Magnets in a carriageway part 2; magnetic background noise and markers pattern study

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2015-06-30

Abstract

This research project is a continuation of the first part of "Vehicle Positioning with Magnets in a Carriageway". The purpose of this project is to investigate different magnetic background noises and disturbances, and to further investigate the magnetic markers pattern. The same magnetic field test rig as for the previous project was used. Different routes have been driven and a number of magnetic background noise sources have been found such as bridges, electrical cables, tramways and manhole covers. The magnetic markers pattern have been studied, both the type of pattern and if it is possible to encode information within the pattern, as well as how the lateral and the longitudinal pattern should be designed. The conclusions are that there are magnetic disturbances that need to be dealt with, either with stronger magnets or with filters. The standard magnetic marker, used for road without magnetic disturbance, will be a ferrite magnet with the dimensions of Ø40x30 mm that is embedded with the top of the magnet 10 cm below the road surface. The magnetic markers pattern is suggested to be a simple systematic pattern with the road marks as the base, with encoded information and at least three meters as longitudinal distance. The lateral pattern is dependent on the type of road. It is suggested that the density of markers used at the edge lines of the lane are halved compared to the density used in the centre of the lane. Demagnetization of the magnetic markers is considered not possible, but to dig up or shield the magnets could be used as a substitute method. The test road at Fagersta shows that the concept of embedding magnets in the road is feasible.

Acknowledgements

Michael Svensson, ÅF Technology AB

Jonas Ekmark, Volvo Car Corporation

Joakim Lin-Sörstedt, Volvo Car Corporation

David Björklöf, Trafikverket

Anders Lie, Trafikverket

Simon Sternlund, Trafikverket

David Andersson, ÅF Technology AB

Markus Johansson, ÅF Technology AB

Micael Axestål, ÅF Technology AB

Patrik Thede, ÅF Technology AB

Carl Johansson, intern at ÅF Technology AB

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Abbreviations and terminology

CAPL-script	A script language used for CANalyzer.
Catenaries	Contact lines for trams and trains.
CANalyzer	A program used for communication and recording data on CAN.
Centre marker	Magnetic marker that is mounted at the centre of the lane.
Double magnets	Two magnets close to each other.
Edge line marker	Magnetic marker that is mounted at either of the edge lines of the lane.
Magnetic field sensor system	The magnetic field sensor system that is thought to be used in a production vehicle.
RMS-value	Root mean square value, also known as the quadratic mean in statistics.
Road expansion joint	A road joint that goes orthogonal to the direction of the road.
RV	Abbreviation for “riksväg”, the Swedish word for National highway.
Steel slag asphalt	Asphalt where rest products from the steel industry have been added to the compound. Used due to its hard-wearing and noise absorbing properties.
Trafikverket	Swedish Transportation Administration.
Test rig	The magnetic field sensor system for measuring the magnetic field used during this research project.
Vehicle magnetic positioning system	The entire system for positioning the vehicle using magnetic markers, including the magnetic field sensor system and the magnetic markers embedded in the road.

1 Background

This research project is a continuance of the first part of “Vehicle Positioning with Magnets in a Carriageway” – a research project with the aim to investigate if it was feasible to use permanent magnets buried below the road surface for positioning of vehicles on the Swedish public road network [1]. That project made a proposal for what types and dimensions of magnets to use as well as for what pattern to mount the magnets in, and concluded that “a full scale system is possible to achieve within the constrains set by the project’s parameters”. The project also stated a number of further research and development issues to be done in future projects.

As the previous project, this research project is collaboration between ÅF, Volvo Car Corporation and the Trafikverket. This project has been fully financed by Trafikverket.

2 Project definition and delimitations

The purpose of this research project is to pursue and develop the work concluded in "Vehicle Positioning with Magnets in a Carriageway" [1]. This project has proceeded from the assumptions made in the first research project within this area.

2.1 Project definition

This research project consists of two main parts; magnetic background noise and disturbances, and magnetic markers pattern. The question formulisations for each part are stated below.

2.1.1 Magnetic background noise and disturbances

This research project shall investigate which magnetic background noises and disturbances exist, and how to handle that by:

- Investigate how much magnetic background noise and disturbances exist on a number of routes, including the Drive Me route [2].
- Determine how the potential noise from the road or the vehicle shall be handled and if the magnetic field from the suggested magnets from the previous project [1] is large enough to break through the noise.
- Perform measurement on places of specific interest for magnetic background noise, such as steel slag asphalt and electrical cables.
- Investigate the possibility of permanently demagnetize the magnets in the ground.

2.1.2 Magnetic markers pattern

This project shall investigate how the magnetic marker's pattern shall be designed by answering the following questions:

- Investigate if the lateral distance between the magnetic markers can be expanded to 3 meters or beyond.
- Investigate alternative patterns for the magnetic markers.
- Investigate if it is possible to simplify the magnetic markers pattern and/or add additional information into the pattern.
- Examine if the distance between the magnetic markers can vary due to road obstructions.
- Analyse and compare the benefits and drawbacks for the following concepts:
    - Mounting of magnetic markers with total accuracy in a simple systematic pattern where no map is needed in order to translate the information within the pattern.
    - Mounting of the magnetic markers with high accuracy based on the white road markers.
    - Mounting of the magnetic markers with low accuracy in a flexible pattern. Scaling and map is a necessity in order to translate the information within the pattern.

2.2 Delimitations

Delimitations have been necessary in order to limit the project scope. The delimitations made are:

- Only situations where all four wheels of the vehicle are on the road are considered.
- Vehicle speeds are limited from 0-150 km/h.
- The distance from the test rig sensor and the road surface is set to 21 cm ± 1,5 cm (see d_{sensor} in Figure 1). Before and after all measurements were done, the distance between the test rig sensors and road surface was measured and if needed adjusted to be 21 cm for all of the sensors.

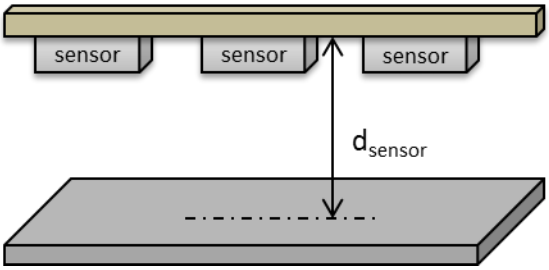

Figure 1: Distance between the test rig sensors and road surface

- The test rig is made of wood – in the car the sensors will probably be shielded by the vehicle's steel carriage body. The effects of the carriage body and the internal magnetic fields of the vehicle have not been taken into consideration.
- The magnetic markers are assumed to be mounted with their top 10 cm below the road surface (see d_{magnet} in Figure 2).

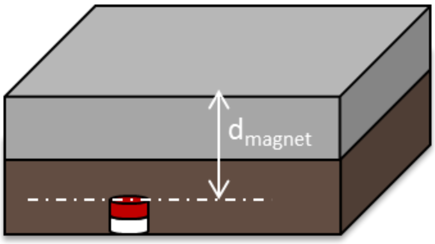

Figure 2: Distance between road surface and top of magnet marker

- The project will discuss if it is possible to use different filters to handle the magnetic disturbance, but will not go into technical details regarding specific filters.
- The tolerance that is needed for the magnetic markers placement in x/y/z-direction and angle of placement has not been determined within this project.

3 Magnetic background noise and disturbances

Magnetic background disturbances are important to understand since these levels are vital to know what types of magnets are possible to use where. In this research project, all magnetic field amplitudes below 15 µT are considered as background noise and amplitudes above 15 µT are considered as disturbances for the magnetic markers. Note that the magnetic field disturbances cannot be solved with more sensitive sensors.

3.1 Measurement methods

The magnetic field sensor system for measuring the magnetic field, hereon called the "test rig", used in this project is the same as was used in the previous project. The test rig is shown in Figure 3. For further information and more details regarding the test rig, please see chapter 4 in "Vehicle Positioning with Magnets in a Carriageway" [1]. The test rig has been updated and improved during the course of this project; the main update is the switch from two separate unshielded cables for power supply and signal data to one shielded cable including both. This change limited the magnetic effect the power supply cable had on the measurement sensors.

Figure 3: Test rig used for magnetic background noise measurements

To reduce the amount of CANalyzer data when measuring Swedish highways, a CAPL-script filter was made. This filter reduces the output from 15 sensors with x-, y-, z-direction to four sensors with only z-direction of the magnetic field. The following sensors were chosen:

- AU1 sensor 1
- AU2 sensor 1
- AU2 sensor 5
- AU3 sensor 5

Another CAPL-script was made to get the statistics of the roads for the analyses. The roads were checked for:

- Shorter peaks or other disturbances that will interrupt the measurement of an ordinary magnet placed in the road. For more information of the data and the result from highway test, see chapter 3.5.
- The CAPL-script also set the zero point to where the ordinary magnetic background noise is when there is no disturbance.

At the replay of the CAN data the CAPL-script analyses the data and the result given is the percentage of the total distance that is affected by magnetic disturbance. The intensity of the difference magnetic fields were chosen to be the same as the intensity from the different magnets in Fagersta (see chapter 6).

The transformations from sensor values to µT were set in the CANalyzer database.

3.2 Measurement routes

Different routes were driven in order to collect as many different road situations as possible. During the first route driven, the Drive Me route, it was found that some objects caused greater magnetic disturbances than other and that information yielded which routes to focus on. Maps of the different routes can be found in *Appendix A – Background noise measurement routes*.

To get an overview of the magnetic background noise from the national highways, some of the main roads in Sweden were driven as well as the Drive Me route in Göteborg.

Göteborg to Stockholm and Uppsala, E4
The route between Göteborg and Stockholm is mostly dual carriageway motorway, but sections of the route consist of either single carriageway road or 2 + 1 highway (5% and 8% respectively of the total distance of the route). The route was driven from Göteborg via Borås, Gränna, Stavsjö and Hägersten to Uppsala.

Uddevallabron to Göteborg, E6
The road between Uddevallabron and Göteborg is a part of the national highway to Oslo in Norway and consists of a dual carriageway motorway.

Göteborg to Heby
The route consists of varying types of roads; from smaller roads with speed limits of 70-90 km/h mixed with 2+1 highway and motorways around the bigger cities. The route starts at Göteborg and goes to Heby via Lekåsa, Laxå, Kumla and Västerås.

Heby to Fagersta
The route consists of single carriageway roads that wind between smaller villages with general speed limits of 70-80 km/h.

The Drive Me route
The Drive Me route is based on the "Drive Me Project" [2] and was therefore chosen as one of the most important routes. The route consists of the ring road around Göteborg, starting with the E20, Tingstadstunneln, Lundbyleden including Lundbytunneln, Älvsborgsbron, Västerleden including Gnistängstunneln, Söderleden and then back to the E20 again.

The Göteborg City route

The Göteborg city route consisted of driving around Göteborg to find different noise sources. The city route consists of many different elements such as tramway crossings at Korsvägen, driving along the tramway at Svingeln, roads with noise barriers at Wieselgrensgatan, railway crossings and switchgear at Lackarebäcksmotet, electrical lines in the air above the road at Kallebäcksliden. It also includes some additional bridges (Röde orm, Götaälvbron) and tunnels (Götatunneln).

The Huskvarna steel slag asphalt route

This purpose of this route was to measure if steel slag asphalt yielded any magnetic disturbances and was performed at E4 outside of Huskvarna between Trafikplats Huskvarna Södra and Trafikplats Huskvarna Norra.

The bridge route

The bridge route was performed to find as many bridges of different types as possible. The route consists of the following bridges; Angeredsbron, Jordfallsbron, Nordreälvbron, Stenungsöbron, Källösundsbron, Tjörnbron, Skåpesundsbron, Nötesundsbron and Uddevallabron.

The Fagersta route

The Fagersta route was conducted in order to use the test rig to measure the magnetic markers that Trafikverket has placed in their test road, RV68 in Fagersta.

3.3 Magnetic markers reference measurements

In order to understand how large the magnetic background noise is compared to the suggested magnets, reference measurements were conducted. The method used and further results from the measurements can be found in *Appendix B – Magnetic intensity measurements.* Each sensor has its own scale factor to convert from the sensor test rig's scale to µT, see Table 1.

Table 1: Scale factor for each sensor for converting from the test rig's scale to µT.

AU	Sensor	Volt	Scale factor
AU1	**1**	3,3001	***0,2219***
	2	3,2813	***0,2232***
	3	3,2818	***0,2232***
	4	3,3071	***0,2215***
	5	3,2927	***0,2224***
AU2	**1**	3,2895	***0,2227***
	2	3,3083	***0,2214***
	3	3,3022	***0,2218***
	4	3,3026	***0,2218***
	5	3,3102	***0,2213***
AU3	**1**	3,2993	***0,2220***
	2	3,3012	***0,2219***
	3	3,3030	***0,2217***
	4	3,2937	***0,2224***
	5	3,3114	***0,2212***

3.4 No significant magnetic disturbance

Several situations that were expected to yield magnetic disturbances did no such thing. Measurements were conducted at the following situations;

- Roads close to switchgears.
- Roads where electrical power lines are crossing the carriageway (see chapter 3.8.5).
- Crossroads with traffic lights.
- Some types of tunnels.
- Slag steel asphalt.

Figure 4 displays specific sites where these situations can occur. None of these situations yielded any fluctuation on the test rig used.

The tunnels themselves did not yield any magnetic disturbance but the entries and exits of the tunnels, where road expansion joints are placed, caused some fluctuation. This will be presented in chapter 3.7.3.

Figure 4: Situations where no magnetic disturbance was found, from top left to bottom right; Lackarebäck switchgear, Kallebäcksliden electrical power lines, Elisedal traffic lights, Gnistängstunneln, Huskvarna Steel Slag Asphalt. [3]

3.5 Highways measurement results

The measurement results for some of the national highways in Sweden as well as the Drive Me route in Göteborg have been processed in order to get an overview of the magnetic background noise and disturbances.

To understand the need of different magnets for the highways, the magnetic field intensity was divided into zones. These zones were defined according to the measured values from the magnets embedded in the road at Fagersta (see chapter 6) and the magnetic fields found during the highway routes, making it possible to distinguish how much of the driven distance on a highway route consists of magnetic noise that surpasses the intensity of each suggested magnet type. In chapter 3.1, it is presented how the measured data was taken care of and analyzed.

The long distances such as Göteborg to Stockholm were divided into smaller routes. The following data was analyzed for each route:

- The percentage of the distance that is in the magnetic disturbance field zone 1 to 4.
    - Zone 0 0-15 µT
    - Zone 1 15-60 µT
    - Zone 2 60 -150 µT
    - Zone 3 150-300 µT
    - Zone 4 300 and over
- Noise Max (µT)
- Noise Count
- Longest Noise Period (s)
- Average Noise Period (s)

In *Appendix C – Highway routes investigation* all the analyzed data from each of the four measured sensors can be found. A summary of the measurement data is presented in Table 2.

Table 2: Summary of the highway measurement results.

Route	Distance [km]	Disturbance worst case of total distance [km]	Disturbance worst case of total distance [%]	Worst intensity [µT]
Göteborg - Stockholm - Uppsala	536	18,5	3,5	432
Uddevalla - Göteborg	83	1,8	2,2	147
Göteborg - Heby	429	3,1	0,7	411
Heby - Fagersta	75	0,6	0,8	380
Drive Me (clockwise)	30	1,8	6,0	234

3.6 Highways analysis

After the analysis of each part in the route it is possible to understand how many strong magnets are needed for the magnetic disturbances at the national highways.

At the route between Hägersten (close to Stockholm) and Uppsala there are a lot of bridges lasting for more than five minutes (see Figure 14). Most of the bridges were in the Stockholm area. The percentage that needs strong magnets were in worst case 9,2% for this route (see *Appendix C – Highway routes investigation*). The rest of the route had 1% disturbance for the total distance. For the Drive Me route, the percentage of the road with disturbance is high, as seen in the area of Stockholm. The Drive Me route is the ring road around Göteborg, and many parts are bridges over or under other roads.

The highest value during all tests was detected at the route between Stavsjö and Hägersten; 430 µT (see Figure 5).

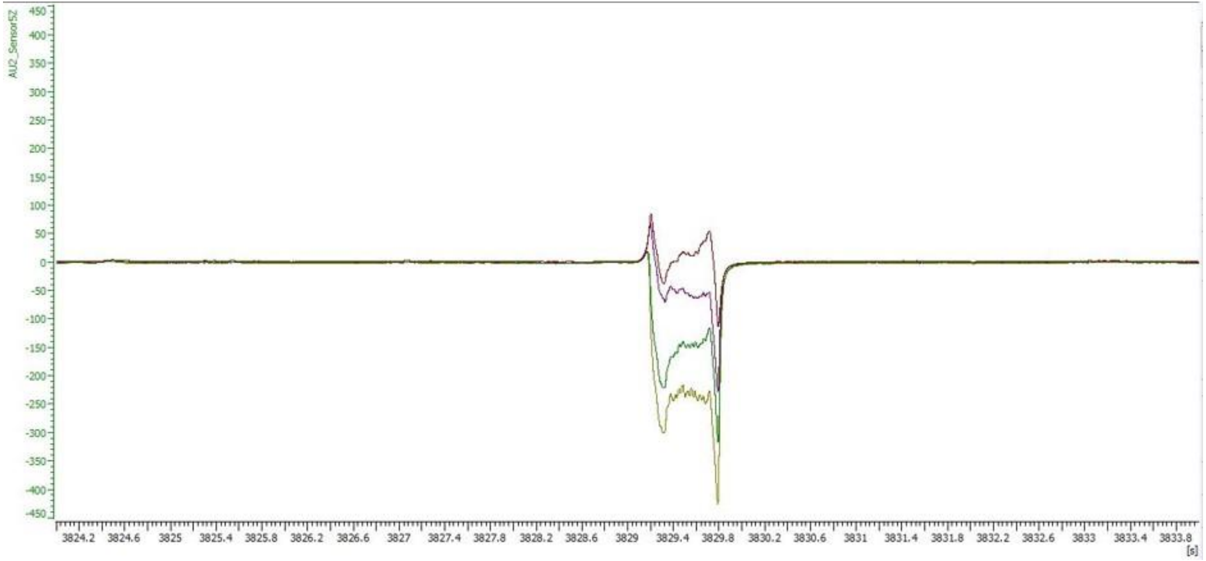

Figure 5: The highest value during all tests was detected at the route between Stavsjö and Hägersten; 430 µT. X-axis represents time [s] and Y-axis represents magnetic field [µT].

In general there are not many sections of the national highways that need strong magnets, less than 1% outside the big cities. In the big cities motorways are often on viaducts or other bridges that cause much magnetic field disturbance.

3.7 Magnetic disturbances from infrastructure

In this chapter bridges and road expansion joints are studied. The measurements of the road expansion joints are presented separately, since they occur at entrances/exits for bridges as well as for tunnels.

During the project several bridges have been measured, including:

- Älvsborgsbron
- Götaälvbron
- Angeredsbron
- Jordfallsbron
- Nordreälvbron
- Stenungsöbron
- Källösundsbron
- Tjörnbron
- Skåpesundsbron
- Nötesundsbron
- Uddevallabron
- Pedestrian tunnels under the motorway (to be regarded as small bridges)

3.7.1 Bridges measurement results

Some of the bridges cause extreme peaks up to 366 µT (see Figure 14). At short bridges, levels above 400 µT have been observed.

The bridges were sometimes measured in both directions, and often the results were not mirrored when driving in the opposite direction of the bridge; they can have a different amplitude and frequency. An example of this is Tjörnbron.

Some of the bridges have an access ramp that is very noisy, such as Jordfallsbron.

The bridges with the highest disturbances or the most interesting behaviour have been chosen and are presented below. The colours in the charts represent the z-axis for the four sensors used in the measurements (see chapter 3.1).

Älvsborgsbron

This bridge is part of the Drive Me route in Göteborg and it clearly shows of a high magnitude (see Figure 6).

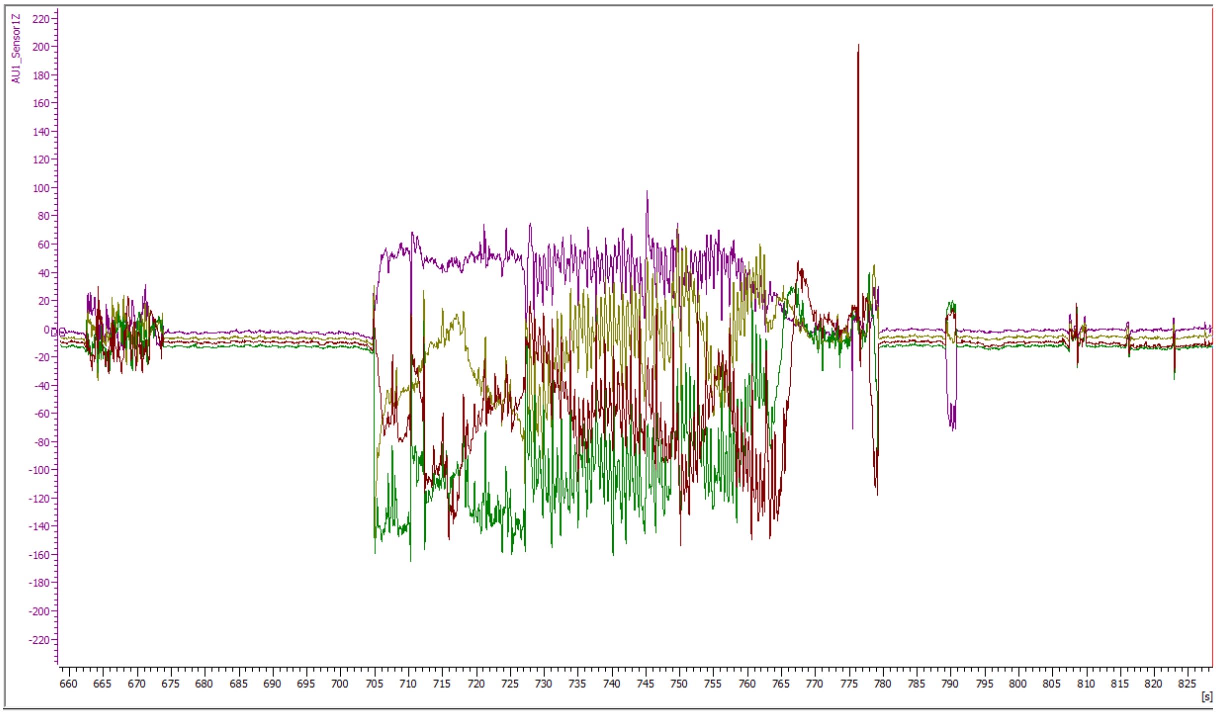

Figure 6: Älvsborgsbron in Göteborg on the Drive Me route in direction Frölunda. X-axis represents time [s] and Y-axis represents magnetic field [µT].

Tjörnbron

Tjörnbron is interesting due to the very high levels of noise on some of the signals. This bridge has the same average noise level as other bridges, but in some parts the bridge has peaks on AU1 sensor 2 that were above the measurable on the magnetic rig. Due to the fact that the bridge has been measured many times and the extreme value always occurs at the sensor 2, this sensor is probably faulty at very high values.

The bridge differs between driving directions concerning amplitude, frequency or where the peaks are situated on the bridge; it is not a symmetric bridge when going in the opposite direction (see Figure 7 and Figure 8).

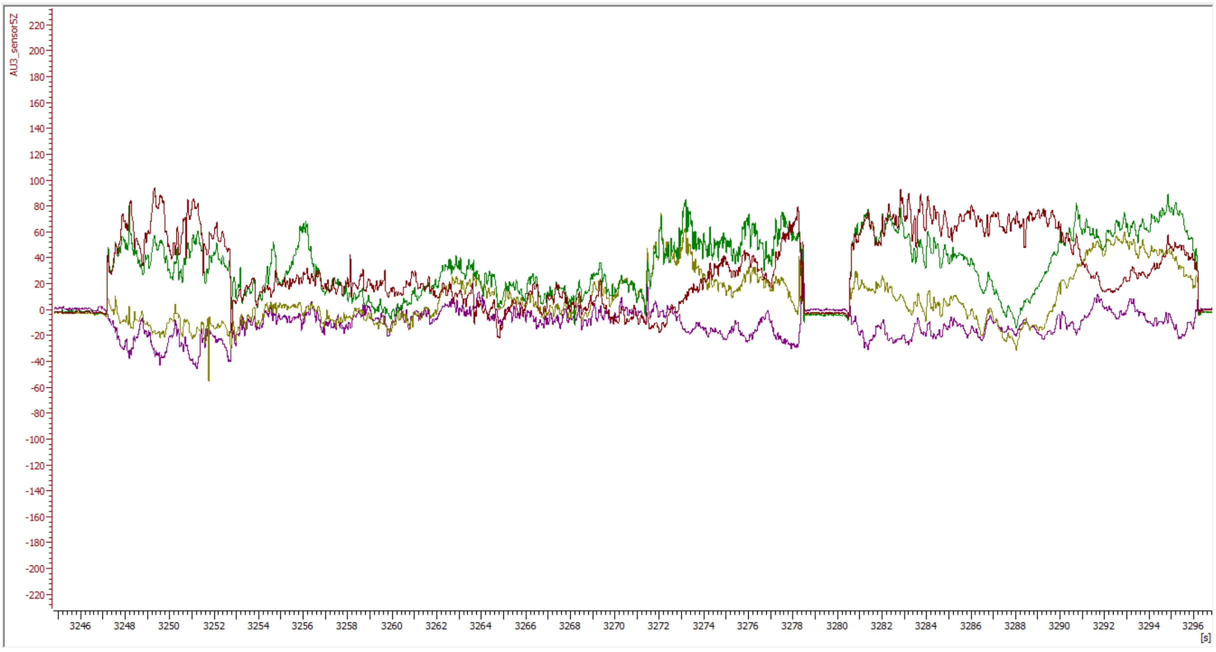

Figure 7: Tjörnbron in direction Orust. X-axis represents time [s] and Y-axis represents magnetic field [µT].

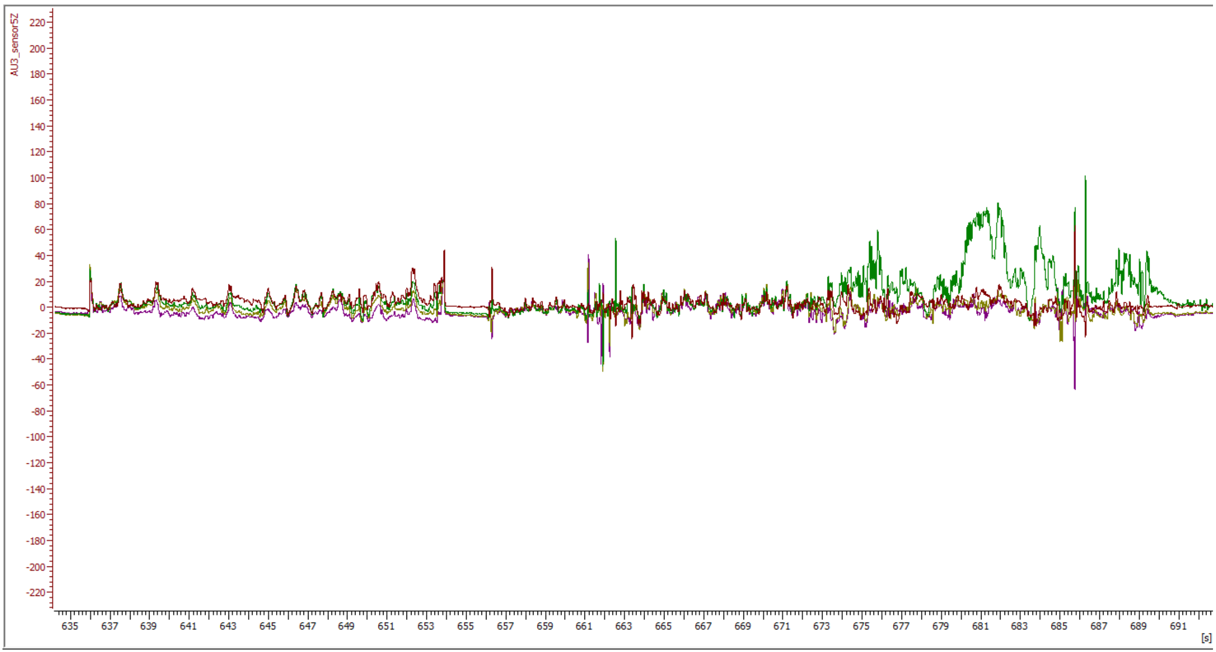

Figure 8: Tjörnbron in direction Göteborg. X-axis represents time [s] and Y-axis represents magnetic field [µT].

Tjörnbron has been measured in different speeds in order to see if the disturbance is speed dependent. There is no speed dependence (see Figure 9).

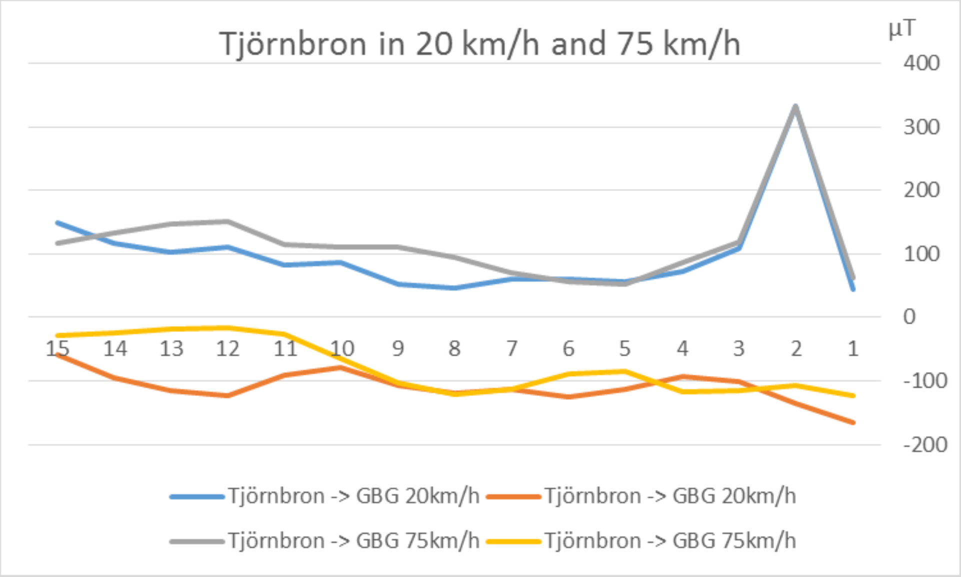

Figure 9: There is no velocity dependence for the magnetic field on Tjörnbron. X-axis represents the sensors 1-15 and Y-axis represents the highest and lowest peaks in the magnetic field for each sensor [µT].

Jordfallsbron

The access ramp to Jordfallsbron, with peaks up to 190 µT, is worse than the bridge itself, with peaks up to 55 µT (see Figure 10). The access ramp ends with a roundabout before the bridge, where the vehicle needed to stop; that is why there are two bursts of noise before the very bridge.

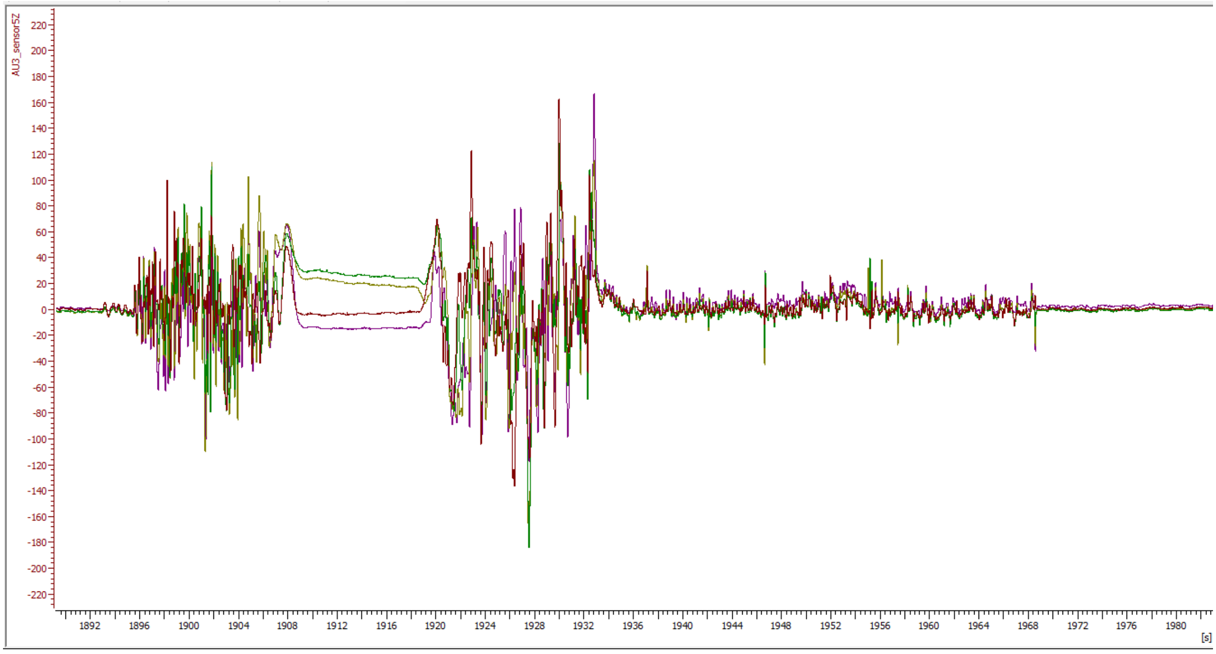

Figure 10: Jordfallsbron with the access ramp. The first part shows the access ramp then a stop for other cars in a roundabout and then driving in the roundabout before the actual bridge, Jordfallsbron that has a small magnetic field. X-axis represents time [s] and Y-axis represents magnetic field [µT].

Uddevallabron

On this bridge most of the signals are of the same pole direction, see Figure 11 and Figure 12, whereas some other bridges have random noise with signals of both pole directions at the same time.

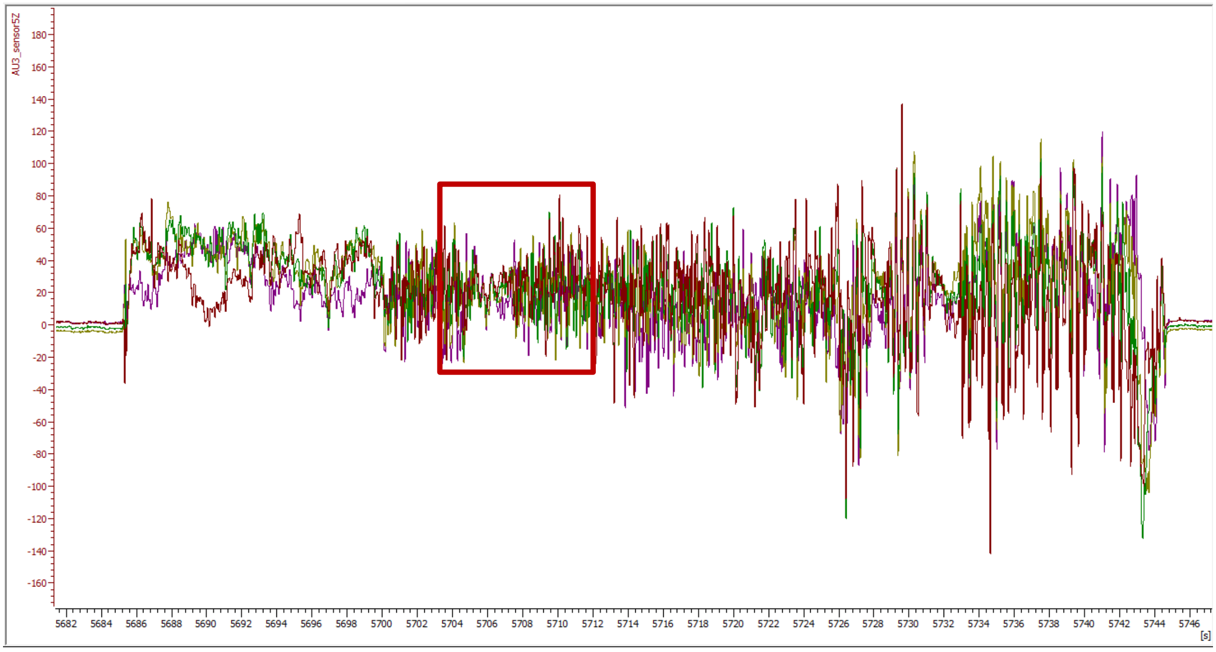

Figure 11: Uddevallabron; a bridge with some of the highest peaks and also a bit symmetric. The marked area is presented in Figure 12. X-axis represents time [s] and Y-axis represents magnetic field [µT].

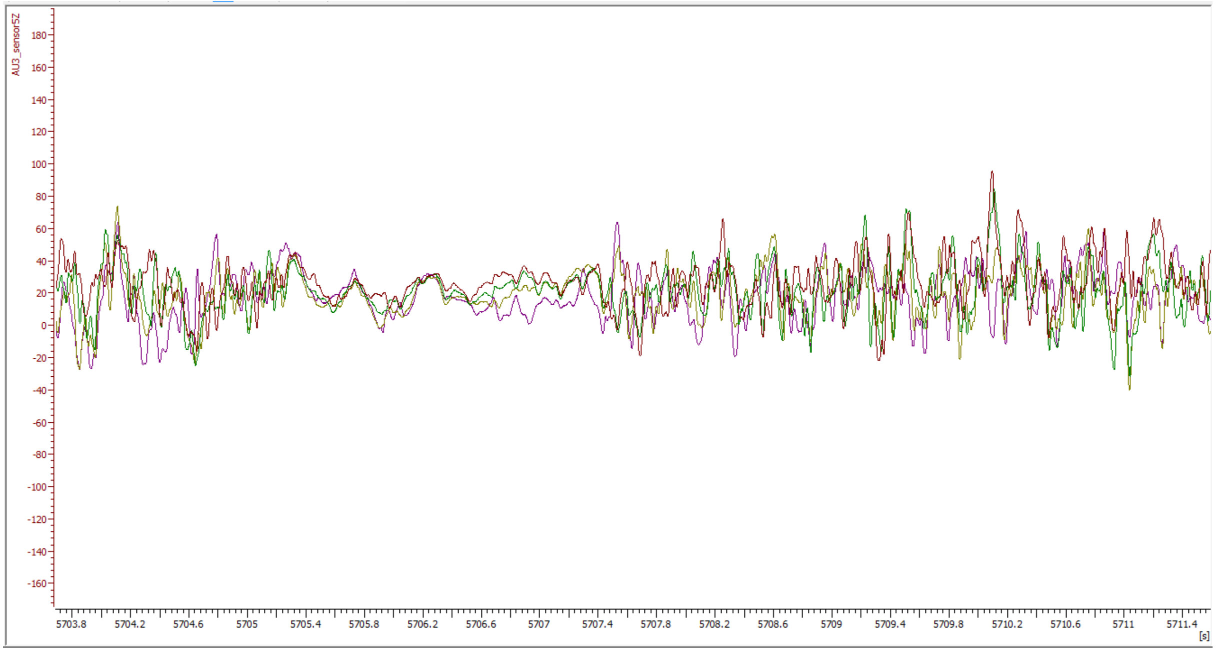

Figure 12: Part of Uddevallabron; note that the signals follow each other more or less. X-axis represents time [s] and Y-axis represents magnetic field [µT].

Magnetic offset bridge

Some of the bridges have a magnetic field offset (see Figure 13). This type of bridge may be possible to filter.

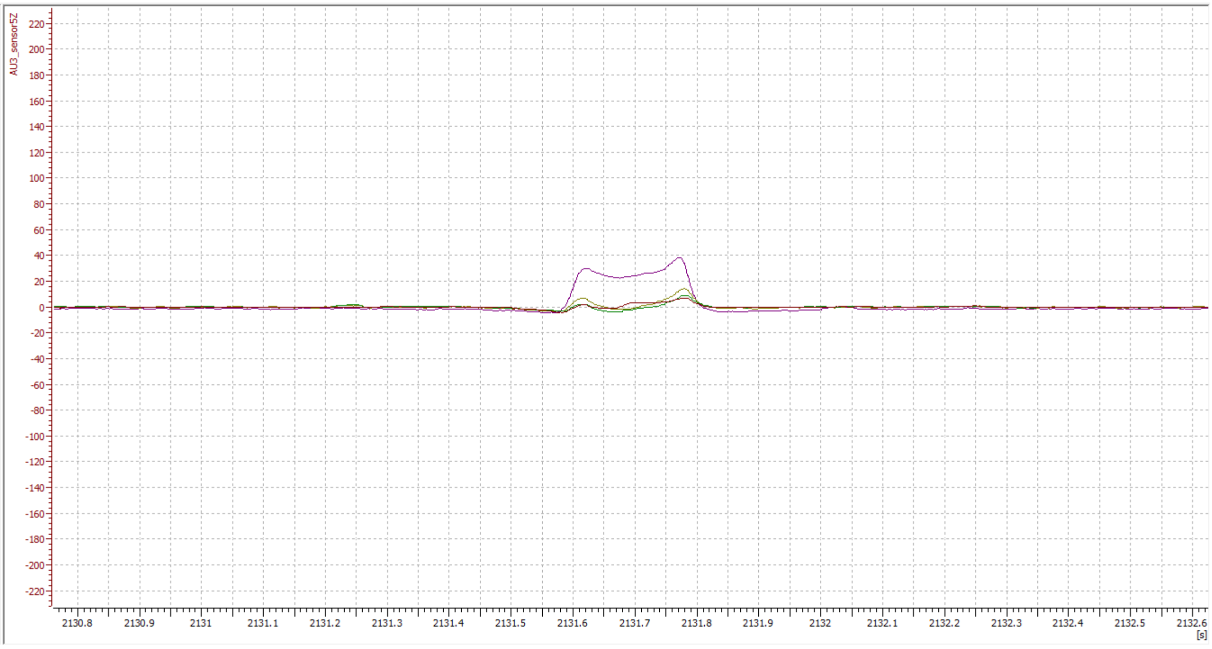

Figure 13: A bridge with an offset. X-axis represents time [s] and Y-axis represents magnetic field [µT].

Bridges from the Highway measurements

After the motorway exit 154 in Hägersten, close to Stockholm, heading towards Uppsala there are a lot of bridges with extremely high peaks – the worst peaks were at + 180 µT to -366 µT (Figure 14).

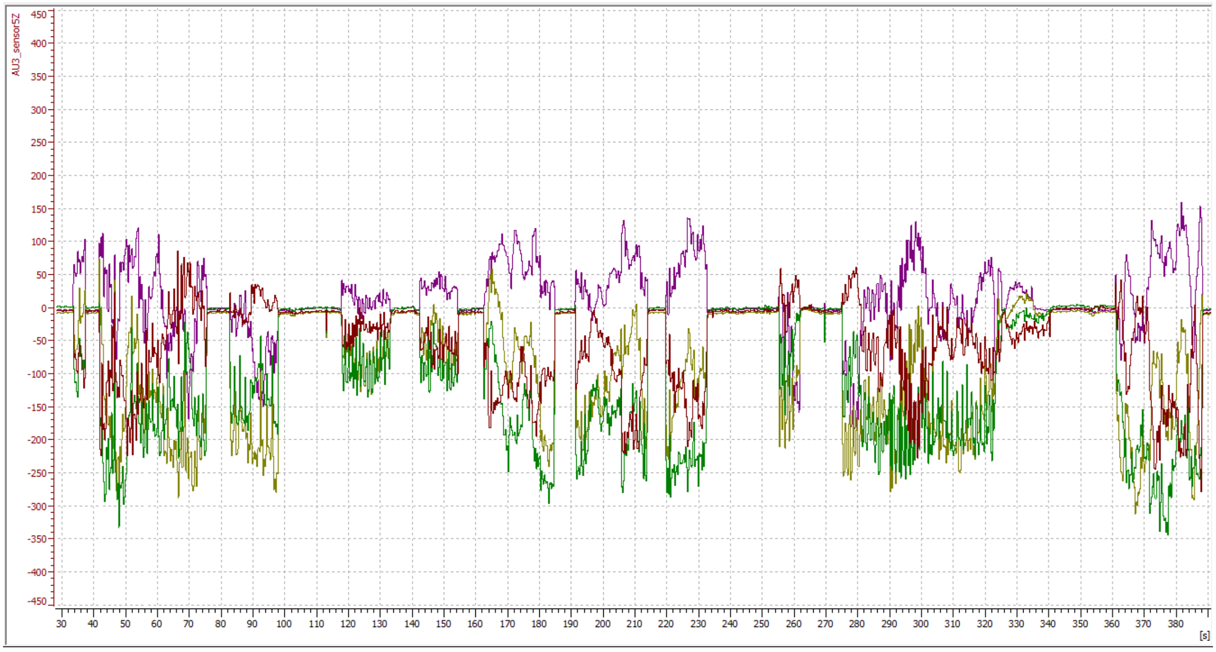

Figure 14: Cascade of bridges directly after Hägersten, close to Stockholm, on the way to Uppsala. X-axis represents time [s] and Y-axis represents magnetic field [µT].

Pedestrian and other small tunnels

There are many small tunnels under the main roads especially near the cities. In the road from Göteborg to Uppsala there were 109 small peaks < 0,5 s and many of them were recognized as small tunnels. The tunnels in the road are like very short bridges for the road above the tunnel, only a couple of meters long.

3.7.2 Bridges analysis

The bridges are made of different materials and constructions; that can be a possible reason that the bridges are so different in how the magnetic disturbances occur, both in amplitude frequency and pole direction. Some bridges have many random peaks and other bridges only have an offset.

If the sensors on a bridge get a coherent measurement result, as for Uddevallabron, it should be possible to filter the bridge. If the bridge has a magnetic offset it may be possible to use a filter.

The magnetic disturbance from bridges is often irregular; thus the filter must be more complex. If the bridge has a symmetrical noise then it should be possible to filter. Maybe the x- and y-directions of the sensor can help making a better filter for all of the bridges. This needs to be further analysed.

Another suggestion is to place two magnets close to each other, hereon called “double magnets”, at each magnet position - one North and one South Pole direction. These should be easier to find in the random noise. Maybe a combination of stronger double magnets and a filter is the best solution.

Bridges need to be independently examined to understand how big the magnets need to be or if it is possible to filter.

3.7.3 Road expansion joints measurement results

As mentioned in chapter 3.4, there was a noise found when entering and/or exiting tunnels due to the road expansion joints. Similar noises were observed at the entrances and exits of some of the investigated bridges. The peaks that come from the road expansion joints are often equivalent to the peaks on the very bridge.

In tunnels there are road joints at entrances and exits and in between there is little or no magnetic disturbance. Götatunneln is an exception, it has an access ramp and after there are extreme values up to 233 µT for a long time (see Figure 15). The tunnel is 1600 m where middle section 1000 m between is through the rock. The tunnel entry and exit is made of concrete reinforcement [4].

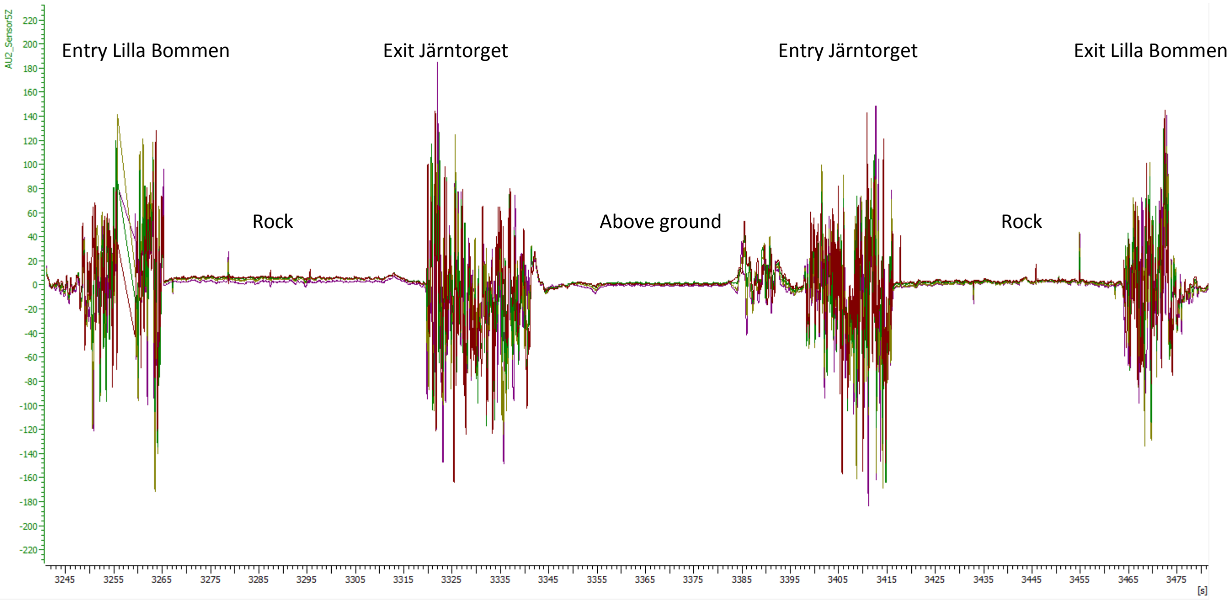

Figure 15: Götatunneln driven in both directions – note the long part of extreme magnetic disturbance for the entrance and exit in the tunnel. X-axis represents time [s] and Y-axis represents magnetic field [µT].

3.7.4 Road expansion joints analysis

The road expansion joints often cause large but short peaks in the beginning and end of the bridge. According to Anders Lie, Trafikverket, these are places where it is common to place different types of traffic measurement equipment for measuring traffic flow, speed etc [5]. This can be one potential source of disturbance. The road expansion joints look like they are done of iron; that can be another source of disturbance.

The road expansion joints should be possible to filter if all the measuring sensors get the same pole direction for the road expansion joints.

It should also be possible to put a strong magnet before them to mark that there will be a road expansion joint.

3.8 Magnetic disturbance from electrical sources

Tramways, railways and electrical power lines all have magnetic fields that can cause disturbance to the magnetic field sensor system. They are all presented in this chapter.

3.8.1 Tramways measurement results

The trams in Göteborg are running on 750 V and typically 1000 A direct current, DC [6]. The magnetic field occurs mainly from the flow of current through catenaries, through the electric motor, with the return in the rails. There is almost no magnetic field from the electric motor because it decreases by the third power of the distance from the electric motor.

A DC magnetic field from a tram is not totally static; it changes depending on the current from the tram. The track will have a magnetic field all the time where the current is supplied and not only when a tram passes by. Measurements in Göteborg showed that after the last tram on a line had stopped for the evening, there was still a magnetic field on the line. This magnetic field came from the return current from other lines' trams, which were still in traffic [6].

The measurements for trams

Three tests were performed with the test vehicle to see how the magnetic field behaved:

1. Driving along the rails.
2. Driving across the rails.
3. Parked near the line.

Trams in general have a noise level with most peaks less than +100 µT and -100 µT. Peaks up to +163 µT -206 µT have been measured at acceleration.

Driving along the rails

At the road from Svingeln to Polhemsplatsen two different tests were performed.

In the first test the vehicle followed right behind the tram. The tram had a peak +137 µT at acceleration and then the levels were constant at about +60 µT and – 40 µT (see Figure 16).

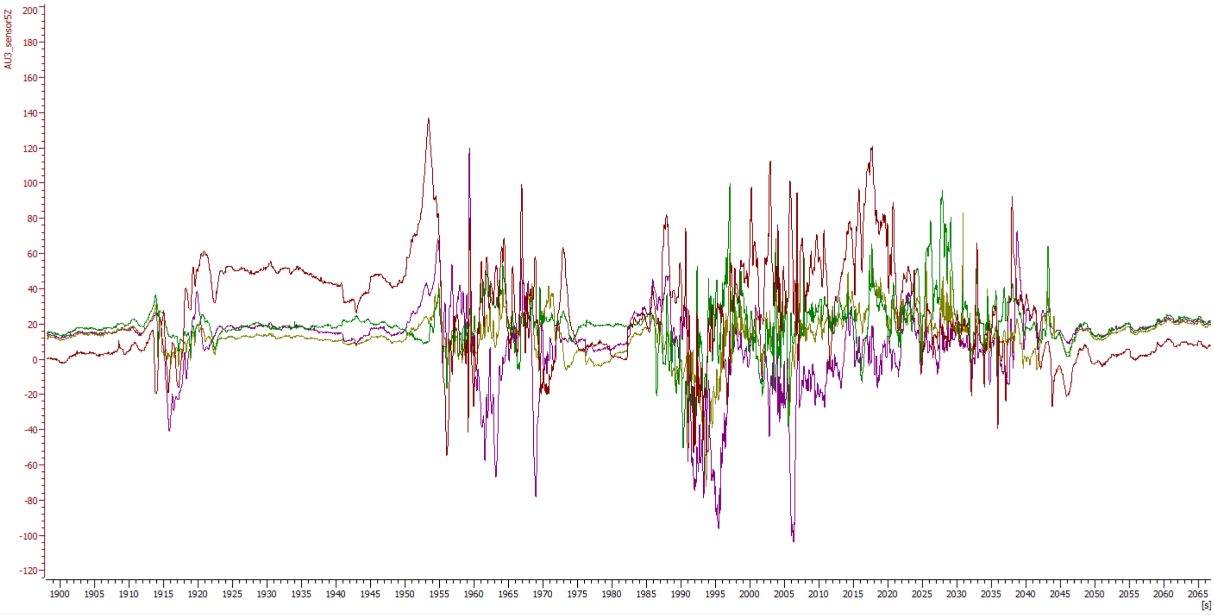

Figure 16: Vehicle follows a moving tram. X-axis represents time [s] and Y-axis represents magnetic field [µT].

For the second test, as the tram went by the vehicle entered the rails and stood still on the rails and measured the magnetism. During the total period of 68 seconds the tram level were in average about +20 µT to -40 µT and with peaks about -150 µT (see Figure 17).

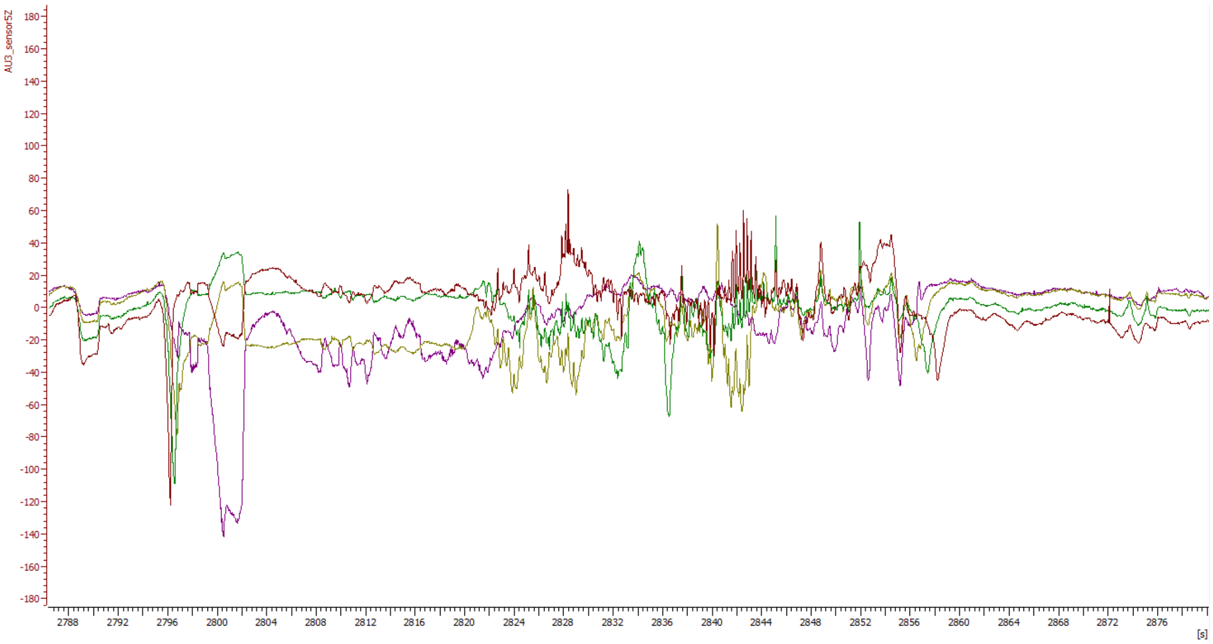

Figure 17: Vehicle on the rails measures the magnetic field of the tram that moves away from the vehicle. X-axis represents time [s] and Y-axis represents magnetic field [µT].

Driving across the rails

At the large roundabout Korsvägen in Göteborg some tests were performed. The level was measured after the tram had passed the vehicle; then the rails were crossed.

1. **Accelerating tram**

   This test had the biggest impact for magnetic field; the levels are around -150 µT to -200 µT.
2. **Decelerating tram**

   This test also gives a high level +65 µT to 162 µT and -100 µT to -140 µT but lower than for acceleration.

Parked car near rail

The vehicle was parked close to the tram rails, next to the passport office in Svingeln in Göteborg. Therefore it was possible to isolate how the passing trams affect the magnetic field in their proximity.

The effects when the vehicle is parked near the rails are:

- The noise level has about 190 % larger average amplitude than the usual magnetic background noise (see Figure 18).
- During an eight minutes period five trams (old, medium old and new trams) passed in the meeting direction and one in the vehicle's direction. None of them caused a magnetic field visible above the usual magnetic background noise level for the car parked near the rail.

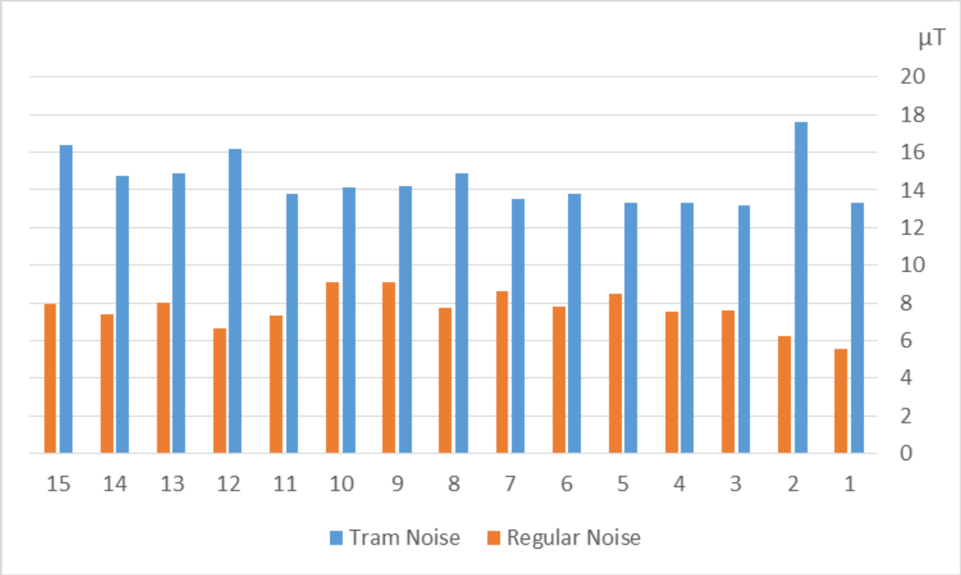

Figure 18: Noise measurement at a vehicle parked next to the rail and normal magnetic background noise when driving a vehicle. The levels of sensor 1 to 15 are shown.

3.8.2 Tramways analysis

Most parts of Göteborg have separated lanes for vehicle and trams or the vehicles only cross the rails. At Svingeln, Vasaplatsen and Sahlgrenska there are trams and vehicles in the same lane for shorter distances. Due to the high magnetic fields up to 200 µT, strong magnets in the road are needed for crossing and driving in tram lanes.

Tramways are probably difficult to filter because they have DC magnetic fields with changing amplitude. The different sensors on the test rig do not have the same amplitude and pole direction all the time.

Note that this report does not take into account if the public transportation administration in Göteborg, Västtrafik, has any issues with the permanent magnets in the road possibly disturbing their trams.

3.8.3 Railways measurement results

The magnetic field in railways in Sweden occurs mainly from alternating current, *AC,* with a frequency of 16 2/3 Hz. The locomotive motor does not yield any magnetic field that the measuring vehicle will notice. The magnetic field occurs mainly from the flow of current through catenaries, through the electric motor, with the return in the rails. To eliminate stray currents and disturbances from the return rails that will interfere with the surroundings a booster transformer is used, obliging the return current to flow to the return conductor (see Figure 19) [7], [8]. Usually the distance between the booster transformers is 5000 m so the magnetic field persists as long as the locomotive is in the section between two booster transformers. When Trafikverket did an investigation of the magnetic fields in the not yet built Västlänken they suggested having 1000 m between the booster transformers, so the magnetic field should last for a shorter period of time [8]. The maximum magnetic field is during the acceleration of the train. The magnetic field can differ a lot depending on the train and how it is driven, and also if there are more than one train between the booster transformers.

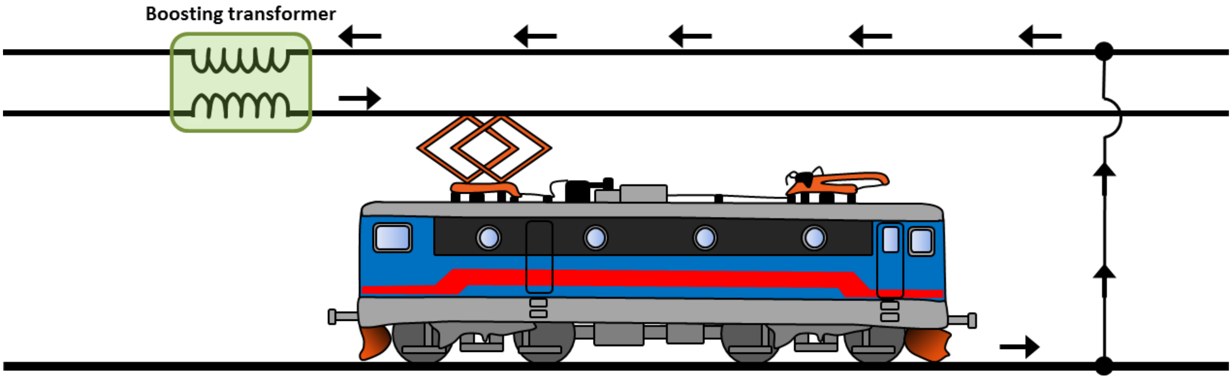

Figure 19: Schematic illustration of a boosting transformer for railways.

The Trafikverket document [8] states that during 24 hours the maximum RMS-value was 8,28 µT and that the distance from the centre of Gårda train tunnel to the road above is 13,1 meters.

When measurements were performed on a bridge near the ÅF house in Göteborg, with moderate disturbance level +26 µT to +38 µT and -15 µT to -32 µT and a passing train underneath, the magnetic field from the train was not discernible through the noise from the bridge.

3.8.4 Railways analysis

The railways are only in proximity to road vehicles at bridges over or under the roads or in railway tunnels under the road.

To deal with the railway magnetic field on the bridge the stronger magnets that are needed for the bridge itself ought to be enough. For railway tunnels under the road it will be more difficult to find out exactly where they disturb. A filter for 16,7 Hz magnetic field will eliminate the need to find these disturbances.

Most bridges across railways need magnets that are stronger than the disturbance from the railway, thus there is no need for a filter.

3.8.5 Electrical power lines measurement results

Most of the measurements from electrical power lines are not recognized at all, as was the case in Kallebäcksliden in Göteborg. In Sala there are power lines that show the typical 50 Hz AC magnetic field (see Figure 20 and Figure 21), but the magnetic field disturbance is low.

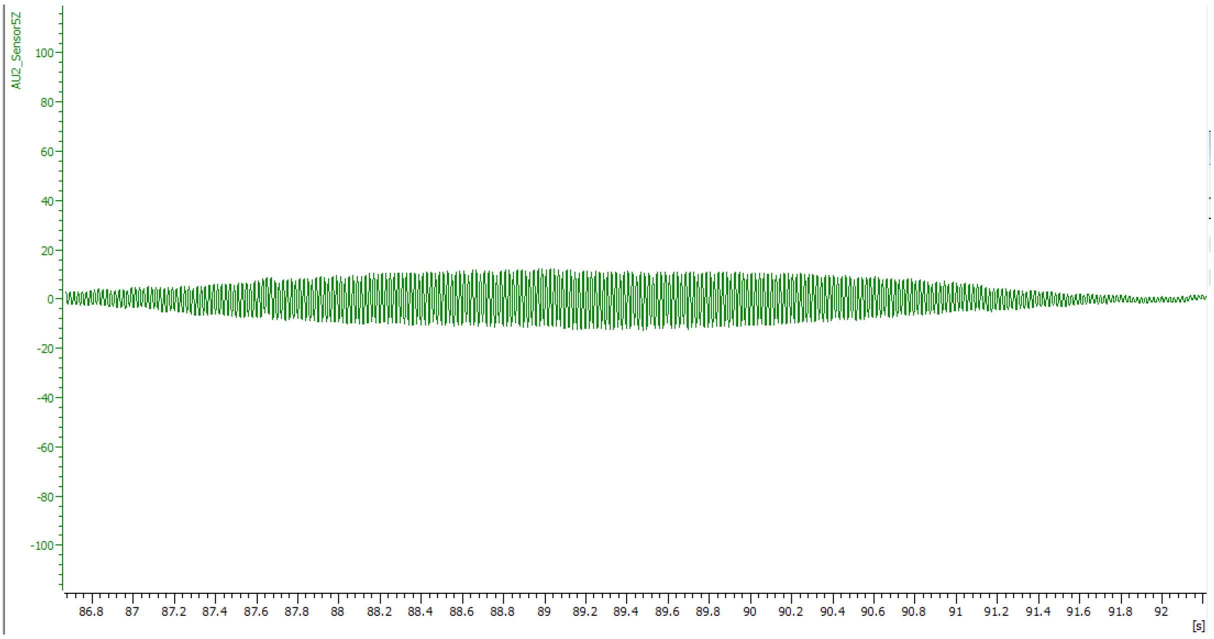

Figure 20: Magnetic field below the power line at Sala. X-axis represents time [s] and Y-axis represents magnetic field [µT].

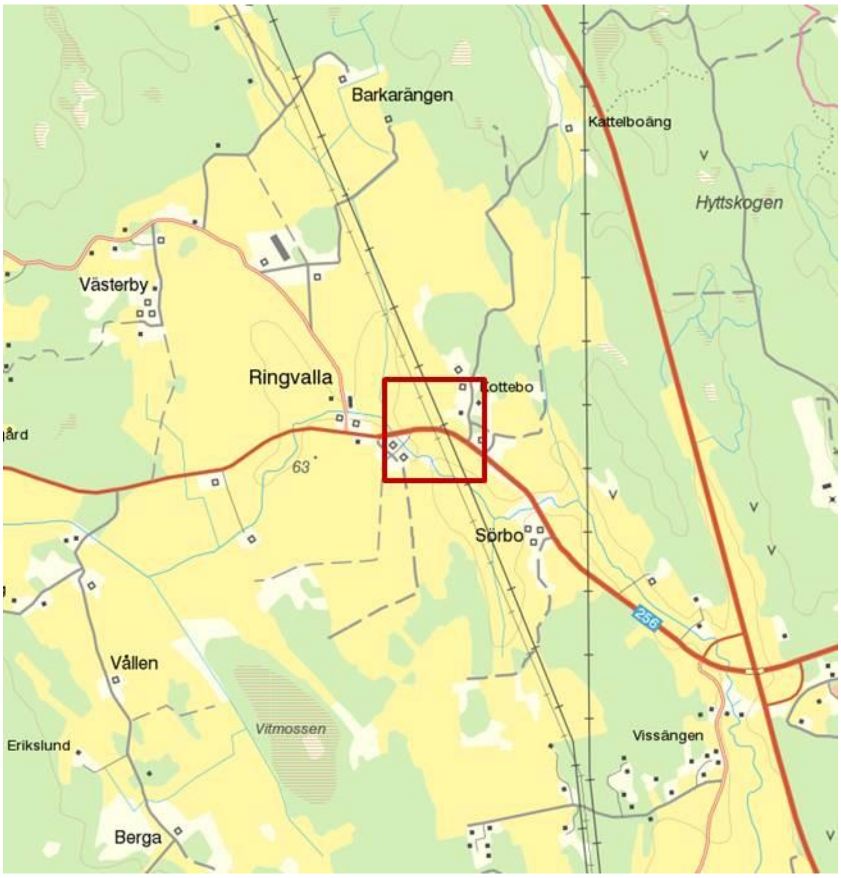

Figure 21: Map of the power lines in Sala [9]. GPS position: N 59.917172; E 16.511523 is marked in the red square.

The Strålskyddsmyndigheten brochure [10] states that right below the largest power lines (400 kV AC) the magnetic field is 10 µT to 20 µT (see Figure 22). There can be momentary values up to 100 µT right under the largest power lines (400 kV AC) at high power consumption [11].

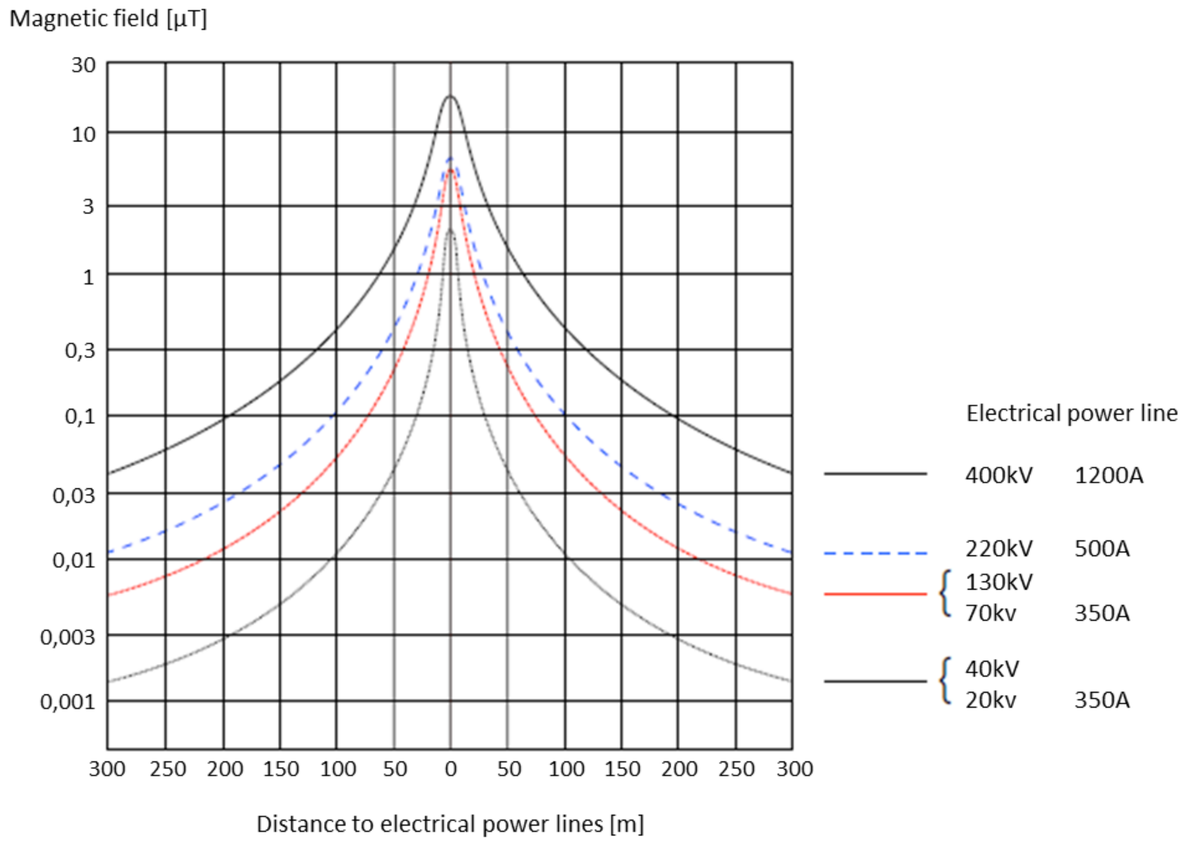

Figure 22: The magnetic field for different AC power lines [10].

3.8.6 Electrical power lines analysis

AC power lines usually cause a small magnetic disturbance; below the largest power lines (400 kV) the magnetic field is 10 µT to 20 µT [10] with momentary values up to 100 µT [11]. Due to the high magnetic fields of up to 100 µT, strong magnets in the road are needed right below the biggest power lines.

An idea is to make a filter that can eliminate the 50 Hz frequency (see Figure 20), but the suggestion is to add stronger magnets.

3.9 Magnetic disturbance from other sources

In this chapter other sources for magnetic fields, such as manhole covers and noise barriers, are presented.

3.9.1 Manhole covers measurement result

The manhole covers have a nice peak in the same way as a magnet has (see Figure 23). Magnetic field values about 30 µT have been measured.

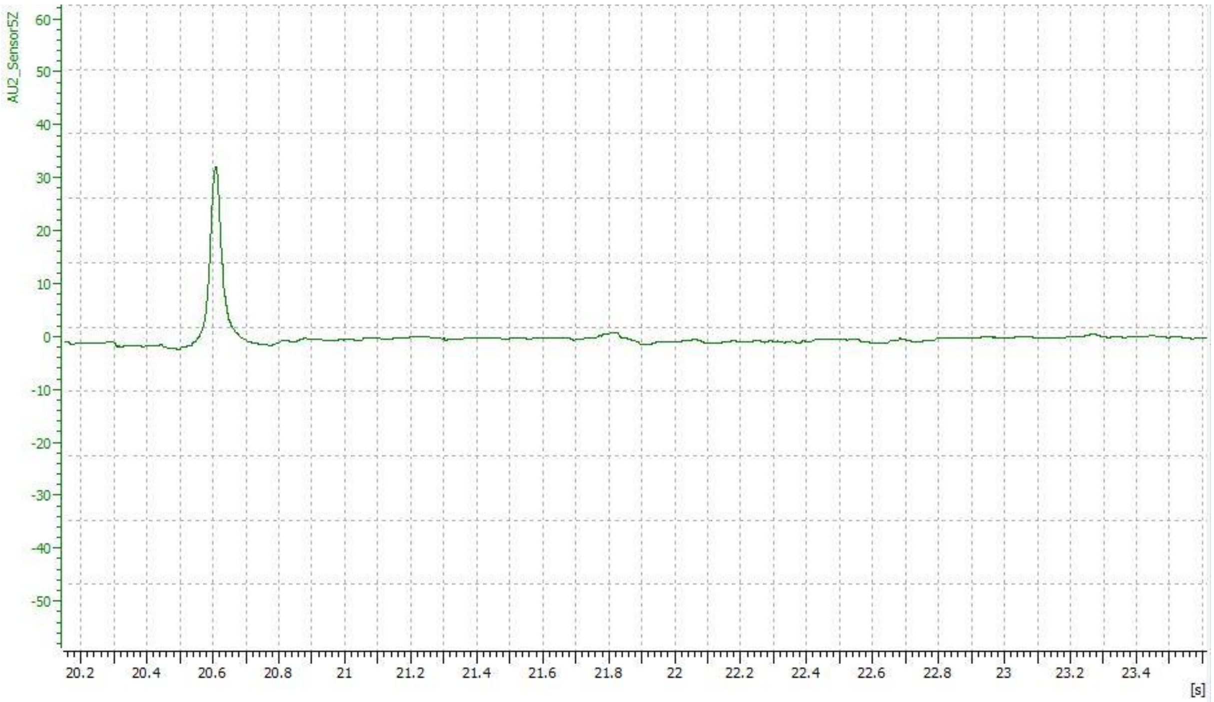

Figure 23: Manhole cover measurement. X-axis represents time [s] and Y-axis represents magnetic field [µT].

3.9.2 Manhole covers analysis

When driving over them, the manhole cover looks like a magnet to the magnetic field sensor system. The manhole cover differs from the magnets since it is bigger in diameter, but it could still be used as a reference for the position. There is no need to filter manhole covers out if there is a map where their position could be pointed out. Without a map, stronger magnets are needed to be detected over the magnetic field of the manhole covers.

3.9.3 Noise barriers measurement results

One street in Göteborg, Wieselgrensgatan, lined with noise barriers was found to have a larger background noise than other streets. The noise barriers that lined this road, the Kohlhauer Planta® [12], are made out of an aluminium frame, galvanized steel grid, plastic net and rock wool insulation [13] (see Figure 24). The distance between the lane and the barrier differs between the driving directions and the most noise was found when driving on the side that was further away from the barrier.

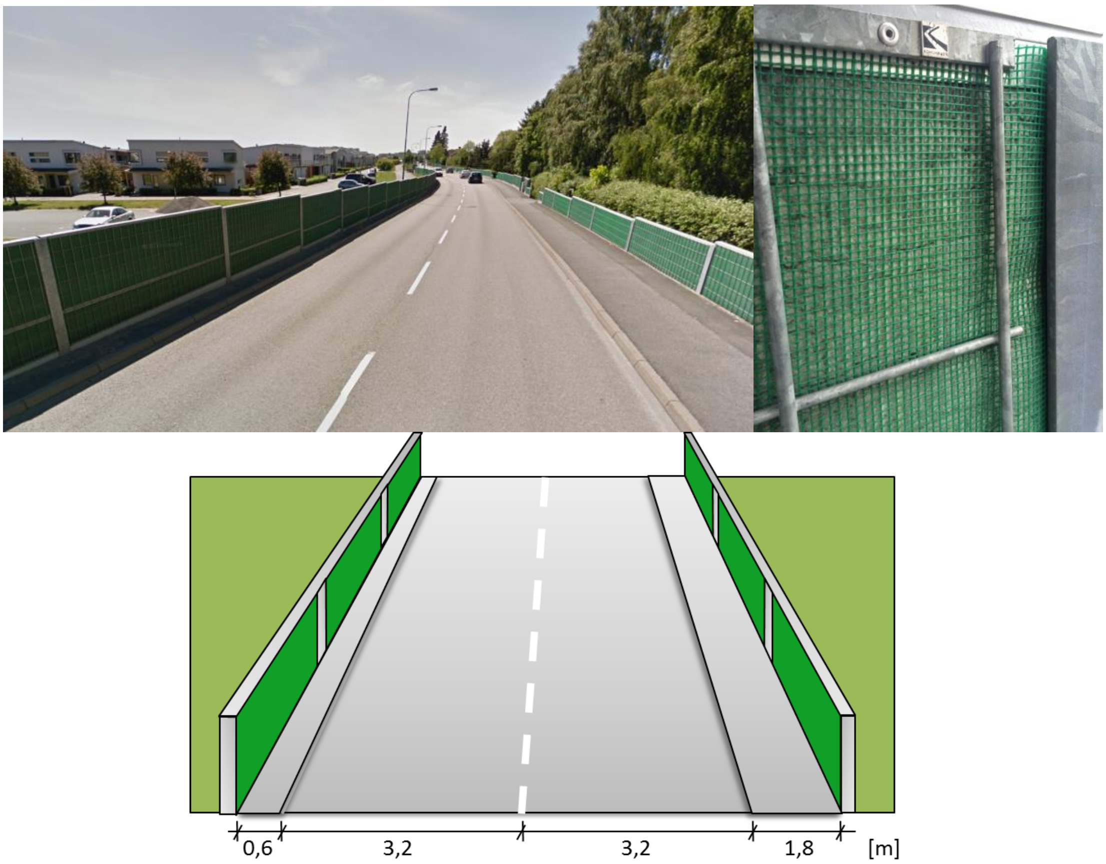

Figure 24: Noise barriers at Wieselgrensgatan in Göteborg. [3]

3.9.4 Noise barriers analysis

On this street, lined with noise barriers, some sort of magnetic noise is added to the measurements. Remarkably, the noise was larger when driving on the lane situated further away from the noise barrier. According to Anders Lindgren from GreeNest Form AB, the agency for these kinds of noise barriers in Sweden, this is probably due to electrical cables and similar buried in the ground. When mounting the noise barriers at this specific road (Wieselgrensgatan in Göteborg) it was found that a lot of cables were buried beneath the road [12]. The only material in the noise barrier that would cause the effect seen would be the galvanized steel, since neither aluminium nor plastic or stone wool is magnetic. It is unclear whether it is the noise barriers or the cables in the road that yield the background noise; thus further investigations regarding noise barriers are suggested.

3.10 Magnetic disturbance filtering

Some of the sources of magnetic disturbances, such as power lines, may look simple to filter at first. Filtering in real time, however, is far more complicated since it demands both knowledge of the upcoming disturbance and the need to apply the filter fast enough. Such filtering operation puts high demands and tough requirements on all the systems used for the vehicle magnetic positioning system.

Other sources of disturbances are not at all easy to filter, such as random noise bridges. Filters for these kinds of disturbances are complex and the possibility to use filters needs to be studied for each unique disturbance.

Applying filters to the sensor system may interfere with other on-board vehicle systems or take data priority before other systems. There is also a risk that an incorrect filter may disturb the detection of the magnetic markers. Using a complex filter may require a more complex hardware.

3.11 Required magnetic markers intensity

It is important that the vehicle magnetic positioning system is reliable, and thus robust. It is proposed to use a magnet about 4 times the value measured [2]. During the highway routes many of the national highways were measured; bridges had peaks up to 350 µT in Stockholm and on the route between Stavsjö and Hägersten the highest value during all tests was detected at 430 µT. The peak duration was < 0,1 s and the vehicle travelled in 30 m/s (see Figure 5).

The magnet needed for the worst cases will have a magnetic field of 1600 µT at 30 cm above the top of the magnet – this will require a big magnet. Anders Lie at Trafikverket proposed that for places with extreme magnetic disturbances, the magnet could be at the surface of the road instead of 10 cm below the surface which will induce magnets with less intensity and volume [5]. The total distance from the top of the magnet to the sensor will then be 20 cm. These magnets need to be the neodymium type instead of ferrite to keep the magnets’ volume moderate. The neodymium magnets have much stronger magnetic field than the ferrite magnets for the same volume.

In contact with Magnet Fabriken AB they told that it is not possible to calculate the size for the magnet to be optimal for the magnetic field, it is better to measure it [14]. A neodymium magnet and a ferrite magnet do not have the same behaviour; the ferrite works better as a disk and neodymium works better as a cylinder which is why they are measured in this report and not calculated. All the measurements have been performed in air and no magnets are below the asphalt in the tables below. The measurements of the Neodymium Neo35 have been done by Magnet Fabriken AB to help with these special magnets. The strongest magnet they have in stock is a Neodymium Neo35 with the diameter 75 mm and the height 10 mm. To get the right dimension they need to stack them together (see Table 3).

Table 3: Magnetic field intensity of Neo35 magnets measured by Magnet Fabriken AB.

Type of magnet	Dimension Diameter × height [mm]	Magnetic field distance sensor to top of magnet 200 mm [µT]	Magnetic field distance sensor to top of magnet 300 mm [µT]
Neo35	20x30	220	80
Neo35	75x20	1700	550
Neo35	75x30	2300	800

The measurements of the ferrite magnets have been done at ÅF, using the test rig and the same sort of disk magnets as used at the Fagersta test road stacked together to get the right dimension (see Figure 25).

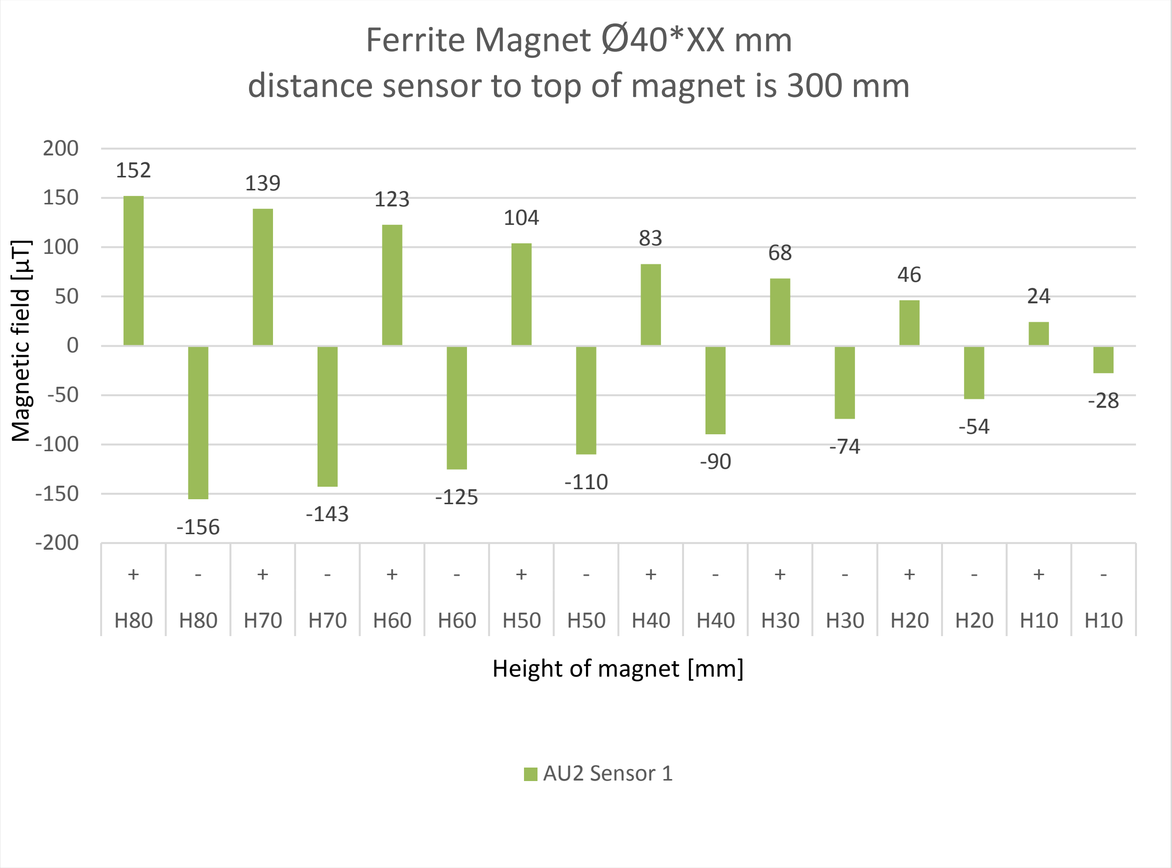

Figure 25: Diagram shows the magnetic field for the ferrite magnets with diameter 40 mm and the height from 10 mm to 80 mm, measured at distance of 300 mm.

The neodymium magnet is made of rare earth metals, so it is recommended not to use it except at special places where it is impossible to get the strength of the magnet with a ferrite magnet and still fit it in the asphalt at bridges and other places with special needs to penetrate the magnetic field disturbance. To roughly understand how many magnets of the different sizes are needed, the zone division from chapter 3.5 is used (see Table 4). As seen in Table 4, it is suggested that the standard magnetic marker shall be a ferrite magnet with the dimensions of Ø40x30 mm that is embedded with the top of the magnet 10 cm below the road surface.

Before magnets are purchased in big quantities, it is recommended to optimize the right size of the magnets and test them embedded in a road with the correct magnetic noise and disturbances.

Table 4: Zone division used in highway measurement compared to different magnets.

	Magnetic disturbance [µT]	12dB [µT]	Type of magnet	Dimension Diameter x height [mm]	Sensor to top of magnet [mm]	Magnetic field [µT]
Zone 0	0-15	60	Ferrite	40 x 30	300	70
Zone 1	15-60	240	Neo35	20 x 30	200	220
Zone 2	60-150	600	Neo35	75 x 20	300	550
Zone 3	150-300	1200	Neo35	75 x 20	200	1700
Zone 4	300 and above	1600	Neo35	75 x 20	200	1700

3.12 Magnetic disturbance discussion

The magnetic disturbance can be divided into three categories:

- Magnetic fields that do not need to be eliminated.
- Magnetic fields that may be possible to filter away.
- Magnetic fields that cannot be filter away and where the suggested solution is to install magnets that are stronger than the standard magnetic marker of Ø40x30 mm ferrite magnets.

Some cases may need a combination of magnets that are stronger than the suggested standard magnetic marker as well as a filter – these are discussed with the third case; stronger magnets.

Magnetic field disturbances that do not need to be eliminated
If a map is used the magnetic field peaks from manhole covers can be used as additional magnets for positioning.

Magnetic field disturbances that can probably be filtered away
All of the magnetic disturbance from electrical AC sources like railways and electrical power lines may be possible to filter.

Road expansion joints may be possible to filter if all the measuring sensors get the same pole direction for the peak.

The problems with filters are that it may be complex to filter in real time, and that the filters may interfere with both other on-board vehicle systems and the detection of the magnetic markers. Complex filters are probably required and such filters may need more complex hardware.

Magnetic field disturbances that need strong magnets
Some of the bridges cause extreme magnetic field values. It would be wise to make an investigation about each extreme value bridge to see if it is possible to filter disturbances away totally or to an acceptable level. Another suggestion is to place two magnets close to each at each magnet position - one North and one South Pole direction. These should be easier to find in the random noise. Maybe a combination of stronger double magnets and a filter is the best solution.

Due to disturbances from trams, strong magnets are needed. The disturbance is probably difficult to filter because the tramway has a DC magnetic field with an amplitude changes all the time.

4 Magnetic markers pattern

In "Vehicle Positioning with Magnets in a Carriageway" [1] it was concluded that the pattern of the magnetic markers is very important in detecting and predicting the vehicle's position. The suggested pattern consisted of 7 lateral lanes of magnets with the longitudinal distance of 2,8 m. This research project investigated if the pattern can be changed to use fewer magnetic markers and if information can encoded into the pattern.

4.1 Simple or complex systematic pattern

The first question to study regarding the magnetic markers pattern is if the pattern shall be simple or complex systematic – the specification of the pattern is decided by this. The pattern needs to be robust enough to be detected by all vehicles with a magnetic field sensor system. Arbitrary pattern has been ruled out since there are no winnings with such a pattern and since a systematic pattern is needed to fulfil the project specifications of detecting magnetic markers both laterally and longitudinally. Figure 26 shows three different systematic patterns and an arbitrary pattern.

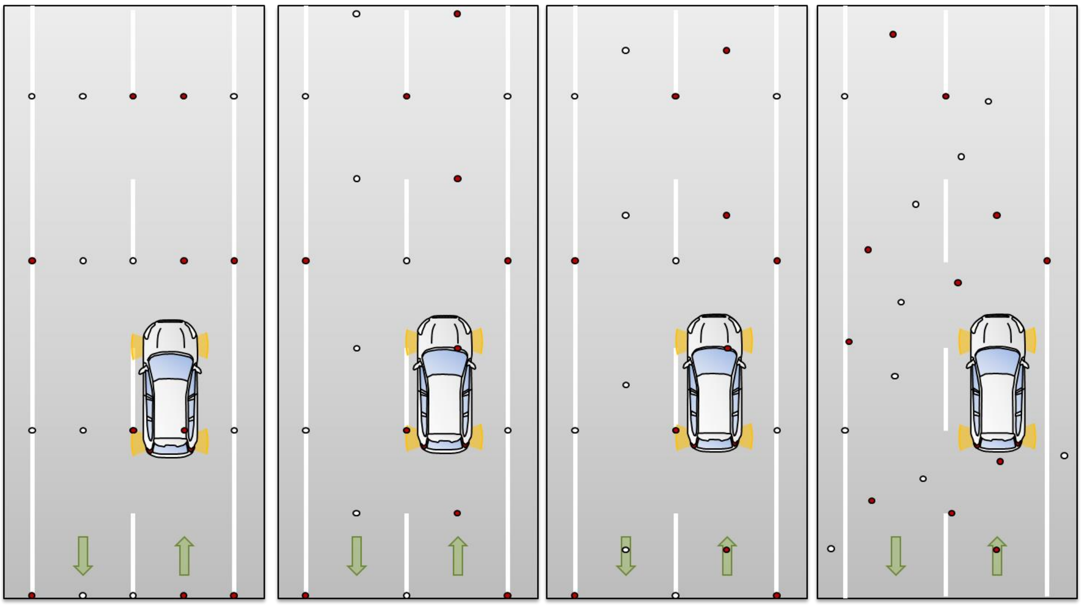

Figure 26: Example of three systematic and one arbitrary pattern, where the vehicle in the arbitrary pattern does not detect any magnetic markers.

4.1.1 Simple or complex systematic pattern theory

A simple systematic pattern, based on the already existing road marks, have many benefits:

- It is easy to mount since the pattern is using the existing road marks as base, thus less tolerance is needed during mounting.
- A simple pattern does not need scaling and makes it easy to predict when the next marker will appear during driving.
- A simple pattern should be easy to make detectable by all vehicles. It can also be used for current vehicles that have no map but have an advanced active safety system in conditions where road marks cannot be detected by any other means but the magnetic markers (for example in snowy conditions).
- It is not necessary to use a map for a simple systematic pattern, but it can still be useful for the positioning of the vehicle and to inform about magnetic field disturbances.

A drawback of a simple systematic pattern based on the road marks is that if the vehicles become narrower or the lanes become wider, then there is a risk of the distance between the markers being too wide to detect them with the magnetic field sensor system (see chapter 4.3 for more regarding this).

The main reason for using a complex systematic pattern is that a well thought-out pattern may require a smaller amount of magnetic markers. However, the complex pattern has drawbacks such as:

- A complex pattern is difficult to mount using the road marks as base and needs higher tolerance when mounting.
- Scaling is needed to determine where the markers are, thus a map is necessary for a complex systematic pattern. If a map is not used, the algorithms used for positioning will be very complex since it will be harder to predict where the upcoming markers are and to get information regarding magnetic disturbances.
- The pattern is not only complex in its appearance, but also complex to determine the layout in order to gain any benefits regarding amount of markers used.
- It is difficult to ensure that the most effective pattern when it comes to amount of markers used is detectable for all vehicles due to higher demands on margins and mounting tolerances.

4.1.2 Simple or complex systematic pattern analysis

As seen in chapter 4.1.1, there are both benefits and drawbacks for each pattern.

The simple systematic pattern is suggested to be based in the already existing road marks, such as edge lines and lines between lanes, and to place all markers on the same lateral axis. This will simplify the mounting and the algorithms for predicting when upcoming magnetic markers will appear. Between that and the fact that less mounting tolerance is needed than for a complex systematic pattern, the mounting cost could be limited. A complex systematic pattern requires a complex solution on how the pattern itself will be designed and higher mounting tolerances, yielding a more difficult mounting of the markers than for the simple pattern – a saving in cost from decreasing the number of markers would be decreased or even eliminated by the additional cost of pattern design and mounting. A complex pattern will also increase the difficultness of predicting where the next marker is compared to with a simple pattern and makes it harder to ensure that all vehicles can detect the magnetic markers they need.

Comparing these two types of patterns yields to the conclusion that a simple systematic pattern based on already existing road markers is suggested and will therefore be the base of further chapters regarding magnetic markers pattern study.

4.2 Encoded information within the pattern

The magnetic markers pattern can be used to encode information within the road. In this chapter the possibility to do so is studied. It is assumed that a simple systematic pattern is used, in accordance to chapter 4.1.2.

4.2.1 Encoded information within the pattern theory

To encode information within the pattern is obviously possible in a systematic pattern. The information can be encoded in different ways, such as using the magnet's pole orientation and changing the density or intensity of the magnetic markers (i.e. placing them closer or further to each other).

The benefits with encoding information within the pattern are many. It would be possible to indicate which side of the road the car is on by have the south poles of the magnets facing up in one direction and north poles facing up in the other. It would be possible to distinguish between different longitudinal marker lines if the magnetic poles are used differently in each line, for example alternating between North and South Pole up in the lines that indicate the different lanes and, as said before, keeping the same pole up in the middle of the lanes (see Figure 27). It would also be possible to add more markers close to each other or stronger magnetic markers for information. One way to use this is to indicate if the longitudinal distance between the markers is to change or if the magnetic markers road is ending. It can also be used for indicating an exit from the road or similar, or to indicate upcoming obstacles on the route.

The drawback with encoding information into the magnetic pattern is that it is very hard to change. There is of course a possibility to dig up and replace the magnetic markers or to shield them (see chapter 5) but it is a costly operation.

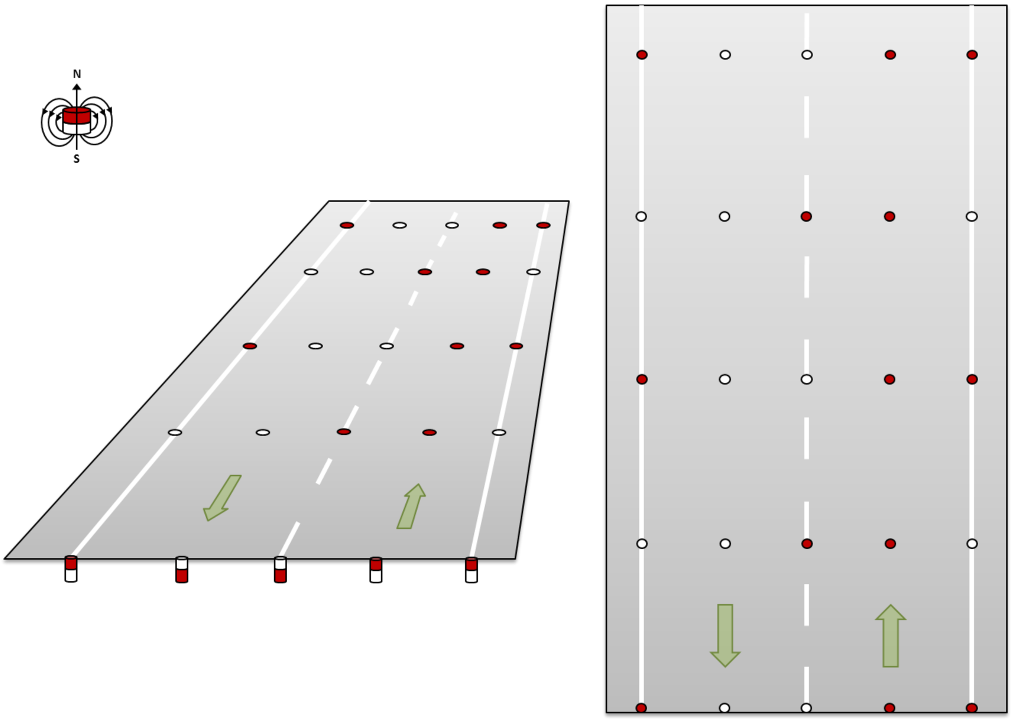

Figure 27: Example of how the magnetic poles can be used in order to encode information in the pattern.

4.2.2 Encoded information within the pattern analysis

To encode information into the magnetic markers pattern is a good idea in many ways. It can ease the positioning and help inform the system of changes in the road. By adding multiple or stronger markers at specific places on the road, the system can get information when a road with magnetic markers is about to end, if the distance between the markers are changing, if there is an upcoming obstacle on the road etc. Using the pole orientation of the magnets can help the system determine where in a lane the vehicle is placed and if the lane's driving direction is the same as the vehicle's driving direction.

Not being able to change the pattern in an easy way is of course a big drawback, but that has to be weight against how often a change is needed and if the change is possible to do during other road work to save cost, for example when repaving the road. Another way to change the pattern is to change the interpretation of the information on a specific road section. This would however require a map in the system that knows where the specific road section is.

A further analyse of the future needs to change pattern compared to what the cost would be is needed before it is possible to determine if encoding information is feasible for the Swedish roads.

4.3 Lateral pattern

This chapter will broach the subject of the lateral pattern of the magnetic markers. It is assumed that a simple systematic pattern is used, in accordance to chapter 4.1.2.

4.3.1 Lateral pattern theory

In "Vehicle Positioning with Magnets in a Carriageway" [1], the suggestion was 7 magnetic markers lateral for a single carriage road. The two additional markers were due to the requirement of being able to detect markers even though only two of the vehicle's wheels were on the roadway. That requirement has been relieved so that all four wheels are assumed to be on the roadway and therefore the two outer markers can be removed, remaining only 5 markers according to the first example in Figure 28.

Another pattern solution that has been investigated in this project is to keep only the two markers that are in the middle of each lane. This would yield a lot lower density of magnets thus keeping the cost down. The restraint is that the vehicle's magnetic field sensor system always has to be able to detect the magnetic markers in the middle of the carriageway no matter where in the lane it is positioned. To avoid a situation where the vehicle can drive in the middle of the road, between the markers, an additional third marker can be added in the middle of the road. Figure 28 illustrates the different lateral patterns compared to a Volvo V60 with a magnetic field sensor system that detects approximately 15 cm outside the vehicle width.

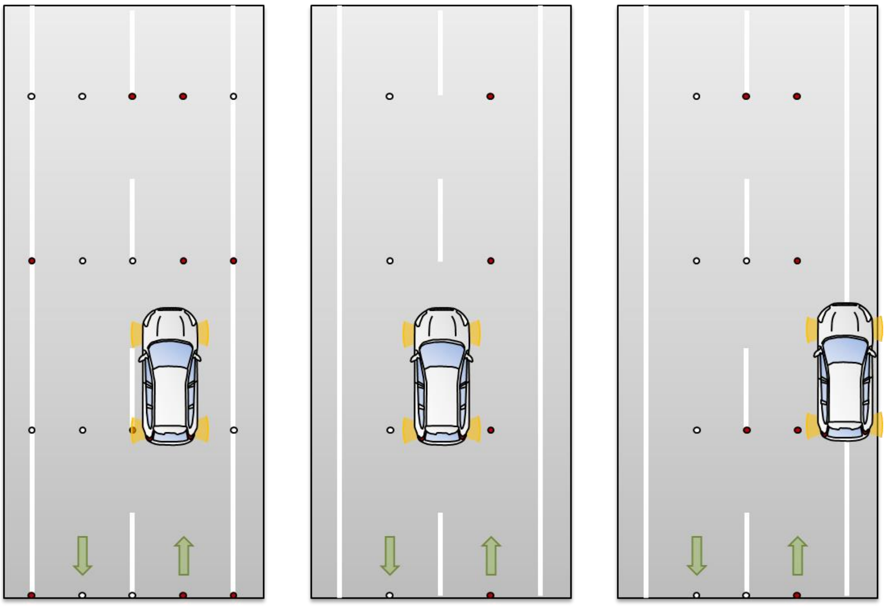

Figure 28: Different lateral patterns compared to the width of the Volvo V60 with a magnetic field sensor system detecting approx. 15 cm outside the vehicle's width.

The lateral pattern is depending on the width of the road and the detection range of the magnetic field sensor system. The magnetic field sensor system's range for detecting magnets is affected by both the vertical and the horizontal distance between the magnet and the sensor. The magnets are suggested to be mounted approximately 10 cm below the surface of the road, and the distance to the sensors from the road will depend on the ground clearance of the vehicle in question. Looking at the Volvo Car Group vehicle fleet, the worst case is the 2016 XC90 with a ground clearance of 23,8 cm (see Table 5). This yields a total distance of 33,8 cm between the magnetic field sensor system and the magnets.

Table 5: Technical specifications for the Volvo cars which represent the most extreme values for length, width and ground clearance compared to the two most extreme of type vehicle P from Trafikverket. The type vehicle P is used when dimensioning the Swedish roads [15].

Vehicle (model 2016 for all)	Length [cm]	Width [cm]	Ground clearance [cm]
Volvo V40 [16]	436,9	185,7	12,1-14,4-
Volvo V60 [17]	463,5	189,9	13,6
Volvo XC90 [18]	495,0	192,3	23,8
Type vehicle P, mini [15]	345,0	147,0	N/A
Type vehicle P, large [15]	496,0	178,0	N/A

The vertical and horizontal range of the magnetic field sensor system is presented in Figure 29 and Figure 30. As can be seen, the intensity is decreasing fast with the horizontal distance from the sensor. Assuming a distance of 30 cm between the sensor and the magnet, a magnet placed at 20 cm from the centre of the sensor the magnetic field is almost not detected at all. The vertical detection is also decreasing rapidly with a longer distance between the magnet and the sensor.

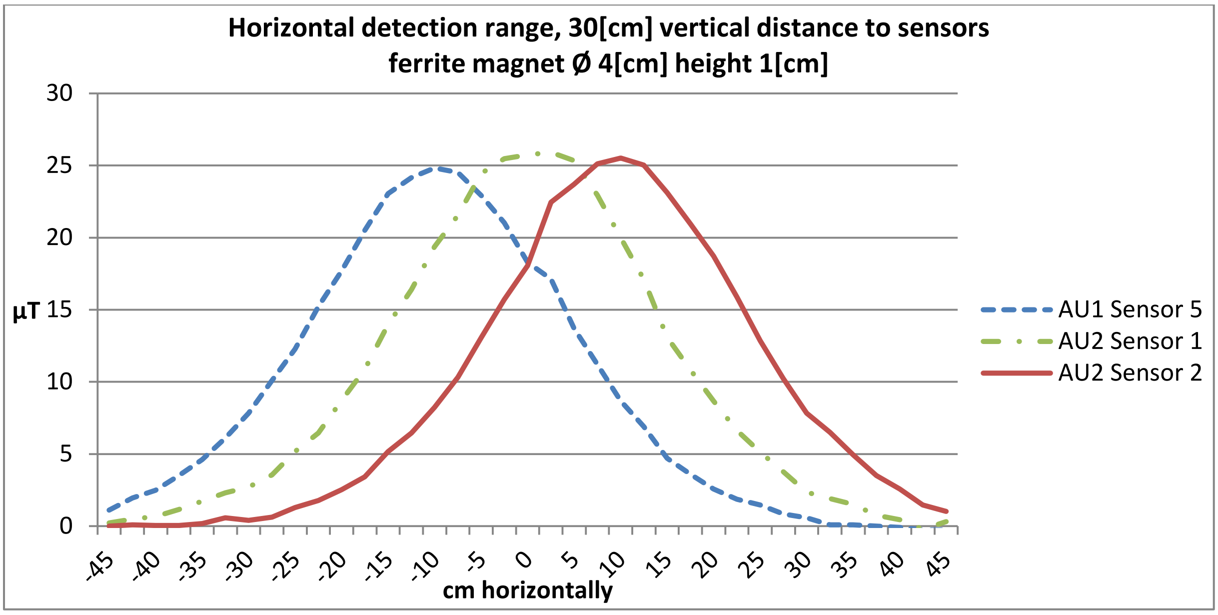

Figure 29: The horizontal detection range for the magnetic field sensor system.

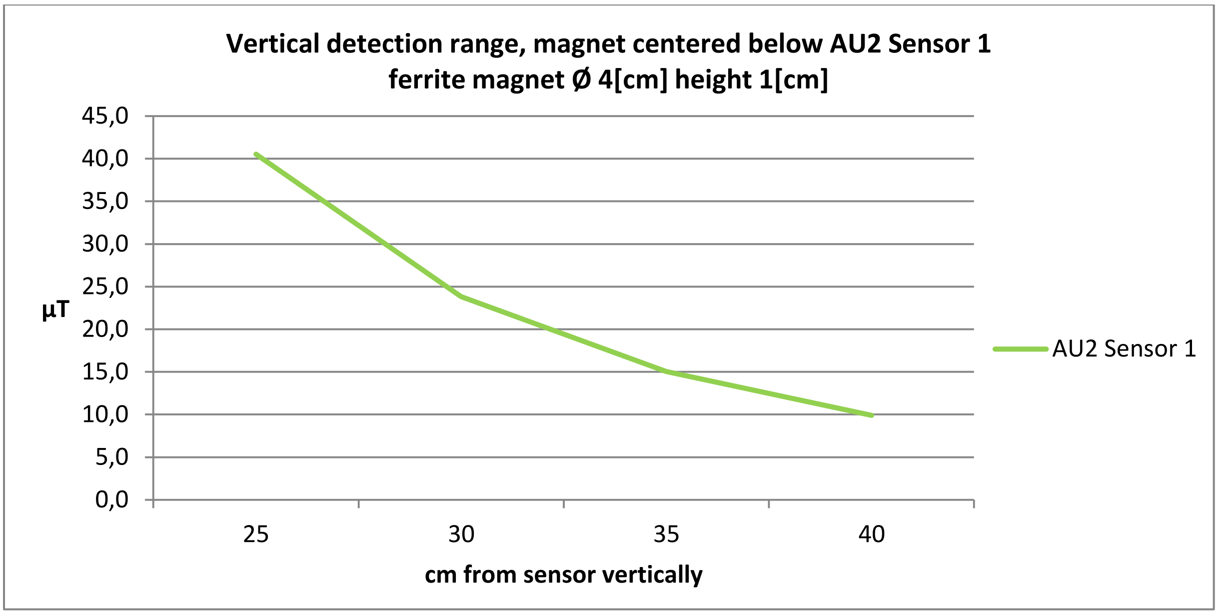

Figure 30: The vertical detection range for the magnetic field sensor system.

There are a number of different road widths represented in Sweden; the lateral pattern will have to be adjusted to fit the width of the road where the mounting will be. The general rule is that the lane width shall be between 3,0 m – 4,0 m wide [19]. The shoulder width of the road depends on the type of road and if there are any objects such as crash barriers or tunnel walls next to the shoulder. Trafikverket's requirements on new built roads basically limit the minimum width, but not the maximum width of the road. The minimum requirements for some of the roads can be found in Table 6, Table 7 and Table 8. The Fagersta test road, where Trafikverket has mounted magnetic markers according to *Appendix E – Magnetic markers test road, RV68 Fagersta,* has a lane width of 3,4[m] [20].

Table 6: Road width specifications for different types of motorways in Sweden. [21] [22]

Road type	Speed limit [km/h]	Type	Outer lane [cm]	Inner lane [cm]	Inner shoulder [cm]	Outer shoulder [cm]	Space between directions [cm]	Total width per side [cm]	Total road width [cm]
Motor-way	***110/ 120***	***Road***	350	350	50	200	250	950	2150
		Tunnel	350	350	100	200	-	1000	2000
Motor-way close to cities	***100***	***Road***	325	325	50	200	50	900	1850
		Tunnel	350	350	50	200	-	950	1900
	100/ 80/ 60	***Road***	325	325	50	75	50	775	1600
		Tunnel	350	350	50	75	-	825	1650
	80/ 60	***Road***	325	325	50	50	50	750	1550
		Tunnel	350	350	50	50	-	800	1600

Table 7: Road width specifications for new built 2+1 highways in Sweden. [23]

Road type	Speed limit [km/h]	Type	Outer shoulder [cm]	Outer lane [cm]	Inner lane [cm]	Inner shoulder [cm]	Space between directions [cm]	Inner shoulder [cm]	Opposite lane [cm]	Outer shoulder [cm]	Total road width [cm]
2+1 High way	***100/ 110***	***with separated walk and cycle path***	50	350	350	50	30	95	375	100	1400
		without separated walk and cycle path	100	350	325	45	30	75	375	100	1400

Table 8: Typical road width specifications for single carriageway roads in Sweden. [24] [19]

Road type	Speed limit [km/h]	Type	Outer shoulder [cm]	Outer lane [cm]	Outer lane [cm]	Outer shoulder [cm]	Total road width [cm]
Single carriageway	***100/ 80/ 60***	***with separated shoulder***	75	≥300	≥300	75	≥750
		with separated shoulder	50	≥300	≥300	50	≥700
		with separated shoulder and barrier	25	≥300	≥300	25	≥650

4.3.2 Lateral pattern analysis

The choice of the lateral pattern is, as stated before, depending on the width of the road, the mounting tolerances, the width and ground clearance of the vehicle, and the range of the magnetic field sensor system. Since the magnetic field sensor system needs to detect at least one magnetic marker, the distance between the markers cannot be wider than the magnetic field sensor system's range. The worst case is therefore a very narrow car on a very wide road. The widest roads are motorways with a lane width of 350 cm, an inner shoulder of 100 cm and an outer shoulder width of 200 cm (see Table 6) – this road is going to be set as a worst case scenario road for the lateral pattern in this project. As stated in Table 5, type vehicle P mini is the narrowest car used by Trafikverket when dimensioning the Swedish roads with its width of 147 cm. It is assumed that this particular vehicle has a ground clearance of 20 cm since that would yield a worst case vehicle.

As seen in Figure 29 the magnetic field sensor system loses its detection range quite fast out to the sides. The total range of the magnetic field sensor system is calculated as

$$R_{total} = W_{vehicle} + 2 \times R_{sensor}$$

where

R_{total} = the total horizontal range of the magnetic field sensor system
$W_{vehicle}$ = the width of the vehicle, here 147 cm
R_{sensor} = the horizontal range of the sensor, here 15 cm to each side assuming that the sensors need to detect at least 15 µT

This yields that the vehicle in this case has a total sensor range of R_{total} = 177 cm.

If a pattern of five markers is assumed according to the first example in Figure 28, and with an outer shoulder of 200 cm, it is possible to fit the 177 cm wide vehicle between the edge of the road and the lane without detecting any magnetic markers. The distance between the markers for a motorway like this would be according to Figure 31.

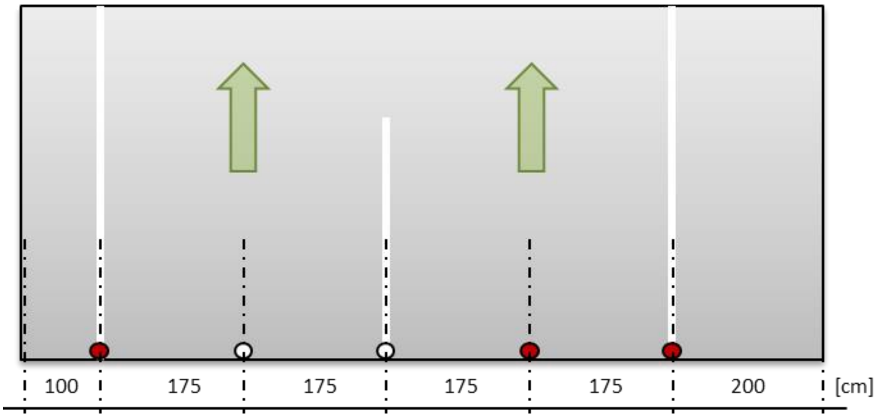

Figure 31: Example of distances between five magnetic markers on a motorway.

The fewer the lateral magnetic markers there is, the longer the distance between them will be. Hence, all other pattern examples shown in chapter 4.3.1 are to sparse; only two magnets yields a pattern where only one distance is short enough, and adding a third magnet in the middle of those two only solves one of two spaces that are too wide (see Figure 32).

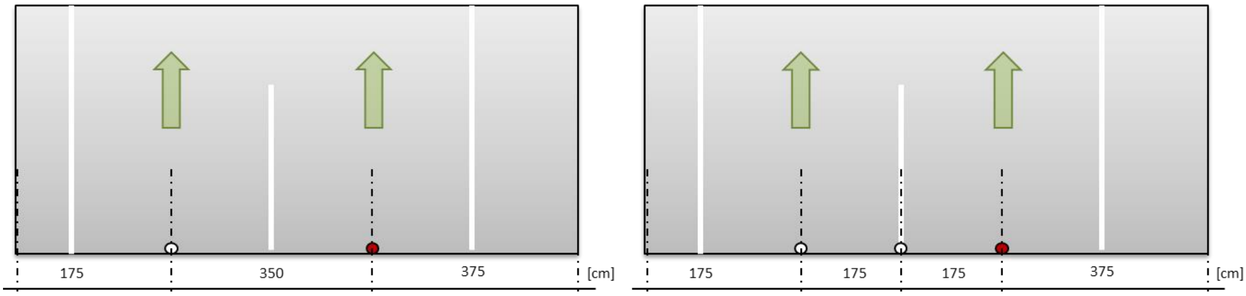

Figure 32: Example of distances between two and three magnetic markers respectively on a motorway.

A motorway of this dimension needs six markers laterally in order to always detect at least one marker with a magnetic field sensor system mounted on a vehicle that is 147 cm wide. This vehicle width is maybe a bit extreme, but the road's dimensions are not. However, a Volvo V60 with a width of 189,9 cm and a ground clearance of 13,6 cm would most likely not fit on the shoulder of 200 cm since it would have a total sensor range of at least 220 cm, if not more. For this vehicle, five markers would be enough for each side of a two lane motorway yielding a total of ten markers for all four lanes.

The lateral pattern can be adapted to fit different roads; according to the values in Table 7, the 2+1 highways would need three markers on the one lane side and five markers on the two lane side, which could be adjusted to just four markers depending on which vehicle is used for reference. That is, the marker closest to the crash barrier on the two lane side might be possible to remove if the reference vehicle is a Volvo V60 (see Figure 33). A very narrow single carriageway road would need only three markers and it would still be possible to detect all markers with both a vehicle P, mini, and a Volvo V60 (Figure 34).

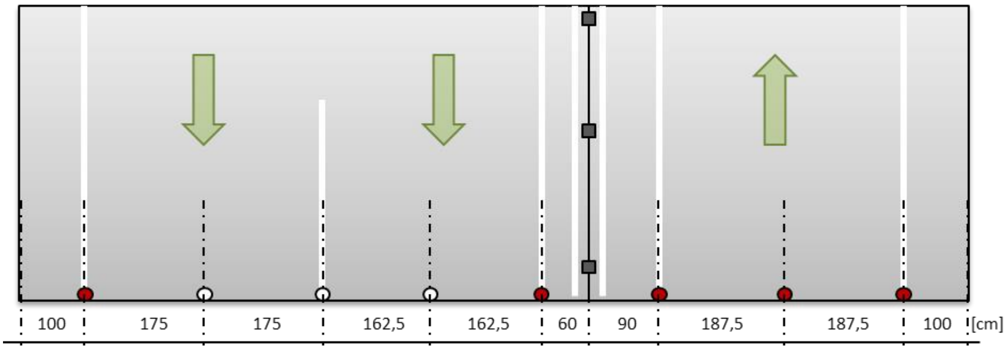

Figure 33: Example of distances between magnetic markers on a 2+1 highway.

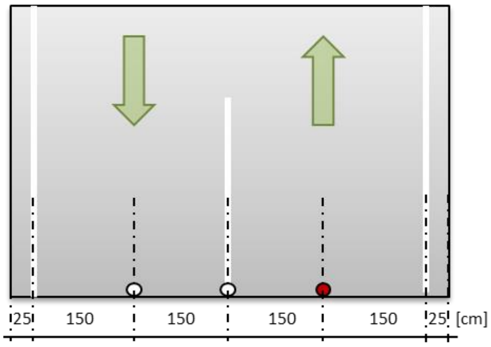

Figure 34: Example of distances between magnetic markers on a narrow single carriageway road.

4.4 Longitudinal pattern

In this chapter, the longitudinal distance between the markers will be studied. It is assumed that a simple systematic pattern is used, in accordance to chapter 4.1.2.

4.4.1 Longitudinal pattern theory

Having a shorter distance between the markers would have the benefit of ease to find the next marker; the risks of missing a marker or driving between two markers are a lot lower. On the other hand, a high density of markers would yield a higher cost in both material and mounting.

The suggestion in chapter 4.1.2 is to use the road markers as a base from which the markers would be mounted. The distances of 3 m, 6 m, 9 m, 12 m and so on have been evaluated since these correspond well to the longitudinal distances for different road markers (see Table 9 and Figure 35).

Table 9: Length of road markings in Sweden [25].

Type of road	Edge line marking+distance [m]	Lane line marking+distance [m]
Motorway ≥ 80 [km/h]	Continuous	3 + 9
2 + 1 high way	Continuous	3 + 9
Single carriageway road ≥ 80 [km/h]	1 + 2	3 + 9
Single carriageway road < 80 [km/h]	1 + 2	3 + 9
City motorway/ dual carriageway road	Continuous	3 + 9
City artery/thoroughfare	1 + 2	3 + 3

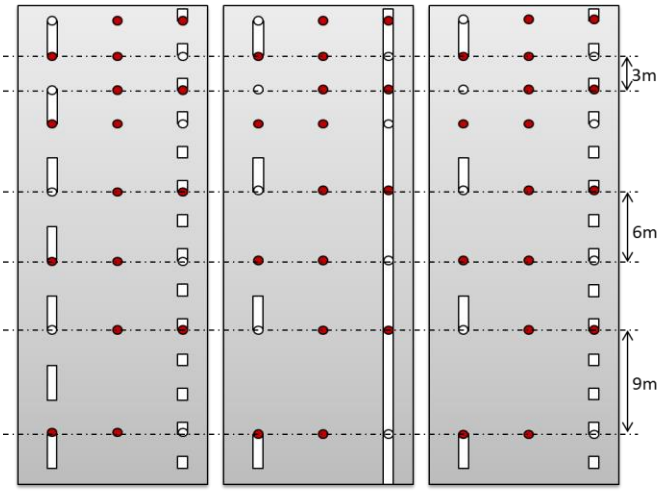

Figure 35: Different longitudinal distances between magnetic markers mounted to fit road markers.

In order to know which longitudinal distance would meet the maximum lateral positioning error of 0,10 m [1], the dead reckoning for this error were investigated by driving a specific route and comparing the actual position with the calculated position using values from the yaw rate sensor. Figure 36 shows en example of the driven route and how the actual position differs from the calculated position. For more information regarding the dead reckoning, see *Appendix D – Dead reckoning data.*

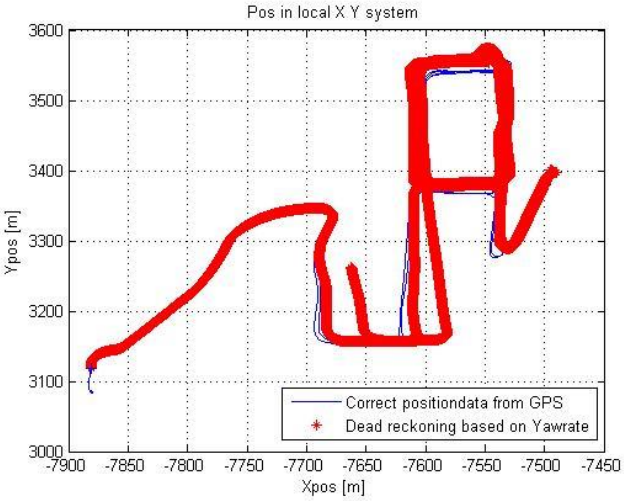

Figure 36: Difference between the actual position of the vehicle and the calculated position.

Table 10 states that for all measured routes the error is smaller than 0,10 m at a longitudinal distance of 3,0 m. For all but one route the distance can be extended to 6,0 m and still meet the requirement. The speed of the vehicle does not seem to matter in the calculated values nor does the layout of the road; that is if it is a straight road or a curved one.

Table 10: Dead reckoning for the lateral positional error for different speeds and road types.

Type of road	Curved		Straight		Slightly curved	
Speed [km/h]	9,6		28,4		16,9	
	Distance [m]	*Deviation [m]*	*Distance [m]*	*Deviation [m]*	*Distance [m]*	*Deviation [m]*
	3	0,0531	3	0,0962	3	0,1080
	6	0,0708	6	0,0440	6	0,0174
	9	0,0401	9	0,1369	9	0,1326
	12	0,1202	12	0,0343	12	0,1537
	15	0,2179	15	0,2665	15	0,0709

Type of road	Straight		Straight	
Speed [km/h]	17,8		22,5	
	Distance [m]	*Deviation [m]*	*Distance [m]*	*Deviation [m]*
	3	0,0359	3	0,0351
	6	0,0386	6	0,1318
	9	0,0392	9	0,1931
	12	0,0765	12	0,2524
	15	0,0995	15	0,1623

The comfort of an autonomous vehicle using magnetic markers for positioning is depending on the markers embedded in the centre of the lane. The lateral positioning tolerance needs to be good enough to prevent the vehicle from moving from side to side to correct its position [26]. However, the markers embedded in the edge lines are mainly used for preventing the vehicle from leaving the lane. The same lateral positioning tolerance as the markers in the middle of the lane is not needed since any correction done for the edge lines is needed in order to keep the vehicle within the lane.

4.4.2 Longitudinal pattern analysis

The dead reckoning study shows that it is at least possible to extend the longitudinal distance between the magnetic markers from 2,8 m to 3,0 m. The results also indicate that a distance of 6,0 m between the markers should still meet the wanted maximal positioning error of 0,1 m. It has to be said that the dead reckoning study is not as thorough as was wanted and therefore the results are a bit difficult to interpret. A further and more thorough study, where different vehicles are used and the routes are driven multiple times by these vehicles, is recommended before selecting the longitudinal distance between the markers.

Given the results in Table 10, it looks like neither the vehicle speed nor the curvature of the road affects the dead reckoning outcome. In one of the measurements the value exceeds the maximal lateral positioning error and then falls below it again, which is a typical behaviour of a micromechanical yaw rate sensor of this price range. For another of the measurements, similar behaviour of the yaw rate sensor is seen; the value increases and then decreases again. If a more expensive yaw rate sensor is used, such as a ring laser gyroscope, this behaviour is likely reduced and the longitudinal distance between the markers can probably be increased.

The road markers are a good base for the mounting of the magnetic markers, since it will ease the mounting itself and also facilitate the prediction of where the next marker will be.

Different longitudinal density of magnetic markers can be used between the centre of the lane and the edge lines. The centre markers need to be close enough to ensure that the dead reckoning is not effecting the comfort of the ride – a vehicle that is positioning itself off often will wind during driving, causing a most discomfort ride. According to Jonas Ekmark, Volvo Car Corporation, it could be acceptable to half the number of markers used at the edge lines of the lane since they only should be used to keep the vehicle within the lane and are not affecting the comfort of the ride [26]. Thus, if magnetic markers are needed each three meters for the centre of the lane it would be possible to mount markers each six meters at the edges of the lane – a pattern that would clearly decrease the number of markers needed.

4.5 Magnetic Markers Pattern discussion

As seen in previous chapters, it is difficult to determine one pattern that would work for all roads. A simple systematic pattern is preferable to a complex systematic pattern since it will be easier and cheaper to both design and mount (see chapter 4.1). Encode information within the pattern would help the system to better understand the road ahead, but it comes with the drawback of costly and difficult re-programming of the encoded information (see chapter 4.2).

Looking at a double carriageway motorway, the suggestion would be to mount the magnetic markers in compliance with the road marks, and to have three edge line magnetic markers each 12 meters and two markers in the centre of the lane each six meters for each driving direction (see Figure 37). It is suggested that the magnetic pole orientation is used to determine which longitudinal marker rows are lane lines and which marks the middle of the lane. That would yield a total of seven markers per 12 meters of each driving direction, adding up to 1167 markers per kilometre of road for both driving directions. If it is possible to increase the longitudinal distance of the centre markers from six meters to 12 meters, that would of course half the amount of magnetic markers needed and yield 583 markers. If that distance in turn can be doubled to 24 meters, the amount of markers will decrease accordingly to 292 markers per kilometre and so on.

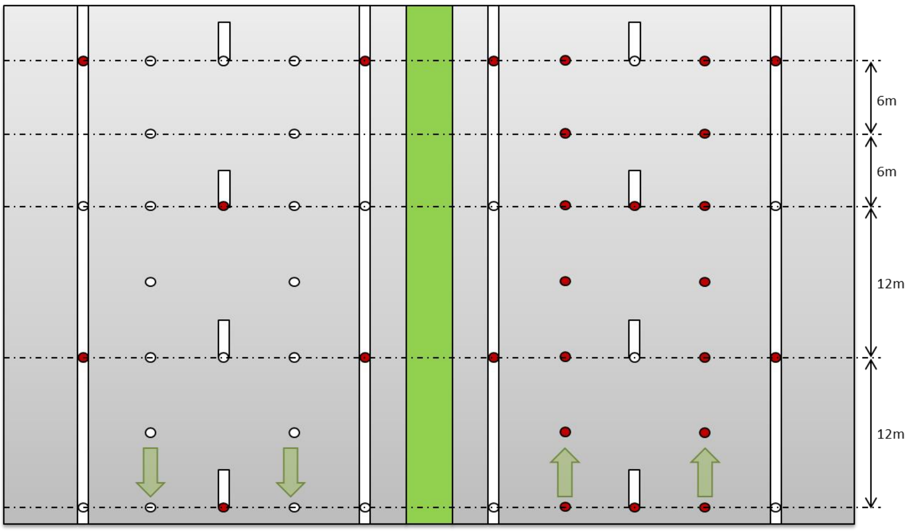

Figure 37: Longitudinal pattern where the amount of markers in the edge lines is half as many as the markers in the centre of the lane on a dual carriageway motorway.

As seen in chapter 4.3, a narrow single carriageway road can use only three markers and still meet the requirements. At a longitudinal distance of six meters for the centre lane markers, the total amount of markers for such road will be 333 markers per kilometre if the number of in between line markers is halved compared to the number of centre of lane markers. The 2+1 highway would in turn need 11 markers per 12 meters, adding up to a total of 917 markers per kilometre (see Figure 38).

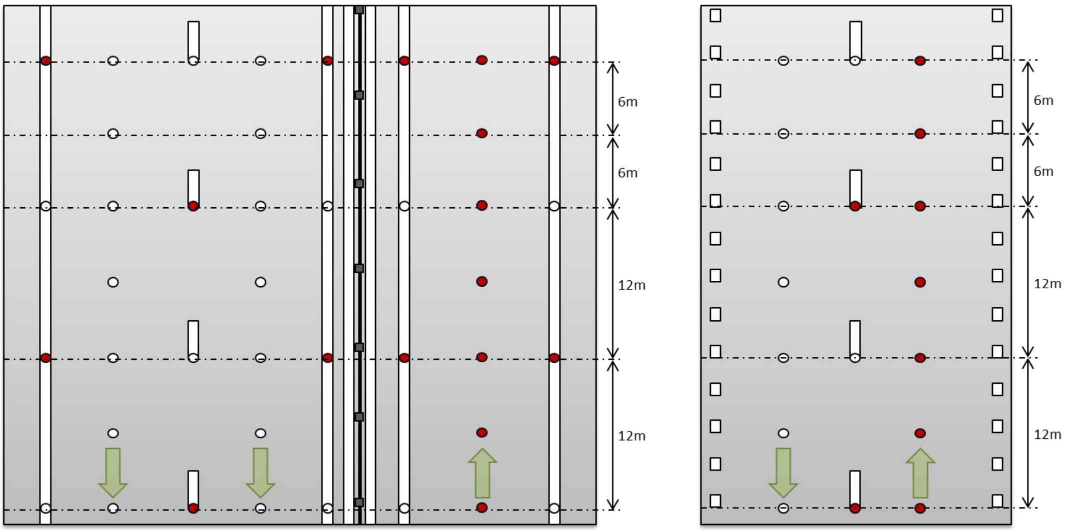

Figure 38: Longitudinal pattern where the amount of markers in the edge lines is half as many as the markers in the centre of the lane on a 2 + 1 highway (left) and narrow single carriageway road (right) respectively.

Further reducing the number of magnetic markers needed is only possible by increasing the longitudinal distance between them, and can be done by using a more expensive yaw rate sensor. The lateral pattern is most likely set due to the limited range of the magnetic field sensor system – a better system would indeed increase the range and if the horizontal range of the magnetic field sensor system can be wider then it may be possible to decrease the number of magnetic markers used in lateral direction.

5 Demagnetization

When a road is changed it is necessary to change the magnets embedded in the road to avoid that the autonomous vehicle is driving according to the old magnetic markers and not the new ones. This chapter discusses the possibilities on how that can be done.

5.1 Demagnetization theory

There are different ways to demagnetize a permanent magnet;

1. **Temperature:** If the permanent magnet is heated up to the Curie temperature it will be demagnetized. The Curie temperature is different for permanent magnets of different materials.
2. **Breaking:** A broken magnet may no longer have the same magnetic properties as before. Ferrite magnets are inherently brittle, like ceramic. Neodymium is fairly brittle.
3. **Corrosion:** Corrosion is bad for neodymium but not for ferrite. Often the neodymium magnet is covered with zinc or plastic for protection.

The standard way to demagnetize a magnetized metal is to submit it to a strong oscillating magnetic field with the right frequency and gradually lower amplitude, eventually zero. This has not been proven to work with permanent magnets.

5.2 Demagnetization discussion

In a meeting with Magnus Gustafsson [14] he explained that many customers asked if permanent magnets can be demagnetized. The company Magnet Fabriken AB has made a lot of tests to get a permanent ferrite magnet to be demagnetized, which turned out to be impossible.

Another solution is to cover the magnet with a shielding steel plate; making the magnetic field to reach the steel but not the road. It should be possible to press down a steel plate and then seal it with asphalt. Magnus Gustafsson explained that a 3 mm thick steel plate with a diameter at least as the magnet probably should be OK to shield the magnetic field, but this need to be tested [14].

When a road is reconditioned there is often a detour. Big steel plates can be placed over the magnets in the beginning of the rebuild area, and temporary magnets that lead into the detour can be set in the road surface. The steel plates can be temporary attached to the road surface and when the road is ready it is easy to take the steel plates away, making the magnets work again.

To dig up the magnets and remove them is yet another solution that should be considered.

6 The Fagersta test road

Trafikverket has set up a test road at RV68 in Fagersta in order to test the concept of the vehicle magnetic positioning in reality. Magnets of different intensity have been mounted within the road, specifications of this road can be found in *Appendix E – Magnetic markers test road, RV68 Fagersta*. Figure 39 shows an overview of how the magnetic markers have been mounted.

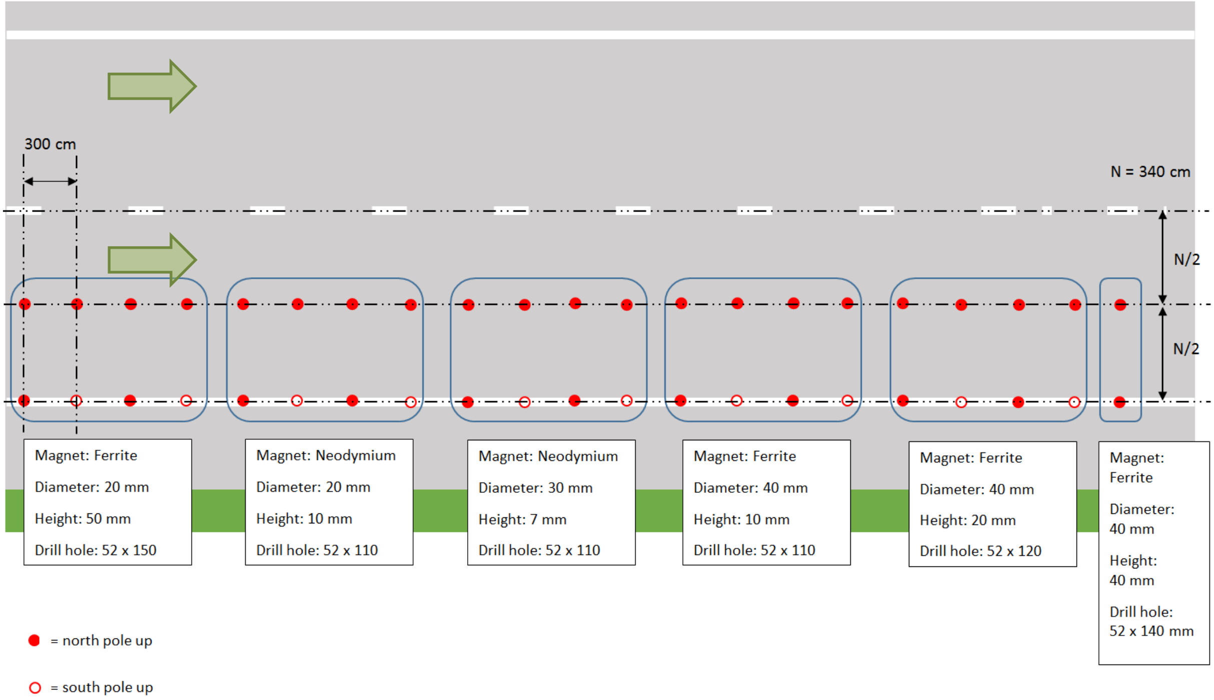

Figure 39: Overview of how the magnetic markers at Fagersta test road have been mounted.

The test road has been driven with the test rig attached to a vehicle, before repaving the road. Trafikverket has done measurements after the repaving was done with similar results.

The test results were positive – the magnetic markers were easy to detect (see Figure 40 and Figure 41). The test was performed in the speeds 20 km/h, 30 km/h, 40 km/h, 50 km/h, 60 km/h, 70 km/h, 80 km/h and 90 km/h to see that the amplitudes are the same on all of the tests. There was no difference in amplitude between the speeds; all of the figures look the same.

The mounting of the magnetic markers were performed by Trafikverket (see *Appendix E – Magnetic markers test road, RV68 Fagersta*). The method used at Fagersta, measuring then drilling and mounting the marker by hand, cost approximately 600SEK per marker – a cost that is assumed to be lowered to approximately 450SEK per marker once the process is more effective. Trafikverket estimates that using a new method where a machine drills a hole and mounts the marker would yield a cost of 100SEK per marker given large volumes [27].

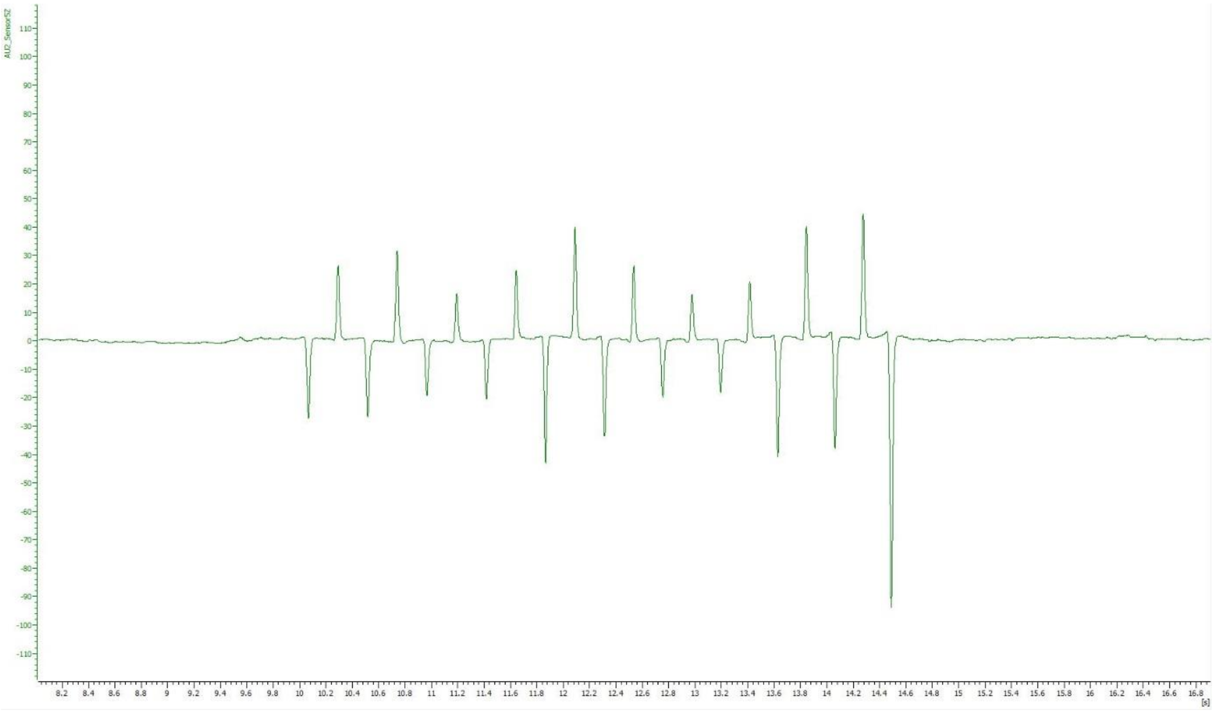

Figure 40: The magnets in the edge line, measured on the test road in Fagersta.

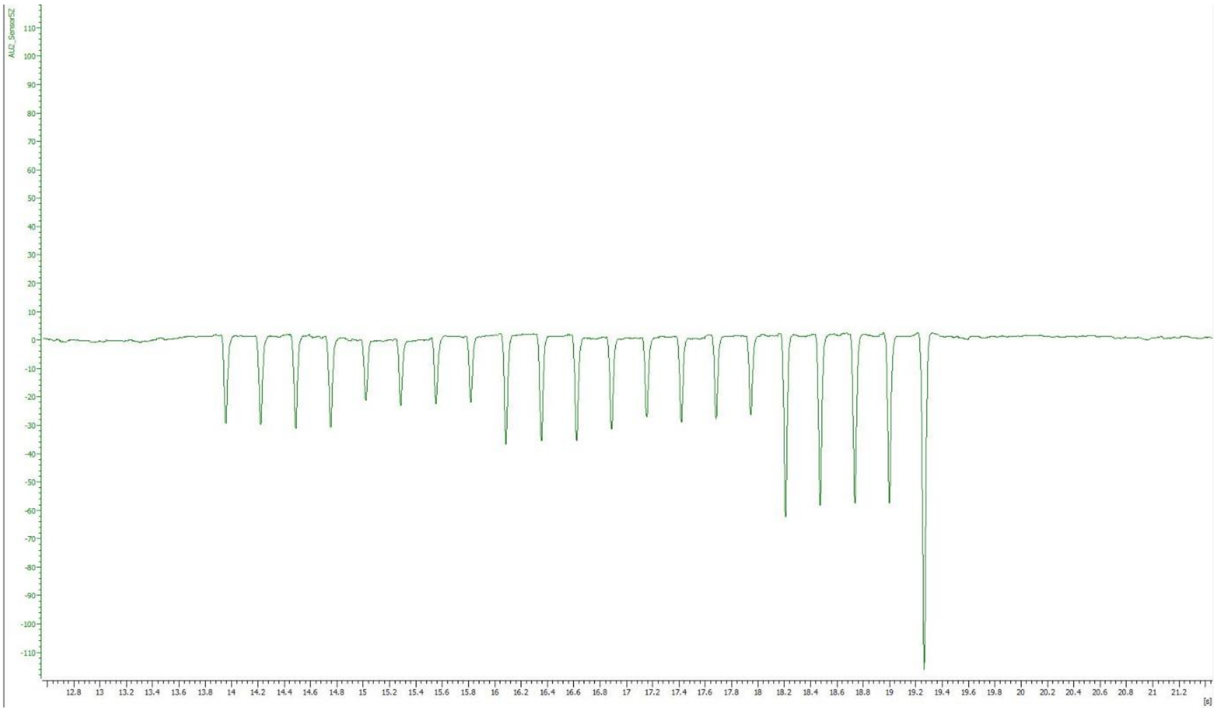

Figure 41: The magnets in the centre of the lane, measured on the test road in Fagersta.

7 Conclusion

A number of routes have been driven in order to find magnetic noise that will disturb the normal way to locate the magnets, including the Drive Me route. Difference sources have been found such as; bridges, access ramps, road expansion joints, tramways, railways, electrical lines and manhole covers. The magnetic disturbance can be divided into three categories:

- Magnetic fields that do not need to be eliminated.
- Magnetic fields that may be possible to filter away, but applying filters to the sensor system may interfere with other systems, and may need more complex hardware.
- Magnetic fields that cannot be filter away and where the suggested solution is to install magnets that are stronger than the ones used as standard magnetic markers.

It is suggested that the standard magnetic marker, used for road without magnetic disturbance, will be a ferrite magnet with the dimensions of Ø40x30 mm that is embedded with the top of the magnet 10 cm below the road surface.

The conclusion drawn from the magnetic markers pattern studies is that a simple systematic pattern based on the road markers is recommended. It is possible to encode information within the pattern, however, with the drawback that it is difficult to reprogram the pattern. The number of magnetic markers needed in the lateral direction differs depending on the type of road. A double carriageway motorway is suggested to have five markers in each direction, yielding a total of ten markers for the entire road width. The longitudinal distance between the markers need to be further investigated, but it is definitely possible to extend the distance from 2,8 m to 3,0 m. It is suggested that the density of markers used at the edge lines are halved compared to the density used in the centre of the lane – thus drastically decreasing the number of magnetic markers needed per kilometre of road.

Demagnetization has been found to not be an option for editing the magnetic markers pattern. A suggestion is to investigate if a steel plate mounted above the magnet as a shield it can be used as a substitute for demagnetization, or to dig up the magnets and remove them.

Driving the Fagersta test road indicates that the concept with magnetic markers embedded within the road is feasible.

8 Further research and development

It is recommended that future projects take into account the following items:

- Further measurements are needed for dead reckoning in order to assure which longitudinal distance is acceptable. It is recommended that the measurements are done with several test vehicles and with different routes where each combination is executed several times.
- Further studies are recommended in order to define the magnetic intensity needed to penetrate the magnetic disturbance.
- Investigation regarding which magnets at which size and magnetic intensity correspond to the different magnetic disturbance levels is recommended before purchasing any magnets.
- Further studies of filters to reduce the magnetic disturbance are recommended as well as studying if the x- and y-directions of the sensor can be used.
- It is suggested that the Fagersta test road measurement data is further analysed to understand how the data is affected by Notch filters and other filters for 16,7 Hz and 50 Hz.
- Further studies regarding magnetic disturbance sources such as noise barriers, passing lorries and concrete roads are recommended; if they yield any magnetic disturbance or not. It has been noticed that lorries have some disturbance but this has not been confirmed.
- It is suggested to study the effect of the magnetic field for bridges consisting of steel/concrete steel when a magnet is embedded into the construction.
- It is recommended to study the effect of a shielding above the magnetic field sensors in regard to the noise measurement sensitivity from sources not in the ground.
- The effect of the magnetic field sensor system integrated in the test vehicle needs to be studied with regards to the carriage body and the vehicle's own magnetic field.
- It is recommended to investigate the relations between the comforts needed for Autonomous drive versus the longitudinal distance between the magnetic markers versus the requirements on the yaw rate sensor.

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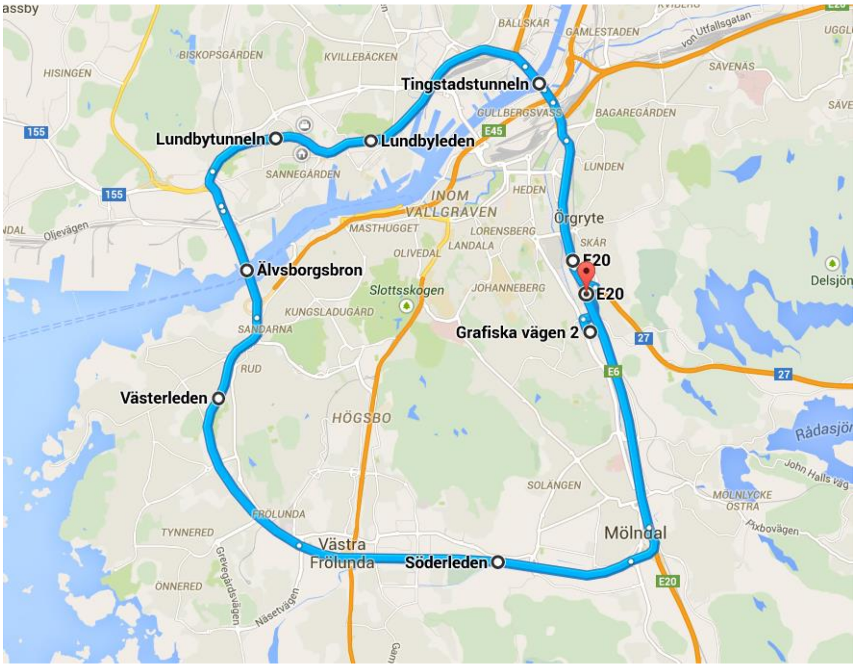
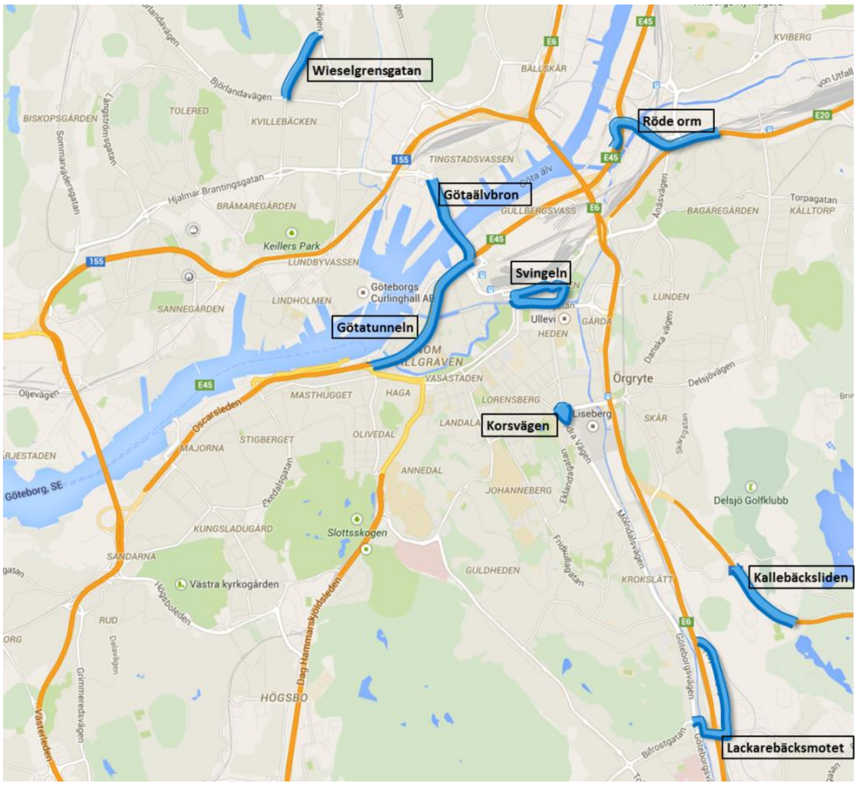
Appendix A – Background noise measurement routes

In this appendix, the different background measurement routes are described through maps.

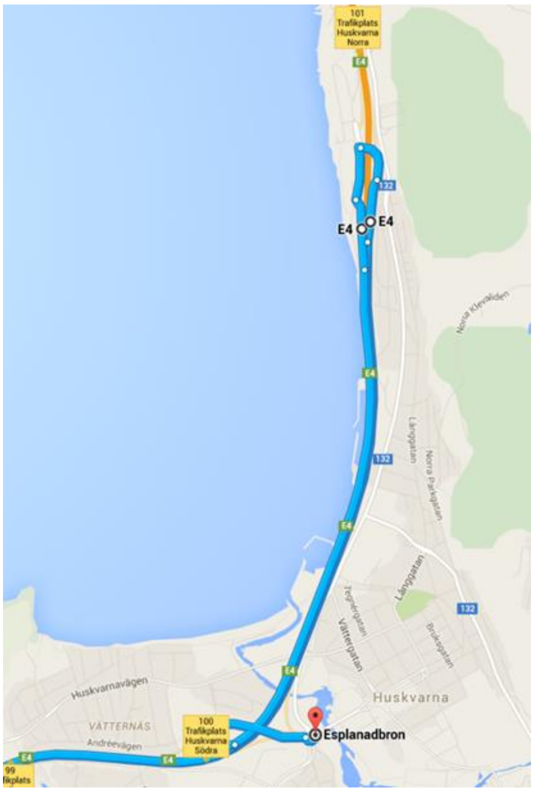
The Drive Me route, Göteborg



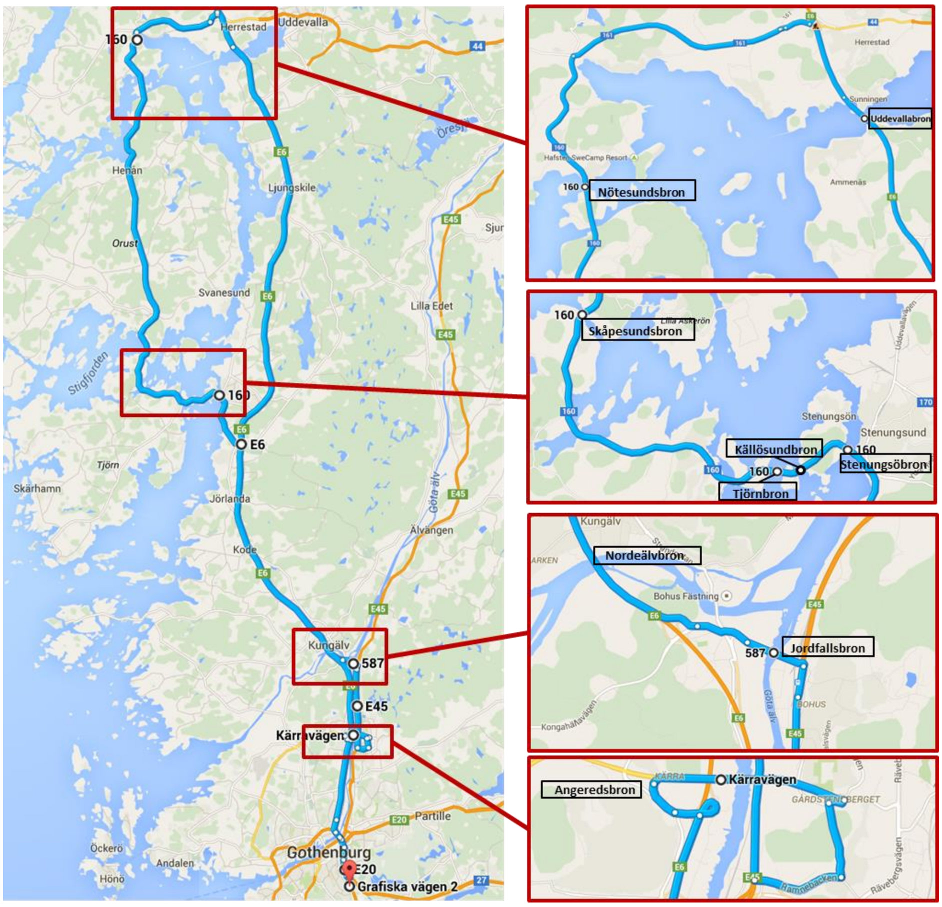
The Göteborg City route



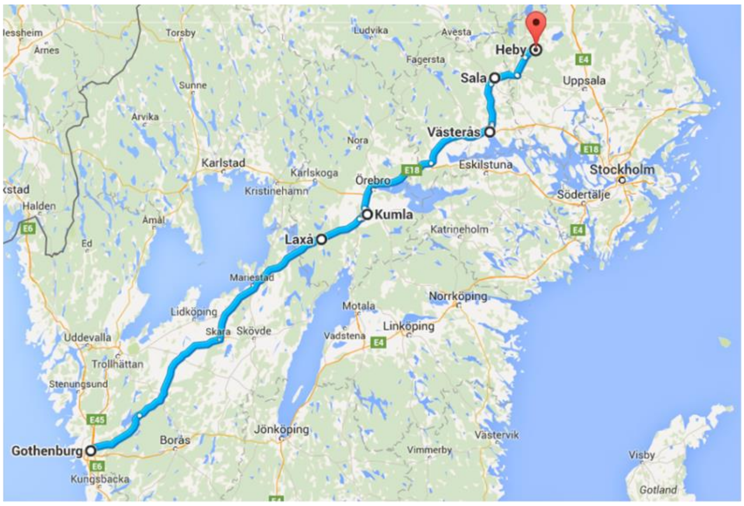
The Huskvarna steel slag asphalt route

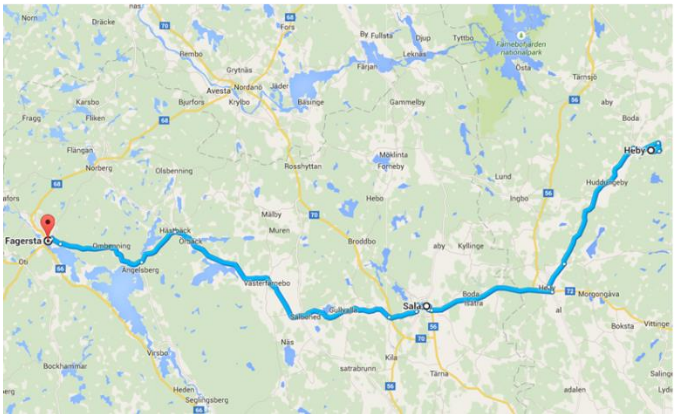


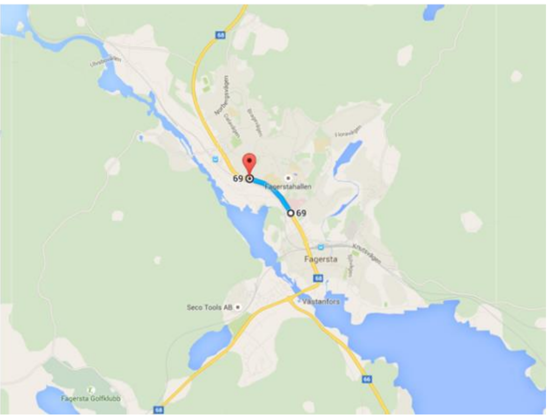
The bridge route, Göteborg – Uddevalla via Tjörn/Orust



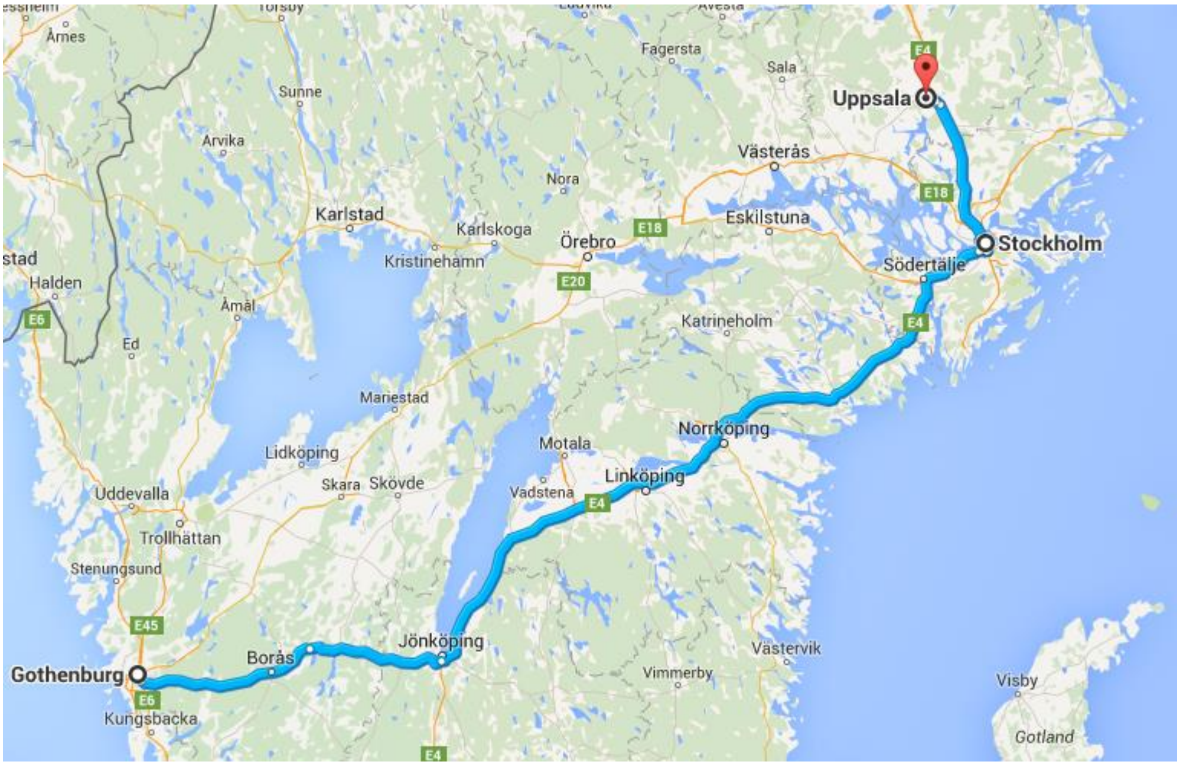
The Fagersta route, Göteborg – Fagersta via Heby







Göteborg – Stockholm - Uppsala



Appendix B – Magnetic intensity measurements

In order to understand how the measurement scale of the magnetic background noise measurements compared to µT, magnetic intensity measurements were conducted and are presented in this appendix. The magnetic fields of the magnets were measured by Trafikverket and these values were used to convert the measured values from the test rig to µT.

The magnets used for these measurements were Ferrites of diameter 40mm and height 10mm, always with the North Pole pointing down.

Magnetic field measurements

The magnetic field measurements were conducted with the use of a hand held magnetometer, held at different heights above the magnets. The results can be found in Table B 1.

Table B 1: Magnetic field from the magnets measured with a magnetometer.

Distance to magnet (north pole down) [cm]	Magnetic field total [µT]	Magnetic field x-direction [µT]	Magnetic field y-direction [µT]	Magnetic field z-direction [µT]	Magnetic field from magnet (i.e. with the magnetic field of the Earth subtracted) z-direction [µT]
10	531,4	-53,2	5,4	-528,6	*482,1*
15	220,2	-32,2	1,3	-217,8	*171,3*
20	127,1	-23,6	-4,7	-124,9	*78,4*
25	91,6	-20,7	-6,9	-88,9	*42,4*
30	74,6	-19,5	-7,9	-71,5	*25,0*
35	66,7	-19,2	-8,8	-63,3	*16,8*
40	62,2	-18,7	-8,6	-58,6	*12,1*
45	60,3	-18,4	-8,7	-56,6	*10,1*
No magnet	50,6	-18,7	-6,7	-46,5	

Converting sensor scale to µT

The equation for converting sensor range values to µT is

$$B_{\mu T} = \frac{B_{sensor}}{U_{sensor}} \times \frac{U_{maxsensor}}{Res_{sensor}}$$

where

$B_{\mu T}$ = the magnetic field in µT
B_{sensor} = the magnetic field measured in the sensor's scale
U_{sensor} = the applied voltage for each sensor, according to Table B 2
$U_{maxsensor}$ = the total voltage of the sensors range, here 3000 mV
Res_{sensor} = the resolution of the sensor's range, here 12 bits or 4096 steps

Each sensor has its own scale factor for conversion, due to that the applied voltage tends to vary between different sensors. The calculated scale factor for each sensor is presented inTable B 2.

Table B 2: Measured applied voltage and shift in scale for each sensor.

AU	Sensor	Start value +/- 5	35cm 10mm*40mm Ferrite (PEAK)	Difference	Volt	Scale factor
AU1	**1**	2158	2259	101	3,3001	***0,2219***
	2	2505	2602	97	3,2813	***0,2232***
	3	2375	2469	94	3,2818	***0,2232***
	4	2325	2424	99	3,3071	***0,2215***
	5	2500	2596	96	3,2927	***0,2224***
AU2	**1**	2260	2358	98	3,2895	***0,2227***
	2	2375	2466	91	3,3083	***0,2214***
	3	2495	2590	95	3,3022	***0,2218***
	4	2415	2510	95	3,3026	***0,2218***
	5	2335	2428	93	3,3102	***0,2213***
AU3	**1**	2555	2650	95	3,2993	***0,2220***
	2	2335	2436	101	3,3012	***0,2219***
	3	2370	2466	96	3,3030	***0,2217***
	4	2500	2600	100	3,2937	***0,2224***
	5	2345	2446	101	3,3114	***0,2212***

Magnetic field sensor system range measurements

The test rig's range was measured in two different ways; horizontally and vertically. The setup was similar for both measurement types. The top of the magnet was placed at a certain distance from the sensors (see $d_{sensor/magnet}$ in Figure B 1).

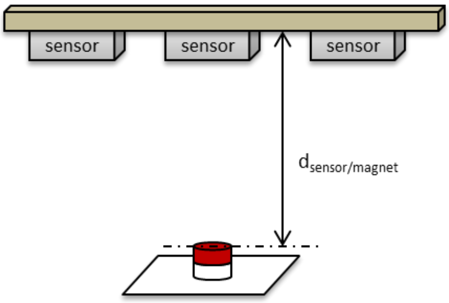


Figure B 1: Schematic illustration of how the reference measurements were conducted.

For the vertically measurement, the test rig was placed at different distances from the top of the magnets according to Table B 3. The measurement was conducted for one sensor at a time. Each height was measured 5 times for each sensor and the mean value is used (see Table B 3). The spectrum for sensor 1 is presented in Figure B 2 and Figure B 3.

For the horizontally measurement, three sensors next to each other were used simultaneously. The vertical distance between the sensors and the top of the magnet was consistent and the magnet was moved horizontally towards each side until no magnetic field could be detected by the sensors. Each spot distance was measured 5 times and the mean value is used (see Table B 4).The result is represented in Table B 4 and Figure B 4.

Table B 3: The measurement values from the vertical measurement.

Positive polarity	REF	AU1 sensor 5	AU 2 sensor 1	AU2 sensor 2	5	5	5	5	5	1	1	1	1	1	2	2	2	2	2
10	482,1	253,6	1880,8	303	2711	2707	2705	2712	2707	4081	4081	4081	4081	4081	2612	2608	2607	2616	2609
15	171,3	243	886,4	430	2698	2701	2694	2695	2701	3090	3090	3082	3083	3088	2632	2632	2628	2629	2630
20	78,4	160,4	356,6	203,6	2619	2618	2613	2614	2612	2559	2558	2556	2555	2556	2513	2513	2508	2511	2510
25	42,4	99,4	182	133	2552	2553	2556	2554	2556	2382	2378	2385	2381	2385	2439	2439	2444	2438	2442
30	25	69,4	107	82,2	2523	2522	2526	2523	2527	2306	2305	2309	2307	2309	2388	2387	2395	2387	2391
35	16,8	52,2	67,6	52,2	2508	2509	2504	2506	2508	2269	2268	2267	2266	2269	2360	2362	2358	2357	2361
40	12,1	31,8	44,4	42,6	2488	2487	2484	2489	2485	2246	2246	2242	2247	2242	2350	2351	2348	2354	2347
45	10,1	23,2	28,8	28,2	2476	2479	2480	2476	2479	2226	2230	2231	2226	2232	2333	2338	2336	2333	2338
50	-	-9,2	21,2	22,6	2471	2476	2329	2476	2476	2218	2223	2219	2224	2223	2327	2332	2329	2332	2330

Negative polarity		AU1 sensor 5	AU 2 sensor 1	AU2 sensor 2	5	5	5	5	5	1	1	1	1	1	2	2	2	2	2
10		211,8	2066	361,8	2244	2241	2244	2243	2243	135	135	133	134	134	1945	1946	1946	1945	1946
15		263	850,8	381,4	2261	2258	2256	1927	2257	1351	1349	1348	1351	1348	1929	1924	1924	1927	1926
20		183,6	382,8	193,2	2272	2273	2272	2270	2269	1818	1823	1817	1813	1816	2114	2118	2114	2112	2113
25		117,6	191,2	117,8	2336	2338	2336	2340	2336	2009	2008	2008	2011	2009	2189	2188	2189	2192	2190
30		77,2	113,8	79,8	2379	2376	2379	2376	2378	2087	2084	2086	2086	2089	2228	2226	2230	2227	2227
35		50,6	74,6	58	2403	2404	2406	2406	2402	2123	2126	2126	2128	2125	2248	2248	2250	2253	2248
40		37,2	53,4	41,8	2417	2419	2419	2416	2417	2145	2147	2150	2146	2146	2264	2267	2268	2265	2264
45		23,8	35,6	28,8	2434	2433	2430	2428	2430	2167	2166	2163	2163	2164	2279	2281	2277	2279	2277
50		17,2	26,2	22	2437	2440	2435	2436	2440	2172	2175	2173	2172	2178	2284	2289	2285	2283	2286

Offset	Measurement 1	2	3	4	5	Sum 1:5	Snitt
AU1 Sensor 5	2453	2457	2459	2452	2453	12274	2454,8
AU2 Sensor 1	2200	2201	2202	2199	2199	11001	2200,2
AU2 Sensor 2	2305	2309	2309	2308	2306	11537	2307,4

		Positive polarity			Negative polarity		
cm	REF	AU1 sensor 5	**AU2 sensor 1**	AU2 sensor 2	AU1 sensor 5	**AU2 sensor 1**	AU2 sensor 2
10	482,1	253,6	1880,8	303	211,8	2066	361,8
15	171,3	243	886,4	430	263	850,8	381,4
20	78,4	160,4	356,6	203,6	183,6	382,8	193,2
25	42,4	99,4	182	133	117,6	191,2	117,8
30	25	69,4	107	82,2	77,2	113,8	79,8
35	16,8	52,2	67,6	52,2	50,6	74,6	58
40	12,1	31,8	44,4	42,6	37,2	53,4	41,8
45	10,1	23,2	28,8	28,2	23,8	35,6	28,8
50	-	-9,2	21,2	22,6	17,2	26,2	22

Positive polarity			Negative polarity		
value*scale factor					
AU1 sensor 5	**AU2 sensor 1**	AU2 sensor 2	AU1 sensor 5	**AU2 sensor 1**	AU2 sensor 2
56,4	**418,8**	67,1	47,1	**460,0**	80,1
54,0	**197,4**	95,2	58,5	**189,4**	84,4
35,7	**79,4**	45,1	40,8	**85,2**	42,8
22,1	**40,5**	29,4	26,2	**42,6**	26,1
15,4	**23,8**	18,2	17,2	**25,3**	17,7
11,6	**15,1**	11,6	11,3	**16,6**	12,8
7,1	**9,9**	9,4	8,3	**11,9**	9,3
5,2	**6,4**	6,2	5,3	**7,9**	6,4
-2,0	**4,7**	5,0	3,8	**5,8**	4,9

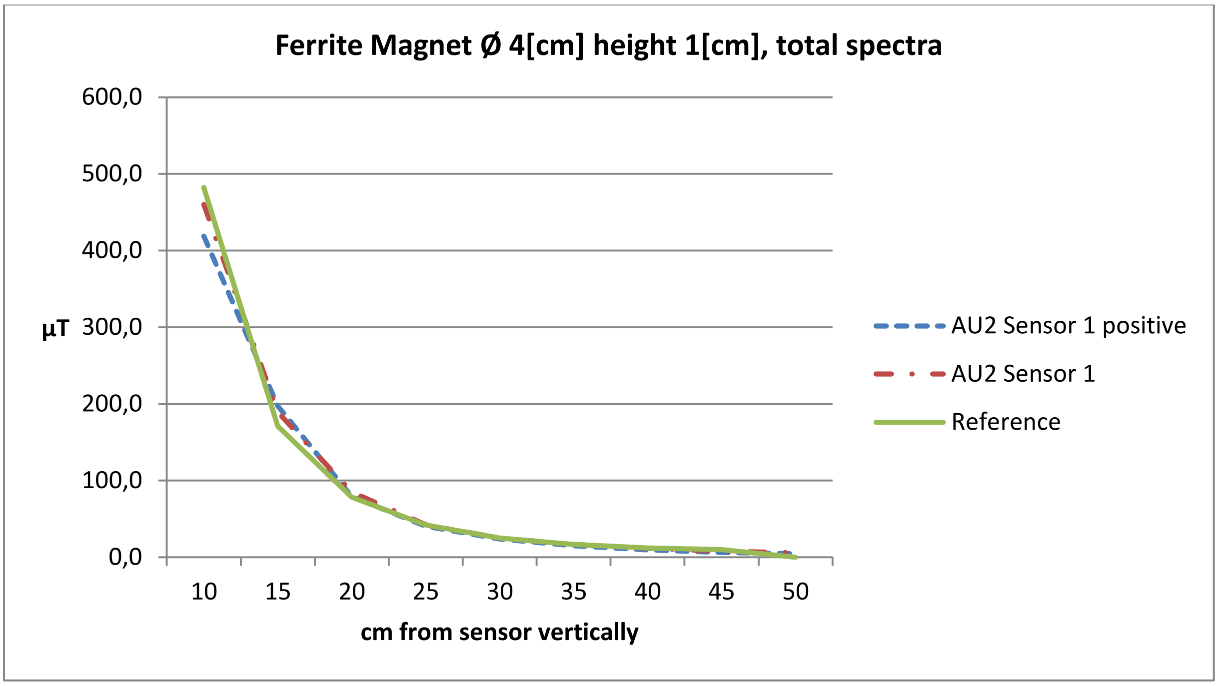


Figure B 2: The vertical spectra of the test rig AU2 sensor 1.

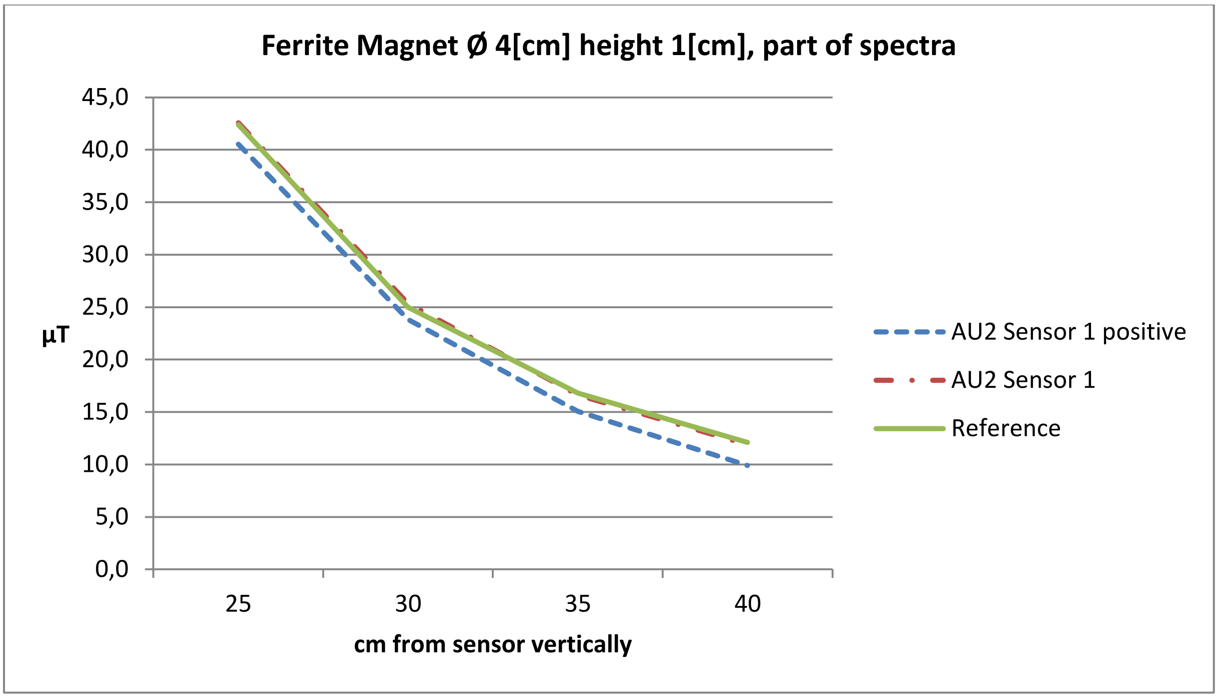


Figure B 3: A close up of the vertical spectra of the test rig AU2 sensor 1, for the distance most likely to be used between test rig and magnetic markers.

Table B 4: The measurement values from the horizontal measurement.

Distance from center to side

	-45	-42,5	-40	-37,5	-35	-32,5	-30	-27,5	-25	-22,5	-20	-17,5	-15	-12,5	-10	-7,5	-5	-2,5	0	2,5	5	7,5	10	12,5	15	17,5	20	22,5	25	27,5	30	32,5	35	37,5	40	42,5	45
AU1 sensor 5	2461	2464	2465	2471	2476	2483	2492	2501	2510	2523	2536	2548	2561	2563	2567	2565	2557	2550	2539	2531	2517	2505	2494	2487	2476	2472	2467	2464	2461	2459	2459	2456	2458	2456	2457	2452	2454
	2460	2466	2468	2471	2475	2484	2490	2501	2511	2522	2533	2547	2558	2565	2568	2565	2559	2550	2536	2532	2516	2507	2494	2489	2474	2470	2465	2465	2463	2461	2458	2458	2454	2453	2455	2456	2452
	2460	2463	2466	2470	2477	2483	2491	2500	2510	2523	2534	2548	2557	2564	2568	2566	2558	2551	2539	2530	2517	2506	2495	2485	2478	2473	2469	2462	2462	2459	2458	2456	2454	2457	2453	2454	2456
	2461	2463	2466	2474	2477	2482	2490	2502	2511	2531	2538	2548	2559	2563	2567	2566	2558	2548	2537	2530	2519	2506	2494	2485	2478	2471	2468	2464	2463	2459	2457	2454	2457	2454	2456	2455	2455
	2460	2465	2468	2470	2476	2482	2490	2500	2511	2520	2534	2547	2560	2565	2565	2566	2560	2551	2537	2539	2516	2505	2495	2486	2477	2472	2466	2464	2461	2458	2458	2455	2456	2457	2454	2454	2454
med5	2460	2464	2467	2471	2476	2483	2491	2501	2511	2524	2535	2548	2559	2564	2567	2566	2558	2550	2538	2532	2517	2506	2494	2486	2477	2472	2467	2464	2462	2459	2458	2456	2456	2455	2455	2454	2454
AU2 sensor 1	2204	2197	2198	2200	2207	2208	2208	2213	2220	2225	2234	2245	2261	2268	2284	2296	2304	2311	2312	2312	2309	2302	2290	2277	2254	2247	2238	2225	2221	2213	2206	2204	2205	2199	2201	2198	2200
	2197	2196	2200	2204	2207	2206	2209	2212	2222	2226	2236	2246	2256	2271	2285	2292	2311	2310	2313	2313	2313	2298	2286	2273	2255	2244	2237	2227	2219	2215	2207	2205	2204	2199	2200	2197	2198
	2196	2201	2201	2199	2203	2207	2207	2215	2217	2226	2237	2246	2260	2272	2281	2293	2308	2311	2310	2312	2307	2298	2290	2271	2254	2246	2235	2227	2219	2212	2209	2206	2200	2203	2200	2197	2199
	2195	2201	2199	2204	2204	2207	2210	2212	2218	2227	2236	2247	2260	2270	2285	2292	2305	2312	2311	2311	2312	2300	2283	2273	2257	2244	2236	2225	2221	2216	2204	2207	2202	2198	2198	2196	2195
	2197	2200	2201	2203	2202	2208	2211	2212	2223	2225	2237	2244	2261	2271	2284	2295	2305	2312	2316	2318	2312	2301	2284	2274	2258	2246	2233	2229	2219	2213	2211	2205	2207	2202	2195	2191	2199
med1	2198	2199	2200	2202	2205	2207	2209	2213	2220	2226	2236	2246	2260	2270	2284	2294	2307	2311	2312	2313	2311	2300	2287	2274	2256	2245	2236	2227	2220	2214	2207	2205	2204	2200	2199	2196	2198
AU2 sensor 2	2307	2304	2301	2302	2306	2308	2304	2306	2307	2312	2312	2320	2327	2329	2341	2351	2362	2375	2385	2405	2407	2416	2423	2417	2406	2400	2389	2372	2359	2347	2336	2331	2327	2318	2318	2310	2310
	2305	2302	2303	2304	2305	2304	2304	2306	2312	2308	2314	2320	2323	2333	2341	2349	2366	2373	2384	2407	2412	2415	2418	2415	2406	2398	2388	2375	2362	2352	2338	2333	2327	2316	2316	2308	2306
	2301	2304	2306	2301	2302	2305	2306	2307	2307	2311	2316	2318	2326	2334	2337	2348	2362	2375	2384	2405	2410	2414	2419	2415	2408	2399	2387	2378	2361	2348	2339	2334	2322	2321	2316	2310	2307
	2302	2304	2303	2305	2306	2306	2305	2306	2308	2315	2315	2320	2328	2332	2342	2350	2359	2374	2384	2406	2412	2417	2417	2415	2409	2396	2390	2374	2365	2351	2337	2333	2324	2319	2312	2309	2308
	2301	2304	2304	2305	2301	2306	2306	2305	2311	2310	2316	2315	2329	2334	2341	2351	2362	2374	2387	2400	2410	2421	2415	2419	2409	2396	2385	2376	2359	2349	2343	2332	2328	2321	2312	2312	2308
med2	2303	2304	2303	2303	2304	2306	2305	2306	2309	2311	2315	2319	2327	2332	2340	2350	2362	2374	2385	2405	2410	2417	2418	2416	2408	2398	2388	2375	2361	2349	2339	2333	2326	2319	2315	2310	2308

Values in sensor scale without adjustment

	-45	-42,5	-40	-37,5	-35	-32,5	-30	-27,5	-25	-22,5	-20	-17,5	-15	-12,5	-10	-7,5	-5	-2,5	0	2,5	5	7,5	10	12,5	15	17,5	20	22,5	25	27,5	30	32,5	35	37,5	40	42,5	45
AU1 Sensor 5	2460	2464	2467	2471	2476	2483	2491	2501	2511	2524	2535	2548	2559	2564	2567	2566	2558	2550	2538	2532	2517	2506	2494	2486	2477	2472	2467	2464	2462	2459	2458	2456	2456	2455	2455	2454	2454
AU2 Sensor 1	2198	2199	2200	2202	2205	2207	2209	2213	2220	2226	2236	2246	2260	2270	2284	2294	2307	2311	2312	2313	2311	2300	2287	2274	2256	2245	2236	2227	2220	2214	2207	2205	2204	2200	2199	2196	2198
AU2 Sensor 2	2303	2304	2303	2303	2304	2306	2305	2306	2309	2311	2315	2319	2327	2332	2340	2350	2362	2374	2385	2405	2410	2417	2418	2416	2408	2398	2388	2375	2361	2349	2339	2333	2326	2319	2315	2310	2308

Values in sensor scale

	-45	-42,5	-40	-37,5	-35	-32,5	-30	-27,5	-25	-22,5	-20	-17,5	-15	-12,5	-10	-7,5	-5	-2,5	0	2,5	5	7,5	10	12,5	15	17,5	20	22,5	25	27,5	30	32,5	35	37,5	40	42,5	45
AU1 Sensor 5	5	8,8	11,2	15,8	20,8	27,4	35,2	45,4	55,2	68,4	79,6	92,2	103,6	108,6	111,6	110,2	103	94,6	82,2	77	61,6	50,4	39	31	21,2	16,2	11,6	8,4	6,6	3,8	2,6	0,4	0,4	0	-0,4	-1,2	-1,2
AU2 Sensor 1	1	2,2	3	5,2	7,8	10,4	12,2	16	23,2	29	39,2	48,8	62,8	73,6	87	96,8	109,8	114,4	115,6	116,4	113,8	103	89,8	76,8	58,8	48,6	39	29,8	23	17	10,6	8,6	6,8	3,4	2	-1	1,4
AU2 Sensor 2	0	0,4	0,2	0,2	0,8	2,6	1,8	2,8	5,8	8	11,4	15,4	23,4	29,2	37,2	46,6	59	71	81,6	101,4	107	113,4	115,2	113	104,4	94,6	84,6	71,8	58	46,2	35,4	29,4	22,4	15,8	11,6	6,6	4,6

Values in µT

	-45	-42,5	-40	-37,5	-35	-32,5	-30	-27,5	-25	-22,5	-20	-17,5	-15	-12,5	-10	-7,5	-5	-2,5	0	2,5	5	7,5	10	12,5	15	17,5	20	22,5	25	27,5	30	32,5	35	37,5	40	42,5	45
AU1 Sensor 5	1,112	1,957	2,491	3,515	4,627	6,095	7,83	10,1	12,28	15,21	17,71	20,51	23,04	24,16	24,82	24,51	22,91	21,04	18,28	17,13	13,7	11,21	8,675	6,896	4,716	3,603	2,58	1,868	1,468	0,845	0,578	0,089	0,089	0	-0,089	-0,267	-0,267
AU2 Sensor 1	0,223	0,49	0,668	1,158	1,737	2,316	2,716	3,562	5,166	6,457	8,728	10,87	13,98	16,39	19,37	21,55	24,45	25,47	25,74	25,92	25,34	22,93	19,99	17,1	13,09	10,82	8,684	6,635	5,121	3,785	2,36	1,915	1,514	0,757	0,445	-0,223	0,312
AU2 Sensor 2	0	0,089	0,044	0,044	0,177	0,576	0,399	0,62	1,284	1,771	2,524	3,409	5,181	6,465	8,236	10,32	13,06	15,72	18,07	22,45	23,69	25,11	25,5	25,02	23,11	20,94	18,73	15,9	12,84	10,23	7,837	6,509	4,959	3,498	2,568	1,461	1,018

Mean values sensor with no magnets

AU1 s5	AU2 s1	AU2 s2
2455	2197	2303
2456	2194	2301
2455	2199	2304
2456	2199	2306
2455	2195	2302
2455	2197	2303

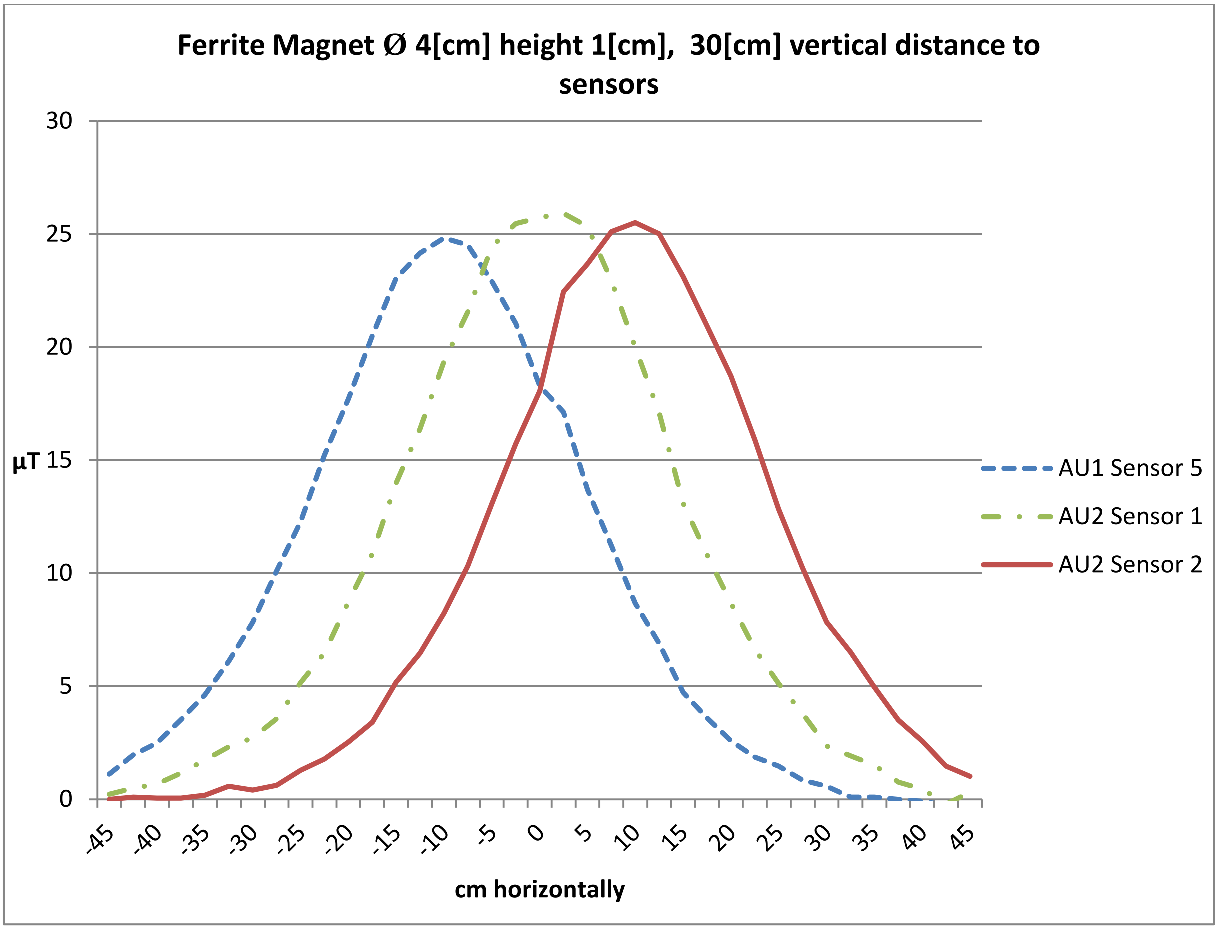
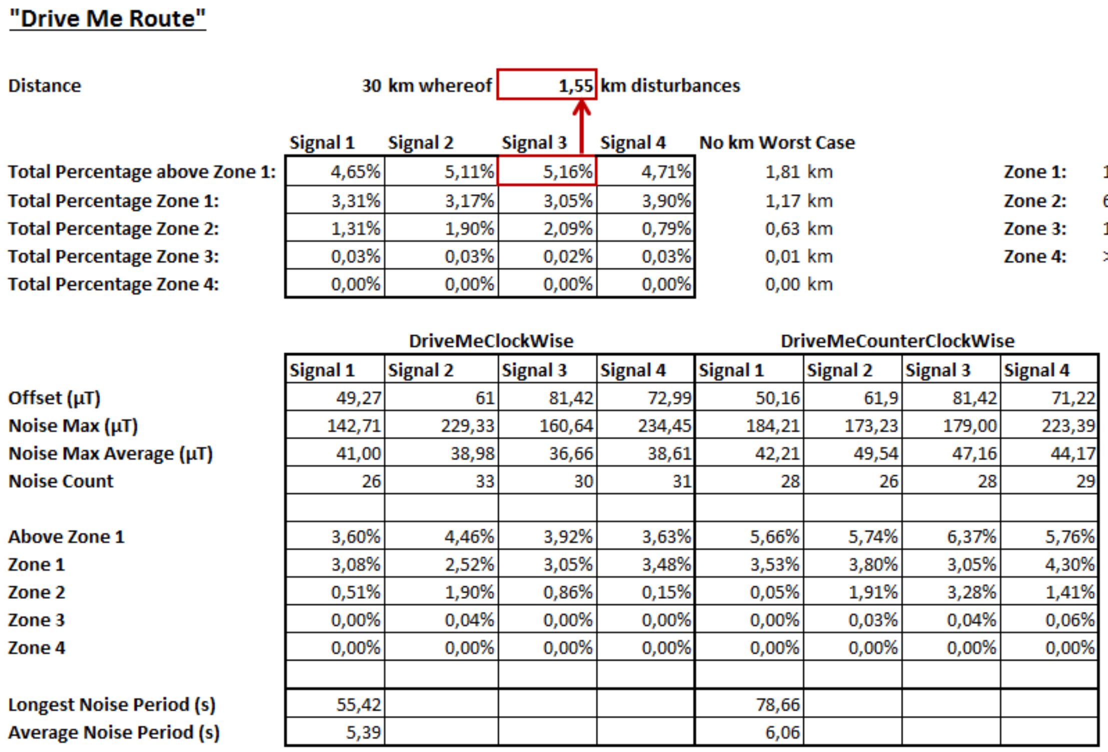


Figure B 4: The horizontal spectra of the test rig AU1 sensor 5, AU2 sensor 1 and AU2 sensor 2.

Appendix C – Highway routes investigation

In this appendix, the investigation regarding how much of the driven distance on a highway route consists of magnetic disturbance that is above the suggested magnet intensity.



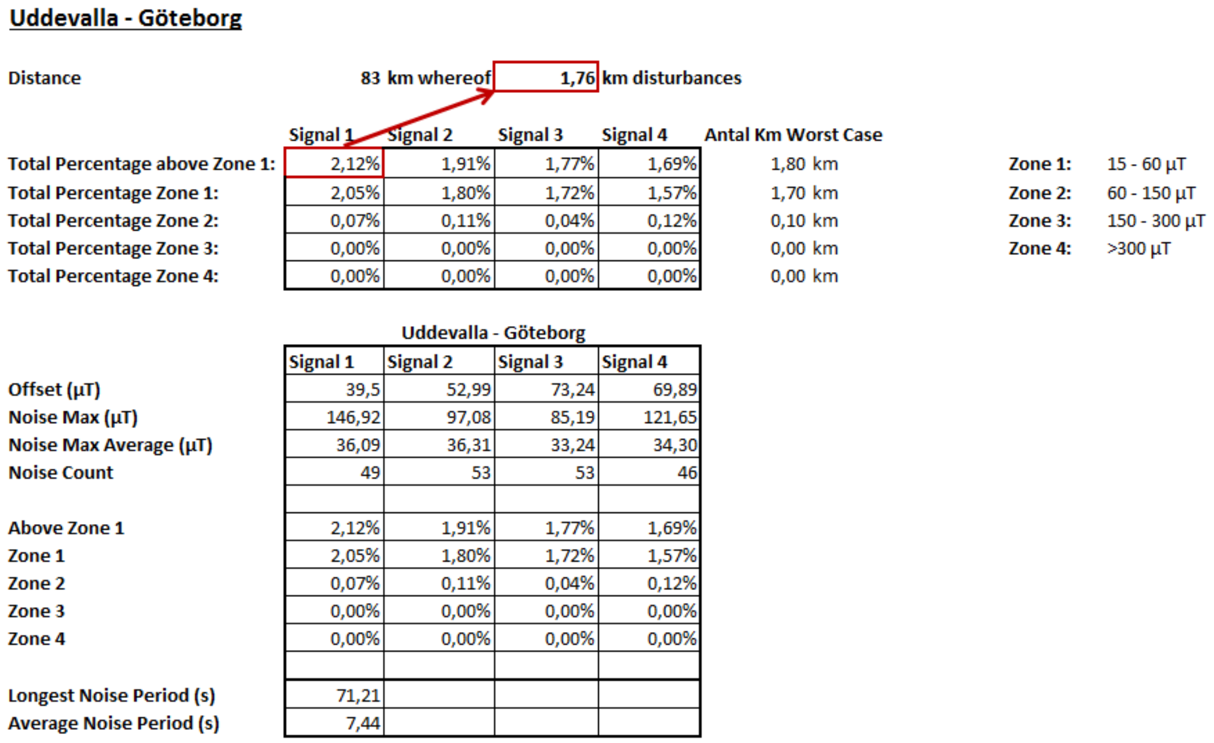
"Drive Me Route"

Distance 30 km whereof 1,55 km disturbances

	Signal 1	Signal 2	Signal 3	Signal 4	No km Worst Case
Total Percentage above Zone 1:	4,65%	5,11%	5,16%	4,71%	1,81 km
Total Percentage Zone 1:	3,31%	3,17%	3,05%	3,90%	1,17 km
Total Percentage Zone 2:	1,31%	1,90%	2,09%	0,79%	0,63 km
Total Percentage Zone 3:	0,03%	0,03%	0,02%	0,03%	0,01 km
Total Percentage Zone 4:	0,00%	0,00%	0,00%	0,00%	0,00 km

Zone 1:	15 - 60 µT
Zone 2:	60 - 150 µT
Zone 3:	150 - 300 µT
Zone 4:	>300 µT

	DriveMeClockWise				DriveMeCounterClockWise			
	Signal 1	Signal 2	Signal 3	Signal 4	Signal 1	Signal 2	Signal 3	Signal 4
Offset (µT)	49,27	61	81,42	72,99	50,16	61,9	81,42	71,22
Noise Max (µT)	142,71	229,33	160,64	234,45	184,21	173,23	179,00	223,39
Noise Max Average (µT)	41,00	38,98	36,66	38,61	42,21	49,54	47,16	44,17
Noise Count	26	33	30	31	28	26	28	29
Above Zone 1	3,60%	4,46%	3,92%	3,63%	5,66%	5,74%	6,37%	5,76%
Zone 1	3,08%	2,52%	3,05%	3,48%	3,53%	3,80%	3,05%	4,30%
Zone 2	0,51%	1,90%	0,86%	0,15%	0,05%	1,91%	3,28%	1,41%
Zone 3	0,00%	0,04%	0,00%	0,00%	0,00%	0,03%	0,04%	0,06%
Zone 4	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Longest Noise Period (s)	55,42				78,66			
Average Noise Period (s)	5,39				6,06			



Uddevalla - Göteborg

Distance 83 km whereof 1,76 km disturbances

	Signal 1	Signal 2	Signal 3	Signal 4	Antal Km Worst Case
Total Percentage above Zone 1:	2,12%	1,91%	1,77%	1,69%	1,80 km
Total Percentage Zone 1:	2,05%	1,80%	1,72%	1,57%	1,70 km
Total Percentage Zone 2:	0,07%	0,11%	0,04%	0,12%	0,10 km
Total Percentage Zone 3:	0,00%	0,00%	0,00%	0,00%	0,00 km
Total Percentage Zone 4:	0,00%	0,00%	0,00%	0,00%	0,00 km

Zone 1:	15 - 60 µT
Zone 2:	60 - 150 µT
Zone 3:	150 - 300 µT
Zone 4:	>300 µT

	Uddevalla - Göteborg			
	Signal 1	Signal 2	Signal 3	Signal 4
Offset (µT)	39,5	52,99	73,24	69,89
Noise Max (µT)	146,92	97,08	85,19	121,65
Noise Max Average (µT)	36,09	36,31	33,24	34,30
Noise Count	49	53	53	46
Above Zone 1	2,12%	1,91%	1,77%	1,69%
Zone 1	2,05%	1,80%	1,72%	1,57%
Zone 2	0,07%	0,11%	0,04%	0,12%
Zone 3	0,00%	0,00%	0,00%	0,00%
Zone 4	0,00%	0,00%	0,00%	0,00%
Longest Noise Period (s)	71,21			
Average Noise Period (s)	7,44			

Göteborg - Stockholm - Uppsala

Distance 536 km whereof 13,90 km disturbances

	Signal 1	Signal 2	Signal 3	Signal 4	No km Worst Case
Total Percentage above Zone 1:	2,40%	2,57%	2,59%	2,39%	18,48 km
Total Percentage Zone 1:	1,51%	1,06%	0,81%	1,32%	8,12 km
Total Percentage Zone 2:	0,82%	0,78%	0,67%	0,76%	4,38 km
Total Percentage Zone 3:	0,07%	0,72%	1,07%	0,30%	5,74 km
Total Percentage Zone 4:	0,00%	0,01%	0,05%	0,00%	0,25 km

Zone 1: 15 - 60 µT
Zone 2: 60 - 150 µT
Zone 3: 150 - 300 µT
Zone 4: >300 µT

	Gbg-Borås				Borås - Gränna				Gränna - Stavsjö				Stavsjö - Hägersten				Hägersten - Uppsala			
	Signal 1	Signal 2	Signal 3	Signal 4	Signal 1	Signal 2	Signal 3	Signal 4	Signal 1	Signal 2	Signal 3	Signal 4	Signal 1	Signal 2	Signal 3	Signal 4	Signal 1	Signal 2	Signal 3	Signal 4
Offset (µT)	41,72	56,33	77,88	67,24	43,06	55,88	76,11	63,48	43,06	55,44	76,56	65,91	43,28	55,44	76,11	69,67	44,39	55,66	7722	65,03
Noise Max (µT)	125,84	138,27	152,89	157,04	158,46	152,96	194,71	179,82	181,32	353,58	324,37	273,82	344,89	431,50	357,12	216,54	215,06	336,88	367,30	306,78
Noise Max Average (µT)	38,25	39,71	39,79	37,64	45,11	42,73	38,98	36,65	64,85	79,87	81,70	65,23	65,72	110,40	103,83	60,50	54,95	65,67	63,92	47,40
Noise Count	32	33	30	28	48	45	45	40	62	61	54	55	90	85	84	81	70	68	56	50
Above Zone 1	1,44%	1,25%	1,23%	1,24%	0,68%	0,56%	0,53%	0,45%	0,98%	0,90%	0,93%	0,90%	1,93%	2,38%	2,42%	2,31%	8,27%	9,08%	9,19%	8,26%
Zone 1	1,35%	1,15%	1,13%	1,13%	0,48%	0,49%	0,47%	0,36%	0,56%	0,40%	0,24%	0,39%	1,13%	0,97%	0,84%	1,48%	5,06%	2,92%	1,82%	3,98%
Zone 2	0,09%	0,10%	0,10%	0,11%	0,20%	0,07%	0,07%	0,08%	0,40%	0,37%	0,28%	0,42%	0,65%	0,83%	0,57%	0,53%	3,06%	2,82%	2,67%	3,04%
Zone 3	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,01%	0,02%	0,13%	0,40%	0,09%	0,15%	0,57%	0,96%	0,30%	0,15%	3,30%	4,50%	1,23%
Zone 4	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,01%	0,05%	0,00%	0,00%	0,04%	0,20%	0,00%
Longest Noise Period (s)	13,94				12,03				9,89				58,08				65,54			
Average Noise Period (s)	1,77				1,14				0,88				2,17				5,02			

Göteborg - Heby

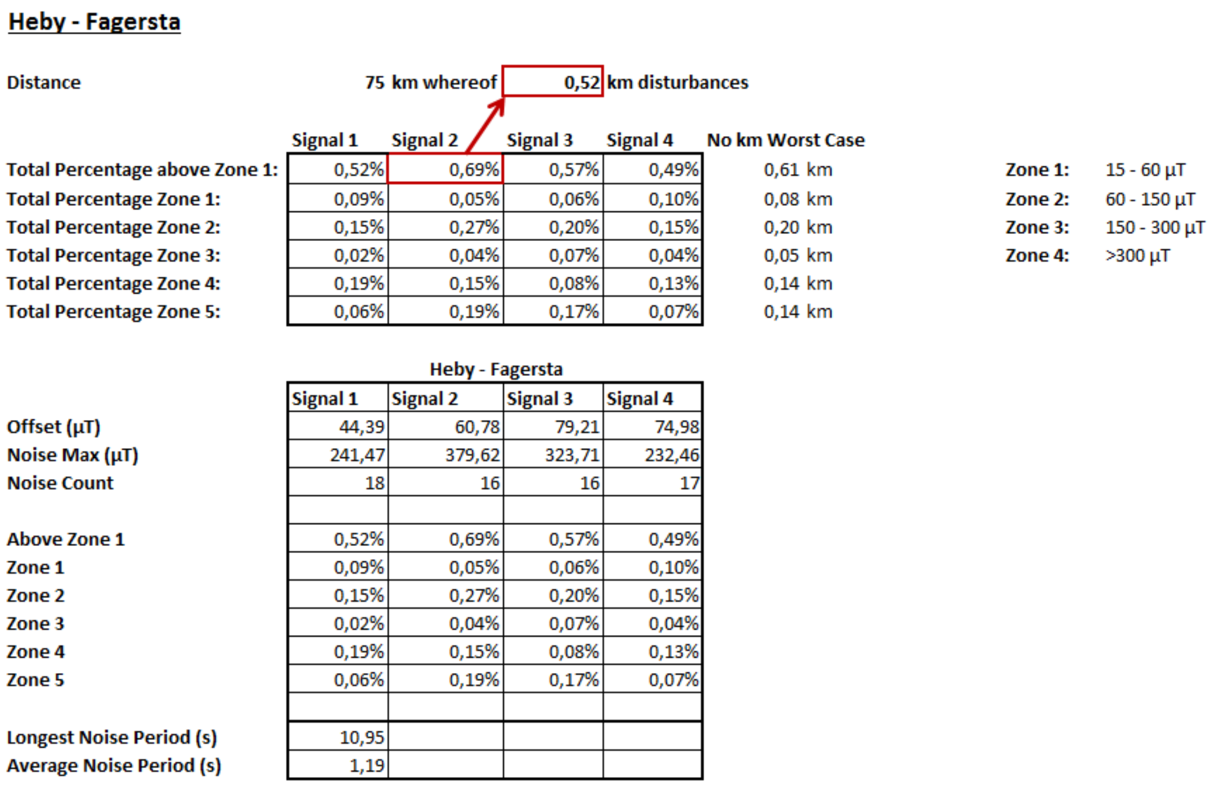
Distance 429 km whereof 2,53 km disturbances

	Signal 1	Signal 2	Signal 3	Signal 4	No km Worst Case
Total Percentage above Zone 1:	0,45%	0,50%	0,42%	0,59%	3,09 km
Total Percentage Zone 1:	0,31%	0,28%	0,29%	0,50%	2,17 km
Total Percentage Zone 2:	0,09%	0,13%	0,11%	0,08%	0,57 km
Total Percentage Zone 3:	0,05%	0,08%	0,02%	0,00%	0,33 km
Total Percentage Zone 4:	0,00%	0,00%	0,00%	0,00%	0,01 km

Zone 1:	15 - 60 µT
Zone 2:	60 - 150 µT
Zone 3:	150 - 300 µT
Zone 4:	>300 µT

	ÅF Huset - Sävedalen				**Sävedalen - Lekåsa**				**Lekåsa - Laxå**			
	Signal 1	**Signal 2**	**Signal 3**	**Signal 4**	**Signal 1**	**Signal 2**	**Signal 3**	**Signal 4**	**Signal 1**	**Signal 2**	**Signal 3**	**Signal 4**
Offset (µT)	40,17	60,34	78,55	72,3	44,17	60,56	78,33	70,77	42,83	60,34	78,77	70,56
Noise Max (µT)	76,57	79,93	105,32	126,52	109,64	93,07	98,90	92,90	410,59	112,89	139,40	112,14
Noise Average (µT)	25,92	27,12	25,06	26,54	24,68	24,86	24,08	24,17	39,05	32,95	33,21	33,78
Noise Count	15	12	8	12	28	28	29	26	30	30	32	33
Above Zone 1	0,93%	1,07%	0,91%	0,84%	0,25%	0,30%	0,26%	0,27%	0,21%	0,20%	0,21%	0,22%
Zone 1	0,86%	1,04%	0,86%	0,76%	0,23%	0,24%	0,19%	0,26%	0,20%	0,18%	0,16%	0,20%
Zone 2	0,07%	0,03%	0,05%	0,08%	0,02%	0,06%	0,07%	0,02%	0,01%	0,02%	0,04%	0,02%
Zone 3	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Zone 4	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Longest Noise Period (s)	3,82				2,11				1,85			
Average Noise Period (s)	0,72				0,44				0,54			

	Laxå - Kumla				**Kumla - Västerås**				**Västerås - Heby**			
	Signal 1	**Signal 2**	**Signal 3**	**Signal 4**	**Signal 1**	**Signal 2**	**Signal 3**	**Signal 4**	**Signal 1**	**Signal 2**	**Signal 3**	**Signal 4**
Offset (µT)	43,72	60,78	79,88	71	45,72	61,9	80,98	71,88	45,27	62,12	81,42	76,09
Noise Max (µT)	68,14	101,31	120,81	87,59	329,36	407,90	308,44	195,75	63,70	59,45	72,13	69,01
Noise Average (µT)	20,21	25,34	26,64	25,36	86,13	92,01	62,67	43,02	27,30	25,45	24,43	21,87
Noise Count	8	10	10	8	73	65	61	61	5	7	7	5
Above Zone 1	0,32%	0,39%	0,37%	0,39%	0,94%	1,07%	0,84%	0,91%	0,12%	0,13%	0,11%	0,11%
Zone 1	0,32%	0,37%	0,32%	0,25%	0,46%	0,36%	0,49%	0,76%	0,12%	0,13%	0,11%	0,11%
Zone 2	0,00%	0,02%	0,05%	0,14%	0,29%	0,41%	0,28%	0,15%	0,00%	0,00%	0,00%	0,00%
Zone 3	0,00%	0,00%	0,00%	0,00%	0,19%	0,28%	0,07%	0,01%	0,00%	0,00%	0,00%	0,00%
Zone 4	0,00%	0,00%	0,00%	0,00%	0,00%	0,01%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Longest Noise Period (s)	11,62				11,69				1,02			
Average Noise Period (s)	2,11				0,82				0,32			



Heby - Fagersta

Distance 75 **km whereof** 0,52 **km disturbances**

	Signal 1	Signal 2	Signal 3	Signal 4	No km Worst Case
Total Percentage above Zone 1:	0,52%	0,69%	0,57%	0,49%	0,61 km
Total Percentage Zone 1:	0,09%	0,05%	0,06%	0,10%	0,08 km
Total Percentage Zone 2:	0,15%	0,27%	0,20%	0,15%	0,20 km
Total Percentage Zone 3:	0,02%	0,04%	0,07%	0,04%	0,05 km
Total Percentage Zone 4:	0,19%	0,15%	0,08%	0,13%	0,14 km
Total Percentage Zone 5:	0,06%	0,19%	0,17%	0,07%	0,14 km

Zone 1:	15 - 60 µT
Zone 2:	60 - 150 µT
Zone 3:	150 - 300 µT
Zone 4:	>300 µT

Heby - Fagersta

	Signal 1	Signal 2	Signal 3	Signal 4
Offset (µT)	44,39	60,78	79,21	74,98
Noise Max (µT)	241,47	379,62	323,71	232,46
Noise Count	18	16	16	17
Above Zone 1	0,52%	0,69%	0,57%	0,49%
Zone 1	0,09%	0,05%	0,06%	0,10%
Zone 2	0,15%	0,27%	0,20%	0,15%
Zone 3	0,02%	0,04%	0,07%	0,04%
Zone 4	0,19%	0,15%	0,08%	0,13%
Zone 5	0,06%	0,19%	0,17%	0,07%
Longest Noise Period (s)	10,95			
Average Noise Period (s)	1,19			

Appendix D – Dead reckoning data

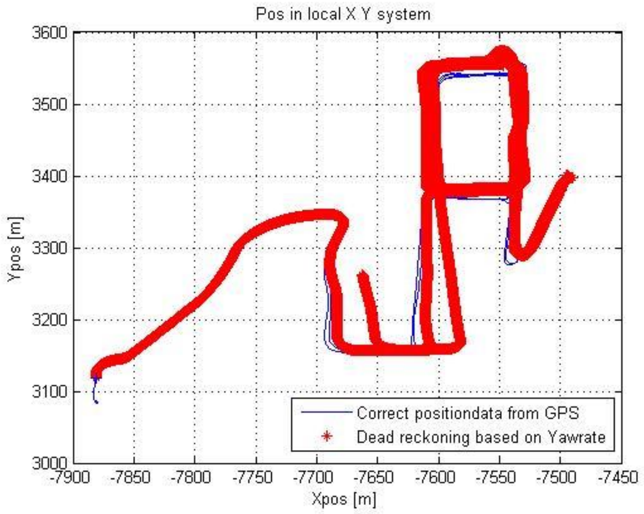
This appendix covers the dead reckoning for the lateral positioning error that has been investigated by Patrik Thede and test data by David Andersson, both ÅF employees stationed at Volvo Car Corporation.

Name of calculation	start_90000_15m		Start_100000_15m		start_120000_15m	
Type of road	Curved		Straight		Slightly curved	
Speed [m/s]	2,5	2,9	7,6	8,3	4,7	6,7
Speed [km/h]	9	10,3	27,2	29,7	16,9	24,1
	Distance [m]	***Deviation [m]***	***Distance [m]***	***Deviation [m]***	***Distance [m]***	***Deviation [m]***
	3	0,0531	3	0,0962	3	0,1080
	6	0,0708	6	0,0440	6	0,0174
	9	0,0401	9	0,1369	9	0,1326
	12	0,1202	12	0,0343	12	0,1537
	15	0,2179	15	0,2665	15	0,0709

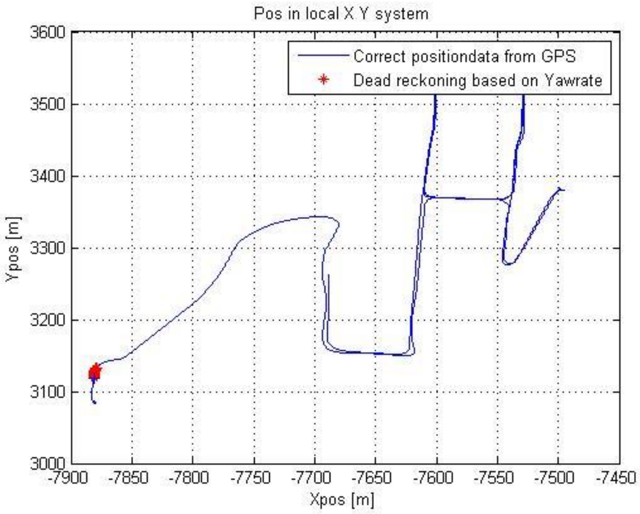
Name of calculation	start_130000_15m		start_175000_15m	
Type of road	Straight		Straight	
Speed [m/s]	4,7	5,2	6,2	6,3
Speed [km/h]	16,9	18,7	22,4	22,7
	Distance [m]	***Deviation [m]***	***Distance [m]***	***Deviation [m]***
	3	0,0359	3	0,0351
	6	0,0386	6	0,1318
	9	0,0392	9	0,1931
	12	0,0765	12	0,2524
	15	0,0995	15	0,1623

In the following figures, the different calculations are shown.

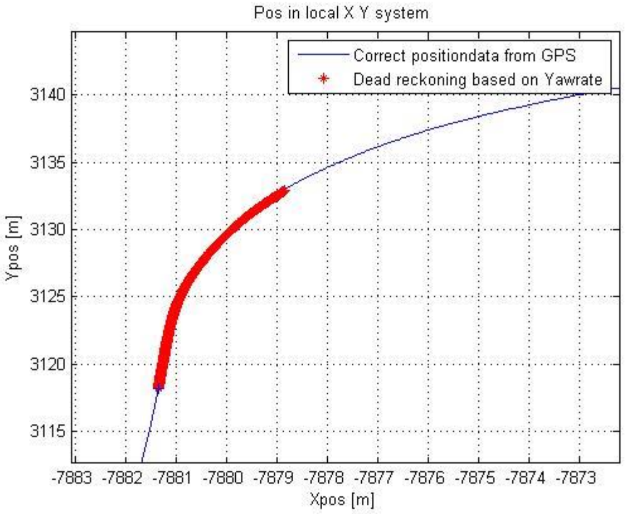
Dead reckoning overall route



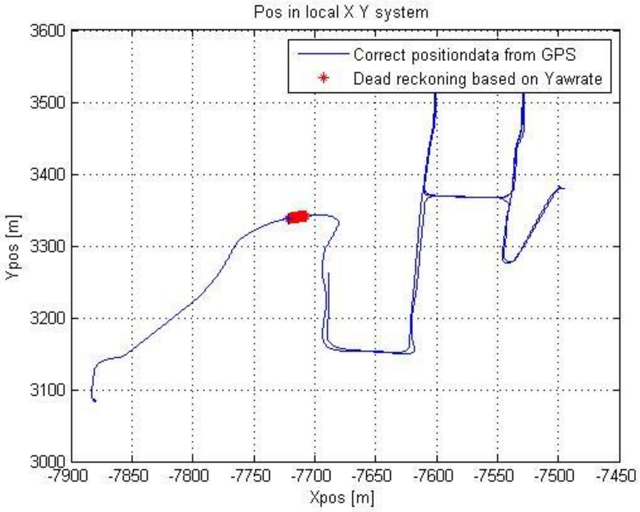
Dead reckoning start_90000_15m



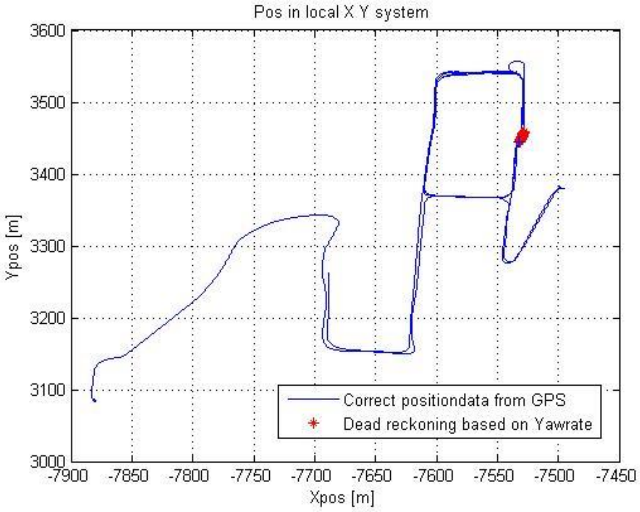
Dead reckoning start_90000_15m_zoom



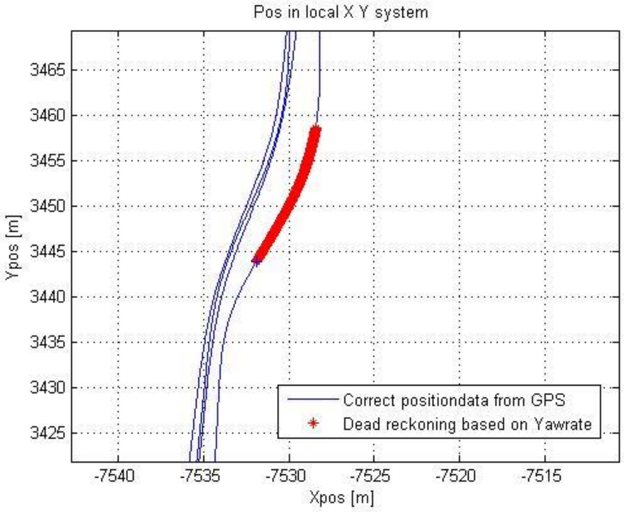
Dead reckoning start_100000_15m



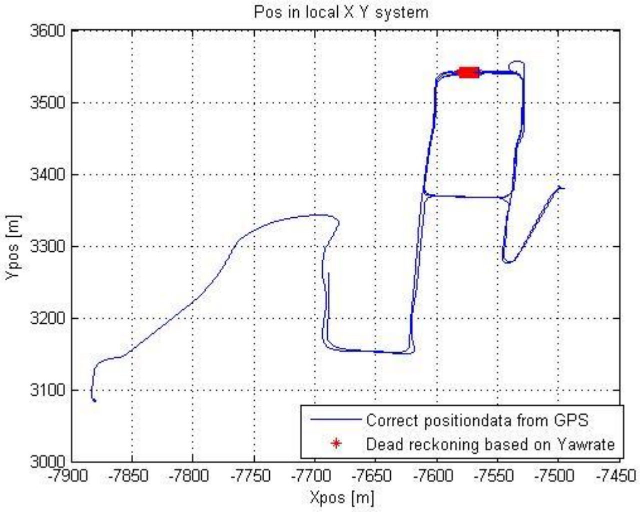
Dead reckoning start_120000_15m



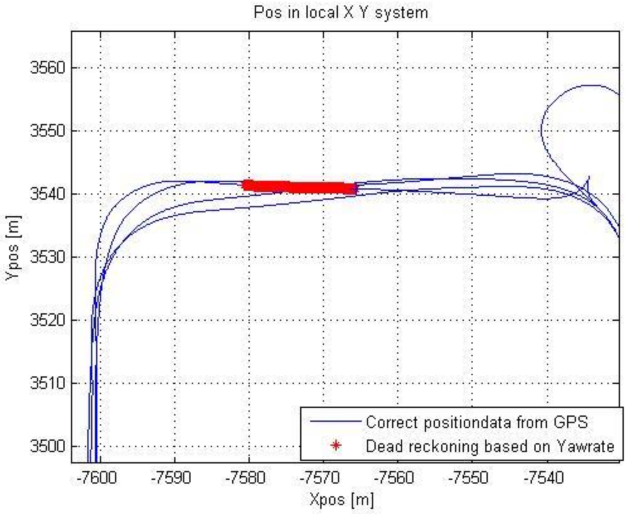
Dead reckoning start_120000_15m_zoom



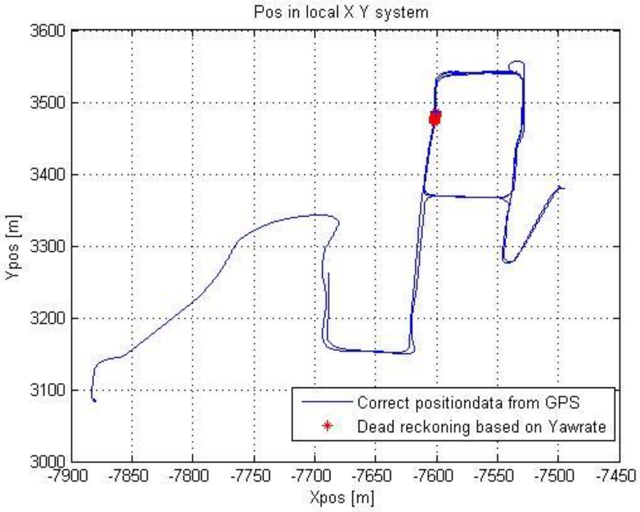
Dead reckoning start_130000_15m



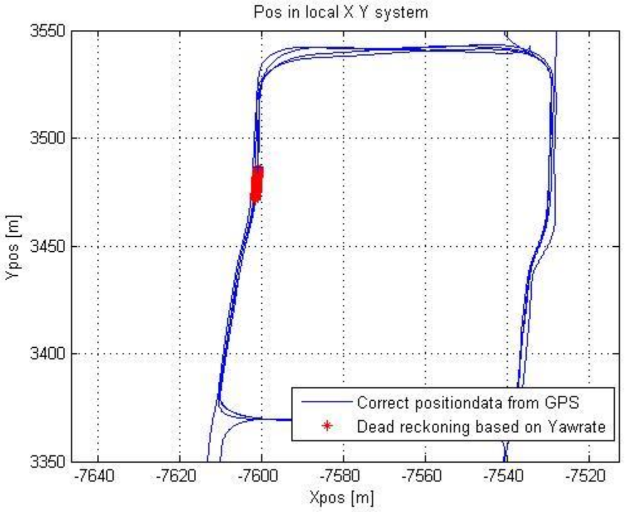
Dead reckoning start_130000_15m_zoom



Dead reckoning start_175000_15m



Dead reckoning start_175000_15m_zoom

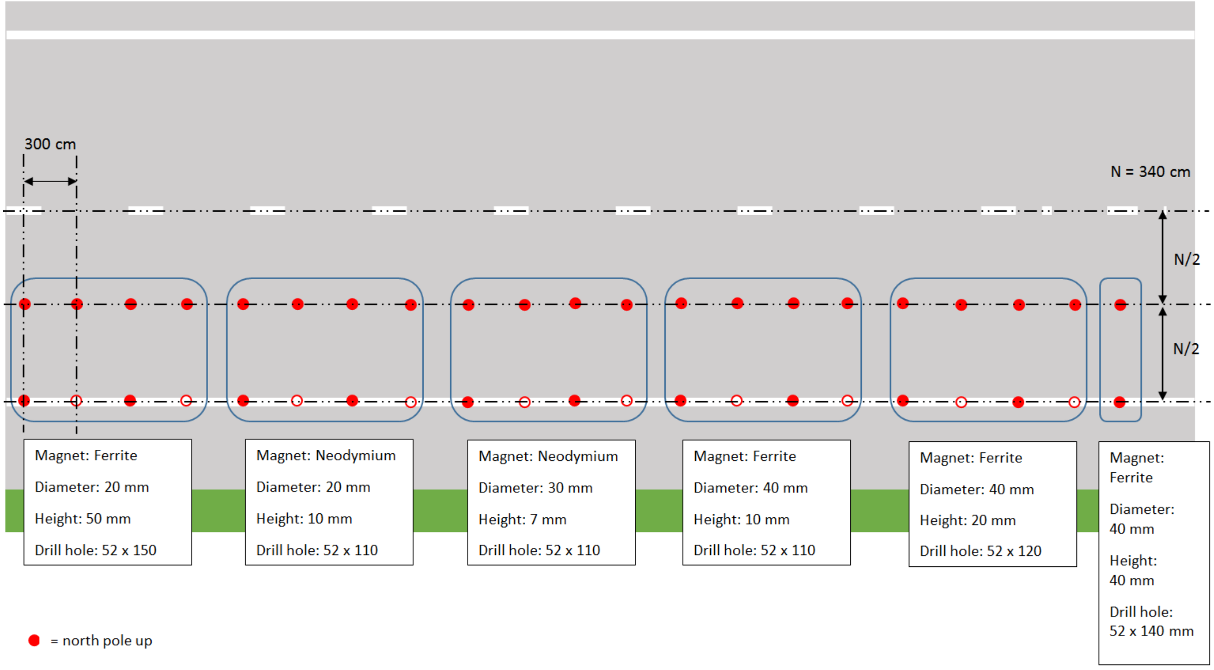


Appendix E – Magnetic markers test road, RV68 Fagersta

Magnetic markers of different sizes have been mounted at a test road, RV 58 in Fagersta by Trafikverket (see Figure C 1). This appendix explains how they are mounted and what magnetic fields have been measured for each marker. The information has been compiled by David Björklöf, Specialist at Trafikverket.

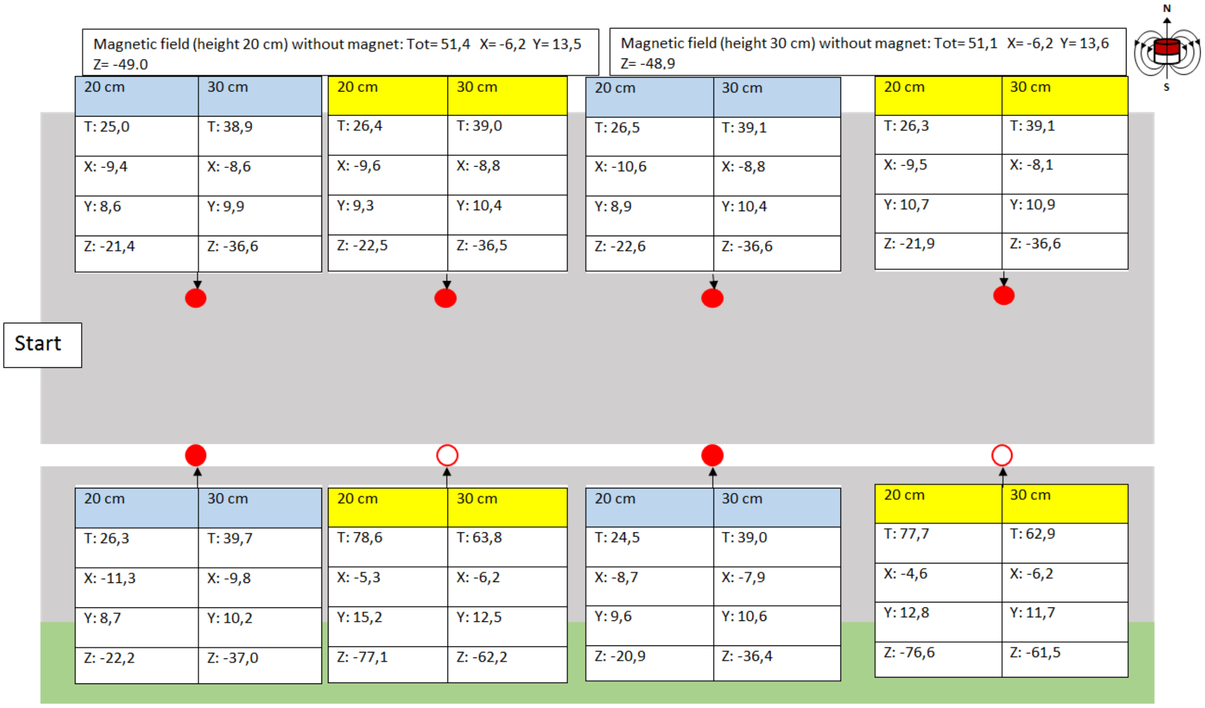
Figure C 1: The part of the test road, RV68 in Fagersta, where the magnetic markers have been mounted.

Overview of mounted magnetic markers



All measurements have been performed at two different heights; 20 and 30 cm above road surface (corresponds to 30 and 40 cm above magnet respectively).

Ferrite diameter 20 mm height 50 mm
5 magnets 10 mm high linked together.
Drill hole: diameter 52 mm, deep 150 mm



Magnetic field (height 20 cm) without magnet: Tot= 51,4 X= -6,2 Y= 13,5 Z= -49.0

Magnetic field (height 30 cm) without magnet: Tot= 51,1 X= -6,2 Y= 13,6 Z= -48,9

20 cm	30 cm
T: 25,0	T: 38,9
X: -9,4	X: -8,6
Y: 8,6	Y: 9,9
Z: -21,4	Z: -36,6

20 cm	30 cm
T: 26,4	T: 39,0
X: -9,6	X: -8,8
Y: 9,3	Y: 10,4
Z: -22,5	Z: -36,5

20 cm	30 cm
T: 26,5	T: 39,1
X: -10,6	X: -8,8
Y: 8,9	Y: 10,4
Z: -22,6	Z: -36,6

20 cm	30 cm
T: 26,3	T: 39,1
X: -9,5	X: -8,1
Y: 10,7	Y: 10,9
Z: -21,9	Z: -36,6

20 cm	30 cm
T: 26,3	T: 39,7
X: -11,3	X: -9,8
Y: 8,7	Y: 10,2
Z: -22,2	Z: -37,0

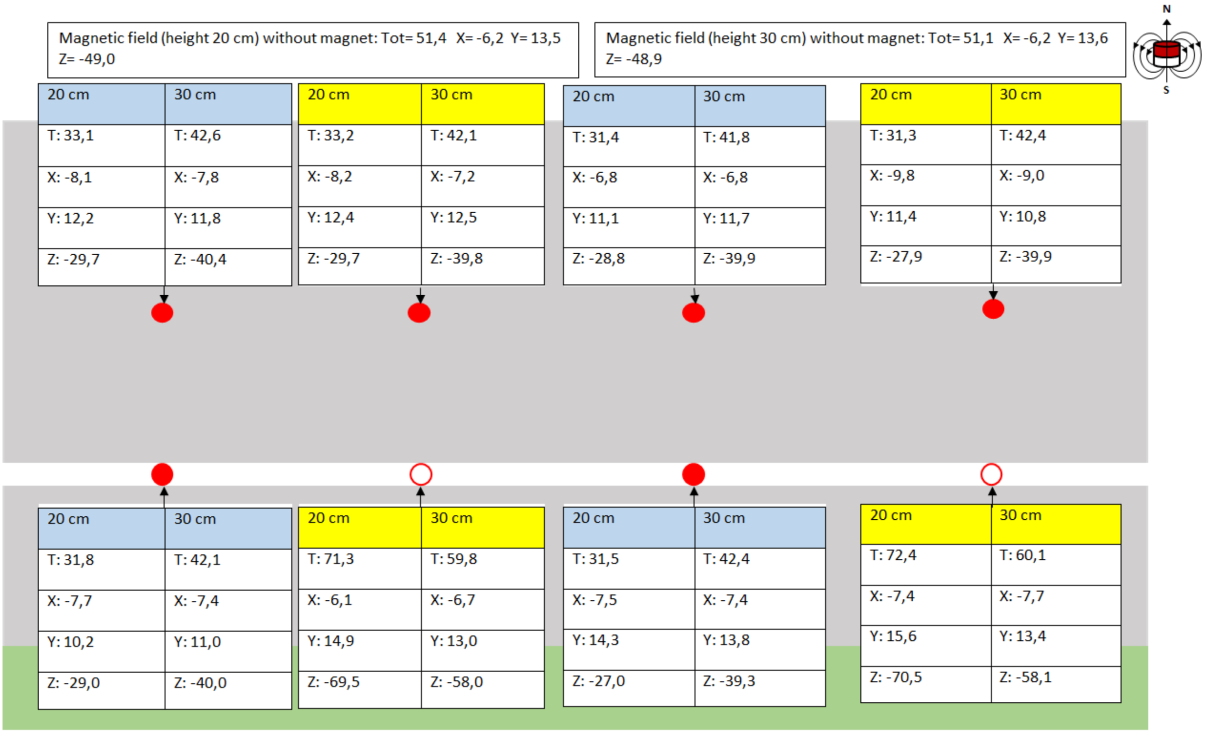
20 cm	30 cm
T: 78,6	T: 63,8
X: -5,3	X: -6,2
Y: 15,2	Y: 12,5
Z: -77,1	Z: -62,2

20 cm	30 cm
T: 24,5	T: 39,0
X: -8,7	X: -7,9
Y: 9,6	Y: 10,6
Z: -20,9	Z: -36,4

20 cm	30 cm
T: 77,7	T: 62,9
X: -4,6	X: -6,2
Y: 12,8	Y: 11,7
Z: -76,6	Z: -61,5

Neodymium diameter 20 mm height 10 mm

Drill hole: diameter 52 mm, deep 110 mm



Magnetic field (height 20 cm) without magnet: Tot= 51,4 X= -6,2 Y= 13,5 Z= -49,0

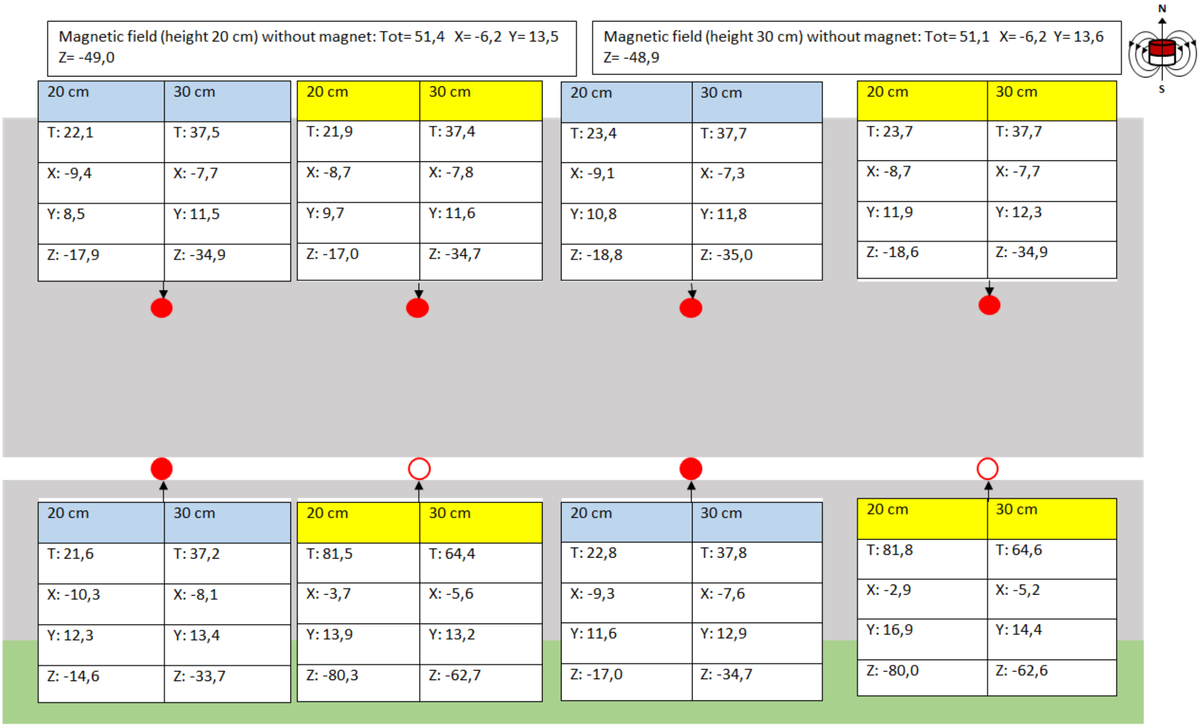
Magnetic field (height 30 cm) without magnet: Tot= 51,1 X= -6,2 Y= 13,6 Z= -48,9

20 cm	30 cm	20 cm	30 cm	20 cm	30 cm	20 cm	30 cm
T: 33,1	T: 42,6	T: 33,2	T: 42,1	T: 31,4	T: 41,8	T: 31,3	T: 42,4
X: -8,1	X: -7,8	X: -8,2	X: -7,2	X: -6,8	X: -6,8	X: -9,8	X: -9,0
Y: 12,2	Y: 11,8	Y: 12,4	Y: 12,5	Y: 11,1	Y: 11,7	Y: 11,4	Y: 10,8
Z: -29,7	Z: -40,4	Z: -29,7	Z: -39,8	Z: -28,8	Z: -39,9	Z: -27,9	Z: -39,9

20 cm	30 cm	20 cm	30 cm	20 cm	30 cm	20 cm	30 cm
T: 31,8	T: 42,1	T: 71,3	T: 59,8	T: 31,5	T: 42,4	T: 72,4	T: 60,1
X: -7,7	X: -7,4	X: -6,1	X: -6,7	X: -7,5	X: -7,4	X: -7,4	X: -7,7
Y: 10,2	Y: 11,0	Y: 14,9	Y: 13,0	Y: 14,3	Y: 13,8	Y: 15,6	Y: 13,4
Z: -29,0	Z: -40,0	Z: -69,5	Z: -58,0	Z: -27,0	Z: -39,3	Z: -70,5	Z: -58,1

Neodymium diameter 30 mm height 7 mm

Drill hole: diameter 52 mm, deep 110 mm



Magnetic field (height 20 cm) without magnet: Tot= 51,4 X= -6,2 Y= 13,5 Z= -49,0

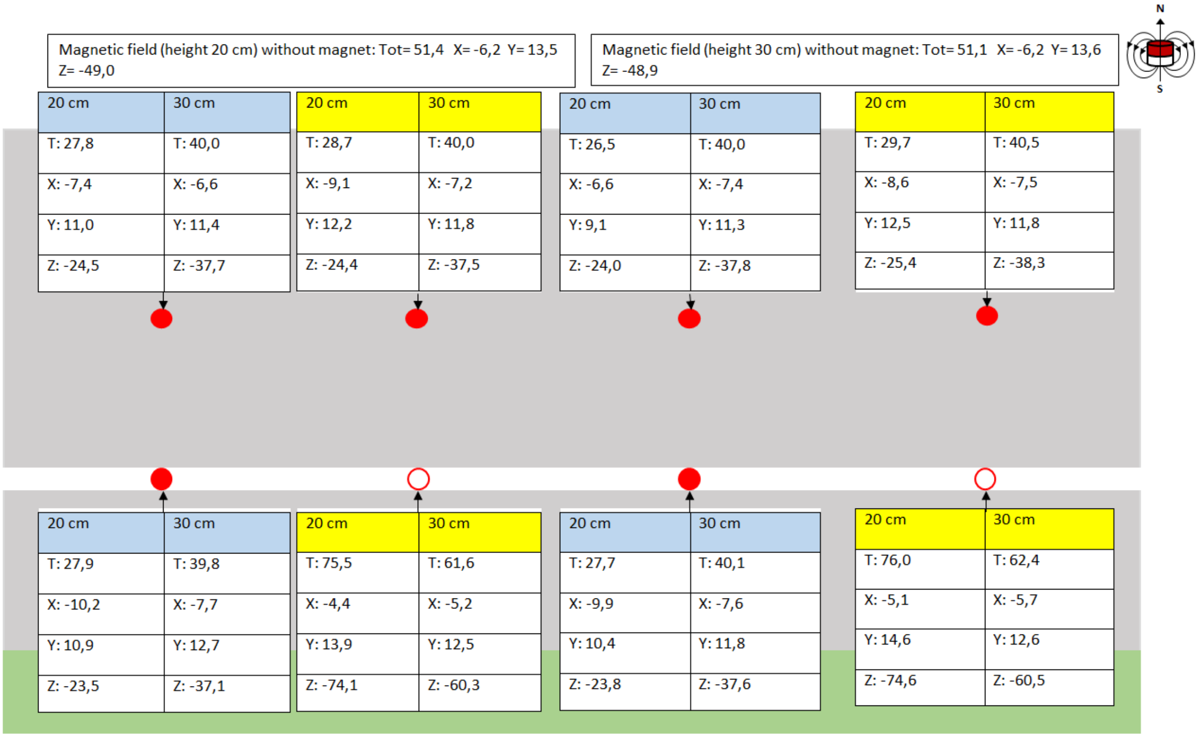
Magnetic field (height 30 cm) without magnet: Tot= 51,1 X= -6,2 Y= 13,6 Z= -48,9

20 cm	30 cm	20 cm	30 cm	20 cm	30 cm	20 cm	30 cm
T: 22,1	T: 37,5	T: 21,9	T: 37,4	T: 23,4	T: 37,7	T: 23,7	T: 37,7
X: -9,4	X: -7,7	X: -8,7	X: -7,8	X: -9,1	X: -7,3	X: -8,7	X: -7,7
Y: 8,5	Y: 11,5	Y: 9,7	Y: 11,6	Y: 10,8	Y: 11,8	Y: 11,9	Y: 12,3
Z: -17,9	Z: -34,9	Z: -17,0	Z: -34,7	Z: -18,8	Z: -35,0	Z: -18,6	Z: -34,9

20 cm	30 cm	20 cm	30 cm	20 cm	30 cm	20 cm	30 cm
T: 21,6	T: 37,2	T: 81,5	T: 64,4	T: 22,8	T: 37,8	T: 81,8	T: 64,6
X: -10,3	X: -8,1	X: -3,7	X: -5,6	X: -9,3	X: -7,6	X: -2,9	X: -5,2
Y: 12,3	Y: 13,4	Y: 13,9	Y: 13,2	Y: 11,6	Y: 12,9	Y: 16,9	Y: 14,4
Z: -14,6	Z: -33,7	Z: -80,3	Z: -62,7	Z: -17,0	Z: -34,7	Z: -80,0	Z: -62,6

Ferrite diameter 40 mm height 10 mm

Drill hole: diameter 52 mm, deep 110 mm



Magnetic field (height 20 cm) without magnet: Tot= 51,4 X= -6,2 Y= 13,5 Z= -49,0

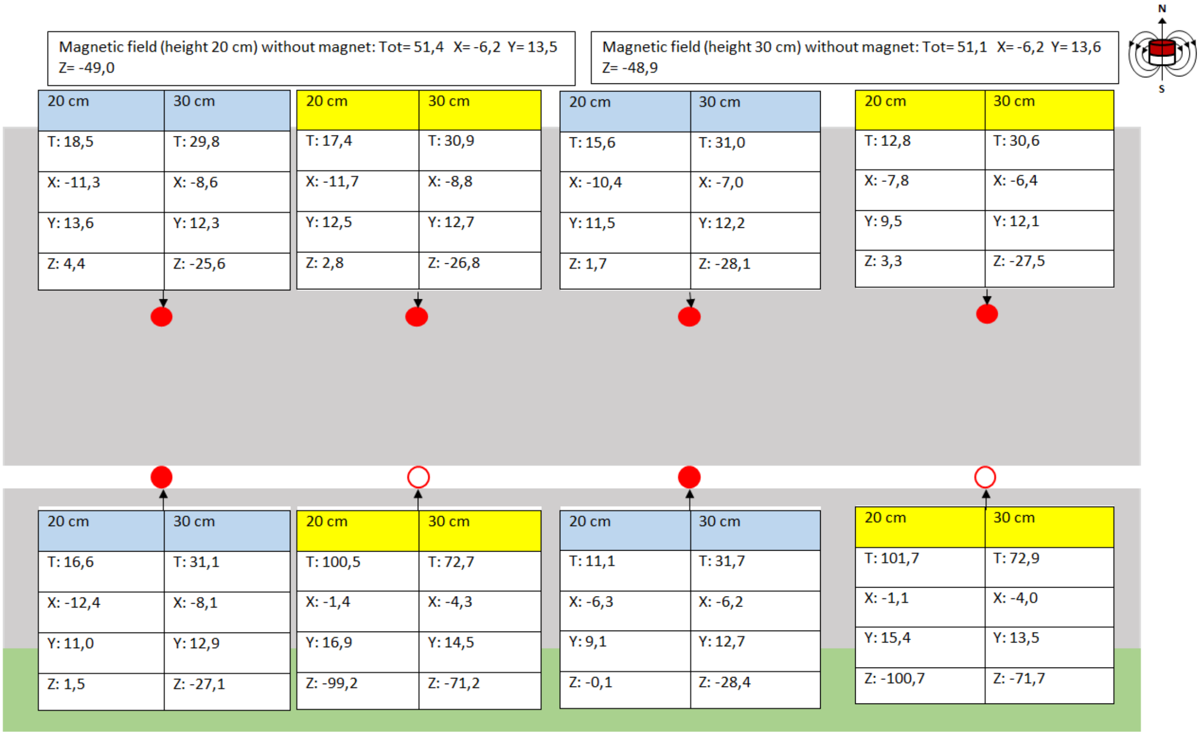
Magnetic field (height 30 cm) without magnet: Tot= 51,1 X= -6,2 Y= 13,6 Z= -48,9

20 cm	30 cm	20 cm	30 cm	20 cm	30 cm	20 cm	30 cm
T: 27,8	T: 40,0	T: 28,7	T: 40,0	T: 26,5	T: 40,0	T: 29,7	T: 40,5
X: -7,4	X: -6,6	X: -9,1	X: -7,2	X: -6,6	X: -7,4	X: -8,6	X: -7,5
Y: 11,0	Y: 11,4	Y: 12,2	Y: 11,8	Y: 9,1	Y: 11,3	Y: 12,5	Y: 11,8
Z: -24,5	Z: -37,7	Z: -24,4	Z: -37,5	Z: -24,0	Z: -37,8	Z: -25,4	Z: -38,3

20 cm	30 cm	20 cm	30 cm	20 cm	30 cm	20 cm	30 cm
T: 27,9	T: 39,8	T: 75,5	T: 61,6	T: 27,7	T: 40,1	T: 76,0	T: 62,4
X: -10,2	X: -7,7	X: -4,4	X: -5,2	X: -9,9	X: -7,6	X: -5,1	X: -5,7
Y: 10,9	Y: 12,7	Y: 13,9	Y: 12,5	Y: 10,4	Y: 11,8	Y: 14,6	Y: 12,6
Z: -23,5	Z: -37,1	Z: -74,1	Z: -60,3	Z: -23,8	Z: -37,6	Z: -74,6	Z: -60,5

Ferrite diameter 40 mm height 20 mm

Drill hole: diameter 52 mm, deep 120 mm



Magnetic field (height 20 cm) without magnet: Tot= 51,4 X= -6,2 Y= 13,5 Z= -49,0

Magnetic field (height 30 cm) without magnet: Tot= 51,1 X= -6,2 Y= 13,6 Z= -48,9

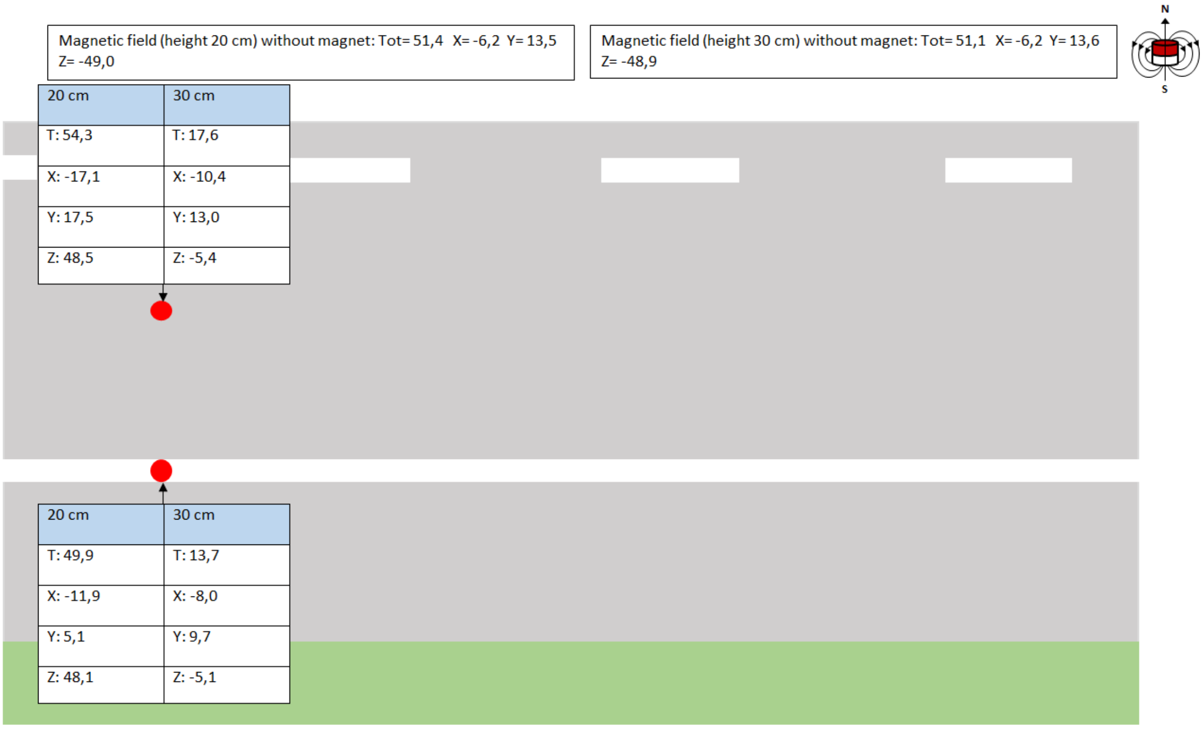
20 cm	30 cm	20 cm	30 cm	20 cm	30 cm	20 cm	30 cm
T: 18,5	T: 29,8	T: 17,4	T: 30,9	T: 15,6	T: 31,0	T: 12,8	T: 30,6
X: -11,3	X: -8,6	X: -11,7	X: -8,8	X: -10,4	X: -7,0	X: -7,8	X: -6,4
Y: 13,6	Y: 12,3	Y: 12,5	Y: 12,7	Y: 11,5	Y: 12,2	Y: 9,5	Y: 12,1
Z: 4,4	Z: -25,6	Z: 2,8	Z: -26,8	Z: 1,7	Z: -28,1	Z: 3,3	Z: -27,5

20 cm	30 cm	20 cm	30 cm	20 cm	30 cm	20 cm	30 cm
T: 16,6	T: 31,1	T: 100,5	T: 72,7	T: 11,1	T: 31,7	T: 101,7	T: 72,9
X: -12,4	X: -8,1	X: -1,4	X: -4,3	X: -6,3	X: -6,2	X: -1,1	X: -4,0
Y: 11,0	Y: 12,9	Y: 16,9	Y: 14,5	Y: 9,1	Y: 12,7	Y: 15,4	Y: 13,5
Z: 1,5	Z: -27,1	Z: -99,2	Z: -71,2	Z: -0,1	Z: -28,4	Z: -100,7	Z: -71,7

Ferrite diameter 40 mm height 40 mm

2 magnets 20 mm high linked together

Drill hole: diameter 52 mm, deep 140 mm



Magnetic field (height 20 cm) without magnet: Tot= 51,4 X= -6,2 Y= 13,5 Z= -49,0

Magnetic field (height 30 cm) without magnet: Tot= 51,1 X= -6,2 Y= 13,6 Z= -48,9

20 cm	30 cm
T: 54,3	T: 17,6
X: -17,1	X: -10,4
Y: 17,5	Y: 13,0
Z: 48,5	Z: -5,4

20 cm	30 cm
T: 49,9	T: 13,7
X: -11,9	X: -8,0
Y: 5,1	Y: 9,7
Z: 48,1	Z: -5,1

Mounting of magnetic markers

The magnetic markers embedded in the test road were mounted by Trafikverket and NCC as follows:

The placements of the markers were marked by hand. The holes were made using a vehicle mounted core drilling machine with diameter 52 mm. A handheld drilling machine with 25 mm diameter was tested for the smaller magnets, but didn´t work since asphalt got stuck inside the core drill.

The bottoms of the holes were then filled with gravel to ensure the correct depth of the magnetic markers. The markers were placed in the holes and then the holes were covered with asphalt by hand.

Trafikverket estimates the tolerances of these mountings to be

- Mark down of drilling holes: approx. ± 2 cm lateral and longitudinal.
- Drilling: approx. ± 1 cm lateral and longitudinal (due to that the drilling crown may move a bit at contact with the asphalt).
- Placement of magnetic marker in the drilling hole:
    - approx. ± 0,5 cm lateral and longitudinal for markers of diameter 30 mm and 40 mm, and ± 1 cm lateral and longitudinal for markers of diameter 200 mm (using a smaller hole will improve the tolerances).
    - Approx. ± 0,5 cm depth, mounting angel between 5-10 degrees.

Measurements of magnetic fields at test road RV68 Fagersta

The magnetic fields from the magnets embedded in the road at Fagersta were measured two times; at mounting 2015-05-05 and when repaving of the road had been done 2015-06-25.

Magnets embedded at the centre of the lane

Measurement height 20 cm above road surface (30 cm above the top of the magnet)

			Date of measurement 2015-05-05				Date of measurement 2015-06-25				Change on z-axis
Nr	Type of magnet (diameter x height)	Polarity	Tot [µT]	x-axis [µT]	y-axis [µT]	z-axis [µT]	Tot [µT]	x-axis [µT	y-axis [µT	z-axis [µT]	[µT]
1	Ferrit 20x50 mm	North Pole up	25,0	-9,4	8,6	-21,4	23,5	-9,7	9,0	-19,4	2,0
2	Ferrit 20x50 mm	North Pole up	26,4	-9,6	9,3	-22,5	25,6	-11,7	11,2	-20,2	2,3
3	Ferrit 20x50 mm	North Pole up	26,5	-10,6	8,9	-22,6	2701,0	-14,9	9,6	-20,6	2,0
4	Ferrit 20x50 mm	North Pole up	26,3	-9,5	10,7	-21,9	22,7	-6,2	8,0	-20,2	1,7
5	Neodymium 20x10 mm	North Pole up	33,1	-8,1	12,2	-29,7	33,0	-12,7	10,0	-28,5	1,2
6	Neodymium 20x10 mm	North Pole up	33,2	-8,2	12,4	-29,7	31,2	-11,5	8,4	-27,6	2,1
7	Neodymium 20x10 mm	North Pole up	31,4	-6,8	11,1	-28,8	30,1	-10,0	10,7	-26,2	2,6
8	Neodymium 20x10 mm	North Pole up	31,3	-9,8	11,4	-27,9	33,5	-15,6	10,9	-27,4	0,5
9	Neodymium 30x7 mm	North Pole up	22,1	-9,4	8,5	-17,9	21,6	-10,1	1,1	-19,1	-1,2
10	Neodymium 30x7 mm	North Pole up	21,9	-8,7	9,7	-17,0	20,7	-9,1	1,0	-18,4	-1,4
11	Neodymium 30x7 mm	North Pole up	23,4	-9,1	10,8	-18,8	22,0	-11,7	2,3	-18,5	0,3
12	Neodymium 30x7 mm	North Pole up	23,7	-8,7	11,9	-18,6	20,6	-11,5	5,2	-16,1	2,5
13	Ferrit 40x10 mm	North Pole up	27,8	-7,4	11,0	-24,5	26,4	-7,7	2,9	-25,2	-0,7
14	Ferrit 40x10 mm	North Pole up	28,7	-9,1	12,2	-24,4	26,7	-13,2	9,2	-22,1	2,3
15	Ferrit 40x10 mm	North Pole up	26,5	-6,6	9,1	-24,0	26,1	-11,6	5,3	-22,8	1,2
16	Ferrit 40x10 mm	North Pole up	29,7	-8,6	12,5	-25,4	28,9	-14,5	5,2	-24,4	1,0
17	Ferrit 40x20 mm	North Pole up	18,5	-11,3	13,6	4,4	13,8	-12,9	3,4	3,4	-1,0
18	Ferrit 40x20 mm	North Pole up	17,4	-11,7	12,5	2,8	7,9	-7,6	2,4	2,2	-0,6
19	Ferrit 40x20 mm	North Pole up	15,6	-10,4	11,5	1,7	12,6	-12,2	2,9	1,3	-0,4
20	Ferrit 40x20 mm	North Pole up	12,8	-7,8	9,5	3,3	19,9	-19,1	5,5	1,1	-2,2
21	Ferrit 40x40 mm	North Pole up	54,3	-17,1	17,5	48,5	57,5	-22,0	-3,0	53,1	4,6

Magnets embedded in the edge line

Measurement height 20 cm above road surface (30 cm above the top of the magnet)

			Date of measurement 2015-05-05				Date of measurement 2015-06-25				Change on z-axis
Nr	Type of magnet (diameter x height)	Polarity	Tot [µT]	x-axis [µT]	y-axis [µT]	z-axis [µT]	Tot [µT]	x-axis [µT	y-axis [µT	z-axis [µT]	[µT]
1	Ferrit 20x50 mm	North Pole up	26,3	-11,3	8,7	-22,2	25,1	-15,8	3,9	-20,6	1,6
2	Ferrit 20x50 mm	South Pole up	78,6	-5,3	15,2	-77,1	82,7	-10,1	9,4	-81,6	-4,5
3	Ferrit 20x50 mm	North Pole up	24,5	-8,7	9,6	-20,9	25,1	-11,0	10,7	-19,1	1,8
4	Ferrit 20x50 mm	South Pole up	77,7	-4,6	12,8	-76,6	83,1	-11,8	9,0	-81,8	-5,2
5	Neodymium 20x10 mm	North Pole up	31,8	-7,7	10,2	-29,0	32,3	-13,1	9,3	-28,1	0,9
6	Neodymium 20x10 mm	South Pole up	71,3	-6,1	14,9	-69,5	73,5	-8,7	18,0	-70,5	-1,0
7	Neodymium 20x10 mm	North Pole up	31,5	-7,5	14,3	-27,0	30,7	-9,5	2,8	-26,3	0,7
8	Neodymium 20x10 mm	South Pole up	72,4	-7,4	15,6	-70,5	75,0	-10,1	14,8	-72,9	-2,4
9	Neodymium 30x7 mm	North Pole up	21,6	-10,3	12,3	-14,6	21,0	-5,9	4,0	-19,7	-5,1
10	Neodymium 30x7 mm	South Pole up	81,5	-3,7	13,9	-80,3	86,1	-11,1	24,0	-82,1	-1,8
11	Neodymium 30x7 mm	North Pole up	22,8	-9,3	11,6	-17,0	17,4	-5,0	2,8	-16,4	0,6
12	Neodymium 30x7 mm	South Pole up	81,8	-2,9	16,9	-80,0	86,4	-14,1	24,4	-81,5	-1,5
13	Ferrit 40x10 mm	North Pole up	27,9	-10,2	10,9	-23,5	25,3	-5,3	1,4	-24,5	-1,0
14	Ferrit 40x10 mm	South Pole up	75,5	-4,4	13,9	-74,1	79,6	-13,0	15,0	-77,0	-2,9
15	Ferrit 40x10 mm	North Pole up	27,7	-9,9	10,4	-23,8	26,2	-11,2	3,0	-23,4	0,4
16	Ferrit 40x10 mm	South Pole up	76,0	-5,1	14,6	-74,6	78,8	-14,2	17,2	-75,4	-0,8
17	Ferrit 40x20 mm	North Pole up	16,6	-12,4	11,0	1,5	13,9	-12,3	3,0	3,4	1,9
18	Ferrit 40x20 mm	South Pole up	100,5	-1,4	16,9	-99,2	107,6	-7,8	24,0	-104,0	-4,8
19	Ferrit 40x20 mm	North Pole up	11,1	-6,3	9,1	-0,1	23,1	-21,8	7,7	-0,8	-0,7
20	Ferrit 40x20 mm	South Pole up	101,7	-1,1	15,4	-100,7	109,4	-12,5	25,2	-105,0	-4,3
21	Ferrit 40x40 mm	North Pole up	49,9	-11,9	5,1	48,1	56,9	6,7	-17,5	54,2	6,1