LIMs. The required performance can be achieved using 70 amp drives operating from a 400v supply.

The reaction plate conductor can be aluminium or copper. Since copper is a better electrical conductor than aluminium we can use a thinner copper sheet for the same thrust. Any reduction in conductor thickness reduces the ***total*** airgap (i.e. conductor plus running clearance). The LIMs have been designed using 1.5mm copper with a reduction in inverter current and increased efficiency.

4.3 LIM Duty Cycle Requirements

A LIM is only energised when sensors indicate the vehicle is present. If the LIM is turned 'on' as the plate front edge is detected and turned 'off' as the trailing edge leaves the total 'on time' is estimated as follows;

on time = (plate length + 2 x LIM length)/velocity

so for a 1m 'cruise' LIM and 3m reaction plate at 12.5m/s the 'on time' is 0.4sec.

The 'off time' depends on how soon the next vehicle comes along. If a vehicle passes once every 3sec then cruise LIM rating is 0.4/3 = 13.3%.

For a car accelerating from rest the LIM 'on time' is 1.5sec and if a car is launched once every 20sec then station LIM rating is 1.5/20 = 7.5%

4.3.1 LIM & Inverter Sizes:

If only one LIM design is used the inverters will be unnecessarily large and expensive. At full speed we want to use the inverter at say, 60-80Hz, and full volts. This means at low speed we would need to reduce both frequency (15-20Hz) and voltage, which implies a high current. This is an ineffective use of the inverter since their cost is a direct function of output current. Hence motor amps should be kept as low as possible to minimise system cost.

To do this we will almost certainly need at least three different LIM designs; two for station acceleration and another for full speed. This enables us to use a low speed LIM working at full volts and lower amps – hence cheaper inverters.

A consequence of this decision is that if a vehicle has to be started from rest on the main line the available acceleration will be lower than in the station area.

4.3.2 Full Speed Drive LIM

The reaction plate chosen is commercial grade copper sheet 1.5mm thick by 300mm wide and 3m long (or 2 pieces each 1.5m long). This is backed by 10mm of mild steel (width need only be 150-200mm). Recommended clearance gap is maximum 5mm.

If we assume no acceleration at full line speed the required thrust is the sum of friction, wind drag, and gradient components.

WGH estimate friction at 235N (2% of mass). A 1 in 50 gradient component also adds 235N, and wind drag at 15m/s headwind is estimated at 650N. To generate 1kW on board from wheel driven generators adds a further 150N load. Hence total thrust = 1,270N.
(Note that 52% of this load is due to headwinds.)

For 1,270N at 12.5m/s we need approx. 54amps per LIM at 400v 3ph.
Rating for this design is 16% ED. Vertical force on reaction plate is 2kN attractive.
Max inverter output rating = 400v x √3 x 54 amps = 38kVA
LIM power factor = 0.7, so inverter power = 38kVA x 0.7 = 27kW.
Inverter input = 40A at 400v 50Hz 3 phase (0.98pf)

A typical LIM is approx. 1080mm x 240mm wide x 80mm deep x 82kg. IP67 construction

Budget cost:	in small quantities	£ 1,800 each
	in reasonable quantities	£ 1,350 each
	minimum, in mass produced quantities	£ 900 each ??

A typical intelligent or 'smart' 60A inverter is CT's UNI3404 approx. 365 x 375 x 360mm, 23kg with UD70 module, input & output dV/dt filters (filter dims/weights to be confirmed)

Budget cost:	in reasonable quantities	£ 3,200 each
	in larger quantities	£ 2,500 each??

A typical 'dumb' 60A inverter is CT's SE53403000 approx. 365 x 375 x 360mm, 22kg with input & output dV/dt filters (filter dims and weights to be confirmed)

Budget cost:	in reasonable quantities	£ 2,200 each
	in larger quantities	£ 1,750 each ??
	minimum, direct factory cost	£ 1,250 each ??

4.3.3 Accelerator LIM(s)

Leaving a station we assume full acceleration from 0m/s up to 5-6m/s. Then we move to a second LIM design up to full line speed (before merge). Friction is included but no allowance is made for gradient or wind drag.

Max acceleration =2.5m/s/s. Hence for 1050kg vehicle we need 2,625N accelerating force. Friction at 235N as before, so total thrust required = 2,860N.

For 2,860N at 0m/s we need around 70amps per LIM at 14Hz 210v 3ph increasing to 30Hz and 400v at 5m/s. The 2nd LIM draws 70 amps at 36Hz and 300v from 6m/s up to 400v and 55Hz at 12m/s.
Rating for a typical design is at least 10% ED, which should be adequate.
Vertical force on plate is a max of 5kN attractive, falling to 2kN at full speed.
Required inverter output rating = 400v x √3 x 70 amps = 49kVA
LIM p.f. = 0.75 average so inverter power = 49kVA x 0.75 = 36kW.
Inverter input = 55A at 400v 50Hz 3 phase (0.98pf)

LIM is approx. 1080mm x 260mm wide x 80mm deep x 85kg. IP67 construction

Budget cost:	in small quantities	£ 1,850 each
	in larger quantities	£ 1,400 each
	minimum, in mass produced quantities?	£ 900 each ??

A typical 'smart' inverter is CT's UNI3405 approx. 365 x 375 x 360mm, 23kg
with UD70 module, input & output dV/dt filters (filter dims and weights to be confirmed)

Budget cost:	in small quantities	£ 3,700 each
	in reasonable quantities	£ 2,950 each ??

A typical 'dumb' inverter is CT's SE53403700 approx. 365 x 375 x 360mm, 22kg
with input & output dV/dt filters (filter dims and weights to be confirmed)

Budget cost:	in small quantities	£ 2,560 each
	in reasonable quantities	£ 2,000 each ??
	minimum, direct factory cost	£ 1,500 each ??

5 Test Track Equipment

According to the WGH test track layout 244 LIMs are to be installed in total. Of these approx. 30 are in the station area and 214 are main line 'cruise' LIMs.

The station area itself consists of at least two LIM types. As described previously there are two designs for the acceleration of the vehicle from rest to the merge point, and there is a further design used in the deceleration zone following the switch.

The deceleration zone includes both permanent magnet brakes and LIMs so that a fully loaded vehicle will always stop short of the platform and then be driven, under LIM control, to a positive and definite stopping position. When an empty or lightly loaded vehicle approaches the station it will stop much sooner than a heavy vehicle. Since it is possible for any vehicle to be brought to rest at any point there must be LIMs all along the station deceleration zone.

It has been assumed that magnetic brakes occupy 25m of deceleration zone spaced at 3m intervals between the deceleration LIMs.

Test Track Drive Inventory:

LIMs

Cruise LIM	214 required
Station LIM 1	15 required
Station LIM 2	15 required

Eddy Current Magnetic Brakes (for station deceleration only)

Station brake	10 required

Control Techniques LIM Drives

SE53403000 380/480v 50/60Hz 30kW incl. RFI input & sinewave output filters	214 required
SE53403700 380/480v 50/60Hz 37kW incl. RFI input & sinewave output filters	30 required

6 Conclusions & Recommendations

The arguments for and against in-track and on-board LIMs concluded that in-track LIMs offer the best solution for a PRT system. This choice results in a simple unintelligent and reliable vehicle and a more complex, intelligent but passive guideway.

The options for inverter control of the in-track LIMs depend on what is required for operational convenience. If synchronous control is acceptable and vehicle platooning discounted then it might be possible to reduce the numbers of inverters by switching them between LIMs. Hardware costs would obviously be reduced.

If asynchronous control is required, and platooning thought to be eventually desirable, then each LIM must have its own individual control inverter. Naturally this increased complexity and flexibility adds to system cost.

However, in the long term it is essential to investigate the possibility for a thyristor based inverter design. If the technology can be made to work the manufacturing cost should be considerably less than for a transistor based drive.

LIMs themselves are presently manufactured in relatively small quantities, almost entirely by manual assembly. If quantities are sufficient it would be worthwhile redesigning the LIM to allow for semi-automated manufacture. In addition, consideration needs to be given to manufacturing the LIMs in areas where labour rates are lower than Western Europe.