EMI Modeling and Evaluation

Durham-Orange Light Rail Transit Project

GO Triangle

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Table of Contents

List of Acronyms and Abbreviations

Acronym/Abbreviation	Definition
AC	Alternating Current
DHVI	Duke Human Vaccine Institute
D-O LRT	Durham-Orange Light Rail Transit
EMI	Electromagnetic Interference
GP	Geomagnetic Perturbation
HZ	Hertz
LRT	Light Rail Transit
LRV	Light Rail Vehicle
MEG	Magnetoencephalography
mG	Milligauss
MRI	Magnetic Resonance Imaging
MRS	Magnetic Resonance Spectroscopy
NMR	Nuclear Magnetic Resonance
nT	Nanotesla
OCS	Overhead Contact System
SCADA	Supervisory Control and Data Acquisition
TEM	Transmission Electron Microscopes
TPSS	Traction Power Sub-Station
µT	Microtesla
UNC	University of North Carolina at Chapel Hill

1. Introduction

Operation of a DC light rail system produces transient magnetic fields that perturb the static background magnetic environment—which is primarily the geomagnetic field—in proximity to the alignment. The Earth's magnetic field varies with location, but it is relatively stable and from a practical standpoint is considered static or DC. In the Raleigh, North Carolina region, the ambient unperturbed geomagnetic field has an overall flux density magnitude of approximately 470 milligauss (mG), pointing mainly down and north.

There are two ways that DC light rail systems create magnetic fields:

- First, magnetic fields are produced by the flow of electric currents on the DC traction system conductors, namely supply currents flowing to LRT vehicles on the overhead contact system (OCS) and returning to traction power substations (TPSS) via the rails. LRT vehicles draw electric power from the OCS via pantographs and provide a return path to the rails via the wheels.

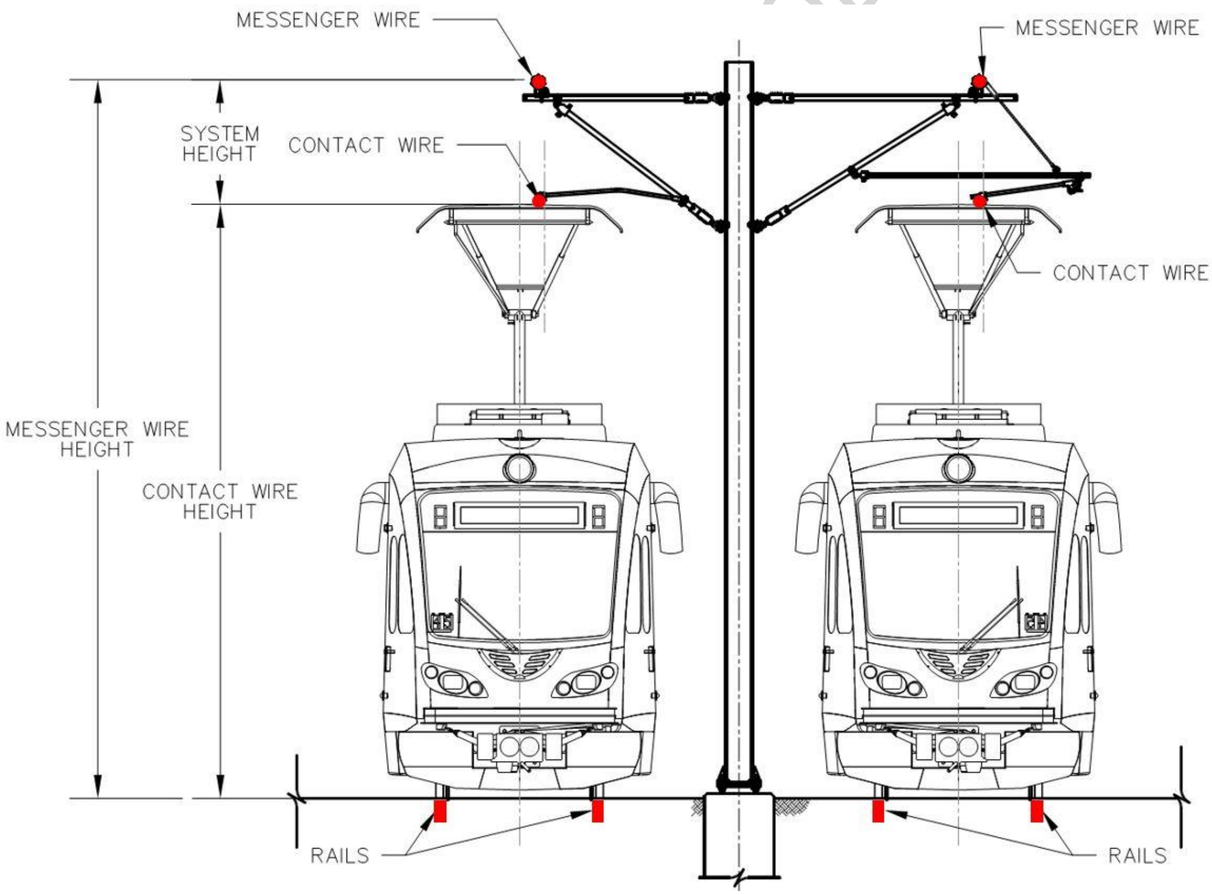

Figure 1. Two-track cross-section showing main electric traction system conductors.

In general, magnetic fields from currents on the DC traction system depend on details of the system layout along with train operations and are proportional to the magnitude of the currents flowing on the various sections of the traction system. As such, the largest magnetic fields occur when the largest currents are drawn by the operating vehicles, e.g. with two trains accelerating simultaneously, and because currents flow from each TPSS to the LRT vehicles, these magnetic fields occur along the entire sections of the alignment over which the currents flow; these magnetic fields are not exclusively at a train location. Furthermore, because the currents are continuously varying with train operations, the magnetic fields are continuously varying as well.

- Second, induced magnetization in the ferromagnetic (steel) mass of the LRT vehicles causes a localized distortion or focusing of the ambient geomagnetic field as the vehicles pass. Because this geomagnetic perturbation is due to the steel mass of the vehicles, it occurs in proximity to a train, i.e., when a train is present. The magnetic fields change as the train passes. Because the effect is associated with the vehicles, geomagnetic perturbation magnetic fields are typically smaller in magnitude and fall-off more rapidly (are more localized) than magnetic fields due to traction currents. This geomagnetic perturbation effect is associated with any moving ferromagnetic body, including all vehicles with steel (buses, trucks, non-electric trains, cars, construction equipment, etc.). The magnitude of the magnetic field disturbance is proportional to the mass of the vehicle.

Both of these magnetic field sources—traction system magnetic fields and light rail vehicle (LRV) geomagnetic perturbation—are transient in nature, and they combine to produce changes, or shifts in the background DC magnetic field environment along the alignment, with characteristic time-scales typically ranging from a fraction of a second to tens of seconds. Light rail magnetic fields add to the background geomagnetic field as vectors, and as such are not always additive (vectors in opposite directions subtract); the resulting magnetic field will change in direction and it can decrease or increase in magnitude. In general, the magnetic field impacts are strongest near the alignment, and decrease rapidly moving away from the tracks.

Magnetic fields from light rail and power lines are generally specified in units of magnetic flux density. The milligauss (mG) unit is commonly used in the United States, but the SI unit of microtesla (μT) or nanotesla (nT) is also used. For reference, 1 mG = 0.1 μT = 100 nT.

Inside buildings, comparable magnetic field shifts can also occur due to other local sources. The electric power system produces continuously varying AC magnetic fields at 60 hertz (Hz). Other magnetic field sources that perturb the background static magnetic field environment include elevators, electromechanical equipment, back-up battery and charging systems, and movement of vehicles such as large trucks at loading docks or other passing vehicles. Small localized magnetic field shifts can be caused by moving steel doors, steel carts, and even a person with a cell phone. Relatively large magnetic fields are produced by magnet systems associated with a range of instruments, especially MRI imaging, and correspondingly large shifts may occur infrequently as the magnet system operational status changes, e.g., is turned off for maintenance, upgrades, or repair, and then turned on for normal operation.

Most electronic equipment is unaffected by typical light rail magnetic field transients, even relatively close to the alignment. This can be attributed to the generalization that light rail magnetic field transients are small on a relative basis (compared to systems that intentionally create magnetic fields) and quite slow (quasi-DC), which means induction via time-varying flux is inefficient on a relative basis.

However, there are a number of specialized measurement, imaging, and research systems that require a very stable magnetic field environment for proper operation. At sufficiently strong levels, transient or time-varying magnetic field disturbances can interfere with proper operation of magnetically sensitive equipment, causing electromagnetic interference (EMI). The sensitivity of various instruments varies widely, so an EMI evaluation requires estimates of magnetic field transients produced by the light rail system (quantifying the source), and identification of potentially sensitive instrumentation or equipment in proximity to the alignment. Comparing expected light rail magnetic field transients with the magnetic field limits of potentially sensitive equipment provides a measure of the likelihood for interference to occur.

This report provides an EMI evaluation focused on transient magnetic fields from the light rail system. The evaluation has two parts. First, an initial review of the planned alignment was performed to look for nearby facilities that might have sensitive equipment or instrumentation. Second, models of the traction system were developed for three sections of the alignment near the potentially sensitive facilities initially identified. These models of the planned alignment were used to calculate magnetic fields as a function of position moving away from the alignment. Contour plots of the magnetic field levels produced by the traction currents were overlaid on satellite photographs, thus showing estimated field magnitudes from the light rail system as a function of position at potentially sensitive facilities along the alignment. By comparing estimated magnetic fields with typical magnetic field limits for sensitive equipment, one can determine the likelihood for interference issues at the respective facilities. This evaluation is qualitative in the sense that the evaluation is based on general facility use, typical levels at which interference can occur, and estimates of light rail magnetic fields from modeling.

2. EMI and Sensitive Facilities

There are two main types of instruments sensitive to changes in the static magnetic field environment:

- Magnet systems requiring a very stable and uniform magnetic field in the bore of the instrument. These are most often superconducting magnets in instruments utilizing magnetic resonance for their operation, such as nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI) systems.
- Imaging systems that rely on electromagnets to precisely steer a beam of ions or electrons. This includes electron microscopes, such as scanning electron microscopes (SEM) and transmission electron microscopes (TEM), and semiconductor or nanotechnology equipment such as focused ion-beam (FIB) deposition, and e-beam lithography. Instruments in this group are generally more sensitive than the first group (NMR, MRI) because the applications involve imaging resolution dimensions on the order of microns (millionth of meter) and tens of nanometers (billionth of a meter).

There are also other areas of research utilizing sensitive instrumentation that detect and measure extremely small voltages, currents, forces, or field quantities. These specialized instruments and experimental systems can also be susceptible to EMI caused by transient magnetic field shifts. One example is magnetoencephalography (MEG), an instrument that utilizes highly sensitive magnetic field detectors to map brain activity.

In a few systems, manufacturers may include shielding and compensation capabilities built into the instrument to reduce the EMI sensitivity. For some superconducting magnet systems, installation involves shielding of the fringe fields from the magnet itself to minimize the magnetic field impact and meet requirements in adjacent spaces (typically 5000 mG). This shielding can provide attenuation of externally produced magnetic fields as well.

While interference occurs in many instruments at sufficiently high levels, for the expected magnetic fields discussed in this report, the following are generally considered unaffected by light rail magnetic fields:

- X-ray imaging equipment
- PET scan system
- CT scanner imaging
- Optical microscopy
- Atomic Force Microscope (AFM)

Also, our experience is that particle accelerators and cyclotrons associated with nuclear medicine are relatively insensitive to light rail magnetic fields.

In general, magnetically sensitive instruments are found at facilities associated with high-tech (semiconductor, nanotechnology, biotechnology), university research (chemistry, physics, engineering), and medical imaging. Thus, this evaluation is focused on sections of the planned alignment near the University of North Carolina (UNC) campus at the west end of the system in Chapel Hill, and Duke University facilities and the Durham VA Hospital along Erwin Road in Durham.

Although 37 potentially sensitive facilities within 500 feet of the alignment were reviewed, the closest facilities, especially research or medical facilities are of special interest.

Specific UNC facilities closest to the west end of the alignment as shown in Figure 2 are:

1. UNC Center for Bioinformatics
2. Marsico Hall, Biomedical Research Imaging Center
3. Genetic Medicine Building
4. Lineberger Cancer Research Center

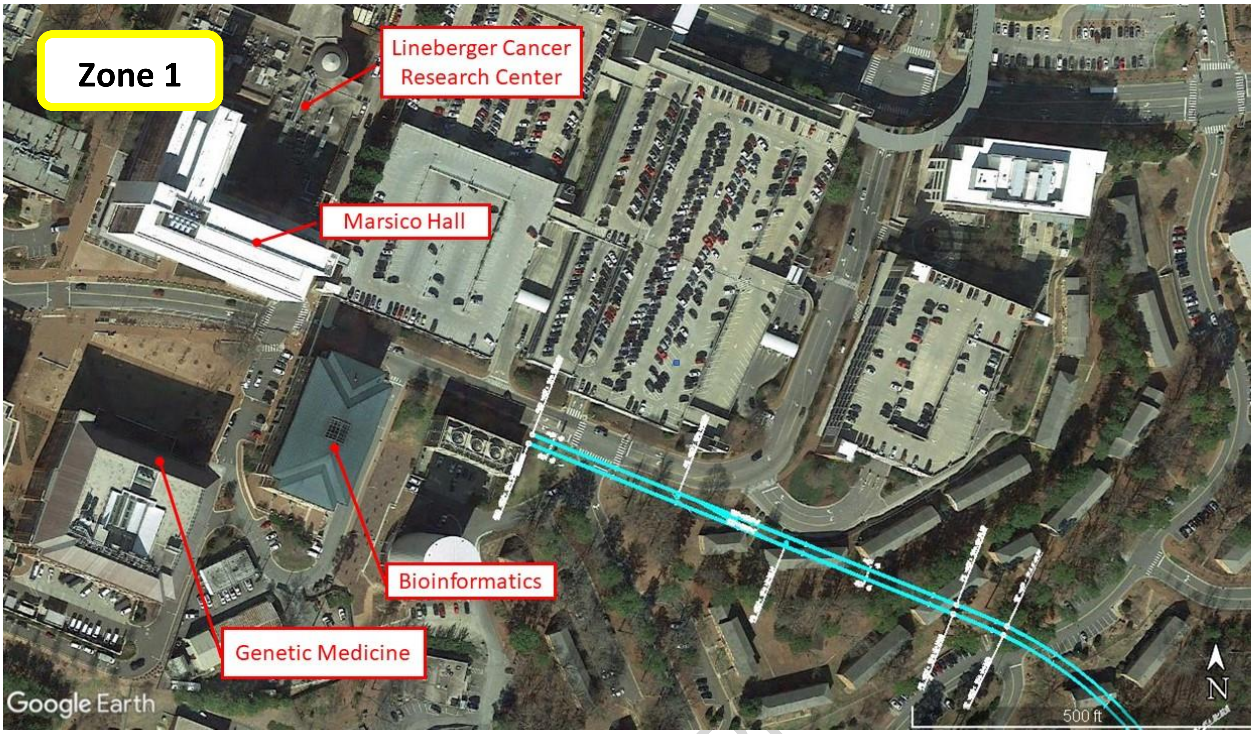

Figure 2. UNC Campus buildings near the end of the alignment: Bioinformatics, Genetic Medicine Research, Marsico Hall, and the Lineberger Cancer Research Center

Duke medical facilities near the alignment (shown in Figures 3 to 5) are:

1. Duke Medicine (McFarland Drive)
2. Lenox Baker Children's Hospital (Erwin Road)
3. (Planned) Duke Health Proton Therapy Center
4. Hock Plaza, Duke Image Analysis Laboratory
5. Global Health Research Building (Duke Regional Bio-Containment Labs)
6. Duke Eye Center
7. Duke University Hospital, Children's Hospital

Other:

1. Durham VA Hospital (north of Erwin Road in Figure 5)

Figure 3 Duke Medicine facility north of the alignment near McFarland Drive in Durham.

Fgure 4. Medical facilities along the west section of Erwin Road include Lenox Baker Children's Hospital, Proton Therapy Center (future), Hock Plaza (Duke Imaging Center), the Global Health Research Building (NIH, Duke Regional Bio-Containment Labs), and the Genome Science Research Building.

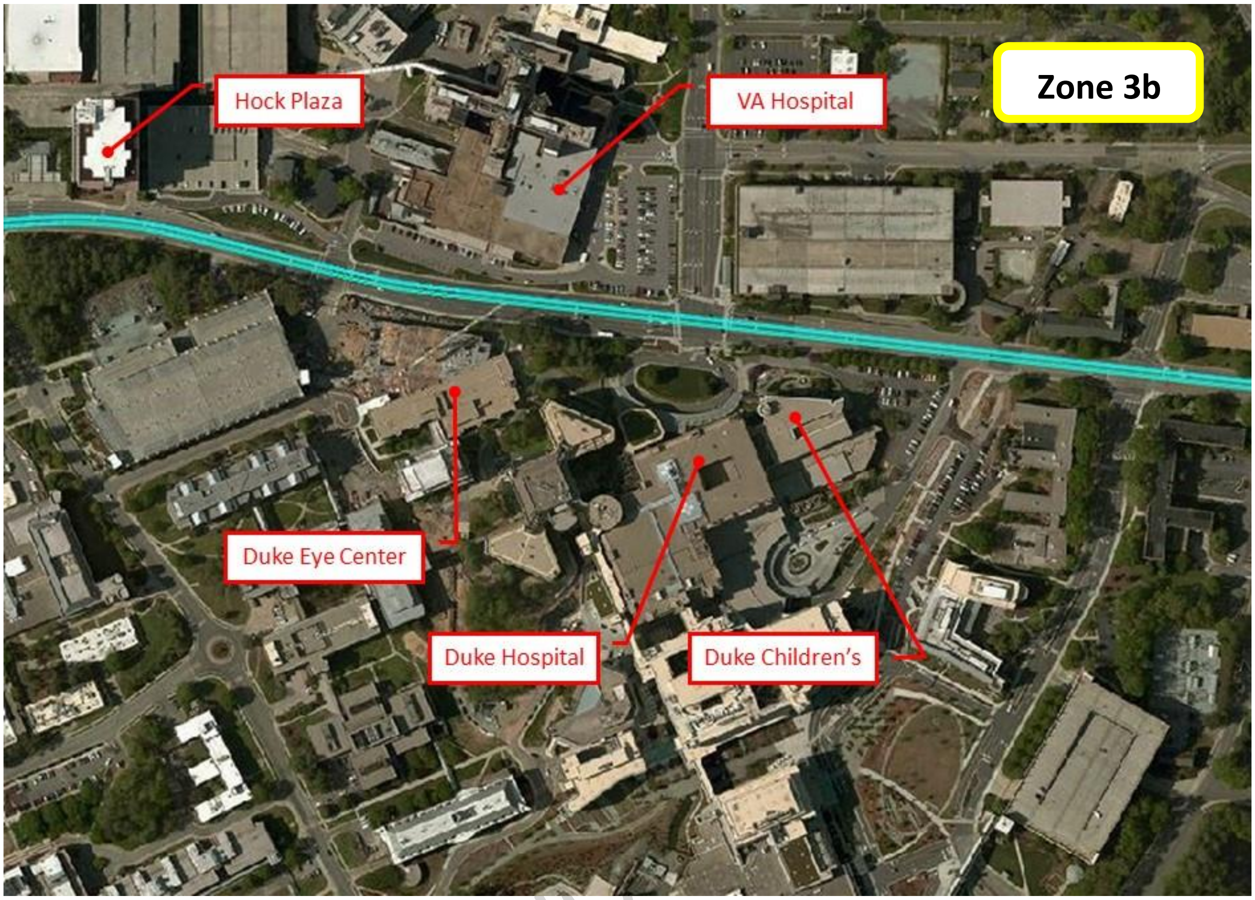

Figure 5. Medical facilities along the east section of Erwin Road include Hock Plaza (Duke Imaging Center, also shown in Figure 4), the Duke Eye Center, Duke Hospital, Duke Children's Hospital, and the Durham VA Hospital.

These facilities are mainly medical and as such the most common medical imaging equipment sensitive to light rail impact would be MRI systems. UNC Marsico Hall, Hock Plaza, Duke University Hospital, and the Durham VA Hospital are all known to have MRI imaging equipment. Also, a list of equipment from Duke showed two electron microscopes, one at the Joseph Wadsworth Eye Center and one at Snyderman Genome Sciences Research Building.

Some of the facilities such as the Bioinformatics Center at UNC, are not believed to have any magnetically sensitive equipment. This general assessment is based on reviews of website information and on the Duke equipment list. As such, the initial evaluation in this report is qualitative in that exact positions, orientations, and sensitivity limits are not known. Rather this evaluation is based on typical magnetic field limits for MRI systems and electron microscopes. A table with the reviewed facilities and initial assessment of likelihood for magnetic field interference specific to each site is provided in the evaluation section of this report.

Sensitivity for MRI systems is generally dependent on the specific manufacturer and model. However, in discussions with Siemens, the indication is that 20 mG in the bore direction, and 40 mG in the lateral direction are presently limits used as part of site selection, and these values apply across all Siemens MRI systems. An older pre-installation document for a GE Healthcare Discovery MR450 1.5T MRI system lists limits of 5 to 50 mG for DC magnetic field shifts depending on the length of time of the disturbance.

In general, these magnetic field limits do not define a sharp transition point for operation/nonoperation; the limits refer to the level of disturbance at which the quality of imaging will begin to degrade. Based on the 'typical' limits noted above for Siemens and GE Healthcare MRI systems, qualitative assessments of low, moderate, and high potential for EMI can reasonably be assigned to the magnetic field ranges of 2-5 mG, 5-10 mG, and greater than 10 mG, respectively. The evaluation will be updated if details of specific MRI system locations, orientation, and magnetic field limits are obtained.

The sensitivity of electron microscopes also varies significantly across different types (model and manufacturer). For example, typical magnetic field limits might be somewhere in the range from 10mG down to 0.1mG. A qualitative assessment of low, moderate, and high potential for EMI with electron microscopes can be assigned initial ranges of 0.1-0.5 mG, 0.5-1.0 mG, and greater than 1.0 mG, respectively. Again, the evaluation can be refined with further details about the electron microscope locations and sensitivity. Also, the evaluation can be updated if other types of magnetically sensitive instrumentation come to light.

Based on the identified medical facilities, modeling was separated into three sections: near UNC (Figure 2), near Duke Medicine at McFarland Drive (Figure 3), and along Erwin Road near multiple medical facilities with MRI systems and two possible electron microscopes (Figures 4 and 5). The next section describes modeling of the traction system magnetic fields to obtain magnetic field estimates at the facilities.

3. Magnetic Field Modeling

As discussed above, the predominant magnetic field impact from light rail is due to the large traction currents that power train operations—supply currents on the OCS and return currents on the rails, as shown in the double-track cross-section of Figure 1.

Looking at a single track, the supply current in one direction on the OCS and returning on the rails in the opposite direction forms a dipole loop of current with magnetic fields (flux lines are only an approximation in figure) per Figure 6. Magnetic fields circulate around the currents and fields are lateral to the tracks. Positive current coming out of the page at the top figure, corresponding to the OCS, and negative current into the page at bottom figure, corresponding to the rails.

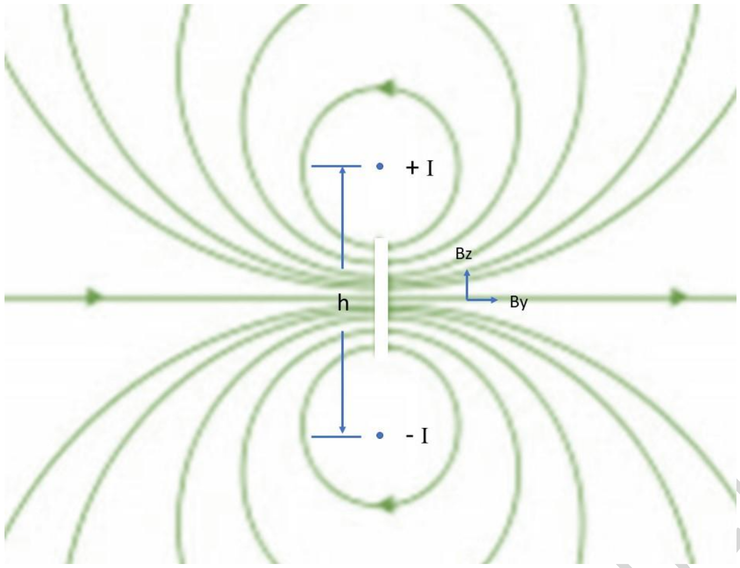

Figure 6. Long straight section of OCS and rail currents can be approximated as a simple two-dimensional dipole.

The magnetic field magnitude in units of milligauss (mG) from a two-dimensional dipole is given by:

$$B\ (mG) = 2\ I\ h\ /\ r^2 \qquad (1)$$

Where I is the current in amperes (A), h is the height in meters, and r is the distance in meters from the center of the dipole. From this equation, one can see three basic concepts. First, magnetic fields are proportional to the current flowing to a train. Second, magnetic fields are proportional to the height of the OCS above the rails. And third, magnetic fields decrease rapidly with distance, as the inverse square of the distance from tracks. This last part means that doubling the distance decreases the magnetic field by factor of four, tripling the distance decreases the magnetic field by a factor of nine, and so on. One can use Equation (1) to estimate magnetic fields from a train drawing 1500A, with the OCS simplified (messenger and contact wire combined) as a single conductor at 22.7 feet (6.9 m) above top of rails. Table 1 lists magnetic field (mG) at 50-foot intervals from 100 feet to 500 feet. Using the dipole equation, magnetic fields have fallen below 5 mG at 250 feet. At 350 feet, the magnetic field is less than 2 mG, and at 500 feet the magnetic fields are less than 1 mG.

Table 1. Simplified magnetic field estimates from dipole equation (1)
with I = 1500A and h = 6.9 m (22.7 ft).

	(ft)	(mG)
Vertical Dipole Magnetic Field I=1500A, h=6.9m	100	22.3
	150	9.9
	200	5.6
	250	3.6
	300	2.5
	350	1.8
	400	1.4
	450	1.1
	500	0.9

The two-dimensional dipole is an extreme oversimplification, only valid for long straight segments of balanced currents, but it is useful as a conservative and quick rule-of-thumb evaluation. Table 1 can be used by any stakeholder as an initial estimate of magnetic field impact from the light rail system based on lateral distance from the nearest track centerline to any point in a building.

Actual current flow on the traction system is more complex and inherently three-dimensional:

- At a train, currents flow vertically from the OCS to the vehicle and down to the rails.
- Also, current flow to a train comes from both directions on the OCS and returns in both directions on the rails.
- A two-track system has two sets of OCS and rails, allowing for simultaneous operation of trains in both directions, eastbound (EB) and westbound (WB). Cross-bonds on the rails join EB and WB rails allowing return currents to distribute across all four rails in flowing back to a TPSS. Similarly, a common positive bus connection inside each TPSS allows supply currents to utilize both sides of the OCS. Thus, OCS and rail currents are not necessarily balanced on each track.

To more realistically estimate magnetic fields, detailed three-dimensional modeling of the traction system was performed. Three models were developed, corresponding to sections of the alignment near potentially sensitive facilities—mainly medical facilities allocated as zones 1,2 and 3. Models representing the traction system OCS and rails consist of a series of connected straight line segments, with each segment defined by start and end point coordinates (along with the current magnitude and direction on that segment). The collection of segments define the traction system conductors. The stationing listed throughout this document corresponded to these models which used the 50% track plan and profile, with the exception of the Erwin Rd/Duke University area. This report was update with the latest track plan and profile plans as of January 16, 2019.

To define the current flow on modeled conductors, current magnitudes and direction are specified to reflect the current flow at a snapshot in time that is representative of a high current scenario, e.g. a train that is accelerating. As the currents change over time with train operations, the magnetic fields change correspondingly. For these calculations, a snapshot was selected with currents at or near a maximum value based on load flow simulations performed by LTK using TrainOps™. Using a high current snapshot provides a more realistic estimate of worst-case magnetic fields produced by the traction system specific to a defined operational scenario.

Magnetic field calculations were performed using a computer program that provides the magnetic field at any point in space relative to a collection of defined line current segments. The basis for the calculations is a closed-form equation, derived from the Biot-Savart integral law, defining the vector magnetic field from a single finite line current at any position in space with any orientation. A single segment of current in space is non-physical in the sense that currents flow in closed loops, but the traction system is modeled with multiple segments, both supply and return, to capture the overall flow of currents for calculating traction system magnetic fields.

Specifically, the modeling program reads an input file defining all of the traction system conductor segments as pairs of coordinates, along with the magnitude and direction of current on each segment. The software allows for evaluation of magnetic fields at any defined output point. This can be a single point, points along a line, or points on a plane. For each specified evaluation point, the magnetic field contribution from each current segment in the model is calculated. The software performs vector addition of all the magnetic field components from all of the defined current segments to obtain the total field at each evaluation point. By defining multiple evaluation points in a plane, a grid of magnetic field results can be obtained to produce contours showing magnetic field magnitude as a function of position relative to the alignment for the modeled high-current snapshot.

The specific line segment coordinates for rails and OCS were extracted from light rail design data and provided by LTK as Northing-Easting coordinates in spreadsheet files. Due to the size of the alignment, three separate models were created for three sections of the alignment, referred to for modeling purposes as Zones 1, 2, 3a, & 3b, near potentially sensitive facilities:

- Zone 1 is the end of the alignment at the UNC Station on Mason Farm Road in Chapel Hill, near UNC facilities, running from Sta 9+68 to Sta 38+38. Although this section is ostensibly near a number of UNC hospitals, they are all set back from the alignment on the north side of Manning Drive. The closest building that appears to have sensitive instrumentation is Marsico Hall which is situated west of the end of the light rail system and UNC Station. Two snapshot models were developed for Zone 1, one with a WB train drawing nearly 1400 amperes of current. While the current draw by the train is at a maximum value, a majority of the current is flows west from the next TPSS that is further east. To model higher currents closer to the UNC campus, a second snapshot model was developed based on an EB train accelerating from the UNC Station, drawing about 1200 amperes.
- Zone 2 is a section toward the middle of the alignment, along McFarland Drive in Durham, running from Sta 380+21 to 557+43. It was selected for proximity to a Duke Medicine facility situated north of the alignment.
- Zone 3a & 3b is a section along Erwin Road that passes Duke University Hospital and the Durham VA Hospital, running from approximately Sta 927+98 to Sta 1006+49. For this snapshot, a train is accelerating WB from the LaSalle Station drawing 1370 amperes, while at the same instant an EB train is accelerating from Duke/VA Station, also drawing 1370 amperes of load current.

Figures 7 to 10 are simplified sketches showing the modeled current flow snapshots for each of the models. The currents listed in the sketches are from the LTK load flow simulation, TrainOps™, assuming two-car consists operating with 7.5-minute headway. A 10-minute headway is planned for actual operations which means the actual peak current magnitudes may be lower due to the additional train spacing. These snapshots are based on the maximum absolute current flow in each of the three zones from the power flow simulation. The second Zone 1 scenario of Figure 8, with an EB train accelerating from UNC Station, was selected to specifically model a snapshot in time with currents further west (closer to UNC Campus), even though the peak current is slightly lower than the Figure 7 scenario.

While the simplified current flow sketches indicate rails as a single line, all four rails are explicitly modeled with the assumption that current is equally shared (each rail carries half of the current). The OCS, also indicated as a single line, actually consists of messenger wire (500kcmil) and contact wire (350kcmil) in parallel, but the model combines them into a single conductor at a height of 22.7 feet to simplify the OCS. This height is a weighted average between the 20-foot height of the contact wire and 24.5-foot height of the messenger wire (at the poles), with the larger messenger wire given greater weight based on the conductor size. The messenger wire height actually decreases through each span, making the constant height assumption conservative. Also, at the train location, the two pantographs and vehicle multiple wheel sets are simplified to single positive (OCS) and negative (rails) connections at the defined train center position.

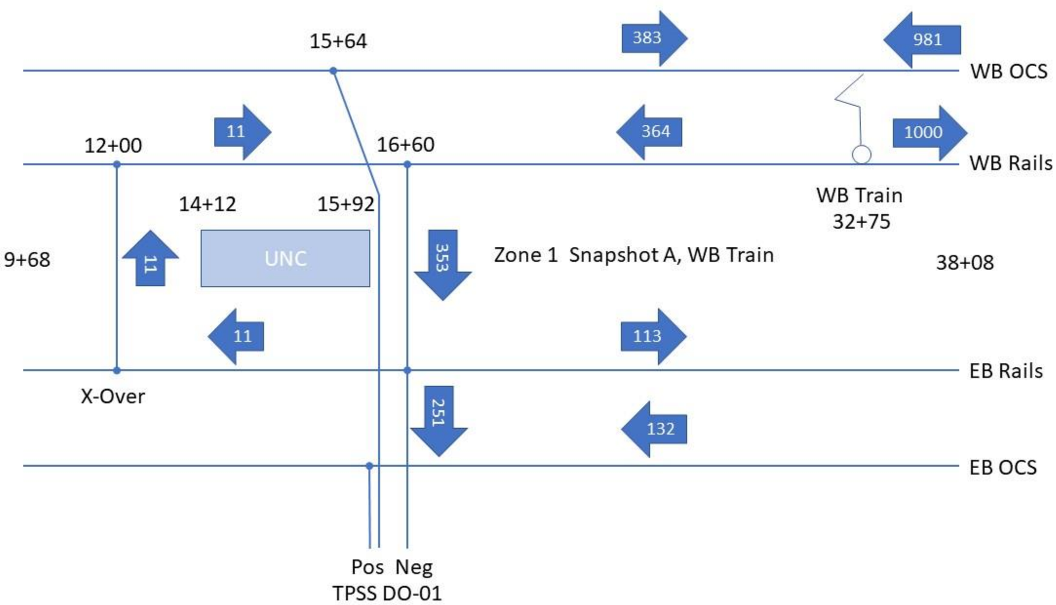

Figure 7. Sketch of Zone 1 current flow snapshot model near UNC Station with WB train.

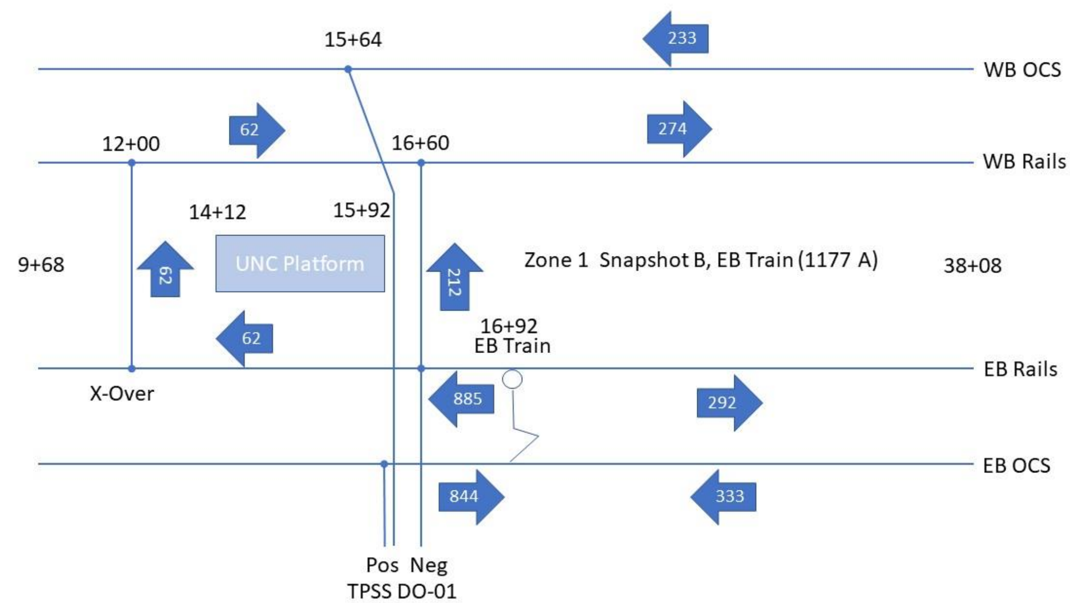

Figure 8. Sketch of Zone 1 current flow snapshot model near UNC with EB train.

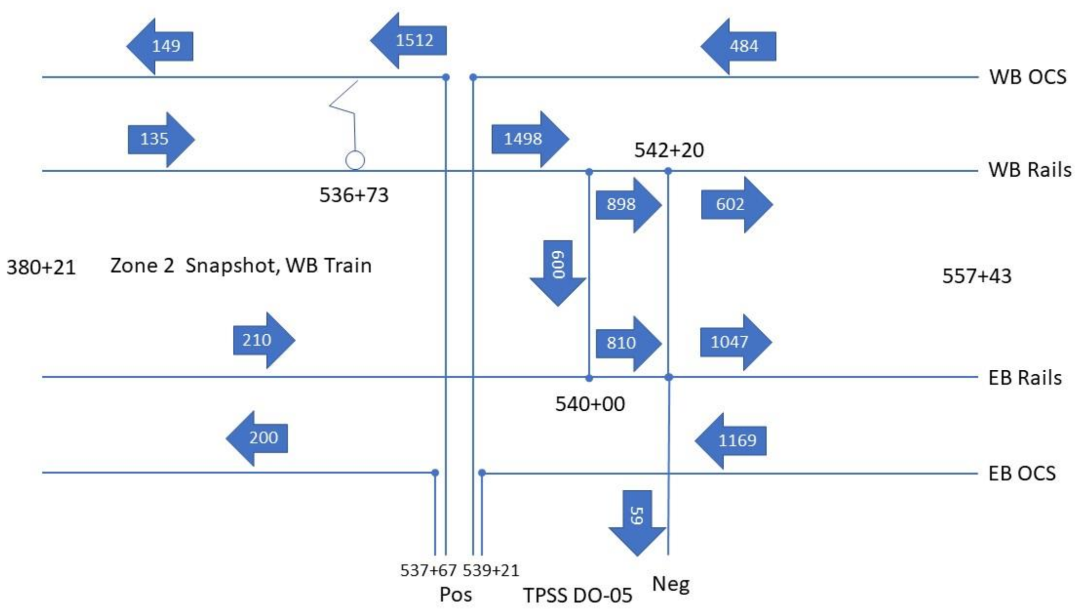

Figure 9. Sketch of Zone 2 current flow snapshot model near McFarland Drive (Duke Medicine) with WB train.

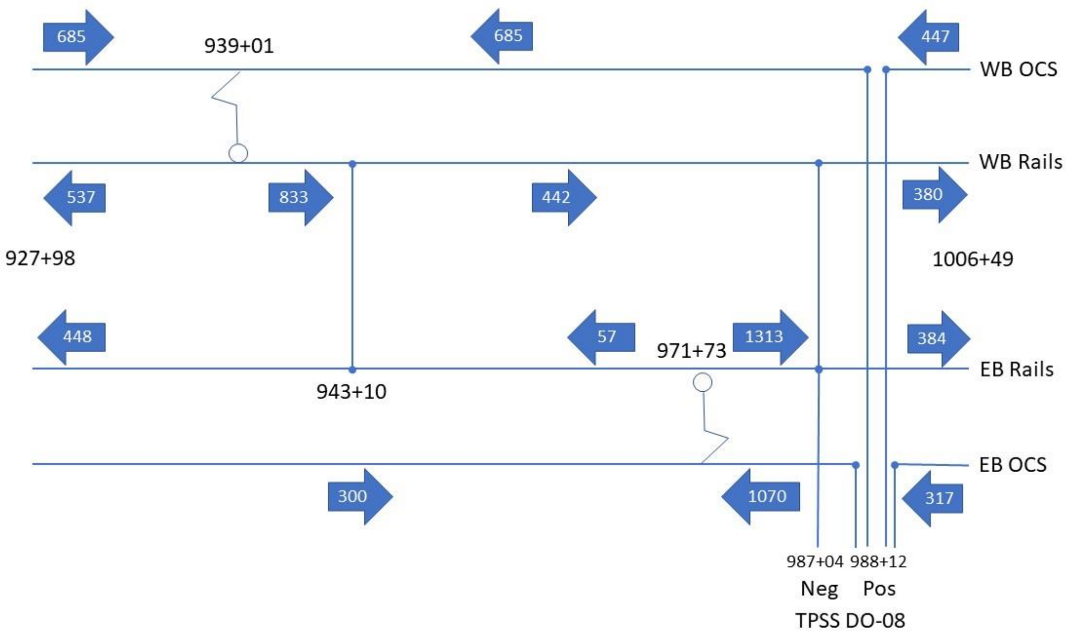

Figure 10. Sketch of Zone 3a & 3b current flow snapshot model along Erwin Road with WB train leaving LaSalle and EB train near Duke and VA Hospitals.

Figures 11 to 15 show calculated magnetic field results from each of the high-current snapshot models, displayed as magnetic field contours overlaid on Google Earth satellite photographs. Contour lines are shown for magnetic field magnitudes of 20, 10, 5, 2, and 1 mG produced by the modeled traction currents.

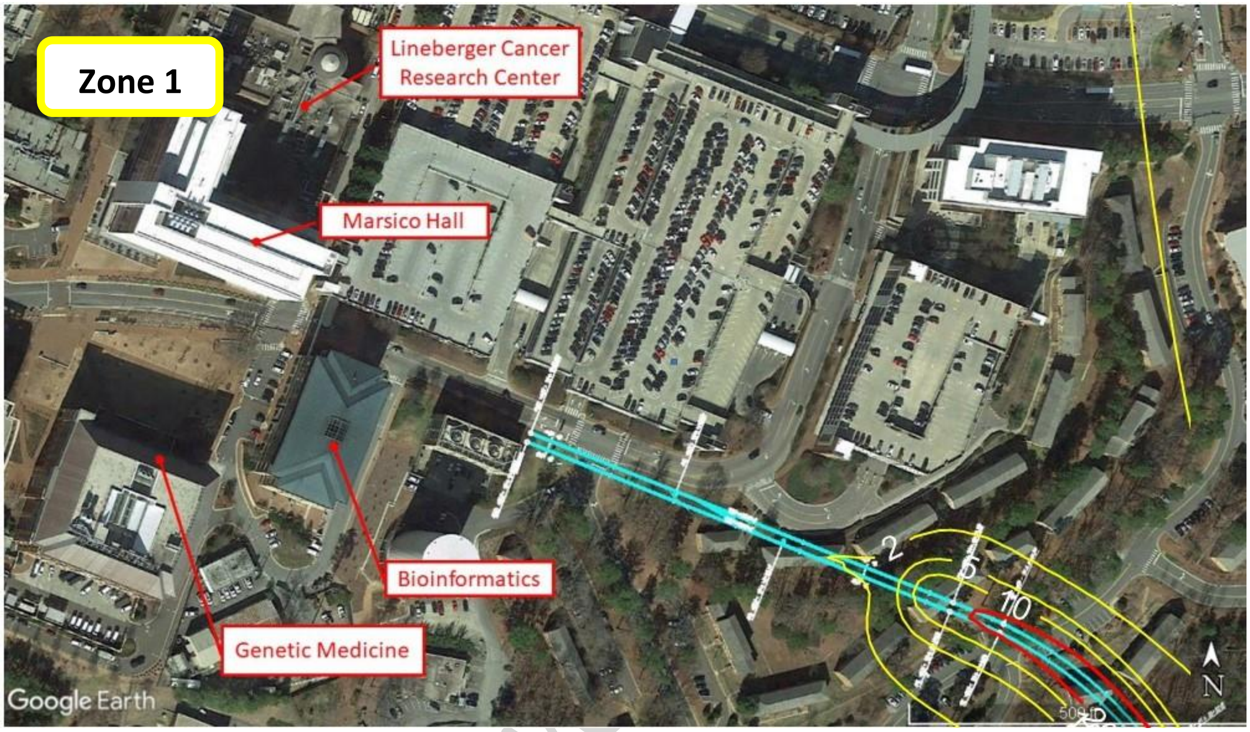

Figure 11. Magnetic field contours near UNC campus for current flow snapshot with WB train as shown in Figure 7.

In Figure 11, the Zone 1 contours don't reach into the UNC campus because the light rail system starts well east of West Drive (along Mason Farm Road), and all current flow for the traction system is to the southeast. As can be seen in the Figure 7 sketch of current flow, the WB train is about 2000 feet to the southeast.

For the second Zone 1 scenario with an EB train accelerating from UNC Station, the Figure 12 contours push out slightly because more current is drawn from TPSS DO-1, and a small loop of current returns to the negative TPSS feeder connection by running back to the cross-over and up to the WB rails. This loop appears to create the 1 and 2 mG contours. Again, however, the contours do not extend into the UNC campus for the same reason that nearly all current is flowing to the southeast.

WB trains that enter the UNC Station will continue west to the tail track and reverse direction through the cross-over to reset as an EB train. For this operation, currents will flow further west in the tail section but at relatively low magnitudes through the cross-over. As such, magnetic fields at the southeast corner of Marsico Hall are expected be less than 2 mG and no EMI impact is expected.

In Figure 13, the Duke Medicine facility has sufficient separation from the tracks that it is just north of the 1 mG contour in the center of the figure.

In Figures 14 and 15, one can see the calculated magnetic field impact across multiple medical facilities along Erwin Road for the modeled current flow sketched in Figure 10.

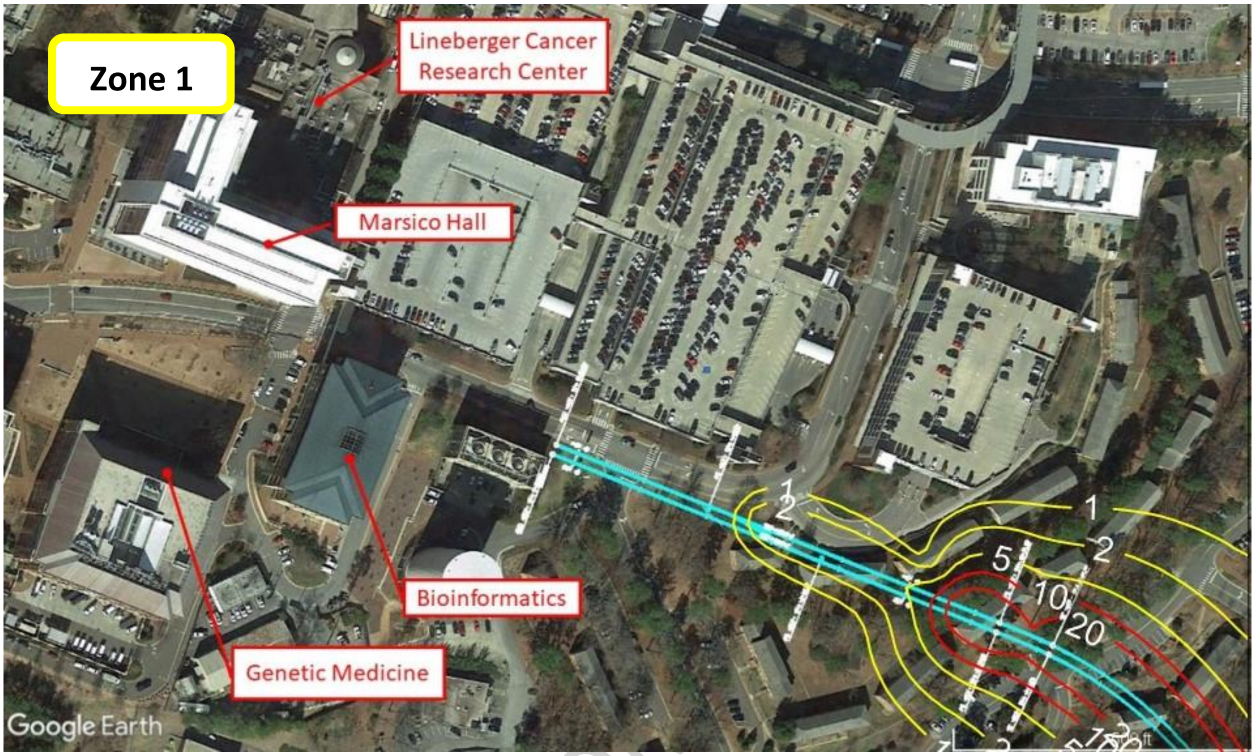

Figure 12. Contours for current flow snapshot with EB train departing UNC Station as shown in Figure 8.

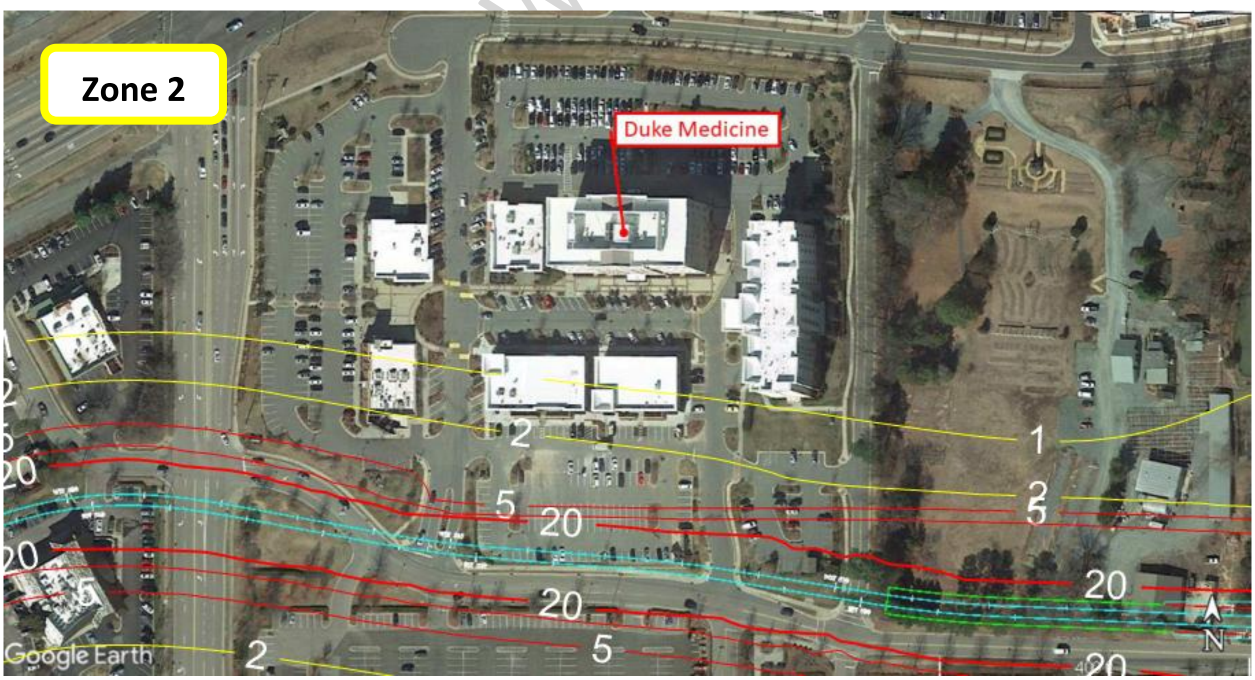

Figure 13. Contours along McFarland Drive near the Duke Medicine building for the current snapshot of Figure 9.

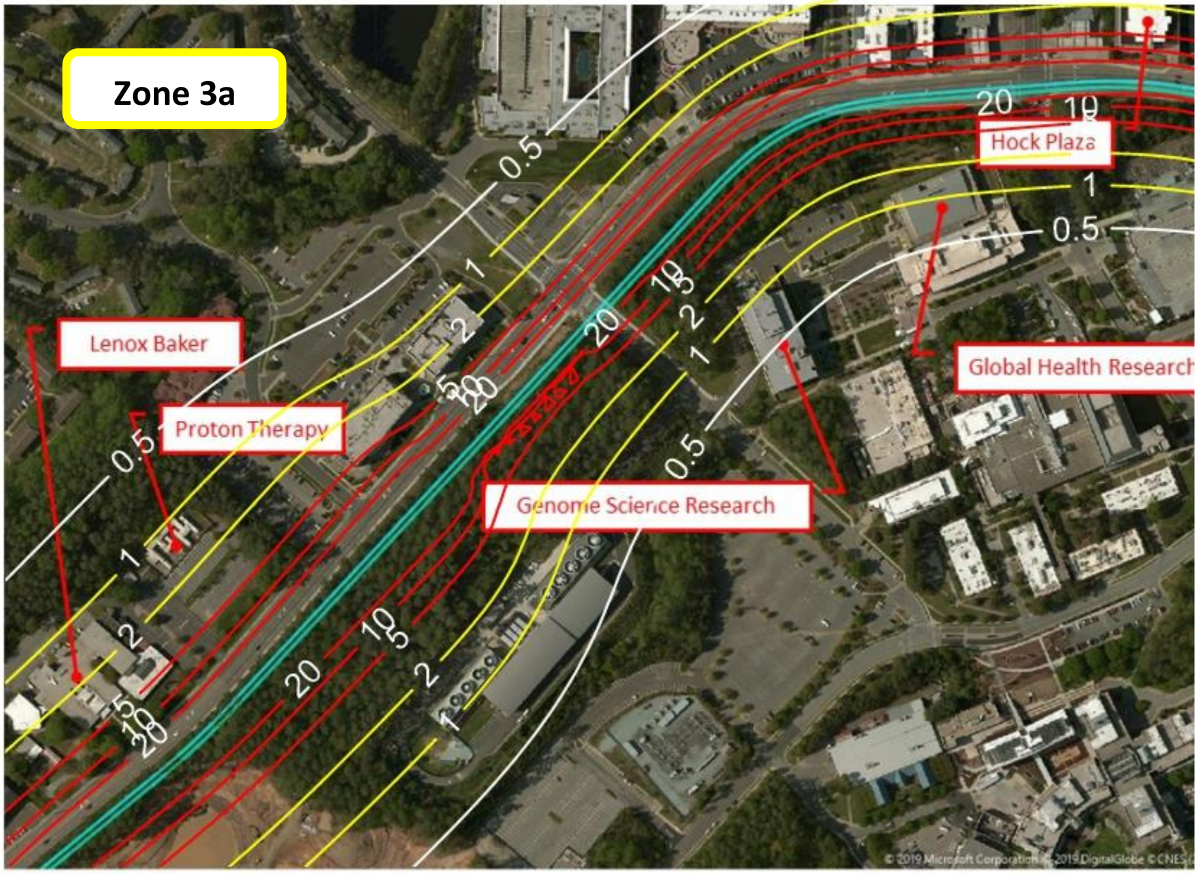

Figure 14. Magnetic field contours along west section of Erwin Road near Lenox-Baker Hospital based on currents as shown in Figure 10.

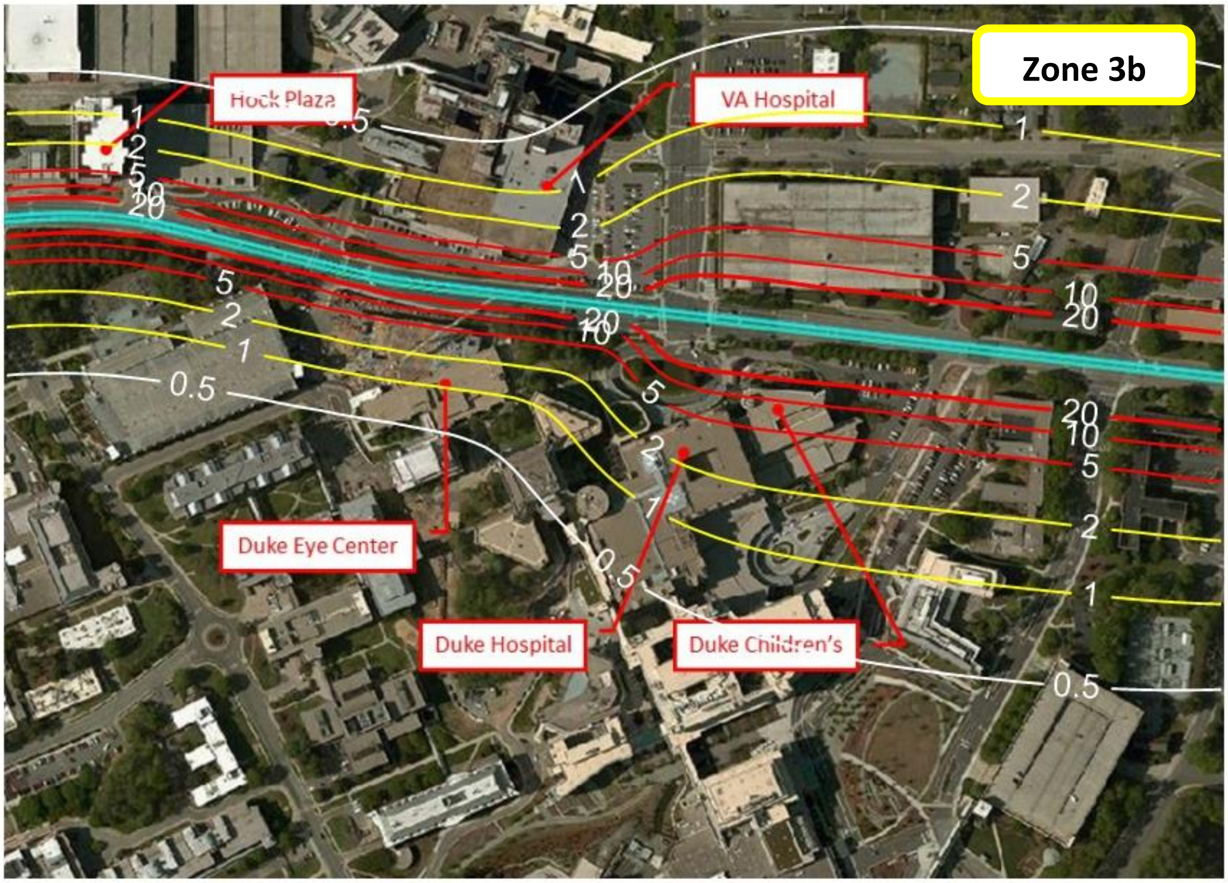

Figure 15. Magnetic field contours along east section of Erwin Road near Duke and VA Hospitals based on currents as shown in Figure 10.

4. Geomagnetic Perturbation

As described in the introduction, the steel mass of the light rail vehicles (LRVs) causes a distortion of the ambient geomagnetic field due to induced magnetization in the steel. Movement of any ferromagnetic object through the Earth's geomagnetic field produces a magnetic field perturbation as the object passes. This geomagnetic perturbation is generally proportional to the mass of the object, and commonly occurs with movement of vehicles such as cars, trucks, and buses.

In terms of LRT-produced magnetic fields, this is a secondary effect relative to the magnetic fields from traction currents because the magnitude (for a given distance from the alignment) is generally smaller, and the effect is more localized, occurring near the vehicles and falling off more rapidly with distance. In contrast, peak traction current magnetic fields have larger magnitudes and occur over larger areas along the length of the alignment (in both directions) from the LRVs back to the TPSS.

Measurements of geomagnetic perturbation were made for two-car light rail consists in Portland (TriMet) and Seattle (Sound Transit) by coasting the LRVs (pantographs down) past magnetic sensors positioned at several distances from the track center line. The average geomagnetic perturbation data from multiple passes at the various distance, B_{ptb} in milligauss, were used to derive a curve-fit equation for two-car consists as shown in Figure 16.

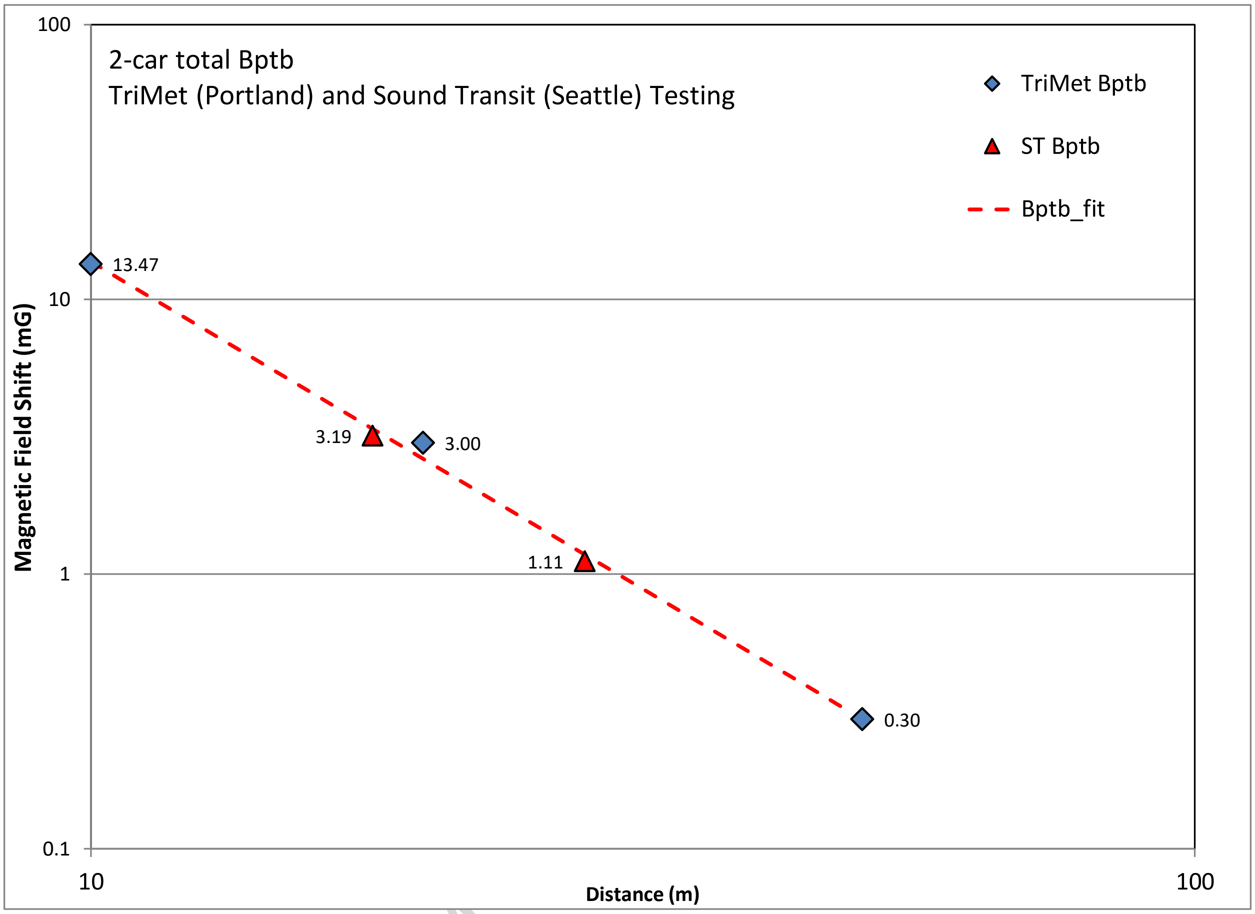

Figure 16. Dashed line shows the estimated geomagnetic perturbation equation based on magnetic field testing of two-car coasting passes by TriMet (Portland) and Sound Transit LRVs.

The curve-fit equation provides an estimated geomagnetic perturbation magnitude at any distance, and Table 2 lists the GP estimates at distances of 50 to 250 feet (from the near-track center line). This equation can be used to estimate the geomagnetic field impact for the buildings which are relatively close to the alignment, less than 200 feet.

Table 2. Two-car consist geomagnetic perturbation (GP) estimates in milligauss.

SUMMARY CURVE FIT	
Dist (ft)	Bptb (mG)
50	5.03
100	0.96
150	0.37
200	0.18
250	0.11

Combining the geomagnetic perturbation (GP) field and the traction current magnetic fields is not straightforward because the former is local to the train and the latter is specific to a peak current draw (a snapshot in time during large currents); they don't necessarily occur at the same time relative to a specific position in a facility. Also, when the two do happen to occur at a position simultaneously, the magnetic field from each source will combine as a vector, and as such, the total impact is not necessarily additive. Nonetheless, the two values can be combined to arrive at a conservative estimate of total LRT-produced magnetic field impact once specific distances for each sensitive instrument is known.

Also, typical ambient variations in buildings due to local sources and vehicle traffic are often in the range of 0.1-0.2mG, and thus from Table 2, the geomagnetic field impact beyond 200 feet would be comparable to existing ambient variations.

As an example, the Figure 14 magnetic field contours (from traction currents) shows the 5mG contour passing through the front part of Hock Plaza at a distance of approximately 110 feet from the WB track center line. Using the curve-fit equation line shown in Figure 16 gives a GP estimate of 0.77mG, thus giving a total LRT magnetic field estimate of 5.8 mG. Per the comment above however, the Figure 16 contours correspond to a WB train leaving LaSalle Station and an EB train leaving Duke.

A similar exercise of adding the impacts would be done at Duke Hospital, where Figure 15 shows the 5mG contour passing through the corner of the facility at the entrance circle drive, a distance of approximately 220 feet to the EB track center line. Using the GP curve-fit equation gives a GP estimate of 0.15mG, for a total LRT magnetic field estimate of near 5.2mG. In this case, the train is actually near the hospital. Figure 17 is a stacked bar chart showing the relative contributions of the geomagnetic perturbation and the traction current magnetic fields for the two examples, Hock Plaza and Duke Hospital at the respective distances corresponding to the 5mG contours in Figures 14 and 15.

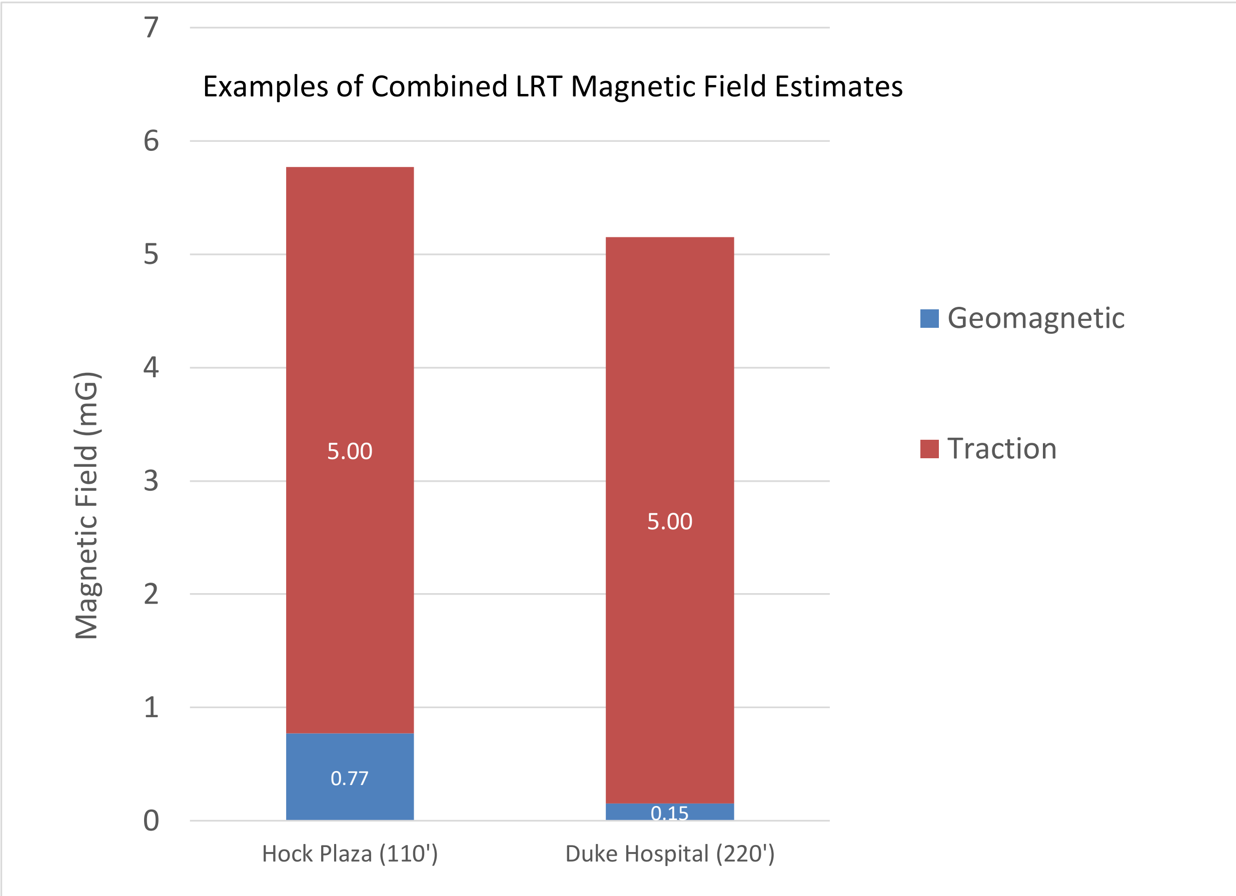

Figure 17. Two examples of combined LRT impact from geomagnetic (blue) and traction (red) magnetic fields at Hock Plaza and Duke Hospital.

5. Magnetic Field Evaluation of Model Results

Based on the Zone 1 contour plots shown in Figures 11 and 12 (WB train scenario and EB train scenario) the alignment is shifted sufficiently far enough east such that the magnetic field impact to the UNC Campus is extremely low, below 1 mG. Marsico Hall is believed to be the closest building with sensitive equipment, and at levels well below 1 mG, no EMI impact is expected. Bioinformatics building and the Genetic Medicine buildings are not known to have any sensitive equipment, and regardless, these two facilities are set well back from the end of the alignment.

Based on the Zone 2 contour plot shown in Figure 13, the 2 mG and 5 mG contours are in the parking lot, and the 1 mG contour passes through the building to the south. Thus, the modeled magnetic fields at the Duke Medicine facility are less than 1 mG. Furthermore, this facility does not appear to have any sensitive imaging equipment.

In Zone 3a & 3b, several of the facilities are known to have MRI systems, and are relatively close to the alignment.

- Hock Plaza houses the Duke Imaging Research Center. This Center lists both MRI and magnetic resonance spectroscopy (MRS) as imaging capabilities. The contour plots show light rail magnetic fields of 5 mG at the front of the building, falling off to 1 mG at the back. Because the predicted magnetic fields at the very front of the building fall within the 5 to 10 mG range, this facility is given a moderate likelihood for EMI impact, however, we note that the majority of the building is less than 5mG, which puts it in the low category.
- The VA Hospital is known to have a Siemens MAGNETOM Aera 1.5T MRI system. Magnetic fields are in the 2-5 mG at the front of this facility falling off to less than 1 mG toward the back (north). Thus, the VA Hospital is assigned a 'low' likelihood of EMI impact.
- The Lenox Baker Children's Hospital is known to have a Siemens MAGNETOM Avanto 1.5T MI system. Contours from the Zone 3 model predict magnetic fields in the 5 mG, down to near 1mG at the back, relatively low because the alignment is situated on the opposite side of the road. The facility is in the 2-5mG range assigned the 'low' likelihood for interference with MRI.
- Also, Duke has plans for installation of a proton therapy system in a new building just east of the Lenox Baker Children's Hospital. Our experience is that cyclotron and particle accelerator systems associated with nuclear medicine and radiation treatment are relatively insensitive to light rail magnetic fields. Based on the existing MRI system and the planned proton therapy system, this location is assigned a 'low' likelihood for EMI impact. This evaluation can be updated once further details of the Proton Therapy system are known, along with the exact location and orientation of the Siemens MRI.
- Duke Hospital North, and Duke Medicine Pavilion are known to have multiple MRI systems. The Zone 3 contours show light magnetic fields of just over 10 mG at the front edge of the Children's Hospital facility, falling off to 2 mG near the back. Duke Medicine Pavilion is further south, sufficiently far that there may be insignificant impact to the MRI systems there. However, based on proximity to Erwin Road, the Duke University Hospital is assigned a 'moderate' likelihood for a light rail EMI impact.
- The Global Health Research Building houses the NIH-funded Duke Regional Bio-Containment Labs that are a shared resource as part of the Duke Human Vaccine Institute (DHVI). In addition to the Containment Labs, this facility houses units for immunology, virology, microbiology, and animal support. The building closest to the alignment has magnetic field contours indicating fields of approximately 2 mG at the front, down to less than 1 mG at the back. With the 1-2 mG magnetic field contours and the possibility for NMR spectroscopy and small-animal MRI imaging, this location is assigned a 'low' likelihood of EMI impact. The Medical Sciences Research Building II is immediately south with contours indicating fields largely less than 0.5mG.
- In general, the Duke Eye Center is not expected to have instrumentation that would be sensitive to the light rail magnetic fields. Typical systems such as optical microscopy, optical coherent tomography, and laser vision treatment (LASIK) would generally be insensitive to magnetic fields. However, the equipment list provided by Duke has an entry for an electron microscope JEM-1400 at the Joseph Wadsworth Eye Center, and on this basis the Eye Center is assigned a 'high' likelihood for interference due to the potential sensitivity of a TEM.

To summarize this evaluation, an EMI impact table was created from a list of identified facilities within 500 feet of the alignment. Based on the traction system modeling, none of the facilities had calculated magnetic fields greater than 10 mG, and thus no facilities were assigned the 'high' likelihood for EMI impact based on MRI equipment. As discussed above, multiple facilities have predicted traction system magnetic fields of 5-10 mG for the 'moderate' likelihood of EMI impact with respect to MRI systems, and large portions of buildings have predicted magnetic fields in the 2-5 mG range for the 'low' likelihood designation. Note that these designations are not a measure of the impact itself, but rather the potential for impacts to occur. The actual interference will depend on the instrument location and the sensitivity specific to that instrument. The qualitative levels (low, moderate, high) for MRI are based on the specified magnetic field limits (5-50 mG) for Siemens and GE Healthcare MRI systems discussed in this report.

With respect to electron microscopes, which are generally more sensitive to magnetic fields than the MRI systems, the Eye Center is predicted to have a 'high' likelihood for interference based on the listing of a JEM-1400, and the Snyderman Genome Science Research Building has a 'moderate' likelihood of interference, also based on a listing of an electron microscope FM-100. Again, the exact location of these instruments relative to the EB track and the sensitivity specific to each electron microscope model will allow for a more accurate assessment.

The next step to refine the EMI evaluation is to determine exact locations and orientation of MRI systems and the two electron microscopes (as well as additional magnetically sensitive systems that are identified), along with gathering equipment specifications and EMI limits, starting in the facilities noted to have 'high', 'moderate' and 'low' likelihood for an EMI impact. With specific distances, the estimated geomagnetic perturbation magnetic field impact can be added to the modeled magnetic fields to obtain total magnetic field estimates. Magnetic fields from the traction currents are expected to be the largest impact, and the geomagnetic perturbation would only be expected to be significant at instruments that are relatively close to the alignment, e.g., less than 200 feet. As noted above, the imaging quality begins to degrade as the magnetic field exceeds the limit for any specific instrument systems. Informal discussions with Siemens indicated that 20mG is the typical limit for new and recently installed MRI systems. Once magnetic field interference with an instrument is identified, the possible options are relocation of the instrument, room shielding, an active cancellation system at the instrument, or modification of the traction system (lower height of OCS, parallel supply feeder with risers), or LRT operational constraints on trains to limit current draw.

DURHAM-ORANGE LIGHT RAIL TRANSIT PROJECT

EMI - Potential Facilities Within 500 Feet Of Track Centerlines

ID	Facility	Address	EMI ZONE #	Potential for EMI IMPACT
1	UNC – Genetic Medicine Research Building	120 Mason Farm Rd., Chapel Hill, NC	Z1	NO
2	UNC – Marisco Hall (Biomedical Research Imaging Center; Radiological Research Laboratory)	125 Mason Farm Rd., Chapel Hill, NC	Z1	NO
3	UNC – Bioinformatics Building	130 Mason Farm Rd., Chapel Hill, NC	Z1	NO
4	UNC – Lineberger Cancer Research Center	450 West Dr., Chapel Hill, NC	Z1	NO
5	UNC – Aycock Family Medicine	111 Mason Farm Rd., Chapel Hill, NC	Z1	NO
6	UNC – Imaging Center and Outpatient Clinic	1350 Raleigh Rd, Chapel Hill, NC	N/A	NO
7	UNC Hospitals medical offices at Meadowmont	300 Meadowmont Vill Cir, Chapel Hill, NC 27517	N/A	NO
8	Duke Primary Care Meadowmont	801 W Barbee Chapel Road, Chapel Hill, NC 27517	N/A	NO
9	Duke Medical Plaza Patterson Place - includes Duke Radiology	5324 McFarland Dr, Durham, NC 72207	Z2	NO
10	PruittHealth (Skilled Nursing & Rehabilitation Center)	3100 Erwin Road, Durham, NC 27705	Z3	NO
11	Lenox Baker Children's Hospital	3000 Erwin Rd. Durham, NC 27705	Z3	LOW
12	Snyderman Genome Science Research Building	905 S. LaSalle St., Durham, NC 27705	Z3	MODERATE
13	Global Health Research Building	909 S. LaSalle St., Durham, NC 27705	Z3	LOW
14	Duke Medial Sciences Research Building	203 Research Dr, Durham, NC 27705	Z3	NO
15	Duke Medical Sciences Research Building 2	2 Genome Ct., Durham, NC 27705	Z3	NO
16	Alexander H. Sands, Jr. Building	303 Research Dr, Durham, NC 27705	Z3	NO
17	Duke Pavilion East at Lakeview	2608 Erwin Rd., Durham, NC 27705	Z3	NO
17a	Hock Plaza (Duke Image Analysis Laboratory)	2424 Erwin Rd, Durham, NC 27705	Z3	MODERATE
18	Duke Albert Eye Research Institute	2351 Erwin Rd., Durham, NC 27705	Z3	MODERATE
19	Duke University Hospital	2301 Erwin Rd., Durham, NC 27705	Z3	MODERATE
20	· Duke Hospital Bed Towers	2301 Erwin Rd., Durham NC 27705		
21	· Brain Imaging and Analysis Center (BIAC)	2301 Erwin Rd., Durham NC 27705		
22	· Duke Hospital North Ancillary	2301 Erwin Rd., Durham NC 27705		
23	· Duke Center for Cardiovascular Magnetic Resonance Imaging (Magnetic Resonance #1, 2, 3)	2301 Erwin Rd., Durham NC 27705		
24	· McGovern-Davidson Children's Health Center	2301 Erwin Rd., Durham NC 27705		
25	Duke Family Medicine Center	2100 Erwin Road, Durham, NC 27705	Z3	NO
26	Durham/VA Medical Center	508 Fulton St, Durham, NC 27705	Z3	LOW
27	Duke Center for Documentary Studies	1317 W. Pettigrew St., Durham, NC 27705	N/A	NO
28	Duke Division of Abdominal Transplant Surgery	330 Trent Drive, Durham, NC 27710	Z3	NO
29	Fresenius Kidney Care West Pettigrew	1507 W Pettigrew St, Durham, NC 27705	N/A	NO
30	Pettigrew Rehabilitation Center	1515 W Pettigrew St, Durham, NC 27705	N/A	NO
31	Hillcrest Convalescent Center	1417 W Pettigrew St, Durham, NC 27705	N/A	NO
32	Durham County Public Health	414 E Main St, Durham, NC 27701	N/A	NO
33	Erwin Terrace II	2812 Erwin Road, Durham, NC 27705	Z3	NO
34	Erwin Terrace I	2816 Erwin Road, Durham, NC 27705	Z3	NO
35	Venable Center	303 Roxboro Road, Durham, NC 27701	N/A	NO
36	The Chesterfield	701 W Main St, Durham, NC	N/A	NO
37	NC Mutual Life Building	411 W Chapel Hill St, Durham, NC	N/A	NO