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TRANSPORTATION RESEARCH FORUM

TRANSPORTATION requirements in urban areas have risen so sharply in the last ten years they can no longer be sufficiently met by existing facilities. There has been a constant rise in the number of people tending to use their own vehicles rather than public transport, with the result that the amount of traffic space available in urban areas is no longer able to meet the demands. There is certainly no other means of transport that can compete with the convenience of the automobile, which at once explains why it is assured of success.[1] At the same time, however, it has given rise to the well known difficulties of urban traffic and because of its noise an emission of exhaust gas it is more detrimental to the environment than any other means of transport.

Our present public transit systems, and more particularly rail-bound transport and buses, are unable to compete with or completely replace the automobile.

This situation compels us to think about developing new transport systems, since this would be our only way of winning over a greater part of the traffic volume, thereby preventing any further upsurge of car traffic in urban areas.

We must also take into account the fact that personnel expenses, which today account for about 70% of the operating costs of public transport, will rise even higher in the future and will thus become prohibitive. It will also become increasingly difficult to obtain personnel for holiday and night work. Only by employing new and fully automatic transit systems will we be able to master these difficulties.

THE DEMANDS PLACED ON ANY NEW TRANSPORT SYSTEM

New transport systems must meet certain demands if they are to fulfill their purpose and be economically viable. Such demands include: low track construction costs, long running time of the vehicle between check-ups, simplicity of repairs, minimal labour requirements for repairs and maintenance, comfortable ride, attractiveness to the passenger, safety, absence of noise and no transmission of vibrations to the environment.

Such demands cannot be met by the present wheel-supported vehicles systems. If they do satisfy the environmental conditions, are noiseless and cause no vibrations, then they become expensive and require a lot of maintenance. The relatively wear-resistant steel wheel on rail systems encumber the environment with noise and vibrations.

Only contactless suspension systems, such as have been increasingly developed in recent years, hold any prospects for a solution. They operate either on the air-cushion principle or on the principle of magnetic levitation. A common characteristic of these suspension systems is that their weight is evenly distributed over a section of the guideway so that concentrated loads are avoided. Costs can therefore be reduced. One disadvantage would lie in the fact that such systems require energy for levitation, and this may be quite considerable in the case of the air-cushion system. Furthermore, expensive precautionary measures will have to be taken to ensure that, during a power failure, the safety and mobility of the vehicle can be guaranteed.

THE PRINCIPLE OF PERMANENT-MAGNETIC LEVITATION

All these difficulties can be avoided, while, at the same time, retaining the advantages of the non-contact suspension system, if we apply the principle of magnetic levitation using permanent magnets.

Here we can put to good use the well known phenomenon that like poles of two permanent magnets will repel one another. If two suitable magnets are used, the forces of repulsion will be so great that, in addition to their own weight, they will be able to support a considerable payload.

The following are the specific characteristics and advantages of the permanent-magnetic suspension: no energy is required, thus ensuring absolute safety and no energy costs; quietness of operation; because of the smooth spring characteristic, no vibrations are transmitted to the environment; smooth and comfortable ride at no additional expense; no wear and tear, no friction, no detrimental affects on the environment and only minimal maintenance costs; passive switches of simple design that are relatively inexpensive.

There are also disadvantages, however, that should not be overlooked: Permanent-magnet systems are stable in one direction only (Earnshaw[2]). Other systems, such as rollers or controlled electro-magnets, must therefore be used for lateral guidance. Permanent magnets are at present still relatively expensive.

The positive features make the permanent-magnetic suspension systems especially suitable for automatic urban transport and more particularly for personal rapid transit. Apart from the physical laws applying to this system and its characteristics, this work is intended to describe some embodiments of the system and discuss a design concept to

Permanent-Magnetic Suspension for Automatically Controlled Transportation Systems

by

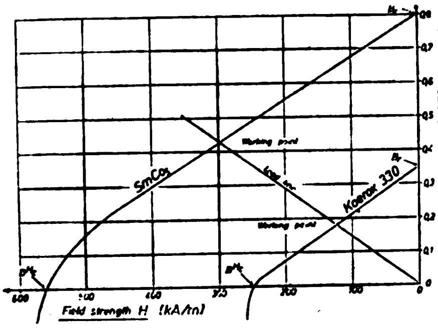
*E. Heff**

indicate the potentialities of permanent-magnetic suspension.

Characteristics

Only certain types of permanent magnets are suitable for producing a large repulsive force. They are characterized by a high coercive force and a substantially straight demagnetization curve, Figure 1. The permanent magnets made of ferrites (barium ferrite and strontium ferrite) possess these qualities. They were developed simultaneously and independently by Krupp and Philips at the beginning of the 1950's.[3,4] They are made from cheap materials by a sintering process and could be manufactured at a reasonable price by mass-production. One disadvantage is their relatively small energy density which limits the load capacity.

A second group of magnetic materials which are just as suitable is based upon the combination of rare earth metals with cobalt (e.g. $Sm\ Co_5$). Their energy density, and consequently their load capacity, is much higher than that of the ferrites. The fact that at present they are extremely expensive is a disadvantage and, for the time being, prevents their being used. Therefore, only the permanent magnets made of ferrites will be discussed in this work.



Demagnetisation curves of $SMCo_5$ and of the ferrite-type permanent-magnet KOEROX 330+). +) KOEROX is a registered trade mark of Fried. Krupp GmbH, Essen.

FIGURE 1

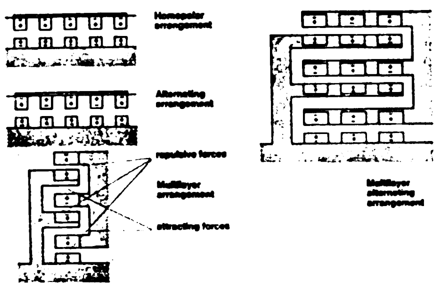
**Krupp Research Institute, Essen.*

The first proposals to utilize permanent-magnets for supporting guided vehicles came from Polgreen[5,6,7] and from Kerr and Lynn.[8] In recent years Baron [9,10] and Henning[11] have made valuable contributions towards the clarification of various questions. An extensive survey of the problems of permanent-magnet levitation system is at present being carried out by Krupp with the support of the Federal Minister for Research and Technology of the Federal Republic of Germany.[12] The theoretical and practical knowledge gained from this developed, make it possible to optimise the dimensions of permanent-magnet levitation systems and to predict their properties under static and dynamic loading.

For supporting the vehicles, several rows of magnets are placed along the guideway in such a way that the rows of magnets and the vehicle are directly over them.

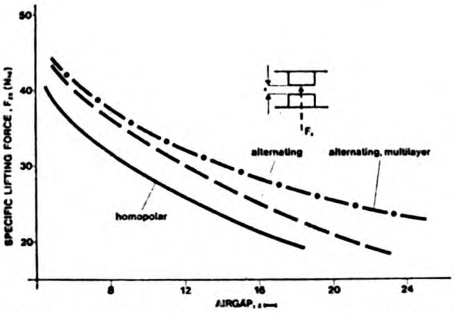
The force of repulsion, and hence the load capacity, depends above all on the geometrical dimensions of the permanent magnets, on the distance between the effective pole surfaces, and on the arrangement of the magnets. The most important arrangements of the numerous possibilities are shown in Figure 2.

The load capacity is appreciably influenced by the polarity of an adjacent



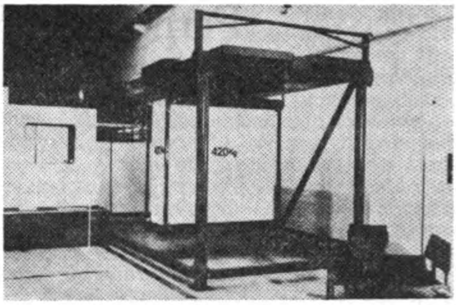
Some possible magnet arrangements for permanent-magnet levitation systems.

FIGURE 2



Specific load capacities of various permanent-magnet arrangements.

FIGURE 3



Experimental system with elevated guideway and permanent-magnet suspended vehicle.

FIGURE 4

magnet rows and by their distance from one another. The specific load capacity F_{zs}, that is the load capacity related to the total magnet weight, is greater for the alternating-pole arrangement than for the homopolar arrangement, Figure 3. A higher levitation force can be attained side by side, but also in layers. In this way it is possible to bring into play not only the repulsive forces but also the attractive forces between unlike poles, which leads to a better utilisation of the material. Still better results can be obtained by the arrangement of several layers of alternating poles. However, changing the air-gap z will alter the load capacity less than before, which is why the multi-layer-arrangement possesses a smoother spring characteristic. The geometrical proportions of the permanent-magnets are a further important parameter. These must be determined by the optimising calculations set up by Baran[10] and Henning.[11] Maximum load capacity will be obtained only if the rows of magnets in the vehicle are placed exactly symmetrically above the magnet rows in the guideway. The vehicle must therefore be guided into this position by the appropriate means, such as rollers.

If it is deflected sideways away from this equilibrium position transverse forces are produced which tend to increase as the vehicle moves further sideways and which have to be absorbed by the guide elements. Along with such lateral displacement, the load capacity will decrease. The magnitude of the lateral forces depends on many factors. For practical purposes it can be taken to be approx. 20% of the load capacity.

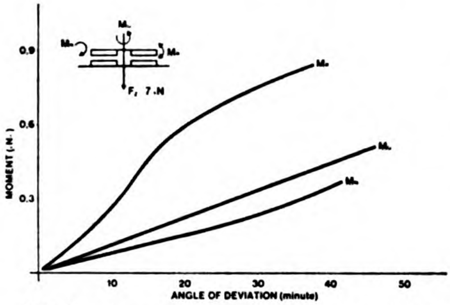
The combination of homopolar or alternating pole multi-row arrangements with multi-layer arrangements results in a large number of suspension magnet lay-outs. They differ from one another not only in their specifics load capacity, but also in their other characteristics. For example, the lateral force of homopolar arrangements is smaller than that of the alternating arrangements, and the elasticity of single-layer arrangements is greater than that of multi-layer arrangements, and so on. Consequently, the suspension characteristics can be altered and adapted to the requirements of every particular application by selecting the appropriate magnet arrangement. Since no generally valid rules can be set up, every case must be dealt with on its own merits.

Rules of Investigations

Further forces and moments arise from rotatory movements of the vehicle. They are partly stabilising (e.g. rolling and pitching) and partly unstable (yawing).

Calculating these moments is not simple, and calculations should therefore be supplemented by measurements reflecting actual conditions. For the purpose of current investigations[12] an experimental system has been set up (Figure 4). A vehicle approx. one meter in length and having a total weight of one metric ton was suspended with an air gap of about 10 mm above a 6 meter long guideway supported on columns. A total of 16 rows of magnets were used in homopolar arrangement. The vehicle was guided by rollers in the central slot of the guideway and propelled by linear induction motors. A special guiding device was fitted to the vehicle so that accurate measurements could be made and the exact positions and directions of forces and moments obtained.

The measurements of the vertical and transverse forces were well in agreement with the theoretical figures. Figure 5 shows the course of pitching, yawing and rolling during rotatory motion. All these values are needed for designing and dimensioning new systems. The most important result of the measurements is the observation that with any permanent-



Pitch, yaw and roll moments of the permanent-magnet levitation system.

FIGURE 5

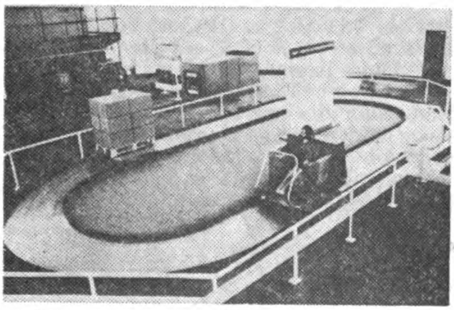
magnet levitation system the motions, forces and moments are inseparably linked with one another. This fact quite considerably impedes the mathematical simulation of the vehicle's movements along the guideway.

One important requirement is the stability of the permanent-magnets against demagnetization. The course of the demagnetization curve shown in Figure 1 indicates that, theoretically, no loss of magnetic forces will take place even when the air gap between the magnets approaches zero.

Practical investigations have confirmed this theory.[12] Here, magnets were repeatedly brought closer to one another, and their stability was verified by measuring the repulsive forces.

In another series of experiments the demagnetization effect was simulated by means of electro-magnets. After several million load cycles, both experiments revealed only an insignificant reduction in repulsive forces.

To find out the effects of further influencing factors a long term experiment was arranged with a permanent-magnet suspended vehicle riding on a small circular guideway, Figure 6. In



Permanent-magnetic suspended transport system with linear induction motor propulsion built for demonstration purposes.

FIGURE 6

the course of this experiment the vehicle covered over 1,200 kilometers without any appreciable loss of load capacity.

Costs

The production costs of ferrite magnets still exceed those of steel. This is mainly due to the fact that only small quantities are being manufactured. Since normally much more magnetic material will have to be employed for the guideway than for the vehicle (total length of track much greater than total length of vehicle) the greatest saving in costs will be secured by minimizing the size of the guideway magnets and selecting a magnet arrangement that results in a high utilization of the material.

Baran[10] and Henning[11] have carried out such optimizations for specific conditions and explained that, despite the present relatively high price of magnets, magnet costs have remained at quite a tolerable level.

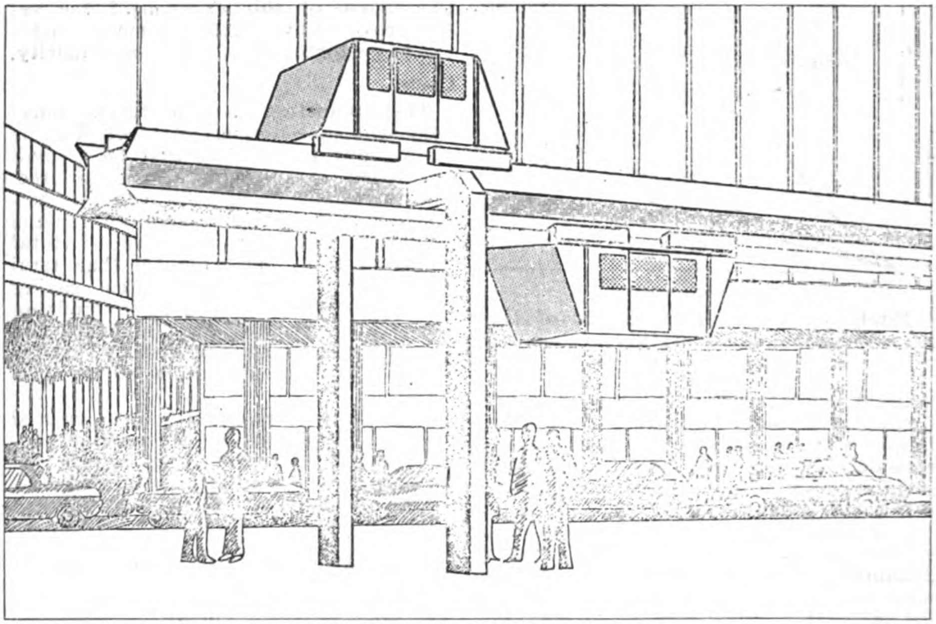
TENTATIVE DESIGN CONCEPT

A tentative design concept for applying the permanent magnet suspension system to an urban transit project is taken as an example. This scheme envisages small, fully-automatically controlled cabs seating 4 people, which would run non-stop between origin and destination on an elevated guideway, Figure 7. These cabs can run both on top of and in suspended fashion underneath the same guideway-beam. They can be transferred from the top to the bottom of the beam and vice versa with the aid of a suitable device.

The advantage of this system lies in its better utilization of the guideway-beam and in minimal requirements of right of way. Other operational advantages include the simpler network realization, easier erection of stub-lines, cheaper "on-line" stations on the less frequented stub-lines, etc. The cabs themselves are propelled by linear induction motors.

The magnet arrangement outlined for these cabs (Figure 8) includes a row of magnets along the track on both sides of the vehicle, each being engaged by two rows of vehicle magnets.

The magnetic forces of the repelling, like poles (above) and the attracting, unlike poles (below) together produce the necessary power for levitation. There is a larger air-gap between the attracting poles, with the result that instabilities are avoided and dynamic movements made possible while the vehicle is in motion. The vehicle magnets are arranged in two bogies to improve the ability of the vehicle to negotiate curves. The function of the magnets is main-

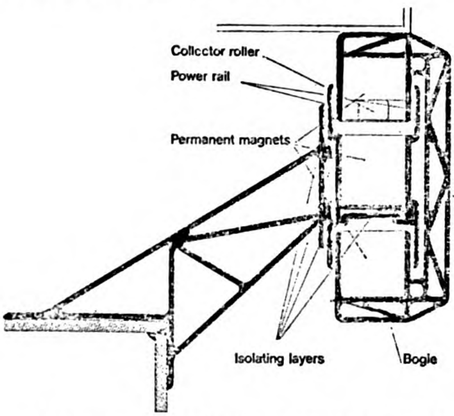


Artist's sketch of an automatic transport system.
FIGURE 7

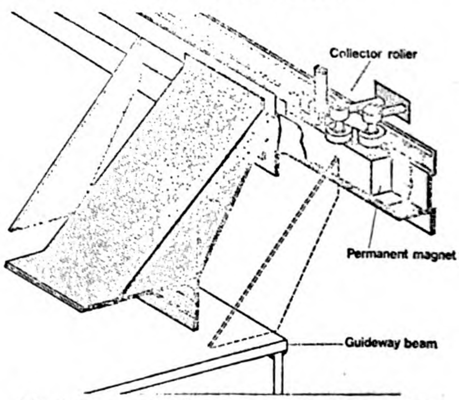
tained when the vehicle is transferred from one side of the guideway-beam to the other. For this reason corresponding rows of magnets on the top and bottom of the guideway-beam have equal polarity.

The magnets on the track are mounted in extruded aluminum sections fastened to a closed box girder (Figure 9). These sections serve several purposes: They hold and protect the magnets, and their inner lateral surfaces act as guiding surfaces for the guide-roller and as conductors for the energy supply. Since the ceramic ferrite magnets are practically dielectric, the mounting sections can be used as three-phase four-wire current supply if their constituent parts are separated from each other by insulating layers.

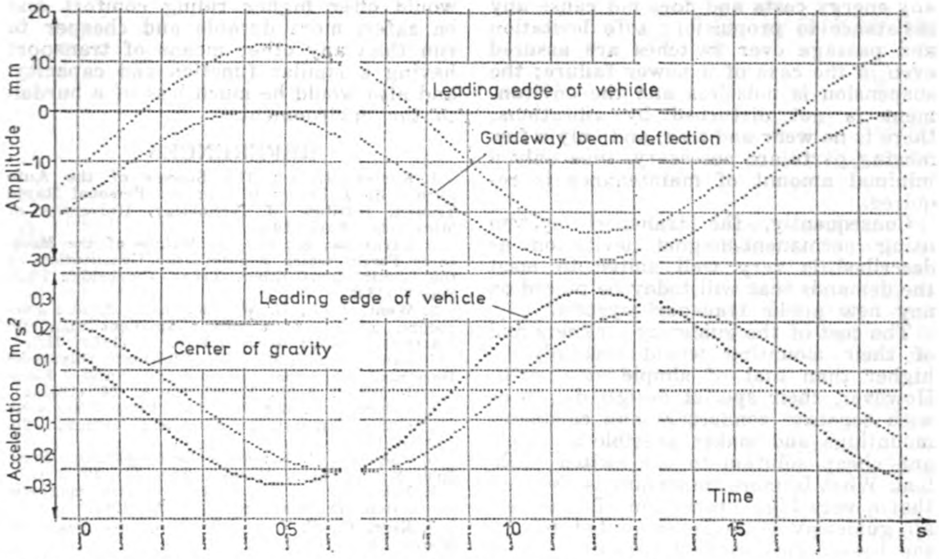
This method of mounting the magnets results in a very compact arrangement, permitting the use of a very simple type of guideway beam and, in addition, offers advantages for alignment and installation. The mechanical design is simplified by the fact that the lateral guide rollers also act as current collectors.



Arrangement of the permanent-magnetic suspension system.
FIGURE 8



Mounting of the permanent-magnets.
FIGURE 9



Estimated vertical movement and acceleration of the vehicle at a speed of 10 m/sec.
FIGURE 10

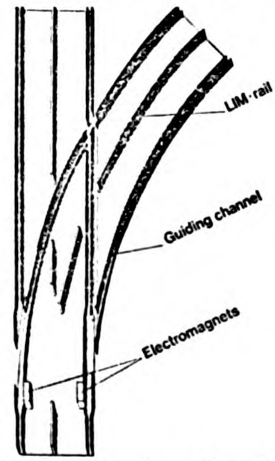
The permanent magnet suspension acts like an undamped spring. At the relatively low speeds which prevail in urban traffic the damping effect produced by the friction of the guide rollers is sufficient. A mathematical simulation of the vehicle's movements, assuming considerable deflection of the guideway, showed that the vehicle would have good riding properties without any superimposed oscillations (Figure 10). Thus no additional suspension is required.

Designing a passive switch with no moving parts poses no difficulties. The lateral forces which arise when the magnets are not guided exactly symmetrically can be utilized for this purpose (Figure 11). Electro magnets fixed on the inner sides of the magnet tracks are switched on individually according to the desired direction of travel. The electromagnets pull the vehicle towards their side of the guideway channel which is a little wider at this point. The permanent-magnetic lateral forces will then hold the vehicle there securely while it is being guided into the desired direction of travel. Such a switch is simple, dependable and not subject to wear and tear.

CONCLUSIONS

The development of ceramic ferrite permanent-magnets has progressed so far that, thanks to the intensive research work of recent years, it will be possible to employ them for the magnetic suspension of guided vehicles. Their favourable properties and complaisance with the environment suggest that they will be used above all for transport systems in urban areas.

The above-mentioned permanent-magnet levitation system for a projected automatic transport system has the following main attributes: the guideway beam and the suspension magnets are utilized very effectively; the design and mounting of the suspension system is simple; the combining of several functions in a few elements reduces costs; sufficient riding comfort is possible without any additional springing; levitation by permanent-magnets does not involve



Outline drawing of switch
FIGURE 11

any energy costs and does not cause any resistance to propulsion; safe levitation and passage over switches are assured even in the case of a power failure; the suspension is noiseless and the environment is not disturbed by vibrations; there is no wear and tear, and only a few moving parts are necessary, thus only a minimal amount of maintenance is required.

Consequently, the transport system using permanent-magnet levitation as described is very well suited to meet the demands that will today be placed on any new public transport system.

The cost of the guideway magnets and of their mounting would certainly be higher than that of simple steel rails. However, their special design dispenses with separate conductors and conductor mountings and makes possible a simple and cheap solution to the switch problem. What is more important is the fact that a very high proportion of the overall guideway costs is accounted for by the beam. This guideway beam is only a simple box girder which can be produced automatically from strip steel, for example, and which carries the magnets for both directions of travel. The economy which can be achieved due to this fact is considerably greater than the higher cost of the permanent magnets. On the basis of the experiments which have been carried out it can be affirmed that means of transport based on such a permanent-magnet levitation system would at least be no less favourable as regards the capital expenditure and would offer higher riding comfort and be safer, more durable and cheaper to run than any other means of transport having a similar function and capacity, and also would be much less of a burden to the environment.

REFERENCES

1. Kieffer, J. A.: The Success of the Auto Should Be a Lesson to Us; in: Personal Rapid Transit, Institute of Technology, University of Minnesota, April 1972.
2. Earnshaw, S.: On the Nature of the Molecular Forces which Regulate the Constitution of the Luminiferous Ether. Trans. Cambridge Phil. Soc. 7 (1842).
3. Went, J. J., G. W. Rathenau, et. al.: Ferrodure, a class of a new permanent magnetic materials. Philips techn. Rdsch. 13 (1952) H.7.
4. Fahlenbrach, H., W. Heister: Oxydische Dauermagnete aus Bariumoxyd und Eisen —(III—)oxyd. Arch. Eisenhuttenw. 24 (1953).
5. Polgreen, G. R.: Transport Possibilities with Magnetic Suspension. Electrical Times, 26. August 1965.
6. Polgreen, G. R.: Magnetic Suspension. Proc. Instn.Mech. Engrs. 1966-67, Vol. 181 Pt 3 G.
7. Polgreen, G. R.: Rail-ways with magnetic suspension. The Engineer, Oct. 25, 1968.
8. Kerr, C., C. Lynn: Westinghouse Engineer, March 1961.
9. Baran, W.: Optimierung eines permanentmagnetischen Abstutzungssystems fur spurgebundene Schnellverkehrsmittel. Z. angew. Phys. 32 (1971) 3.
10. Baran, W.: Der augenblickliche Stand und weitere Entwicklung auf dem Gebiet der permanentmagnetischen Abstutzungssysteme fur spurgebundene Schnellverkehrsmittel. Intern. J. Magnetism, 3 (1972).
11. Henning, G.: Optimierung einer gleichgepolten Magnetanordnung als Abstutzungssystem fur eine Magnetschwebebahn. Techn. Mitt. Krupp, Forsch.-Ber. 30 (1972).
12. Baran, W., E. Hejj et. al.: Untersuchungen zur Entwicklung permanentmagnetischer Tragsysteme fur spurgebundene Fahrzeuge. Report UB 255/72, Krupp Forschungsinstitut (unpublished).