Can we reduce the environmental impact of aggregate transport?

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Aggregates are an important resource for the United Kingdom with about 200 million tonnes being extracted from quarries in the UK. Only about 15 million tonnes is moved by rail with most of the remainder being transported by road[1]. Which causes environmental pollution, damage to the road infrastructure and inevitably some deaths. "The aggregates industry is keen to make full use of all modes of transport. In addition, it is important that the transport of aggregates is carried out as efficiently as possible to minimise carbon emissions, and also minimise the impact of transport on local residents."[1] This article will examine the feasibility using a new mode of transport to cost effectively reduce the environmental impact of aggregate transport.

For the majority of the UKs quarries aggregate is transported to the customer via road or rail, only a small fraction is delivered via barges. Where a rail link already exists and the volumes are sufficiently large then rail represents the best delivery option. Based on industry figures a 200Km journey by rail will cost approximately £0.018/Km-tonne[2] and release 15g of CO2 per Km-tonne[3]. The cost of using trucks to deliver the same service will be approximately £0.118/Km-tonne and release about 90g of CO2 per Km-tonne[3]. So trucks are six times more expensive and six times more polluting than trains. The cost of providing new infrastructure for each transport mode is weighted in favour of trucks. The cost of new rail infrastructure is £11M-£12M per track-km[4], while for roads the equivalent cost is £1.5M-£2.0M per lane-Km [4]. So except for the very largest quarries it is not economically reasonable to install new rail infrastructure and trucks will be the preferred option.

One of the reasons that trucks are so much more polluting than trains is that the ratio of cargo weight to vehicle weight is much lower for trucks than for trains. This has a knock on effect in terms of overall energy efficiency. Using government data[5] only about 30% of the energy supplied is used to transport the aggregate, with the remaining 70% being used to move the truck. Each year this results in approximately 1.5-2.0 million tonnes of CO_2 being unnecessarily released into the atmosphere, the financial cost of this wasted energy being of the order of £500M-£600M per annum.

In this article we will consider a mode of transport that has an operating cost similar to that of rail, is not restricted to moving very large volumes, but has capital investment costs that are similar to roads. It is less polluting than either road or rail, as it can use renewable energy sources, and has a significantly reduced environmental impact. Which means that the environmental impact of aggregate transport can be achieved cost effectively.

Other transport systems

The alternative to road and traditional rail systems that have been developed are either small capsules with a set of wheels at either end that can run in a pipe, or small light rail systems again operating within a pipe or tunnel.In both cases the vehicles used are driverless and so public safety issues require that the system is enclosed.

Capsule-pipelines

The idea of using small capsules inside a pipeline to transport freight, and people, is not new. The earliest proposal for moving goods in pipelines appears to be by George Medhurst in about 1810. A practical application was created by Latimer Clark in 1856 with a pneumatic tube connecting the central station of the Electric Telegraph Company to the London Stock Exchange. This simple technology continues to be used worldwide to move small objects over short distances, such as moving cash between tills and a central office in a supermarket.

The first wheeled capsules made their appearance in 1861 with a 30 inch pipe constructed by the Pneumatic Dispatch Company. The technology was found to be too expensive to operate and the system closed in 1874. A new era for wheeled capsules opened in the 1970's with the construction of two large diameter pipe systems with wheeled capsules. In the USA, Tubexpress Systems Inc built and tested a 1400 ft long 36 inch diameter pipe with 7 ft capsules. Figure 1[6] shows a prototype capsule being inspected by the system designer Dr M.R. Carstens.

Figure 1: Dr M.R. Carstens with a 40 inch prototype for Tubexpress at the Georgia Institute of Technology[6].

In the USSR the Lilo-1 system, figure 2, could transport 25 tons of sand and gravel at a time. The system used a 2.1 Km long pipe of 1020 mm diameter within which six capsules formed a single train. Speeds of up to 50Km/hr were reported. A later system Lilo-2 used an 8Km pipe of 1.27m diameter to move 8 millions tons of gravel and sand per year. Both systems are now believed to be closed[7].

Figure 2: The Lilo-1 system in Russia loaded with aggregate[7]

A test system was constructed by BHRA at Cranfield in the 1970s, which consisted of a 550m loop using a 600mm pipe. The longest continuous test was some 7500Km, at the end of which the capsule was not in need of any essential maintenance.[7] A report published by the British Technology Group which examined why the technology had not been taken up concluded that while many industries were prepared to consider pneumatic capsule pipelines, fears about the mechanical reliability of the system, and unknown financial implications deterred any companies from implementing a pneumatic capsule pipeline system without first seeing a real working example[8].

The most successful applications of the technology have been in Japan. Sumitomo Metal Industries built a 3.2Km pipe of 1m diameter in 1980 to transport limestone to a cement plant, figure 3. The system transports over 2 million tonnes each year, and has reportedly achieved an operation rate in excess of 95%. This system is still in operation today[9].

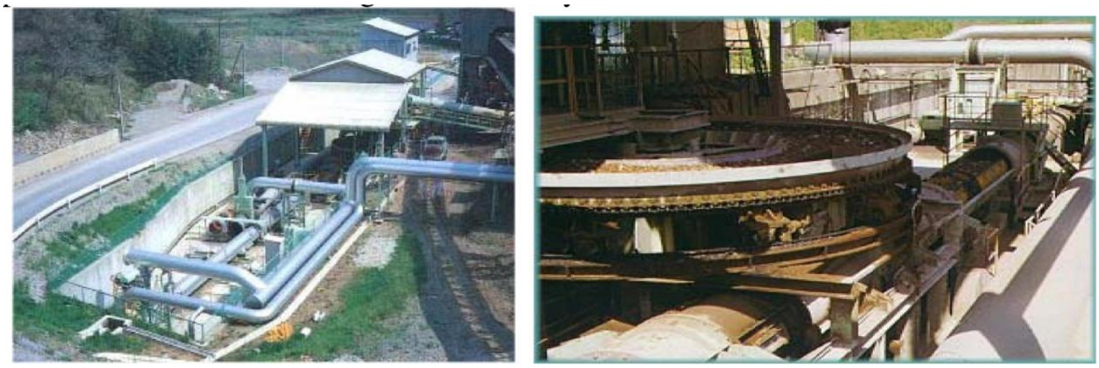

Figure 3: Area view and close up of the capsule loading area of the Sumitomo Metal Industries capsule system[9]

In 1997 the Florida Institute of Phosphate Research commissioned a demonstration project from Magplane Technology Inc for a pipeline capsule system using Linear Synchronous Motors for propulsion. The demonstration pipe was 275m in length and 610mm in diameter, each capsule could carry 300 Kg and achieved a peak speed of 18m/s[10]. The final report, March 2001, prepared by Magplane Technology claimed that preliminary economic studies had shown a satisfactory return on capital. In its conclusions the Florida Institute of Phosphate Research stated that much more testing was needed before the system could be considered as a candidate for commercial operation[11].

Figure 4: Magplane Technology demonstrator capsule carrying 300Kg of phosphate and the linear synchronous motor[10]

Rail based systems

An alternative approach to the capsule pipeline is to use a small railway operating inside a pipeline. An important exemplar of a rail based system for goods is provided by London Mail Rail[12], which opened in 1928 and connected nine stations and moved up to 12 million letters per day before its closure in 2003. The most advanced rail based design currently available is the CargoCap system[13] being developed by Prof. Dr.-Ing. Dietrich Stein at the Ruhr University of Bochum in Germany. This system is based on railed capsules each carrying two Euro-pallets in a pipe of 1.6m diameter, figure 5. The capsules are propelled by a pair of on-board electric motors and controlled by an on-board computer system.

Figure 5: Artist impression of a CargoCap capsule being loaded with two Euro-pallets[13]

A different approach is being applied by Magplane Technology Inc who signed an agreement, in May 2007, to provide a system for the transportation of coal in Inner Mongolia[14]. Their design is a development of the prototype they built for the Florida Institute of Phosphate Research. The design continues to use linear synchronous motors, but the wheeled capsules have been replaced by an overhead monorail[15], figure 6. It is expected that the final system will be able to transport 37 million tonnes per year, a 1 Km test loop capable of handling 5 million tonnes per year is due for completion in 2009.

Figure 6 Capsules for the Magplane Technology Inc coal pipeline suspended from a test track[15]

Design options

In selecting a design for a new system that is cost effective, safe and has reduced environmental impact forces us to consider system enclosed in a pipe. The system will also have to have high reliability and low maintenance. There are four key issues that will need to be addressed:

- Should the basic design be that of a small rail system with rails and trucks similar to the CargoCap system, or should we use wheeled capsules, or can we use the sort of technology used in modern roller coasters where a series of small wheels at different angles to multiple rails control a capsule's location.
- What tyre material should be used, steel as used in most rail systems, rubber compound as used on the Paris Metro and road vehicles, or polyurethane as proposed for a number of light passenger systems.
- What is the best propulsion system, pneumatic blowers at fixed points along the pipeline as used in the Sumitomo Metal Industries system, electric motors attached to each capsule/truck as used in the CargoCap system, Linear Synchronous Motors (LSM) attached fixed to the pipe as used in the MagPlane systems, or Linear Induction Motors (LIM) as used in the most modern roller coasters.
- What to construct the pipeline from, steel as used in the Russian Lilo system, concrete as used in the London Mail Rail, or plastic (polyethylene) which is currently used for water transport.

Clearly not all options are possible, eg steel tyres on a wheeled capsule inside a plastic pipe will not meet the criteria of high reliability as the tyre will quickly wear holes in the pipe.

We are considering the application of this technology to the UK, this means that due to planning requirements the pipeline will almost certainly need to be buried. Preliminary calculations have indicated that to make a system of this nature economic for smaller quarries then the pipeline needs to have a small diameter. The smallest pipeline that we think it would be reasonable for a person to work within for maintenance is 1250mm. So we have used this for all of our designs and calculations.

The advice that we have been given by the rail industry is that rubber compound tyres have a poor wear record and needed replacing at least every 100,000 Km. As this did not fit well with our requirements for high reliability and low maintenance this option was rejected. The rail industry recommended that we use steel tyres in a small rail system. However, rail engineers were concerned about our ability to replace broken rails given the limited access available within the pipeline. Although rail failure would be expected to occur infrequently, it could not be ruled out if we used steel tyres on steel rails. Experience from the design of roller coasters has shown that polyurethane tyres on steel tracks have very good wear characteristics. On test systems it is reported that there is no appreciable wear to be observed in tests of 100,000 Km. We therefore settled on using a polyurethane tyre on either a steel rail or inside a steel pipeline.

A traditional rail wheel has two bearing surfaces, one which contacts the top of the rail and transmits most of the weight. The second surface is the wheel flange that aligns the axel with the rails and guides it round curves. In roller coasters these functions are performed by separate wheels acting on different surfaces within the track. Because a roller coaster track has to support the vehicle and provide the structural integrity as the vehicle moves at high speed through a complex series of manoeuvres the track is quite complex and difficult to construct. For the system we are considering we have been advised by engineers involved in the design of such systems that the four bearing surfaces and the structural elements can be easily formed from strip steel, with the whole assembly resting in the bottom of a pipe. We therefore decided to use roller coaster technology rather than rail technology for the capsule guidance systems. The idea of using wheeled capsules was also rejected as the roller coaster technology was simpler to design, manufacture and maintain.

In figure 7 is a preliminary design for a capsule and the rail system. The figure shows the capsule inside a 1250 mm pipe, which is smaller than the final proposal discussed below. Each capsule is constructed from two identical parts, each of which has two horizontal wheels and two vertical wheels which engage with the rail to support and guide the capsule. The two rails and the support at the base are constructed from strip steel. These rail strips will be manufactured in 12 m lengths and bolted together on site.

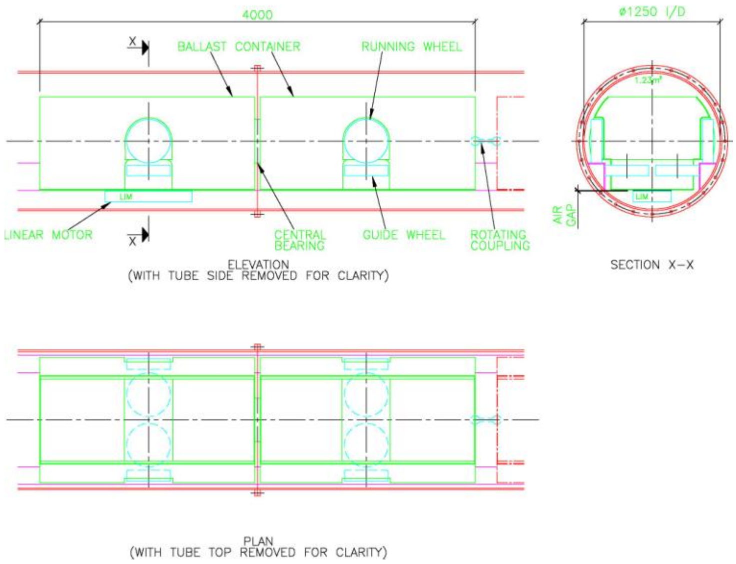

Figure 7: Preliminary design for the proposed capsule system[16].

Having selected the basic elements for the capsule design we were now in a position to choose the material for the pipeline. The roll of the pipeline has by this stage been reduced to keeping the void space open and keeping the water out. All three materials previously suggested are capable of maintaining the void space, although there are some concerns that plastic pipes may deform under applied external stress. Whilst concrete pipes will retain their original shape, they are difficult to seal completely against water ingress. Steel pipes are able to meet both requirements and are regularly used in many applications. However, steel pipes are very expensive to manufacture and to transport to site. We have therefore opted to use plastic pipes of a slightly larger diameter, 1350mm, to allow for possible deformation. It is estimated that plastic pipes will cost only 20% per Km of the cost for steel pipes. This pipe system has the additional advantage that it can be manufactured on site in lengths of 50m, which is four times longer than the maximum length of steel pipe that could have been transported to the site.

The final component is the how the capsule will be propelled forward. The pneumatic approach, which has worked successfully in the Sumitomo Metal Industries system, has the disadvantage that only a small number of capsules can be in the system at anyone time. This severely restricts the maximum capacity of any similar system, and as the pipe becomes longer then the problem gets worse. The option of having an on board motor will require either a battery or a sliding electrical contact within the pipe, the motor itself will also add weight and maintenance issues. This option is therefore rejected as it compromises our objectives of high reliability and low maintenance. The application of either LSM or LIM is very similar in that both are passive motors with no moving parts. In both cases the electrical supply is fixed to the stationary part of the motor. The main difference is that LSM require an array of powerful permanent magnets to be built into the capsule, whilst LIM simply require an aluminium plate. LSM is the more energy efficient system, however it requires a sophisticated control system and it does not cope well with interruptions to its power supply. The biggest problem we see is that the magnets easily capture steel/iron objects, which can easily damage the LSM. In an industrial environment we think that it would be very difficult to ensure that no steel nuts or bolts got attached to a magnet. We therefore have opted to use LIM as the propulsion system for the capsules.

The proposed system will consist of a 1350 mm plastic pipe with a strip steel track assembly in the base. The capsules will be 4 m in length with eight wheels with polyurethane tyres. The drive system will be LIM mounted in the track assembly. Based on data for an airport baggage handling system with 640 LIM which has been operating for eight years, individual LIM have a probability of failure per year no worse than 0.002 . As the LIM in our system will operate less frequently the system should be even more reliable and the LIM are easily replaced. The pipe has an expected life in excess of 100 years and the life of the tyres will be at least one year. The total system will meet our design requirement of being high reliability and low maintenance.

Examples

We have compared and evaluated the proposed system on three examples. The first is based on a requirement to move aggregate from a quarry in Northern England to the nearest motorway, the second is based on a requirement to move aggregate within an existing UK quarry and finally we look at a distance at the limit of a one day round trip for a truck.

Example 1

The quarry being considered is just over 60km, by road, from the nearest motorway junction. A cost effective non-road based transport system would be beneficial to both the quarry operator and the local community. Two possible transfer stations are being considered. The first is 58.4 km from the quarry and is about 5km from the nearest motorway junction, the second can only be reached by passing the site of the first option and is not being considered if trucks are used for the initial movement of the aggregate. The second site could also be accessed by a rail line that also passes near to the quarry. However the rail line would need to be upgraded to cope with the heavy trucks. The cost of upgrading the 56km of track would be approximately £12M per Km[4]. This is not justified economically and will not be considered further in this report. Both sites can be reached with a pipeline. The first site would require a 36 Km pipe, of which 20 Km would be along approximately level ground, 8 Km would involve significant up hill sections, and 8 Km would be down hill. The second site requires 49 Km of pipe which is laid largely on level ground.

Trucking Economics

The cost of moving aggregate by truck is fairly easy to estimate. Based on industry data we can estimate both the fixed costs per day of using a 32 tonne tipper truck, as illustrated in figure 8, and the variable costs per Km. Given the annual production and the average load carried the number of journeys required can be easily calculated. From the length of the journey we can estimate how many trips each truck can make each day. The details of the model are given in table 1.

Figure 8: An example of a 32 tonne tipper truck[5].

Journey length	58.4 Km
Fixed cost per day per truck[17]	£263
Variable cost per Km per truck[17,2]	£0.12
Fuel consumption (loaded/unloaded)[5]	2.30 /4.33 Km/Litre
Fuel cost	£0.90 / Litre
Working days per year	250
Trips per day per truck	3
Average load	20 tonnes

Table 1: Details of the economic model for the trucking option.

We have calculated for annual productions in the range 0.1 million tonnes to 20 million tonnes the cost of transporting the aggregate by truck. The result is largely independent of the production rate and averages £6.87 per tonne for the journey, ie £0.118 per tonne-Km.

Pipeline Economics

The cost of the pipeline is more difficult to estimate, details of the model can be found in the appendix. Once the pipeline route has been chosen so as to avoid towns/villages, archaeological sites and public utilities one needs to estimate the number of LIM required and the power required. Where the pipe is running along level ground we use a short sequence of nine LIMs, spread over 90m, to accelerate a capsule train to 10 m/sec (22 mph) it is allowed to coast 130m, during which time its velocity falls to 6 m/s (13mph), before reaching the next sequence of LIMs. In the event of a power failure on a set of LIM then the train is able to coast to the following set of LIM. On a substantial uphill section it is necessary to place the LIM 5m apart with no coasting gap to keep the train from stopping. On the down hill sections no LIMs are required as the train will coast under gravity. It is assumed that the pipeline can operate 24 hours per day for 250 days per year. If a single pipe is laid then it is necessary to send a fixed number of trains in one direction and then send them back again. To minimise the number of trains that are needed the length of a cycle should be as short as possible whilst ensuring that the required daily rate can be delivered. In the case of a dual pipe the loaded trains are sent along one pipe and returned via the other. The major cost is the civil engineering of laying the pipes which we have estimated at £1,000,000 per Km, the cost of the pipe is £141,000 per Km and the cost of LIM is £60,000-£100,000 per Km depending on the fraction of level pipe. The cost of transporting one tonne of aggregate is in the range £0.50-£0.75 (£0.012-£0.015 per tonne-Km), depending on the route chosen.

To evaluate the economic efficiency we have carried out a discounted cash flow analysis. It is assumed that all of the capital investment happens in year 1 and that operations start in year 2. In any year the income is assumed to be equal to the equivalent cost of moving the aggregate by truck, while the annual expenditure is the cost of the electrical power. It has been assumed that there is no inflation, and that a discount rate of 10% is appropriate. This simple analysis ignores some minor costs, such as maintenance, but is sufficient to determine whether the proposed system is cost effective. A typical current present value curve, shown in figure 9, illustrates what is expected for an annual production rate of two million tonnes. £70M is invested in year 0, if the system operates for 9 years then the investment breaks even, and if the system operates for 30 years then the investment is worth £46M.

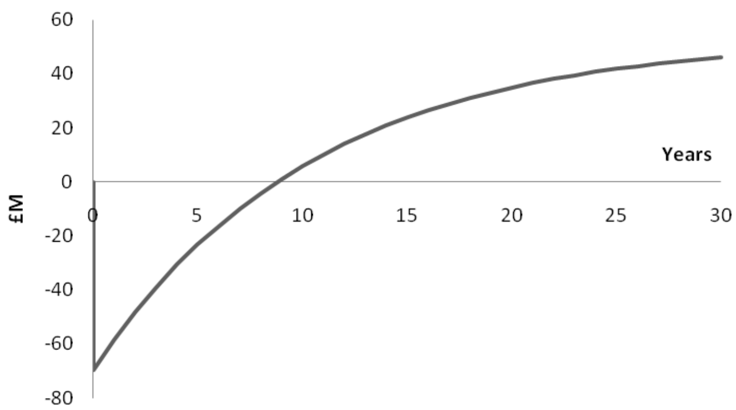

Figure 9: Typical cumulative present value curve for a pipeline system showing the value of the investment (£M) over a 30 year period.

We have calculated the cumulative present value (CPV) for both pipeline routes using single and dual pipes over a 30 year period for a range of annual productions up to 20 million tonnes per year. In each case the CPV is very nearly a linear function of the production. The four functions are given in table2, in table 3 are the annual productions required to break even over 30 years, and in table 4 are the CPV at 30 years for an annual production of 5 million tonnes. For both routes the single pipe option is the more profitable up to the maximum pipe capacity. For production above about 10 million tonnes per year you must use the dual pipe option. The maximum possible annual production is about 20 million tonnes. Beyond this you would either need to use extra pipes, new LIMs that could give higher velocities, or a similar system built at a larger scale.

	49 Km route	36 Km route
Single pipe	-57.0+56.1Q	-43.3+58.4Q
Dual pipes	-68.2+57.2Q	-52.8+59.2Q

Table 2: Equation to calculate the CPV at 30 years in £M as a function of the annual production Q in millions of tonnes

	49 Km route	36 Km route
Single pipe	1.0 M tonnes	0.7 M tonnes
Dual pipes	1.2 M tonnes	0.9 M tonnes

Table 3: The required annual production to breakeven over a 30 year system life

	49 Km route	36 Km route
Single pipe	£223M	£249M
Dual pipes	£218M	£243M

Table 4: The CPV after 30 years for an annual production of 5 million tonnes

Example 2

This second example looks at a short 2 Km haul within an existing quarry. The pipeline has a 1 Km up hill section followed by a 1 Km down hill section, and being within the quarry it is not necessary to bury the pipe which reduces the civil engineering costs to an estimated £200,000 per Km. The cost of the LIMs is £450,000 with a transport cost of approximately £0.04 per tonne. Which compares with a trucking charge of £1.20- £1.40 per tonne. The single pipe option breaks even at 30 years for an annual production of 55,000 tonnes, with the dual pipe option requiring 110,000 tonnes per year. For annual production above 9 million tonnes the dual pipe option is the most profitable. The upper limit for the single pipe option is about 10 million tonnes per year, and for the dual pipe option one could carry about 21 million tonnes. The comparison carried out is not completely correct in that within the quarry one might chose to use a larger vehicle, also one would wish to consider a conveyer belt system.

Example 3

The final case considered is a straight race across level ground over a distance of 350Km with the pipe being buried and the trucks having a motorway to run along. Due to the length the single pipe option is never cost effective, the dual pipe option needs a annual production rate of 2.6 million tonnes to be cost effective. The maximum capacity of the dual pipe system is about 11 million tonnes per year. A larger faster system would probably be a better option in this case.

Conclusions

In selecting the components of our design we have achieved a system that is cost effective compared to the current option of using road trucks, would have a reduced environmental impact and would be highly reliability with low maintenance needs. The system can be installed at a cost of approximately £250,000 per Km, which is significantly cheaper than either building new roads or rail. However if the system needs to be buried, as would be required by UK planning restrictions, then the cost per Km would rise to approximately £1.25M. Typical running costs for the system are £0.015 per tonne-Km which is slightly less than the figure for rail transport, while for trucking the equivalent figure is £0.12 per tonne-Km. This represents a significantly reduced environment impact. The proposed system can also obtain its energy from renewable electrical generation reducing its impact still further.

The analysis that is reported here does not include every possible factor. We believe that all of the issues that have a significant impact have been included. The one exception is the impact of pneumatic pumping which would reduce the number of LIM required. In a previously published report Prof Henry Liu examined a similar concept[18] to the one described here, except that it was rail based, he concluded that you would only need a single LIM sequence at the inlet to the system. The consequence of this was that you need to keep the pipe filled with trains to maintain the pneumatic pump. The system we describe can operate with very few trains which reduces the capital cost. If however the annual production is large the pneumatic pumping may become important and the running costs may be reduced.

To make the proposed system requires further work. First a detailed design needs to be completed so that all aspects of the system and the economics are taken into account, then a demonstration system needs to be constructed. All of the technology that is needed to make this system has been tried and tested elsewhere, so we can be very confident that the system that we describe represents a cost effective way for the quarry industry to reduce the environmental impact of aggregate transport.

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Appendix: Description of the pipeline model

The components of the pipeline model are: the cost of the pipe, the cost of the civil engineering needed to lay, or bury, the pipe, the cost of the capsules, the number and location of the LIM and the cost of powering the LIM. The pipeline can be divided into sections that are up hill, down hill or level. Following consultations with the manufacturers we decided to design the system using a single design of LIM. These LIM are 1m in length, weigh 75 Kg and cost £1500 each. On the up-hill sections they need to be place 5m apart and will propel the train at 9.9m/s with each train requiring 36KJ of energy per LIM to be supplied. On the down-hill sections no LIM are required as the trains will coast under gravity, LIM could be introduced to scavenge energy from the train and slow it down. In the level sections of the pipe we will use a sequence of LIM to accelerate the train to 10 m/s, it is then allowed to coast until the velocity has fallen to 6m/s the train is then accelerated back to 10 m/s. To accelerate the train from 6m/s to 10 m/s will require nine LIM spaced at 10m intervals, the total energy required to do this is 560 KJ. To calculate how far the train will coast we have used equations I-26, I-8, I-9 and I-12 from Prof Liu's report[18] (these equations were originally due to Goa[19]). Numerical solution of these equations give a coasting distance of 130m. If a set of LIM should fail then the train will coast on to the next set of LIM by when the velocity will have fallen to approximately 3m/s.