Reducing the Magnetic Fields around DC Light Rail Systems

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DC electrified light rail or tram systems cause low frequency magnetic fields that may disturb scientific and medical instruments in their environment. A concept was developed that significantly reduces these magnetic fields. The overhead contact line is cut into insulated sections. Each section is powered from a supply cable that runs close to the track. When a pantograph enters such a section, the current to the contact line is supplied from both ends. The system is in operation in Utrecht (NL). It has been built in Lund (Sweden) where it will be tested this year and it is under construction in Delft (NL). Test results in Utrecht show that the horizontal magnetic field at 50 m from the track center line is a factor of 8 to 12 smaller than the field next to a conventional track. The field in the vertical direction shows signs of a net current along the track indicating some stray current.

Reduktion von Magnetfeldern bei Gleichstrom-Nahverkehrsbahnen

Mit Gleichstrom elektrifizierte Stadtbahn- oder Straßenbahnsysteme verursachen niederfrequente Magnetfelder, die wissenschaftliche und medizinische Instrumente in ihrer Umgebung stören können. Es wurde ein Konzept entwickelt, das diese Magnetfelder signifikant reduziert. Die Oberleitung ist in isolierte Abschnitte geteilt. Jeder Abschnitt wird über ein Versorgungskabel gespeist, das in der Nähe der Gleise verläuft. Wenn ein Stromabnehmer in einen solchen Abschnitt einfährt, wird der Strom zur Fahrleitung von beiden Seiten geliefert. Das System ist in Utrecht (NL) in Betrieb. Es wurde in Lund (Schweden) gebaut, wo es dieses Jahr getestet wird, und befindet sich in Delft (NL) im Bau. Testergebnisse in Utrecht zeigen, dass das horizontale Magnetfeld in 50 m Entfernung von der Gleismittenachse um den Faktor 8 bis 12 kleiner ist als das Feld neben einem herkömmlichen Gleis. Das Feld in vertikaler Richtung zeigt Anzeichen eines Stroms entlang des Gleises, die auf einen Streustrom hinweisen.

Réduction des champs électromagnétiques dans les réseaux de trains légers électrifiés en courant continu

Les systèmes de trains légers ou tramway électrifiés en courant continu génèrent des champs magnétiques qui peuvent perturber des instruments scientifiques ou médicaux dans leur contexte. Un concept a été développé qui réduit significativement les champs magnétiques. La ligne aérienne de contact est divisée en sections isolées. Chaque section est alimentée à partir d'un câble d'énergie qui court le long des voies. Lorsqu'un pantographe pénètre sur une des sections, le courant sur la ligne aérienne de contact est fourni bilatéralement. Le système est en service à Utrecht aux Pays Bas. Il a été construit à Lund, en Suède, où il a été testé cette année. Il est en cours de mise en œuvre à Delft aux Pays Bas. Les résultats des essais montrent que le champ magnétique horizontal à 50 m de l'axe de la voie a subi ainsi un facteur réducteur de 8 à 12 comparé à celui pour une voie conventionnelle. Le champ magnétique suivant l'axe vertical montre des signes d'un courant le long de la voie, indiquant ainsi la présence de courant de fuite.

1 Introduction

The DC power supply currents of light rail and tram systems cause substantial magnetic fields which can be above the typical background levels up to distances of a few hundred meters from the track. A current of 1 000 A through the overhead line and returning through the rails generates a total flux density of about 1,7 μT at 25 m from the track and 0,4 μT at 50 m from the track. Those magnetic fields are not purely DC but extremely low frequency (ELF). Those may disturb scientific and medical equipment in universities and hospitals. Electron microscopes, for instance, are only guaranteed by the suppliers to give the specified resolution if the fields are under 20 to 50 nT. Nuclear resonance imaging and image guided radiation therapy installations require background fields of under 500 nT. We found that in several realistic situations a reduction of the magnetic fields from the light rail by a factor of 5 to 10 is required. Transportation authorities want to take passengers as close as possible to their destinations, leading to a conflict of interest. Even if the transportation authority is willing to take the demands from the equipment users into account, there often is not enough space to keep the track far from the buildings. In principle, it is possible to use battery operated trams, but in practice this is a very expensive and maintenance intensive solution. A concept was developed that keeps the operation of the tram unaffected and substantially reduces the magnetic fields. It is robust, maintenance free and cost effective.

2 Magnetic fields from a conventional catenary system

For DC light rail the power supply is provided by a continuous overhead contact line and running rails. Both must be connected to the rectifier group of a substation. The typical distance between adjacent substations for DC 750 V is 1 500 to 3 000 m. This means that the current loop has a typical surface of some square kilometers. This loop causes a significant magnetic field.

The magnetic field next to the track is proportional to the current and to the height of the loop that the current encloses. A conventional contact line system, with a contact wire height $h = 5{,}5$ m and a current $I = 1\,000$ A (Figure 1*a*) generates a flux density B according to Equation 1:

$$B = \frac{\mu_0 \, I \, h}{2 \, \pi \, R^2} \qquad (1)$$

For a 50 m distance the resut is 440 nT and at 25 m distance 1,7 µT. The obvious way to reduce the magnetic field is to bring the supply current and the return current closer together.

3 Power supply from cables at track level

Several suggestions to bring the supply current and the return current closer together have been put forward in the literature or have been installed. *Hernando Grande* et al. [1] suggest to return the current close to the contact wire, which requires the rails to be sectioned.

A more practical solution is to run an insulated supply cable at ground level and connect this supply cable with feeder cables to the overhead line at every support pole. The total supply current is now distributed between the cable at ground level and the contact wire. The degree of field reduction is a matter of current distribution in a network consisting of contact wire and supply and feeder cables. *Bette* et al [2] describe a system in which the feeder cable is positioned at some depth below the tracks. By the correct choice of relative resistance and depth, the

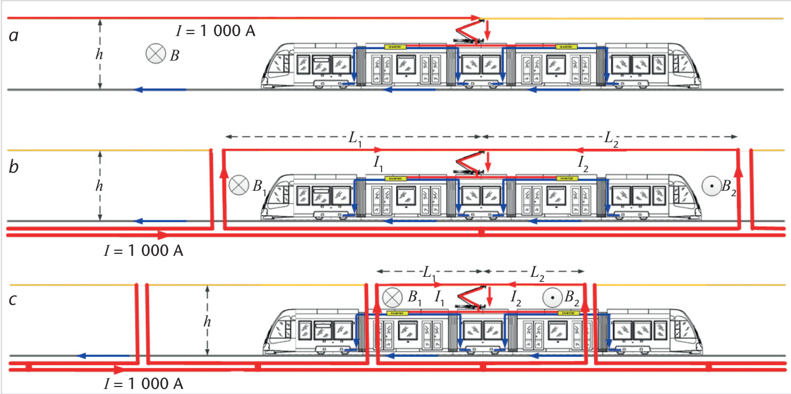

Figure 1:
Magnetic field created by different contact line arrangements (Graphic: Authors).
a – conventional system
b – sectioning system, 40 m sections (note the different diameters of wiring)
c – sectioning system, 15 m sections

magnetic field of the feeder cable can exactly compensate the magnetic field of the catenary wire. The only remaining field comes from the sections close to the vehicle. The system has been installed recently in Ulm (Germany) and measurements show the effectiveness.

4 Design of a *B* field reducing contact line system: sectioning the contact wire.

In order to reach a maximum degree of reduction, we came up with a new solution [3]. This system has now been accepted for the Uithoflijn in Utrecht (NL), Line 19 in Delft (NL) and the C-ESS Line in Lund (SE). It has the following design.

A power supply cable is laid at track level and the overhead wire is electrically interrupted at positions close to the contact line poles. Feeder cables are connected between the power cable and both ends of the individual contact wire sections, using the poles as a support structure (Figure 1*b*). The magnetic effect is threefold.

- First: the current loop width is reduced to the width of one section, between 15 and 40 m, depending on the design.
- Second: only a vehicle within such contact line section will cause currents through the contact wire. Currents in non-occupied sections only flow through power (supply) cables and running rails at ground level.
- Third: the vehicle in an occupied section will cause two sub-loops. Those two sub-loops have opposite current directions and thus two components to the magnetic field which counteract each other because they have opposite vector

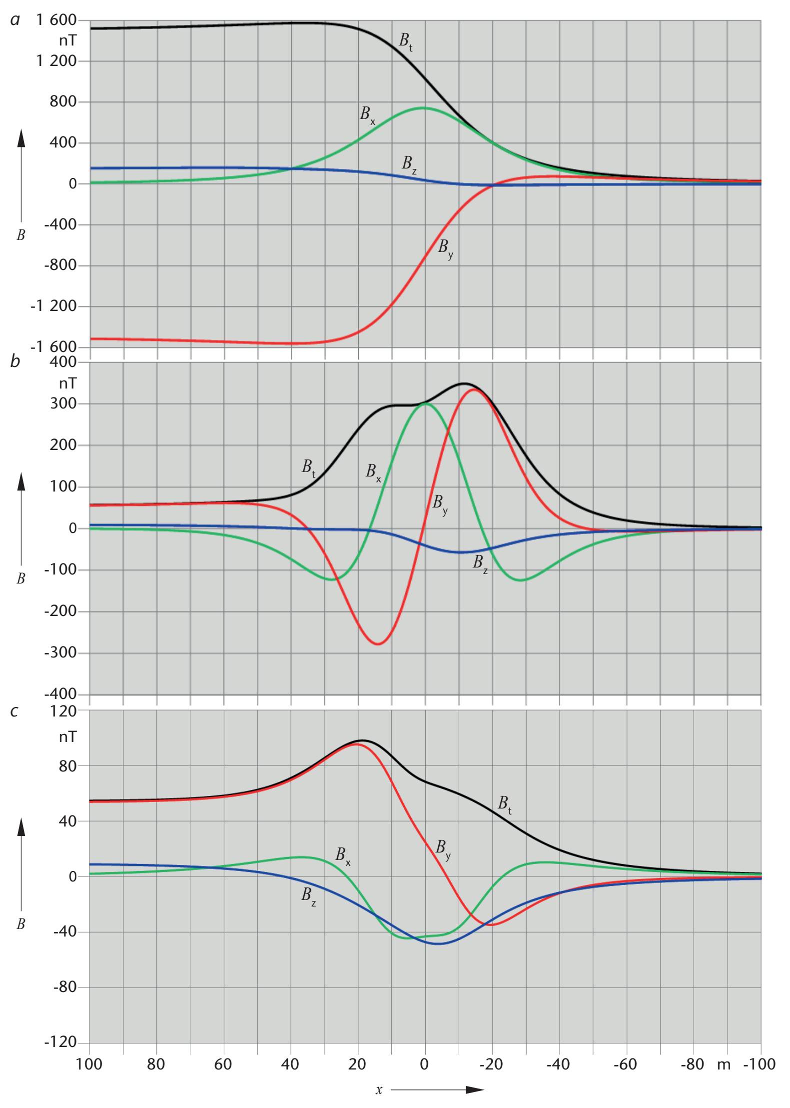

Figure 2:
Calculated B fields, components at 29 m distance from a conventional track (*a*), from a track with sectioning system, 40 m sections (*b*), and from a track with sectioning system, 15 m sections (*c*) (Graphic: Authors).

directions. When the tram moves through a section, the sizes of the loops change, so it may seem that when the vehicle is in one corner of the section, the loop size is still as big as a full section.

However, here comes the essential aspect of the innovation [4]: by choosing feeder cables with much lower resistance than the contact wire, the latter acts as a voltage divider. The result is that the current through the narrow loop is larger than the current through the wider loop. At zero resistance of the feeder cables, the magnetic flux B through both loops would be equal (and opposite), such that at distances larger than the width of the section, the two components will cancel each other. Using the *Biot* and *Savart* equation for both sub-loops shows how the flux in the two loops becomes equal.

$$I_1 = \frac{U}{\rho\, l_1 A} \tag{2}$$

$$I_2 = \frac{U}{\rho\, l_2 A} \tag{3}$$

$$B_1 = \frac{\mu_0}{2\,\pi}\,\frac{I_1 \cdot h \cdot l_1}{R^3} = \frac{\mu_0}{2\,\pi}\,\frac{\frac{U}{\rho\, l_2 A} \cdot h \cdot l_1}{R^3} = \frac{\mu_0}{2\,\pi\,\rho\,A\,R^3}\,\frac{U\,h}{} \tag{4}$$

$$B_2 = \frac{\mu_0}{2\,\pi}\,\frac{-I_2 \cdot h \cdot l_2}{R^3} = \frac{\mu_0}{2\,\pi}\,\frac{-\frac{U}{\rho\, l_2 A} \cdot h \cdot l_2}{R^3} = -\frac{\mu_0}{2\,\pi\,\rho\,A\,R^3}\,\frac{U\,h}{} \tag{5}$$

For a vehicle at the center of a 40 m section, each loop would carry half the current of say 1 000 A total and thus produce about 88 nT at 50 m distance. The field vectors of both loops would have major components in opposite directions, so the resulting field is expected to be even lower.

5 Design and calculations

The concept allows for variation to suit the needs of a specific situation. On the one hand, the types of sensitive equipment determine what is acceptable in terms of magnetic field components NMR's for instance are highly sensitive for variations of external fields in the vertical direction. Electron microscopes are specifically sensitive in the horizontal direction. On the other hand, properties of the light rail system determine the strength of the emitted magnetic fields: The type of vehicles, number of tracks, total current and allowed speed, distance of power substations and service frequency. And of course, distance is an important factor. The larger the distance, the smaller the risk of disturbance. These factors are location specific. So the design of the system will be different for every location.

A number of parameters of the concept can be varied in order to suit the specific location's needs. The basics of the design come down to choosing those parameters in such a way, that the requirements will be achieved with no unnecessary costs. Important parameters are

- length of the sections (distance between consecutive poles),
- length of the segments of application,
- positions of power substations,
- cabling within vehicles and
- maximum service speed versus traction effort.

Calculations for different concepts are done by means of a software package that allows for 3D modelling of the system. Especially for short sections, it is important to model the currents both in the infrastructure and in the vehicles (Figure 1*c*). All relevant current conducting elements can be modelled with high accuracy and the calculator presents the magnetic field components in selected points of a 3D environment. The results allow for assessment of the degree of electro-manetic (EM) emission of the designed system. Normally, the first step in this process is to model a "conventional" infrastructure and determine its EM emission. The design of the sectioning system is an iterative process of design changes and (re)calculation until a satisfactory solution has been found. For example, it is possible to use a single feeder cable between two tracks, or two separate feeder cables, one for each track. Figures 2 and 3 show results of these calculations for a system plus a vehicle with the pantograph in the middle of the section, drawing 1 000 A supply current. The x-axis is defined by the track, the y-axis is perpendicular to the track in the horizontal plane and the z-axis is vertical. Figure 2 shows the results at 29 m next to the center of the rails, Figure 3 at 52 m distance. Note that the y-field in the sectioned system is reduced most significantly. The constant value at negative x is the result of the fact that the supply cable lies slightly below the level of the rails. Somewhat surprisingly, the shape of the x- and y-field changes when going from a 40 m section to a 15 m section. This is a result of the currents inside the tram, which, for this particular vehicle type, create larger loops than the size of the section. The calculations lead to expectations that the sectioning system can reduce the magnetic fields by a factor of at least 10 at 52 m from the track. A shorter section length is clearly beneficial, especially at smaller distances from the track.

6 Implementation

Implementation of the design into a functioning system requires simple hardware, such as cables, line breakers, connection boxes, clamps, nuts and bolts. All of those are components that do not wear and therefor do not need maintenance. The sectioning of the contact wire requires components called line-breakers. Designers usually try to avoid line breakers because due to their mass they are considered a mechanical "hard" point that can cause excessive wear to pantograph collector heads. Tram operators usually have the same feelings, because line breakers must be passed by the vehicles with low current. Because of this and because we needed a current interrupter rather than a voltage separator, a special line breaker was developed (Figure 4). It is light weight, has a separation gap of only a couple of millimeters, has no mechanical contact with the pantograph collector head and allows the vehicle to pass-

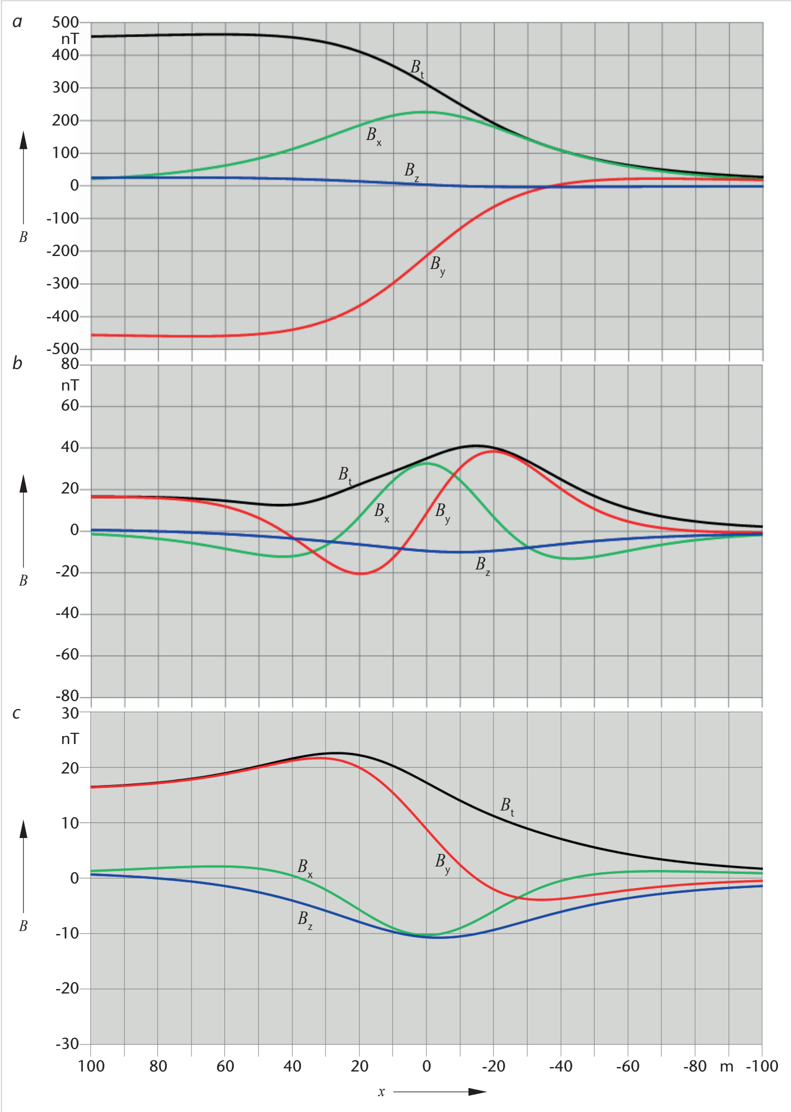

Figure 3:
Calculated B-fields, components at 52 m distance from a conventional track (*a*), from a track with sectioning system, 40 m sections (*b*), and from a track with sectioning system, 15 m sections (*c*) (Graphic: Authors).

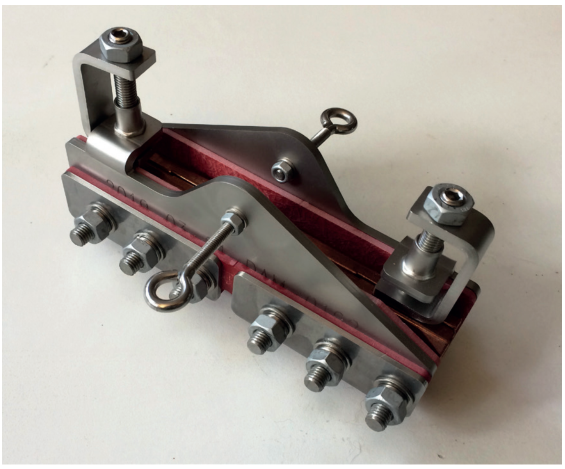

Figure 4:
Insulating connector for contact lines (IRV) (Photo: Authors).

Figure 5:
Cable protection tubes are laid before the concrete is poured (Photo: Authors).

Figure 6:
IRV in contact wire with feeder cables connected at each side (Photo: Authors).

with full current at line speed. This line breaker is called IRV.

Before using the IRV in the sectioning system, it was tested for several years in a regular tram line in normal service. The supply cable at ground level requires cable protection tubes and connection boxes to be integrated into the track design. Construction techniques must be chosen to position the tubes properly within the track bed (Figure 5). Usually, the cable protection tubes must be laid in conjunction with the construction of track beds, especially when it is ballast less. Cables can be pulled through the tubes later on, when contact line construction starts. We typically use 500 mm^2 feeder cables up to the top of the poles, where two more flexible cables connect to the contact wire (Figure 6). The pole positions must be chosen in combination with the overhead contact line design.

Special attention must be paid to the insulation of running rails. Where stray currents are always a major concern because of electrolytic corrosion, it is an even bigger issue when reducing EM emission. This is related to the fact that stray currents can change the balance of currents in the system – less current through running rails – but also can cause undesirable emission from the stray current itself, which might run close to sensitive equipment. Prevention of stray currents also must be looked at from the perspective of locating power substations. If there is a risk that stray currents may become a source of undesired, and often unexpected, EM emission, separate power supply of the segment with the sectioning system must be considered.

7 Test measurements

For the project in Utrecht, the system has been tested by extensive measurements. Flux density measurements were carried out at various locations along the line, especially close to buildings with sensitive equipment. Synchronous current measurements in the infrastructure and in the test vehicles were necessary to determine the real relation between currents in the tram system and its disturbance to the environment. Because the current that could be drawn by the vehicle was varied during the measurement, a so-called disturbance factor (nT/kA) was calculated from the correlation between current and flux density values.

In order to discriminate disturbance by the tram from background magnetic noise, it is necessary to have measurements from the tram which are unique to the tram. That was done in two ways: static and dynamic. Static measurements were performed by

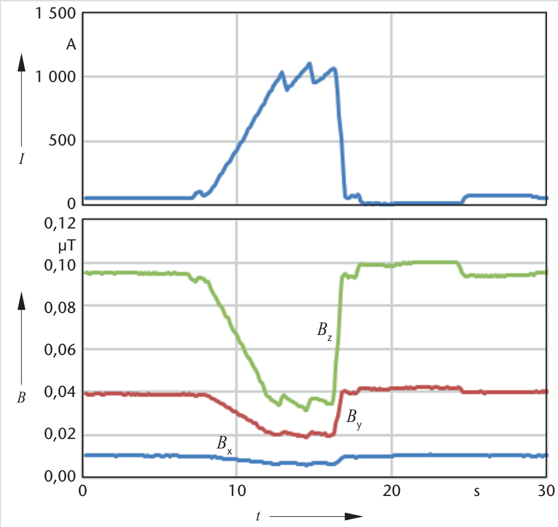

Figure 7:
B-field measurement at 52 m next to track with the measured supply current to the tram; section length is 15 m (Graphic: Authors).

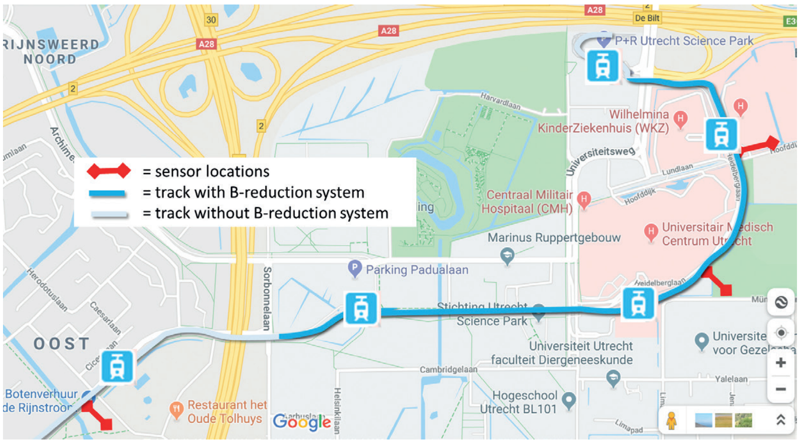

Figure 8:
Map of the area containing the sectioning system in Utrecht (Map basis: Google Maps, modification: Authors).

means of a tram standing still at a certain position and have it run through a series of well-defined power switching operations that cause the vehicle equipment to turn on (and draw current) and turn off. Those measurements give the purest relation between the tram current and the magnetic field, but the maximum current that can be drawn in this way is about 100 A. The resulting magnetic field is relatively small compared to background fields. Dynamic measurements were performed by having a tram start up with maximum acceleration and subsequent stops. That generates a current as a function of time, which is typical for an electric vehicle. For magnetic field measurements close to the track, the field is not proportional to the current anymore because the position of the tram changes during measurement. A particularly nice example of such a measurement is shown in Figure 7. Clearly, the magnetic field in x- and y-direction is much smaller than they would be without the sectioning system. The absolute value is about what was expected from the calculations as given in Figure 3. The field in the z-direction is higher than expected. Stray currents are responsible for this, which are caused by insufficient insulation of the rails.

These test measurements were necessary to convince the responsible organizations that regular service could start without disturbing the sensitive equipment. They also yielded information on stray currents. During the test phase several causes for stray currents were found and eliminated.

8 Measurements during regular operation.

The Utrecht tram started regular scheduled operation on 16th December 2019. *B*-field validation measurements were performed on 23rd December next to the track at a position without the *B*-reduction system and at two locations next to the track with the sectioning system (Figure 8). Sensors of the type *Bartington Mag03MS100 3D fluxgate* were placed at distances of 25 and 50 m from the center line between the two tracks, as determined by a laser distance meter. The analog signals of the sensors were sampled with a rate of 1 kS/s. and in post-processing averaged to give files of values every second. Measurements were taken over a time period between 30 and 60 min, but in the Figures 9 to 12, data were used only for periods of 15 min in order to have sufficient time resolution in the plots. From the data at the locations along the sectioning system, the most southern one were arbitrarily choosen, because the results were essentially the same, even though the more northerly location was closer to a tram stop.

Figure 9 shows the magnetic fields next to the track without *B*-field reduction. The vertical position of the data is arbitrary. The field in the x-direction is the result of a vertical current, clearly visible when the tram leaves the stop in the direction of Utrecht CS and draws current while passing the magnetic field sensor. The field in the y-direction dominates the effect both in amplitude and in frequency of occurrence. This is understandable, since any current in the contact wire that is drawn by a tram in the line returns through the tracks and thus creates a field in the y-direction, regardless the exact position of the tram on the line. The current drawn at the first stop in the direction of Utrecht CS is clearly visible at about 2,5 min after the tram leaves the stop near the sensor.

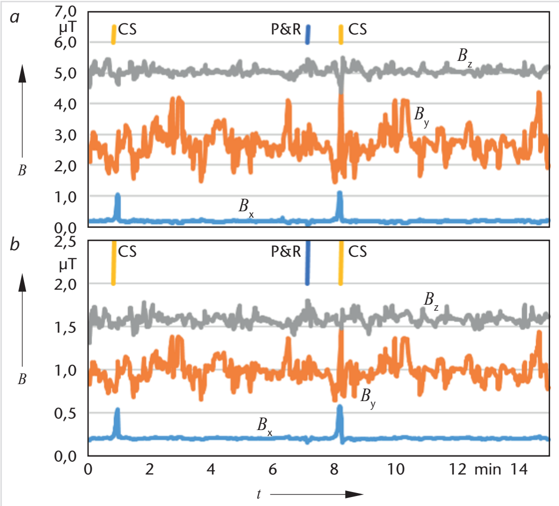

Figure 9:
B-field at 25 m (a) and at 50 m (b) without B-reduction; "CS" indicates when tram direction Utrecht CS is at the stop (Graphic: Authors).

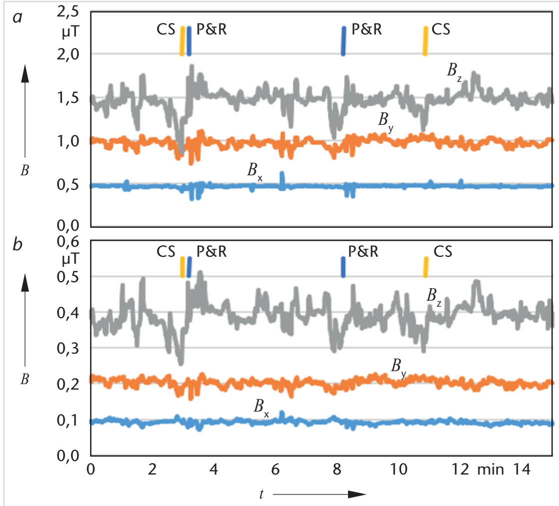

Figure 10:
B-field at 25 m (a) and at 50 m (b) with B-reduction; "CS" indicates when tram direction Utrecht CS is at the stop (Graphic: Authors).

Figure 10 shows the magnetic fields next to the track with B-field reduction. The vertical position of the data is arbitrary because we subtract the earth magnetic field. The trams in the direction P&R is just above the background in the B_x and B_y direction. The reduction in the B-fields as compared to the system without B-field reduction is better visible when displayed at the same scale as shown in Figures 11 and 12. The magnetic field in the y-direction shows the effect of the sectioning system best. This was to be expected, since the effective surface of the current loops was dramatically reduced. The x-component is reduced since the current that flows down through the tram is directed upwards through the current lines at the posts, which are relatively close, 15 m, in the sections where the measurements were

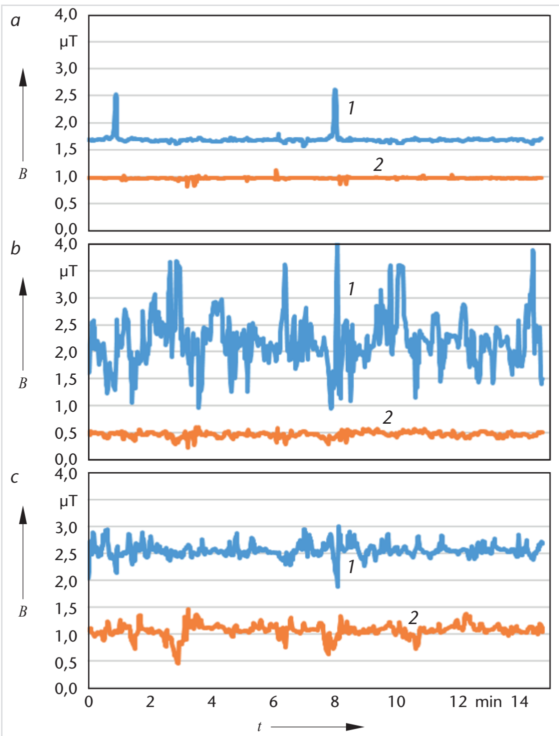

Figure 11:
Comparison of magnetic fields at 25 m from the track, without (*1*) and with (*2*) sectioning system; vertical position is chosen by authors; *a*: B_x, *b*: B_y, *c*: B_z (Graphic: Authors).

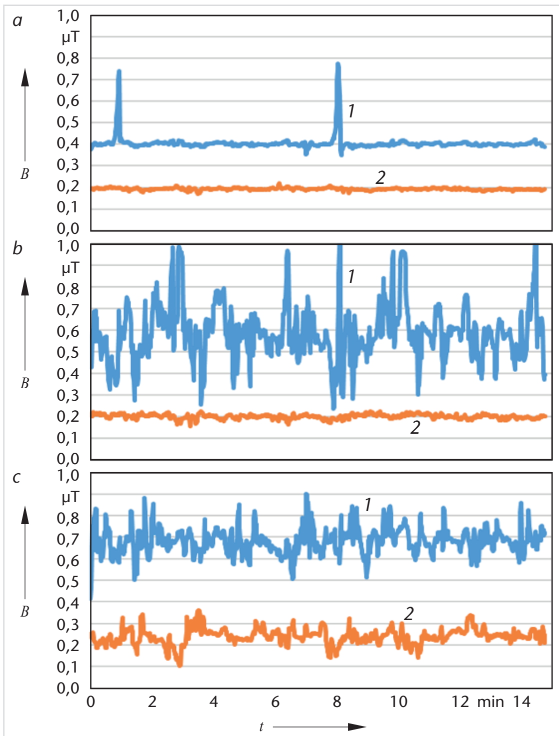

Figure 12:
Comparison of magnetic fields at 50 m from the track, without (*1*) and with (*2*) sectioning system; vertical position is chosen by authors; *a*: B_x, *b*: B_y, *c*: B_z (Graphic: Authors).

taken. One might expect larger fields close to a tram stop, but the measurement results at the location close to the stop were the same, if not even lower.

The largest component next to the track with the sectioning system turns out to be in the z-direction. There are two possible causes for a B_z:

- a net current along the track (power minus return), or
- a different distance from the sensor to the current in the positive x-direction as compared to the current in the negative x-direction.

In the Utrecht system, the supply current for the two tracks are separated and lie in between the rails, so the second cause is unlikely. The first cause would indicate that part of the return current does not flow through the running rails, but has left the rails to stray through the underground. This is a very well-known phenomenon in railway systems. To prevent this, the rails in the Utrecht system were embedded within a layer of insulating material (rubber and foam). A 0,1 µT field at 50 m from the track indicates a stray current of about 25 A. Obviously, the insulation is not complete. At the time of writing this paper, the responsible organization is still looking for solutions.

Table 1 shows the measured peak-peak values and standard deviations plus the reduction in those values reached using the sectioning system. Notice that the peak-peak values of the conventional system are about twice the values that we calculated for a one-directional current, possibly because the effect of several trams is seen at the same time. The reduction factors for the magnetic field in the x- and y-direction are in good correspondence with what was expected from the calculations.

Table 1

Peak-peak values and standard deviations of the data in the Figures 11 and 12.

		sectioning system		sectioning system		reduction factor	reduction factor
		without	with	without	with		
		distance 25 m		distance 50 m		distance 25 m	distance 50 m
peak-peak B_x	nT	1 061	307	423	49	3,5	8,7
peak-peak B_y	nT	3 232	379	863	69	8,5	12,5
peak-peak B_z	nT	1 115	1 003	488	257	1,1	1,9
σB_x	nT	86	16	35	5	5,3	7,1
σB_y	nT	475	48	128	10	9,9	12,4
σB_z	nT	120	117	59	36	1,0	1,7

9 Conclusion

A concept for light rail and tram overhead contact line system and power supply that significantly reduces the magnetic fields caused by the DC supply currents was developed. Magnetic field measurements at the Uithoflijn in Utrecht (NL), where the system is operational, show that the magnetic field in the direction perpendicular to the track, which is usually the largest component, is reduced by a factor of 8 at 25 m from the track and a factor of 12 at 50 m from the track. The field in the direction parallel to the track is reduced by a factor of 3,5 at 25 m and a factor of 8 at 50 m. The field in the vertical direction shows signs of a net current along the track indicating some stray current, which can hopefully be further reduced.

The implementation of the sectioning system during the construction of the light rail or tram line requires some extra work but it is not very difficult. Track laying with extra cable protection tubes and connection boxes does not require complicated technology or effort. Since it has no electronic components, the system is relatively maintenance free. The specially developed light weight line breakers that section the catenary wire have been extensively tested and seem to have sufficient lifetime.

The new concept for reduction of magnetic fields allows future tram and light rail systems to be planned closer to hospitals and university laboratories than was hitherto possible.

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