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Prediction of the Electrical Environment in Vehicles

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Abstract

A method to make a CAD-model of a vehicle suitable for electromagnetic (EM) simulations is presented. Three different EMC problems have been studied by using the derived CAD-models in an Finite Difference Time Domain (FDTD) program. First, the coupling between antennas mounted on the vehicle. Second, the locations of “hot spots”, i.e. places with high field strength inside the vehicle. Finally, the E-field probed in a circle around the vehicle. The agreement between simulations and measurements performed in a semi-anechoic chamber was found to be satisfactorily.

Key words: EMC simulation on vehicles, FDTD, Coupling between antennas
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Preface

This project has last for three years and has partly been financed by NUTEK. The partners have been Chalmers University of Technology (Chalmers), Saab Automobile AB (SAAB), Scania CV AB, SP Swedish National Testing and Research Institute, Volvo Car Corporation (VCC), Volvo Truck Corporation (VTC). This project is a continuation of an earlier project [1,2].

The project leader has been Lennart Nygren, VTC. The steering committee consisted of Lennart Nygren, VTC, Ingemar Söderlund, SAAB, Bengt Blomberg, Scania, Håkan Berg, VCC, Per-Simon Kildal, Chalmers, Jan Welinder, SP.

A number of other persons at the companies have also contributed to the project.
Summary

A method to create CAD-models for electromagnetic (EM) simulations is shown. As a basis simplified CAD-models of mechanical parts for structural dynamics analysis are used. These CAD-models are further simplified and put together to form a CAD-model. In this way the CAD-model is created in a fast, about a week, and inexpensive way. A CAD-model from each automotive company has been created by this method. The program used for the simplification has been ANSA [3]. The CAD-models of the vehicles are imported to the commercial pre-processor CADfix [4]. In this program simple interior and exterior details like chairs, steering wheel, antennas etc are added. A Finite Difference (FD) meshing is done approximating the model of the vehicle with a large number of cubical cells. Finally this file is imported to the Finite Difference in Time Domain (FDTD) program EMA3D [5] where the EM computations are done.

Comparisons between simulations and measurements for three problem types of CAD-models have been done. These were probing of the E-field in a circle around the vehicle, coupling between antennas and field-mapping inside the vehicle. All measurements were done in a semi-anechoic chamber. The simulations were mainly done with EMA3D but some simulations were made with other programs, Wire-MoM [6] and WIPL [7].

Comparisons between simulations and measurements of simple models of a car roof consisting of a metal plate have also been done. The compared parameters were reflection coefficient, E-field and coupling between antennas.

Additional simulations using the derived CAD-models that have been done
- optimal placement of antennas.
- E-field under a vehicle using different media in the ground plane.
- different degree of simplified vehicles.
- different cell sizes.

In Appendix
- Antenna simulations in an unbounded open space by using different kind of absorbing boundary conditions (ABC) and distances to the ABC.
- Impedance and reflection coefficient of a monopole.
- Induced current in a monopole due to another monopole or a plane wave.
- Wave impedance around a monopole.
- Coupling between loop antennas.
1 Introduction

Antennas have during recent years become a frequently used component in vehicles, see Fig. 1.1. The radiation from antennas, either mounted on the vehicle or external, may cause high electromagnetic fields inside the vehicle, so-called "hot spots". These high field strengths may cause EMC problems for electronic equipment and therefore it is preferable to avoid placing electronic equipment in or near "hot spots". By using computer simulations it is possible to predict the locations of these problem areas and thereby give us the possibility to optimise the placement of electronic equipment. Another area of interest is the coupling between antennas, i.e. the amount of unwanted disturbance an antenna is receiving from a transmitting antenna. In this case computer simulations can be used to optimise the placement of the antennas.

Participants from SAAB Automobile, Volvo Truck (VTC), Volvo Car (VCC), Chalmers University of Technology (Chalmers), Scania and SP have been working together in this project [1,2]. The main goal of the project has been to find a method to make CAD-models suitable for electromagnetic simulations in a fast and inexpensive way. The requirement from the industry was that this process should take no more than one week. Other tasks in the project were to use the derived CAD-models to study "hot spots" inside the vehicle and coupling between antennas.

Figure 1.1. Examples of antennas on a modern car.
Figure 1.2. Manufacturing of a prototype vehicle. The under path showing the objective for this project. The upper path showing how the prototypes are made today.

At each automotive company there is a CAD department using CAD systems such as CATIA, Unigraphics etc for creating CAD models of mechanical parts included in the vehicle. All mechanical parts are manufactured and put together to form a prototype vehicle. Thereafter EMC tests of the whole vehicle including electrical units, wire harness and antennas are performed. If the vehicle fails to pass the EMC tests a reconstruction of the electrical units, wire harness or antennas has to be made. This process of reconstruction and the following EMC test is time consuming and expensive. If we instead could use the CAD-data as a basis for EM simulations the testing and reconstruction could be much more efficient.
2 EM simulations of vehicles

EM modelling of vehicles has been an active area of research over a period of many years. In 1995 a project called 'Methods to simulate the Electrical Environment in Vehicles'\cite{1,2} with partners from SP, Chalmers and the Swedish automotive industry was initiated. The first task in this project was to investigate the possibility to predict the electrical environment in a vehicle. It was found that due to the wide bandwidth in vehicular immunity tests (100 kHz to 2 GHz) neither high-frequency nor low-frequency approximations could serve as a basis for an EMC simulation tool. Instead an investigation of EM methods that use the full Maxwell's equations started. These methods can be divided into three main groups, the Finite Difference in Time Domain (FDTD) \cite{8}, Finite Element Method (FEM) and Method of Moments (MoM). None of these methods is the best for every type of simulation. To choose a method the pros and cons for each method have to be considered. Besides that the data should represent an entire vehicle (car or truck) several parameters like the highest frequency, number of frequencies in a frequency band have to be considered. These parameters will also influence the choice of method. The higher up in frequency the more computer memory is needed. The more number of frequencies in a frequency band the longer simulation time is needed.

In the area of EMC one usually is interested in a broadband response. For this case the FDTD method works well because after a Fourier-transform has been done we get results for a wide frequency band. The MoM could be used for certain problems e.g., where only a limited number of frequencies are of interest. With FEM, details can be modelled in an accurate way. If we are interested in low frequency responses a simple model of the vehicle can be used. On the other hand if we are interested in high frequency responses a more accurate model of the vehicle is needed.

After an evaluation of the methods FDTD was found to be the computational method best suited for vehicle simulations. A program based on the FDTD method was bought, XFdtd \cite{9}. Simple test cases were verified against other programs and measurements. These simple test cases consisted of wires, ground planes, boxes and plates. The verification showed good agreement for these simple structures and we then started to examine real and more complex structures like vehicles. From CAD drawings the geometry of a SAAB 9-5 was manually modelled in XFdtd. The cell size or spatial resolution was 20x20x20 mm. In the backseat of the car two test cables, a straight wire and a loop, were placed. In the measurement set-up the car was illuminated by an antenna. In the simulation the car was illuminated by a plane wave. The measured and computed induced currents in the test cables showed an acceptable agreement over the whole frequency range. Thereafter the induced current in an ordinary cable included in the cable harness of the car was measured. In the simulation just this cable was inserted into the simulation model. A much larger amplitude deviation between measurement and simulation could be seen. This could be explained by the fact that the real cable is placed close together with other wires in a multi-wire cable which give a shielding effect. Also the cable was placed close to the vehicle body. Due to the used spatial resolution of 20 mm neither multi-wire cable nor cable close to the vehicle body could be modelled in XFdtd. To resolve the cable-wire harness the resolution would need to be increased to a cell size of 1 mm. Due to the limited size of computer memory and the long simulation time needed it would be impossible with today's computer. Instead a complementary program, BMTL\cite{10} (Branched Multi-conductor Transmission Line), developed at SP was used. In this program a transmission line with up to 9 conductors can be modelled. The program uses output files from the XFdtd program as input files. These files are created with the model of the vehicle present and by calculating the electric field along the cable without actually including it in the model. These files are used as incident fields
in the program BMTL, so that the individual wire currents can be extracted. This method has been used on simple models with good accuracy.

In this earlier project we found that the main difficulties in the simulations using XFDTD were to enter the geometry of the vehicle manually, decide the resolution and determine which geometry details are the most important to include in the model.

In 1998/99 this project which is a continuation of the earlier project was initiated. To overcome the problem of entering the geometry of the vehicle into the simulation program a program called CADfix [4] was bought. This program can import CAD-data, which thereafter can be converted to a model consisting of cells/cubes. A program based on FDTD called EMA3D [5] was also bought. It has an interface to the program CADfix making the EM simulation convenient.

The main goal of this project has been to find a method to make CAD-models suitable for electromagnetic simulations in a fast and inexpensive way. The requirement from the industry was that this process should take no more than one week. Other tasks in the project were to use the derived CAD-models to study “hot spots” inside the vehicle and coupling between antennas.

The CAD-data for a vehicle was simplified before a computer simulation was done. This was done in order to be able to work with the CAD-model in CADfix, and to reduce the amount of meshing problems. The full CAD-data of the vehicle is many hundreds of megabytes and a lot of the information is not needed for the electromagnetic (EM) modelling.
3 Methodology used in the project

3.1 Pre-processing of CAD-model and the Finite Difference Time Domain method (FDTD)

Due to the fact that we wanted to do simulations of large objects and was interested in results in a wide frequency band the FDTD (Finite Difference in Time Domain) method [8] was chosen. It is derived from the differential form of the time dependent Maxwell’s equations and implemented as a system of finite difference equations. It is suitable for a finite region because all of the problem space (computational domain) has to be included.

Before a simulation can be done a problem space, which has the shape of a rectangular box, is created. The CAD-model is put inside the problem space. Then a Finite Difference (FD) meshing routine as a first step checks the CAD-model for incorrect surfaces. They are e.g. not allowed to be twisted and the skewing angle of the surfaces must be small. If all surfaces are correct the FD meshing continues and a uniform spatial discretization of the whole problem space is done. This means that the problem space including the object is approximated with a large number of cubical cells, see Fig. 3.1.

![Figure 3.1. On left problem space including CAD-data of a cone. On right the cone after a FD meshing has been done.](image)

The more surfaces and the more complex the surfaces are the longer time the FD meshing takes to discretize the problem space. Although some surfaces are accepted by CADfix they don’t always pass through the FD-meshing routine. To minimize problems with the FD meshing demands have to be put on the quality of the CAD-file imported to CADfix, see chapter 4.

![Figure 3.2. The problem space is discretized in uniform cubical cells with a size of Δ](image)
When the problem space has been discretized in cubical cells a time discretized source has to be defined. It can be a voltage/current source, a plane wave etc. The amplitude shape of the source in the time domain can e.g. be a sinusoidal or a derivative of a gaussian pulse. However, the most commonly used is a gaussian pulse, see 1. in Fig. 3.3.

Running the FDTD program, which in our case has been EMA3D[5]:
1. The value of the source amplitude for the first time step is input to the problem space. The fields in all cells in the problem space are calculated at that time step.
   The value of the source amplitude for the next time step is input to the problem space and the fields are calculated once again, see 1 in Fig. 3.3.
2. At each time step the fields can be probed anywhere inside the problem space, see 2. in Fig. 3.3. The simulation must converge before the simulation is terminated. This means that the FDTD calculations are continued until a steady state has been reached.
3. An FFT of the probed value (the pulse response) is normalized with the FFT of the excitation source and gives the frequency response, see 3. in Fig. 3.3.

![Figure 3.3. Steps in running the FDTD problem and finally get the result in the frequency domain.](image)

FDTD uses a division of the computational volume in N cubical cells, where the sides of the cell should not be longer than $\lambda/20$ to $\lambda/4$ depending on the wanted accuracy. For RCS (Radar Cross Scattering) computations $\lambda/20$ would be necessary. For some simple cases $\lambda/4$ would be enough. For simulations of vehicles a reasonable length of the cell size would be $\lambda_{\text{min}}/10$ where $\lambda_{\text{min}}$ is the wavelength at the highest frequency of interest.

This means that the total number of cells in the problem space would be $N = \frac{V}{(0.1\lambda)^3}$

where $V$ is the volume in m$^3$ of the problem space and $\lambda$ in m. The highest frequency would be $f_{\text{max}} = \frac{c}{\lambda_{\text{min}}}$. 

The Courant stability criterion says that each time step \( dt \) has to be shorter than
\[
dt \leq \frac{\Delta}{\sqrt{3 \cdot c}}
\]
where \( \Delta \) in this case is given by \( \lambda_{\text{min}} / 10 \).

Parameters which affect the simulation time.
0. The number of cells in the problem space (computational volume).
1. Which ABC (Absorbing Boundary Condition) is used.
2. If probes inside or outside the problem space is used
3. Number of probes.
4. Number of time steps.
5. Type of excitation, voltage/current source or plane wave excitation.

### 3.2 Antennas

For antenna problems most conductors can be approximated as Perfect Electric Conductor (PEC), provided they are thicker than the penetration depth (skin depth) of the field into the conducting material. At this depth the wave amplitude has decreased by a factor \( e \), i.e. to about 37\%. The penetration depth is given by
\[
\delta = \frac{1}{\sqrt{\mu \mu_0 \sigma}}.
\]

Depending on which metal is used the conductivity \( \sigma \) varies between approx. \( 1.1 \times 10^6 \) to \( 6.2 \times 10^7 \) S/m. For \( \sigma = 1.1 \times 10^6 \) S/m the penetration depth is 48, 22 or 16 \( \mu \text{m} \) at frequencies 100, 450 and 900 MHz, respectively.

For the antenna simulations a thin wire approach is used to model the wire/rod. The definition of a thin wire is that the radius is much smaller than the cell size and consequently \( \ll \lambda \). For the simulations of a thin wire in this project a smallest radius of \( 500 \mu \text{m} \) has been used. This radius is smaller than the above calculated penetration depths which means that PEC is a good model.

The thin wires are put along edges of the cartesian grid, see Fig. 3.2 and Fig. 3.4. This means that thin wires parallel to surfaces must be placed at least one cell away from the surface. It also means that a thin wire cannot be put closer than one cell to another wire.

![Figure 3.4. On left CAD model of a thin wire on a metal plate (monopole). On right meshed thin wire (dashed line) is put along the cartesian grid. The original place of the thin wire in the model is marked with a dotted line.](image-url)
3.3 Metallic surfaces

Metallic surfaces are modelled as thin PEC surfaces. For a plane metal surface orthogonal to the coordinate axis one side of the cubical cell is set to PEC. For a surface not orthogonal to the coordinate axis several sides of the cubical cell are set to PEC, see Fig. 3.5.

![Figure 3.5](image)

*Figure 3.5. On left CAD-model of a metal plate. On right FD meshed metal plate now consisting of infinitesimal thin metal plates with a size of $\Delta x \Delta y$*

3.4 Absorbing Boundary Condition (ABC)

Many applications, such as e.g. antenna simulations, involve modelling EM fields in an unbounded open space. Due to the limited memory space in the computer, the problem space has to be truncated. Therefore, a certain type of boundary condition, called absorbing boundary condition (ABC) needs to be applied on the outer boundary of the problem space to simulate the unbounded physical space. Practical absorbing boundary conditions can usually not absorb outgoing waves completely and generate some errors in the solution. It is therefore important to have enough number of cells between the object and the boundary in order to ensure accuracy.

In the simulations we have used three different kind of ABC. The most simple one, Mur-1 [11], works well for outgoing plane waves that are perpendicular to the ABC. In 1992 Fang and Mei [12] proposed a technique which can be applied to many absorbing conditions, e.g. MUR-1, to improve their performance. The best absorbing boundary condition is the perfectly matched layer (PML) [13] which is realized by surrounding the problem space with a lossy material that dampens the outgoing fields. This lossy media that is put outside the problem space consists of several layers of cells, with their special equations, making the problem space even larger. Consequently the memory space in the computer and simulation time increases.
3.5 Excitation of the problem space

The Gaussian pulse provides a broadband input which is suitable when results in a wide frequency band are of interest. The gaussian pulse has for increasing frequencies a decreasing amplitude spectrum. This is important since we would not like to excite higher frequencies than what is supported by the cell size \( f_{\text{max}} = \frac{c}{10 \cdot \Delta} \).

\[
\begin{align*}
    u(t) &= A \cdot e^{-\alpha(t-t_0)^2} \\
    U(\omega) &= A \cdot e^{-i\omega_0} \sqrt{\frac{\pi}{\alpha}} \cdot e^{-\frac{\omega^2}{4\alpha}}
\end{align*}
\]

![Gaussian pulse in time and frequency domain](image)

*Figure 3.6. Gaussian pulse in time and frequency domain.*

The derivative of the Gaussian pulse gives a similar input, in the frequency domain, as the Gaussian pulse except that the DC-component is removed. This is useful for simulations where we have a short-circuit loop. The regular Gaussian could excite DC current flow which if the loop doesn’t has any losses (PEC) gives rise to an infinite current (overflow).

\[
\begin{align*}
    u(t) &= -2\alpha(t-t_0)A \cdot e^{-\alpha(t-t_0)^2} \\
    U(\omega) &= A \cdot i\omega \cdot e^{-i\omega_0} \sqrt{\frac{\pi}{\alpha}} \cdot e^{-\frac{\omega^2}{4\alpha}}
\end{align*}
\]

![Derivative of a Gaussian pulse in time and frequency domain](image)

*Figure 3.7. Derivative of a Gaussian pulse in time and frequency domain.*
3.6 For the vehicle simulations

The frequencies of interest have been in the range of 100 to 900 MHz. The vehicle structure will, therefore, be from about one to around ten wavelengths in size for the given frequency range.

With a cell size of 20 mm the Courant criterion gives $dt < 3.849 \times 10^{-11}$s. In order to ensure stability the time step was decreased to $dt = 3 \times 10^{-11}$s which is 78% of what the Courant criterion gives.

For the monopoles and dipoles the excitation pulse has been a gaussian pulse. For loop antennas a derivative of a gaussian pulse has been used.

The following type of media have been used in the cells of the problem space in this project:
- free space, $\varepsilon_r = 1$ and $\sigma = 0$.
- dielectric media, $\varepsilon_r > 1$ and $\sigma = 0$.
- lossy dielectric media, $\varepsilon_r > 1$ and $\sigma > 0$
- Perfect Electric Conductor (PEC), $\sigma \rightarrow \infty$
- thin wire modelled as PEC.
Magnetic materials have not been included.

3.7 Method for EM simulations using CAD-data

The entire mechanical geometry CAD-data of a vehicle consists of several thousand parts. Each part is very complex in itself including every little shape, folded edges, holes etc. Such CAD-data is far to complex to be used directly in the EM simulation program and therefore we need to make simplifications.

![Diagram](3.8) Method for converting CAD-data from structural dynamics analysis to EM calculations.

In order to make sure that the vehicle can handle all sorts of mechanical stress each automotive company has a special department doing structural dynamics analysis based on CAD-models. These CAD-models have their origin in the complex mechanical CAD-models which have been simplified to a much less complex level. The outcome of the simplification is a FE-meshed CAD-model where each part consists of small quad and triangular surface elements.
Figure 3.9. FE-meshed model of a car body. Model consists of small quad and triangular surface elements.

From this point the actual work to create a CAD-model that can be used for EM simulations starts. By deleting reinforcing plates, small parts, welded edges and so on, approximately only one tenth of the parts are saved for further use. The complexity of the CAD-model is even further reduced by enlargement of the quad and triangular surface elements. Finally, adjacent parts consisting of one or several surface elements are stitched together and small holes are filled. Thereafter, the CAD-model is imported to a pre-processor. We have used a program called CADfix [4]. In this program changes to the model can be made, e.g. interior and exterior details like chairs, steering wheel, rear view mirror etc can be added to the CAD-model, see Fig. 3.10.

Figure 3.10. Simplified CAD-model for EM simulations. Model consists of large quad and triangular surfaces.

Before a simulation can be done a problem space (computational domain), which has the shape of a rectangular box, is created. The CAD-model of the vehicle is put inside the problem space. Then a Finite Difference (FD) meshing, i.e. a user-defined uniform spatial discretization, is done. This means that the problem space including the vehicle is approximated with a large number of cubical cells, see Fig. 3.11.
Figure 3.11. FD-meshed model of a car. The model consists of cubical cells.

This model is exported to the simulation program, which in our case has been EMA3D and the simulation can start. The EMA3D program is based upon FDTD, which is well suited for simulations of large objects and if results in a wide frequency band are of interest.

Figure 3.12. Problem space (computational space) including a vehicle and field probes in a circle.
4 Creation of CAD models for EM simulations

At each automotive company CAD-models are created at different departments. Each specialized in topics like design/styling of the vehicle body, creating mechanical parts of the vehicle, electrical wire harness, computer simulation model etc. To fill the needs in a particular area specialized CAD systems are often used. Commonly used CAD systems are Unigraphics, CATIA, ANSA, IDEAS, CADfix etc. Sometimes there is a need of exchanging CAD-data between different CAD systems. The CAD-data of the first CAD system is then exported to an external file in one of several formats (IGES, STEP, STL,...). This external file is imported to the second CAD system.

![Diagram of CAD-data flow](image)

*Figure 4.1. Creation of CAD-models for EM simulations.*

4.1 CAD entities for a Surface/Face

To exchange CAD-data and for creating simple geometries it is good to have a basic knowledge of some CAD entities. Note that we use the expression surface in this report except in this chapter where the expression face is used instead. Most CAD systems use the expression face.

A face is a combination of an unbounded surface and trimming curves, see Fig. 4.2. The unbounded surface describing a shape can be of much larger size then the wanted face. To represent the unbounded surface Nonuniform Rational B-splines (NURBS) are normally used. They describe the shape of the unbounded surface by a piecewise rational polynomial surface defined by control points; a knot vector and a set of basis functions [14], see Fig. 4.3. Several faces can be connected to each other to form a larger object like a vehicle for example.

![Diagram of unbounded surface and trimming curves](image)

*Figure 4.2. A face is built of an unbounded surface and trimming curves (Reproduced by permission of Transcen Data Europe Ltd).*
4.2 Exchange of CAD-data between different CAD systems

To exchange CAD-data between different CAD systems several standards exist (IGES, STEP, STL etc). The most common and best known is the Initial Graphics Exchange Specification (IGES). It is intended as a "neutral" format, not tied to any particular CAD system. Still, IGES represents the entities of some CAD systems better than it does in others. Support is generally better for simple geometric entities, a little worse for more complex geometric entities.

Exchanging CAD-data using IGES requires two programs one for each CAD system. A program for the first CAD system, called the IGES-OUT translator, reads the CAD-database and produces an external file formatted in accordance with the IGES specification. This file will be moved to the second CAD system and a program called IGES-IN translator will read it and create a CAD-database in the second CAD system, see Fig. 4.4.

![Figure 4.4. Exchanging CAD-data between different CAD systems.](image)

Each step in the chain from CAD system A to B can sometimes cause problems. In the following we will describe some problems.

In CAD system A the CAD-data is created. For a large object, e.g. a vehicle, the surfaces forming the object seems to be connected to each other but in reality there is a gap or overlap between the surfaces. If the surfaces are closer to each other than a given tolerance the CAD system treats them as they are connected. Another reason for problems is the complexity of geometrical structures. For simple structures it is usually no problem. However, for more complex structures each CAD system often have their own mathematical definition which is difficult to transfer to some basic IGES entities.

The next step in the chain is the IGES-OUT translator which tries to translate the CAD-data to entities that exists in the IGES specification. The translators are better implemented in some CAD systems than others. Some complex geometries in a CAD system have no corresponding entity in the IGES specification. This give sometimes during the translation rise to incorrect geometries in the IGES-file. Also the quality of the IGES-IN translator varies between CAD systems. Both translators have, to some extent, the possibility to be influenced by parameter settings. In the CAD system we are using, CADfix, parameters like merging of points if closer than a given tolerance etc, can be set.
The last step in the chain is the receiving CAD system B which will receive CAD-data of a more or less correct model. In case of errors in the received CAD model CAD systems have some kind of reparation facility. CADfix have facilities to merge duplicate points, trim unbounded surfaces with existing curves to reshape a missing face etc, see Fig. 4.5.

![Figure 4.5. Duplicate points and curves which requires merging at appropriate tolerances. Missing face (unbounded surface without trimming curves) which need to be trimmed with existing curves.](image)

4.3 Suitable IGES entities for surfaces

We didn’t know about the CAD-data exchange problems when we started. Without success we spent a lot of time to import several different kind of IGES-files created in different CAD-systems. When it didn’t work we tried to find something else that could solve our problem. We then found that different parameter settings for the IGES-OUT translator could be set. Our first attempt was to import a part of a roof of a truck cabin. The CAD model was modelled in the CAD system CATIA. By using different parameter settings in the IGES-OUT translator we got several different IGES-files. With different parameter settings in the IGES-IN translator these were imported to our CAD system CADfix. The best combination of parameter settings for the IGES-OUT and the IGES-IN translator for this specific roof resulted in a CAD model which can be seen in Fig. 4.6. Green areas represent existing surfaces and white areas missing surfaces. The missing surfaces could be repaired in CADfix but it would cost a lot of time. Other metal parts were also tested but with the same problem of missing surfaces.

![Figure 4.6. Part of a roof after transferring from CATIA to CADfix.](image)

The conclusion was that using existing CAD-data of mechanical parts was not the method to use. Instead, we started from the beginning by modelling simple surface geometries in different CAD systems and transferred them to CADfix. By examining the entities in the IGES-file for the successfully transferred surfaces we found two different combinations of entities in the IGES-files. IGES-file 1 and 2 were created in the CAD systems IDEAS and ANSA, respectively.
Entities in IGES file 1:
Type       Description
126        Rational B-spline curve
128        Rational B-spline surface
142        Trimmed (parametric) surface
144        Curve on parametric surface

Entities in IGES file 2:
Type       Description
126        Rational B-spline curve
128        Rational B-spline surface
141        Boundary
143        Boundary surface

The unbounded surfaces are represented by the IGES-types 126 and 128. The trimming curves are represented by either the IGES-types 142 and 144 or the IGES-types 141 and 143. To have correctly defined surfaces (faces) the number of type 128 must be equal to the number of type 142 and 143. Or if the other parameter setting is used the number of type 128 must be equal to the number of type 141 and 143.
4.4 Methodology to make a CAD model for EM simulations

The decision of how to create a CAD-model depends on factors like type of available CAD-data, demands on precision of the model, time to create model etc. In the following three alternatives will be shown very briefly, see Fig. 4.7.

A. By using CAD drawings a complete new CAD model of the vehicle could be modelled. It would take weeks or months and the precision of the model would not be extremely good.

B. Another way could be to use existing CAD-data for all mechanical parts of the vehicle. Then each mechanical part would be imported to our CAD system CADfix. A lot of time would be spent on reparation of the CAD-data for each mechanical part. Due to the memory requirement a simplification of each mechanical part would be necessary. Finally parts close to each other would be stitched together. Doing this for a vehicle consisting of several hundreds of mechanical parts would take many weeks/months.

C. The third alternative uses as a basis already simplified CAD-models of mechanical parts used for structural dynamics analysis. These CAD-models are further simplified and put together to form a vehicle. In this way the CAD-model is created in a fast, about a week, and inexpensive way. By weighting the pros and cons this method was the one chosen in this project.

![Flowchart of Methodology to make a CAD model for EM simulations](image-url)

*Figure 4.7. Different alternatives to create a CAD-model for EM simulations.*
4.5 Using CAD-data from structural dynamics analysis

In order to ensure that the vehicle can handle all sorts of mechanical stress each automotive company have a department doing structural dynamics analysis based on CAD-models, see dashed squares in Fig. 4.8. These CAD-models have their origin in complex mechanical CAD-data, consisting of several hundred metal parts, which has been imported to the program ANSA (or IDEAS) via the format IGES (.igs). In this program the CAD-models are simplified to a much less complex level. The outcome of the simplification is a FE-meshed CAD-model where each part consists of small quad and triangular surface elements. Unfortunately the size of the IGES-files for vehicles are often over 100 Mb and the amount of surface elements are approx. 30 000 or even more depending on the size of the surface elements, see Fig. 4.9, for a chassis of a car consisting of approx 27 000 surface elements. This amount of CAD-data is impossible to work with in CADfix. To remedy this the complexity of this CAD-model can be decreased without loosing too much of accuracy. CAD-models of other items like hood, doors, trunk etc are also put into the model, see Fig. 4.10.

Figure 4.8. From CAD-models for mechanical parts to EM simulations.

Figure 4.9. Structural dynamics analysis model of the chassis consisting of triangular and quad elements Finite Elements (FE). The size of the IGES-file is 110 Mb and number of surfaces equals 27 000.


4.6 Method

The simplified FE-meshed CAD-model where each part consists of small quad and triangular surface elements from the structural dynamics analysis is used as a basis, see filled squares in Fig. 4.8.

1. The CAD-data is imported to the CAD system ANSA (or IDEAS) via any of the formats IGES (.igs), ANSA (.ans), Universal (.unv), or NASTRAN (.nas). By deleting reinforcing plates, small parts, welded edges and so on not needed for the EM model, approximately only one tenth of the parts are saved for further use.

2. The CAD-model consists of a mixture of complex geometry and simple surface elements. To reduce the amount of CAD-data the CAD-model is exported from ANSA to a NASTRAN-file and then immediately imported to ANSA again. Thereafter a surface has to be added on each element to be able to continue the simplification.

3. The complexity of the CAD-model is even further reduced by enlargement of the quad and triangular surface elements, see Fig. 4.11.

4. Adjacent parts consisting of one or several surface elements are stitched together and small holes are filled, see Fig. 4.12. To avoid problems later on when working with the final CAD-model in CADfix the skewing angle of each surface element must be held low. This procedure is done for all surfaces to create a complete CAD-model of a vehicle.
5. As a final step the CAD-model is exported from ANSA to a NASTRAN-file and then immediately imported to ANSA again. Thereafter a surface has to be added on each element to create a surface element. This CAD-model is exported to an IGES-file. The complexity of the CAD-model has been decreased considerable. In the specific case the size of the IGES-file is 7 Mb and the number of surfaces is about 1700.
4.7 Final CAD models

A CAD-model from each automotive company has been created by the method described in the preceding chapter. These simplified CAD-models consist of simple quad- and triangular surfaces, see Fig. 4.14. The CAD-model of the new SAAB is classified and thereby not shown. The simple surfaces in these CAD-models will make it easy to import in most CAD-systems without any errors. The size of the IGES-files vary between 5.5 to 10 Mb and the number of surfaces vary between 1500 to 2500, respectively, depending on degree of simplification and type of vehicle.

Figure 4.14. A CAD model from three of the automotive companies created by the method of chapter 4.6.

4.8 Add interior and exterior to the CAD-model

The final CAD-model is imported to a pre-processor. We have used a program called CADfix [4]. In this program, changes to the model can be made, e.g. interior and exterior details like chairs, steering wheel, rear view mirror etc can be added to the CAD-model, see Fig. 4.15.

Figure 4.15. Add interior and exterior to the CAD-model.
5 Simulation of simple structures in comparison with simulations of complex vehicles

Before the measurements and simulations on complex models were done, some simple problems were studied in order to compare the agreement between measurements and simulations.

5.1 E-field from antenna mounted on a metal sheet 1x1 m

The same measurement and simulation set-up as in chapter 5 have been used. But instead of a complex vehicle a simplified roof of a car placed 1.4 m over a large ground plane was used. The simplified roof consisted of a 1x1 m metal sheet. With the metal sheet as a ground plane for the monopole a commercial (A), a self-made (B) and a simulated (C) monopole were used. For the self-made monopole a hole was drilled in the middle of the metal sheet into which a rod was mounted. For the real vehicles we weren't allowed to drill holes in the chassis. Instead we used another commercial antenna consisting of a magnetic foot on which a rod was mounted.

5.1.1 Measurements

Measurements of the reflection coefficient $S_{11}$, see chapter 6.3, and probing of the E-field in a circle around the antenna were made for two different types of monopoles (monopole A and B):

Monopole (A), consisting of a rod placed on a magnetic foot (height =55mm) was placed on a metal sheet (1x1m). The monopole was placed 1.4 m over the ground plane in a semi-anechoic chamber. The monopole was connected to a feeding cable on the upper side of the metal sheet, see Fig. 5.1. Measurements of the reflection coefficient $S_{11}$, and probing of the E-field in a circle with a radius of 4m, 1m above the ground plane were made.

![Figure 5.1](image-url)

**Figure 5.1.** On the left, a monopole consisting of a metal sheet (1x1m) with a magnetic foot and a rod 1.4 m over the ground plane in a semi-anechoic chamber. Cable on the upper side of the metal plate. On the right, cross section of the magnetic foot (height =55mm) and the rod. The feeding cable is connected on the left side of the magnetic foot.
Monopole (B), consisting of a rod placed on a metal sheet (1x1m) 1.4 m over the ground plane in the semi-anechoic chamber. The monopole had a feed-through (N-connector) under the metal sheet where the feeding cable was connected, see Fig. 5.2. The height of the antenna corresponds to a length of $\lambda_0/4$ for the three frequencies $f_0$ of interest (100, 450 and 900 MHz).

![Figure 5.2. Monopole consisting of a metal sheet (1x1m) with a rod 1.4 m over the ground plane in a semi-anechoic chamber. On the right, cross section showing the feed-through (N-connector) and the rod. The feeding cable is connected under the metal sheet.](image)

<table>
<thead>
<tr>
<th>Frequency [MHz]</th>
<th>$\lambda_0/4$ -length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>750</td>
</tr>
<tr>
<td>450</td>
<td>166</td>
</tr>
<tr>
<td>900</td>
<td>83</td>
</tr>
</tbody>
</table>

*Table 5.1. Lengths of the rod for monopole (B) at different frequencies.*

### 5.1.2 Simulations

Simulations of the reflection coefficient $S_{11}$, and probing of the E-field in a circle around the monopole were made on one type of monopole (monopole C):

An FDTD simulation model (C) of the monopole consisting of a metal sheet (1x1m) with a rod 1.4 m over an infinite ground plane was made using a cell size of 20 mm. (This resolution gives approx. 16.6 cells per wavelength at 900 MHz.) The monopole was modelled as a thin wire fed by a voltage source at the base of the antenna, see Fig. 5.3. The computational volume was 418x418x130=22 714 120 cells. The outer boundary was Fang-Mei. Three different antennas were modelled with a length of 4, 8 and 37 cells, respectively.

![Figure 5.3. Simulation model of a monopole consisting of a metal sheet (1x1m) with a rod 1.4 m over an infinite ground plane. No cable, just a voltage feed point at the base of the antenna. On the right, cross section showing monopole consisting of a metal plate and a rod which is fed at the base of the antenna.](image)
The number of cells, each 20 mm, was chosen to give a length close to the $\lambda_d/4$-length for the frequencies of interest, see table 5.2. However, the FDTD method adds half a cell at the end, which means that the electrical length of the thin wire in the simulations, called the FDTD-length, varies with the cell size. As an example, the $\lambda_d/4$-length for a monopole of 900 MHz would be approx. 83 mm. In the simulations we have used 4 cells a’ 20 mm which gives an electrical length (FDTD-length) of $(4+1/2)*20 = 90$ mm. Not only the length of the antenna is proportional to the cell size but also the size of the voltage feed gap.

<table>
<thead>
<tr>
<th>Frequency [MHz]</th>
<th>$\lambda_d/4$-length [mm]</th>
<th>No of cells</th>
<th>FDTD-length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>750</td>
<td>37</td>
<td>750</td>
</tr>
<tr>
<td>450</td>
<td>166</td>
<td>8</td>
<td>170</td>
</tr>
<tr>
<td>900</td>
<td>83</td>
<td>4</td>
<td>90</td>
</tr>
</tbody>
</table>

*Table 5.2. Length of the thin wire for the monopoles (C) at different frequencies.*

**5.1.3 Comparison between measurement and simulation of the reflection coefficient**

Comparisons between measurements and simulations of the reflection coefficient $S_{11}$ for Monopole A, B and C have been made.

For the 100 MHz monopoles, see Fig. 5.4, the agreement between monopole B and C for the resonance frequency, approx. 97 MHz, and amplitude is very good. This could be due to the fact that the $\lambda_d/4$-length of monopole B equals the FDTD-length of monopole C. For monopole A the resonance frequency is slightly lower, 96 MHz.

For the 450 MHz monopoles, see Fig. 5.5, the best agreement is between monopole A and B, which have their resonance frequencies at 444 and 439 MHz, respectively. For monopole C the resonance frequency is at 431 MHz, which can be explained by a FDTD-length a little longer than the $\lambda_d/4$-length and therefore the resonance frequency is lower. For additional simulations see appendix C and D.

For the 900 MHz monopoles, see Fig. 5.6, monopole B has a resonance frequency of 890 MHz. The FDTD-length of monopole C is 8% longer than the $\lambda_d/4$-length which gives a resonance frequency of 810 MHz. Finally, monopole A is very broad banded, with an interval from 800 to 950 MHz, and has no distinct resonance frequency.
Figure 5.4. Comparison between measured and simulated reflection coefficient $S_{11}$ for a 100 MHz monopole consisting of a metal sheet (1x1m) and a rod over a ground plane.

Figure 5.5. Comparison between measured and simulated reflection coefficient $S_{11}$ for a 450 MHz monopole consisting of a metal sheet (1x1m) and a rod over a ground plane.
Figure 5.6. *Comparison between measured and simulated reflection coefficient $S_{11}$ for a 900 MHz monopole consisting of a metal sheet (1x1m) and a rod over a ground plane.*

<table>
<thead>
<tr>
<th>Wanted resonance frequency [MHz]</th>
<th>Monopole A diff. [%]</th>
<th>Monopole B diff. [%]</th>
<th>Monopole C diff. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>450</td>
<td>2</td>
<td>2.5</td>
<td>4.5</td>
</tr>
<tr>
<td>900</td>
<td>-</td>
<td>1.1</td>
<td>10</td>
</tr>
</tbody>
</table>

*Table 5.3. Difference in % between wanted and actual resonance frequency.*

The resonance frequency of a monopole is slightly lower than the frequency $f_0$ corresponding to the $\lambda_d/4$-length. Monopole B has been used as a reference with a $\lambda_d/4$-length of the antenna. From table 5.3, we see that the resonance frequency is 1-3% lower than the frequency $f_0$ corresponding to the $\lambda_d/4$-length. For monopole C the resonance frequency differ more higher up in frequency depending on the larger difference between the FDTD-length and the $\lambda_d/4$-length.

From the complex reflection coefficient $S_{11}$ the antenna impedance $Z_a$ can be calculated as:

$$Z_a = \frac{50*(1+S_{11})}{(1-S_{11})}, \text{ in a 50 ohm system}$$
Figure 5.7. Impedance for 450 MHz monopoles.

Figure 5.8. Impedance for 900 MHz monopoles.

As we can see in Fig. 5.4-5.6 the reflection coefficient for the self-made monopole (B) is for the frequencies of interest closest to the simulated monopole (C). The agreement could have been even better if the length of the self-made monopole had been adjusted to the FDTD-length. So the self-made monopole would have been the best. This shows that the simulations are quite good.

To get the best agreement between the simulation and measurement the self-made monopole should have been used. However the difference between the simulated and the commercial monopole is not that bad. The reflection coefficient does not say everything we also have to look at the E-field a distance from the antenna, see next chapter.
5.1.4 Comparison between measurement and simulation of the E-field

The E-field was probed in a circle with a radius of 4 m, 1 m above the ground plane. The total E-field is presented in the diagrams for 100, 450 and 900 MHz. The monopole was directed in the vertical direction which gives a dominant vertical polarization at the probe positions. The amplitude of the electric field components in the \( \hat{\phi} \) (vertical), \( \hat{\varphi} \) (horizontal) and \( \hat{r} \) (outgoing) direction are approximately distributed according to 90, 10 and 0 % except at 100 MHz where it is 70, 30 and 0 %, respectively.

A quite good agreement between the simulation and measurement for all frequencies except at 100 MHz were achieved, see Fig. 5.9-11. The difference is between 3 and 5 dB. The shape of the diagram is smooth at 100 MHz and becomes more complicated as the frequency gets higher.

![Comparison between measured and simulated E-field from an antenna mounted on a 1x1 m metal plate 1.4 m over a ground plane at 100 MHz.](image1)

![Comparison between measured and simulated E-field from an antenna mounted on a 1x1 m metal plate 1.4 m over a ground plane at 450 MHz.](image2)
Figure 5.11. Comparison between measured and simulated E-field from an antenna mounted on a 1x1 m metal plate 1.4 m over a ground plane at 900 MHz.
5.2 Coupling between 2 antennas mounted on a metal sheet 1x2m

As a validation case a metal sheet, 1x2 m with a 100 MHz-antenna and a 450 MHz-antenna on it was chosen. The reasons for choosing this structure were that it was easy to simulate and also that it is similar to the roof of a vehicle with two antennas. One of the monopoles was mounted symmetrically 0.4 m from the left side and had a height of 750 mm and a radius of 1.5 mm. The other monopole was mounted symmetrically 0.4 m from the right side and had a height of 165 mm and a radius of 1.0 mm.

5.2.1 Measurements

The metal sheet was placed in a semi-anechoic chamber with the two magnetic foot antennas mounted on it. To measure the coupling $S_{21}$ between the antennas a network analyser was used.

5.2.2 Simulations

For the simulations we have used two programs. Besides the FDTD program EMA3D a MoM program Wire-MoM [6] has been used. The program Wire-MoM uses wires to build objects. To build the metal sheet a net consisting of 432 wires, with 1111 unknowns, were put together. The radius of the wires were set so that the total surface area of the wires was equal to the area of the homogenous metal sheet. The simulation time for each frequency was approx. 3 min which for 151 frequencies gave a total simulation time of approx. 7 hours.

![Model of a metal sheet 1x2 m with two antennas made in EMA3D (left) and Wire-MoM (right).](image)

In EMA3D a problem space size of 4x3x2 m with a cell size of 20 mm was used. The ABC was a 8-layer PML, simulating free space. Two thin wires, with a height of 37 cells and 8 cells corresponding to an FDTD-length of 750 and 170 mm, respectively, were modelled on the metal sheet. The simulation time for the frequency interval was approx. 3 hours.
5.2.3 Results
The shape of the measured result is jagged over the frequency band with large depths at 330 and 450 MHz. The difference between the EMA3D simulation and the measurement is less than 10 dB except at 80, 330 and 450 MHz. Up to 280 MHz the two simulations are quite similar. At approx. 280 MHz the Wire-MoM result shows a resonance that cannot be seen in the EMA3D result. For higher frequencies the two programs agree quite well again.

Figure 5.13. Comparison between measured and simulated coupling between a 100 MHz- and a 450 MHz-antenna mounted on a metal sheet 1x2 m.
6 Simulations and measurements of complete vehicles

In order to validate the whole process from converting the original mechanical CAD-data via the simulation to the results a number of comparisons with measurements on real vehicles have been made.

6.1 Measurement set-up

The measurements were done in a semi-anechoic chamber (21x12x8m). The floor in the chamber is made of metal and the roof and the walls are equipped with absorbers with a length of 1.2 m. In one end of the chamber a turn-table is placed, making e.g. probing of the E-field in a circle around the vehicle convenient. For all measurements, except when not possible, the vehicles were placed in the middle of the turn-table.

![Image: Measurement in the semi-anechoic chamber.](image.png)

Figure 6.1. Measurement in the semi-anechoic chamber.

6.2 Simulation details

A simulation model describing the measurement set-up including the E-field probes, see Fig. 6.2, was made for each test case. The dimension of the problem space in the xy-plane, was 8.4x8.4 m and the height of the problem space was between 2.5-3.9 m depending on the height of the simulated vehicle. The metal floor in the semi-anechoic chamber was modelled by a PEC-plane extending to infinity. The remaining sides were modelled as free space using the Absorbing Boundary Condition (ABC), Fang-Mei [12].

Given the size of the problem space and available memory in the used computer the smallest cell size that we were able to use was 20 mm. This resolution gives app. 16.6 cells per wavelength at 900 MHz. In order to ensure convergence we found that it was sufficient to use 8192 time steps for all test cases. This all together, on a 800 MHz PIII computer, gives a simulation time ranging from 18 to 32 hours depending on the height of the problem space, see Fig. 6.3.
Figure 6.2. Simulation set-up including E-field probes.

Figure 6.3. Problem space including the vehicle and the ground-plane extending to infinity. Simulation times are on a Pentium III 800 MHz-computer.

For all vehicles the E-field inside and outside the vehicle was probed. The E-field was probed in a plane inside the vehicle, so-called field-mapping see Fig. 6.4, with a resolution of 100 mm. The excitation source were different antennas, see Fig. 6.5, or a plane wave outside the vehicle.
Figure 6.4. Measurement of E-field inside a vehicle.

Figure 6.5. Used antennas during measurements. Magnetic foot antenna, loop antenna and dipole antenna.

6.3 Scattering parameters

Microwave devices are often characterized by the scattering parameters, given by $S_{ij}$, where $j$ is the input port and $i$ is the output port. In the following the scattering parameters are applied to two antennas, antenna 1 and 2.

- $S_{11}$ is the reflection coefficient for port 1 (antenna 1). It is a ratio of the voltage reflected at port 1 (antenna 1) due to impedance mismatch. Its absolute value vary from 0 to 1. When impedance match, i.e. when the feeding system equals the impedance at port 1 (antenna 1), the reflection coefficient equals 0. On the opposite when totally mismatched the reflection coefficient approaches 1 which means that almost all power is reflected at port 1.

- $S_{22}$ is defined in the same way but for port 2 (antenna 2).

- $S_{21}$ is the transmission coefficient, which is a measure of how much energy is received at port 2 (antenna 2) from a source imposed at port 1 (antenna 1).

- In a passive system $S_{12} = S_{21}$ due to reciprocity.
6.4 Measurements

A network analyser was used to measure the scattering parameter $S_{21}$, which is a measure of the coupling between the two ports. In the case shown in Fig. 6.6 it is between two monopoles mounted on a car. The cables between the network analyser and the magnetic foot antennas were held close to the car and the metal floor and fitted with ferrites to minimize disturbances.

![Network analyzer and antennas](image)

*Figure 6.6. Test-setup for measuring the scattering parameters between a magnetic foot antenna on the trunk and a magnetic foot antenna on the roof.*

Before measurement a full 2-port calibration of the network analyser is performed at the ends of the cables connecting to each antenna.

By measuring the scattering parameter $S_{11}$ at the antenna port the antenna impedance can be calculated as

$$Z_a = \frac{50 \times (1 + S_{11})}{(1 - S_{11})} \text{ if a 50 ohm system is assumed.}$$
6.5 Simulations

To calculate all 4 scattering parameters $S_{11}$, $S_{12}$, $S_{21}$ and $S_{22}$ two simulations were done (I and II). In the first simulation (I), antenna A is excited by a voltage source and the currents at antenna A and B are calculated. In the second simulation (II), antenna B is excited by a voltage source and the currents at antenna A and B are calculated, see Fig. 6.7. Then the scattering matrix can be calculated as follows.

![Diagram of two simulations](image)

*Figure 6.7. Two simulations, excitation by voltage sources $V_1$ and $V_2$.*

From simulation I the admittances $Y_{11}$ and $Y_{21}$ are calculated as

$$Y_{11} = \frac{I_1}{V_1 |_{V_2=0}}$$

$$Y_{21} = \frac{I_2}{V_1 |_{V_2=0}}$$

, where $(I_1=I_{11})^*$ and $(I_2=I_{21})^*$

For simulation II the admittances $Y_{22}$ and $Y_{21}$ are calculated as

$$Y_{22} = \frac{I_2}{V_2 |_{V_1=0}}$$

$$Y_{12} = \frac{I_1}{V_2 |_{V_1=0}}$$

, where $(I_2=I_{22})^*$ and $(I_1=I_{12})^*$

* at simulations

The admittance matrix $Y$ equals

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$$

The Scattering matrix $S$ can be computed from the admittance matrix as

$$[S] = ([U] + Z_0[Y])^{-1}([U] - Z_0[Y])$$

where

$$U = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

and

$Z_0=\text{impedance, in the measuring system (usually 50 ohm).}$
When only the reflection coefficient $S_{11}$ is of interest only one simulation needs to be done. First the antenna impedance $Z_a$ is calculated as $Z_a = \frac{U_z}{I_z} - R_s$, where $U_z$ and $I_z$ are complex values of the source voltage and current and $R_s$ is the source resistance. Then the reflection coefficient $S_{11}$ is calculated as $S_{11} = \frac{Z_a - Z_0}{Z_a + Z_0}$. The method for computing the full S-matrix described above is implemented in the Wire-MoM [6] program. When using Wire-MoM it is sufficient to define two sources and the program will automatically compute the S-matrix.
7 Results car Volvo S80

Comparison between measurements and simulations with the FDTD program EMA3D and the MoM program Wire-MoM [6] have been made on three types of problems. These have been probing of the E-field in a circle around the car, coupling between two antennas and field-mapping inside the car.

Two other types of simulations have also been done. The first type shows how simulations can be used to find an optimal placement of antennas. The other type uses a model of the test set-up for immunity testing of vehicles in the semi-anechoic chamber.

An FDTD model of the set-up was made with a problem space of 8.4x8.4x2.5 m using a cell size of 20 mm giving a total of 22 million cells. The outer boundary was ABC set to Fang–Mei. Monopole antennas with three different lengths were mounted on the car.

![Figure 7.1. A Volvo S80 in the semi-anechoic chamber.](image)

7.1 E-field around the car

The car was placed in the middle of the turn-table with a 100, 450 or 900 MHz-antenna mounted on the roof of the car, see Fig. 7.2. The total E-field was evaluated with a 3° resolution in a circle 4 m from the centre and 1 m over the floor (ground plane). At 100 MHz Wire-MoM was used to model a simple wire model including a roof with the antenna, a hood and a trunk. The simulation time for this MoM-model was 16 min at one frequency compared to 18 hours over a frequency band for the more complex CAD-model in EMA3D. For all measurements the front of the car was in the 180 degrees direction.

The antenna, modelled as a thin wire with a radius of 1.5, 1.0, 1.0 mm and an FDTD-length of 750, 170 and 90 mm respectively was mounted on top of the roof. This means that the antennas were mounted in the centre of the problem space.
Figure 7.2. Comparison between measured and simulated E-field for a 100 MHz-antenna mounted on top of the roof. Wire-MoM 1942 unknowns, 16 min/frequency.

Figure 7.3. Comparison between measured and simulated E-field for a 450 MHz-antenna mounted on top of the roof.
Although the shapes of the probed E-field are complex there is an acceptable agreement between the measurement and simulation. The difference in amplitude between measurement and simulation with EMA3D is less than 5 dB. In spite of the simplicity of the Wire-MoM model it gives a quite good shape and amplitude of the probed E-field at 100 MHz.
7.2 Coupling between antennas

In order to study the coupling between antennas mounted on the car a number of different test cases were studied. For example the coupling between antennas mounted on the car and between external antennas and antennas mounted on the vehicle. The coupling shown in Fig. 7.5 is between an antenna mounted on the roof and another mounted on the trunk. Both antennas were modelled as thin wires with an FDTD-length of 750 and 170 mm and with a radius of 1.5 and 1.0 mm, respectively. As can be seen an acceptable agreement between measurement and simulation was achieved. The difference between measured and simulated coupling was for all frequencies less than 10 dB except at 390 MHz. For this case the very simple Wire-MoM model is good enough to predict the coupling.

![Graph showing coupling comparison](image)

*Figure 7.5. Comparison between measured and simulated coupling between a 450 MHz-antenna mounted on the roof and a 100 MHz-antenna mounted on the trunk.*
7.3 Field-mapping inside the car

Field-mapping can be used to determine locations of “hot spots”, i.e. places with high field strength inside the vehicle. These places are not suitable for the placement of electronic units and wire harnesses. In order to create a model that is similar to a real vehicle, chairs and steering wheel were added to the CAD-model, see Fig. 7.6. On the outside of the vehicle an antenna was placed on the middle of the trunk. The antenna, modelled as a thin wire with a radius of 1.5 mm and an FDTD-length of 750 mm, was fed by a voltage source at the base of the antenna. The E-field was mapped, at 100 MHz, 80 mm above each chair. The spatial resolution of the E-field mapping was 20 mm for the simulation and 100 mm for the measurement case.

From the results we can see a “hot spot” located near the drivers seat both in the simulation and measurement. The location of the “hot spot” is probably due to the steering wheel, because the CAD-model is symmetric except for it.

![Figure 7.6. Comparison between measurement (upper) and simulation (lower) of E-field inside a vehicle at 100 MHz. Excitation by an antenna on the trunk.](image-url)
7.4 Placement of antennas

A placement of antennas for a minimal coupling can be found by using simulations. To illustrate this three simulations were done to simulate the coupling $S_{21}$ between a 900 MHz-antenna (GSM) and a 100 MHz-antenna (FM) placed on three different places, see Fig. 7.7.

![Figure 7.7. 900 MHz-antenna position 4 and 100 MHz-antenna position 1-3.](image)

As we could expect antenna 3, with the largest distance to antenna 4, has for almost all frequencies the lowest coupling. If we compare the coupling for antennas 1 and 2 at the frequencies 100 and 900 MHz were the antennas are supposed to work we see no difference at 100 MHz but a 15 dB difference at 900 MHz. To minimize the coupling the 100 MHz-antenna should be mounted on the hood. If that for practical reasons is not possible the next best solution would be on the trunk.

![Figure 7.8. Simulation of the coupling between Antenna (GSM 900MHz) position 4 and antenna (FM 100MHz) position 1, 2 and 3.](image)
7.5  E-field between the car chassis and the ground plane consisting of metal or soil

In EMC testing of vehicles in a semi-anechoic chamber a metal is used as a ground plane. Soil would be a more realistic ground plane. Simulations have been made to see if there is a difference in using a metal ground plane instead of a ground plane consisting of soil. A model of the soil case is shown in Fig. 7.10. A plane wave directed along the car from front to back with incident angle \( \theta_i \) of 23° and vertical polarization was used to excite the problem, see Fig. 7.9. The amount of E-field reflected from the ground, see 1 in Fig. 7.10, depends on the electrical properties of the ground and the incident angle \( \theta_i \). The reflection varies with the electrical properties of the ground and the incident angle \( \theta_i \). The electrical property of a ground plane are determined by the dielectric constant \( \varepsilon_r \), the conductivity \( \sigma \) and the permeability constant \( \mu_r \). These are in turn determined by the chemical properties, the moisture, temperature and frequency.

![Probes Soil](image)

**ABC: 8-layer PML**

*Figure 7.9. Model of the car with the E-field probe plane, 100 mm thick plane of soil and the boundary of the Absorbing Boundary Condition. The arrow represents the incident E-field.*

In the simulations we used a model with material properties simulating dry soil with a dielectric constant \( \varepsilon_r = 4 \), a conductivity of \( \sigma = 10^{-3} \) and permeability constant \( \mu_r = 1 \). In Fig. 7.10 we can see a schematic cross section of the model, with ray traces for reflected and refracted rays. As can be seen number 1 represents direct reflection of the field when it hits the soil. Indirect field, number 2, is reflected from the lower boundary of the soil. Finally some portion of the field is reflected from the ABC due to a not perfect ABC.

The dimension of the problem space was 8.4x6x2.7 m with a cell size of 20 mm which gives approx. 16 million cells. For the simulation case when metal was used as ground plane a time step of 3e-11 s was used. When lossy dielectric (soil) is used as ground plane, the time step has to be reduced by at least a factor \( \sqrt{\varepsilon_r} = 2 \). A time step of 1.5e-11s was used. The remaining sides were modelled as free space using the ABC PML.
Figure 7.10. Model of soil under the car showing the reflected and refracted field traces due to boundaries on the soil and the ABC.

The E-field was mapped under the car on the right side for both cases. The amplitude of the plane wave was 1 V/m and in Fig. 7.11-12 the colours represent the amplification of the E-field compared to the incident amplitude.

The amplification of the E-field under the car when a metal ground plane was used varies between 1 and 7.6.

In the next simulation the metal plane is replaced by a 5 cell (=100 mm) thick lossy dielectric media representing dry soil. The amplification this time is lower, as could be expected, and varies between 0.6 to 2.6. For both simulations the hot spot is under the front seat.

The conclusion is that the measurements in a semi-anechoic chamber represents a worse case than where the vehicle normally is used. The E-field only give a hint of the effect using metal instead of soil as a ground plane. Comparisons, not shown in this report, between measurements and simulations, which were not so good have also been done. To get more accurate E-field under the car wheels, axis, engine etc have to be included in the CAD-model.
Figure 7.11. Probing of E-field under a car at 32.5MHz. The incident field is a vertically polarized plane wave with an amplitude of 1 V/m and the incident angle $\Theta_i$ is 23 degrees. The ground plane (PEC) under car is extending to infinity.

Figure 7.12. Probing of E-field under a car at 32.5MHz. The incident field is a vertically polarized plane wave with an amplitude of 1 V/m and the incident angle $\Theta_i$ is 23 degrees. The ground plane under the car is lossy dielectric media simulating soil ($\varepsilon_r=4$ and $\sigma=10^5$) with a thickness of 5 cells=100mm.
8 Results car concept SAAB

Comparison between measurements and simulations have been made on three types of problems. These have been probing of the E-field in a circle around the car, coupling between two antennas and field-mapping inside the car. Due to secrecy the field-mapping inside the car cannot be shown.

An FDTD model of the set-up was made with a problem space of 8.4x8.4x2.5 m using a cell size of 20 mm giving a total of 22 million cells. The outer boundary was ABC set to Fang-Mei.

8.1 E-field around the car

Measurements and simulations of the probed E-field from an antenna mounted, on several different places, on a vehicle have been performed. The probed E-field was evaluated with a 3° resolution at a distance of 4 m from the centre of the problem space and 1 m over the ground plane. One of the test cases for this problem type can be seen in Fig. 8.1. The antenna, modelled as a thin wire with a radius of 1 mm and an FDTD-length of 170 mm was mounted on the right side of the trunk. This means that the smallest distance (2.3 m) to the circle of E-field probes was in a direction of approximately 60° and the largest distance (5.7 m) in a direction of approximately 210°. For all measurements the front of the car was in the 180 degrees direction.

Although the shapes of the probed E-fields are complex there is an acceptable agreement between the measurement and simulation. The difference in amplitude is less than 5 dB except in deep nulls. It is also interesting to note that the nulls are deeper in the measurements than in the simulations.

Figure 8.1. Comparison between measured and simulated E-field from a 450 MHz-antenna mounted on the trunk of the car.
The 100 MHz-antenna, modelled as a thin wire with a radius of 1.5 mm and an FDTD-length of 750 mm was mounted on the roof of the car. The shapes and amplitudes of the probed E-field are similar. The difference in amplitude is less than 4 dB.

![Diagram](image)

**Figure 8.2.** Comparison between measured and simulated E-field from a 100 MHz-antenna mounted on the roof of the car.

### 8.2 Coupling

For the comparison of the coupling between antennas the same antennas and positions as used in the E-field probing around the car were used.

![Diagram](image)

**Figure 8.3.** Comparison between measured and simulated coupling between a 100 MHz-antenna mounted on the roof and a 430 MHz-antenna mounted on the trunk.

It's an acceptable agreement between measurement and simulation with less than 10 dB difference for all frequencies except at 60-70 MHz.
9 Results truck Volvo FML2H1

Comparison of measurements and simulations have been made on three types of problems. These have been probing of the E-field in a circle around the truck, coupling between two antennas and field-mapping inside the truck.

Two other types of simulations have also been done. The first type investigates how far a model of the truck cabin can be simplified. The other type look at how different cell sizes affect the results.

An FDTD model of the set-up was made with a problem space of 8.4x8.4x3.6 m using a cell size of 20 mm giving a total of 35 million cells. The outer boundary was ABC set to Fang-Mei.

One additional comparison with and without glass on the driver side. (Om beräkningsdator blir reparerad i tid).

![Figure 9.1. Volvo truck in measurement semi-anechoic chamber.](image)

9.1 E-field around the truck

Measurements and simulations of the E-field due to excitation of an antenna around the truck have been performed. The truck was placed in the middle of the problem space/turn-table with a 100, 450 or 900 MHz-antenna mounted on top of the roof. The total E-field was evaluated with a 3° resolution in a circle 4 m from the centre of the problem space/turn-table and 1.8 m over the ground plane. For all measurements the front of the truck was in the 180 degrees direction.

The 100 MHz-antenna, modelled as a thin wire with a radius of 1.5 mm and an FDTD-length of 750, was mounted in the middle on top of the roof, see Fig. 9.2. A comparison between the measurement and simulation gives an amplitude difference less than 3 dB. The shape of the probed E-field for the measurement has a more complex shape than the simulation but there is an acceptable agreement.
The 450 MHz antenna, modelled as a thin wire with a radius of 1.0 mm and an FDTD-length of 170, was mounted on the left rear back mirror. This means that the antenna was close to the E-field probes on the left side and far away in the 'shadow' on the right side. This can clearly be seen when we study the probed E-field, see Fig. 9.3. We had no CAD-model for the rear back mirror and therefore it was modelled afterwards, from photos, by hand in CADFix. This could explain the big difference in angle for the amplitude maximum between the measurement and simulation.

Figure 9.2. Comparison between measured and simulated E-field from a 100 MHz-antenna mounted on top of the roof.

Figure 9.3. Comparison between measured and simulated E-field from a 450 MHz-antenna mounted at the rear back mirror.
9.2 Coupling

In order to study the coupling between antennas mounted on a truck cabin a number of different test cases have been studied. The coupling shown in Fig. 9.4 is between a 100 MHz-antenna on the back and a 450 MHz-antenna in the right corner on the roof. Both antennas have been modelled as thin wires with an FDTD-length of 750 and 170 mm and with a radius of 1.5 and 1 mm, respectively. As can be seen an acceptable agreement between measurement and simulation was achieved.

![Graph showing S12 dB vs Frequency (MHz)](image)

Figure 9.4. Comparison between simulation and measurement of the coupling between two antennas mounted on the roof, one 100 MHz-antenna at the back and one 450 MHz-antenna at the front right corner.

9.3 Field-mapping

In order to create a model that is similar to a real truck, chairs and steering wheel have been added to the CAD-model, see Fig. 9.5. On the outside of the vehicle a 450 MHz-antenna was placed on the left rear back mirror. The antenna, modelled as a thin wire with a radius of 1.0 mm and an FDTD-length of 170 mm, was fed by a voltage source at the base of the antenna. The E-field was mapped, at 450 MHz, 80 mm above each chair. The spatial resolution of the E-field mapping was 20 mm for the simulation and 100 mm for the measurement.

We had no CAD-model for the rear back mirror and therefore it was modelled afterwards, from photos, by hand in CADfix. This could be one reason for the big difference in E-field pattern and amplitude between the measurement and simulation.
Figure 9.5. Comparison between simulation (upper) and measurement (lower) of E-field inside a truck from a 450 MHz-antenna at the rear back mirror.
9.4 Degree of simplification for a truck cabin in EMA3D

These simulations have been done to study how far a CAD-model can be simplified. Of course the degree of simplification that gives acceptable result depends on what type of simulation (coupling, probed E-field etc), where the antennas are mounted on the vehicle, which frequency band is of interest etc. These simulations have been made in order to study the coupling \( \frac{I_{\text{receive}}}{I_{\text{source}}} \) between antennas mounted on the roof of the truck cabin.

We have used a CAD-model of the whole truck cabin, a CAD-model of the roof of the truck cabin and a flat metal sheet 1x2 m, see Fig. 9.6. In the left and right front corner of the roof a thin wire model of a 150 MHz antenna with an FDTD-length of 510 mm have been modelled. The antennas were separated 2 m. The problem space and by that simulation time for the different models varied with the size of the model. The size of the problem space in decreasing order was 2.2, 0.7 and 0.5 million cells. The used cell size was 20 mm, the time step \( dt=2.5e-11 \) s and the number of time steps=16384.

![Figure 9.6. CAD-model of a whole truck cabin, the roof of a truck cabin and a simplified roof modelled in CADfix.](image)

A comparison of the coupling between two antennas mounted on top of the roof for the three models can be seen in Fig. 9.7. If we use the coupling result for the whole truck cabin as a reference we see that the coupling for the roof of the truck cabin is quite similar with a difference in amplitude less than 3 dB except at 35 MHz. The shape of the coupling for the metal sheet over 50 MHz is also quite similar with an amplitude difference of less than 7 dB. Under 50 MHz the largest difference is 13 dB at 34 MHz.
9.5 Comparison of simple roof simulations with different programs

Three different programs were used to simulate the simplified roof with two antennas. The simulation result for the metal sheet was taken from the previous simulation in EMA3D. The two other programs were WIPL [7] and Wire-MoM. In WIPL the roof was modelled as a metal sheet. The program Wire-MoM uses wires to build objects. To build the metal sheet a net consisting of wires, with 52 unknowns, were put together. The radius of the wires were set so that the total surface area of the wires was equal to \(1.5 \times 2.1 = 3.15\) m\(^2\). The simulation time for each frequency was approx. 10 seconds which for 150 frequencies gave a total simulation time of approx. 25 minutes.

As can be seen in Fig. 9.9 the amplitude of the coupling in EMA3D and WIPL are quite similar with a largest difference of 3 dB over 275 MHz. The result of the Wire-MoM simulation shows a good agreement to the other up to 175 MHz. The agreement at higher frequencies could probably be improved by modelling the roof with more wires in Wire-MoM.

Figure 9.7. Comparison between different degree of simplification of the truck cabin for the coupling between two antennas mounted on top of the roof.

Figure 9.8. Roofs from left to right EMA3D, WIPL and Wire-MoM.
Figure 9.9. Comparison between different degree of simplification of the truck cabin for the coupling between two antennas mounted on top of the roof.

9.6 Using different cell size in the truck cabin simulation

By choosing an appropriate cell size we can minimize the used memory space in the computer and also the simulation time. In Fig. 9.10 we have increased the cell size in steps from 20 to 40 to 80 mm. Depending on what type of simulation type and wanted accuracy 80 mm could be enough. We have used a CAD-model of the whole truck cabin, see 8.1.4. In the left and right front corner of the roof a thin wire model of a 150 MHz-antenna has been modelled. When changing the cell size not only the coarseness of the model will be affected but also the electrical length (FDTD-length in table 9.1).

The problem space including the truck cabin and antennas was set to approximately 3.2x3.6x3.2 m. This with a cell size of 20, 40 and 80 mm gives approx. 4.2 mill., 0.5 mill, and 70 thousand cells, respectively. The number of cells for the thin wires were adjusted so that the FDTD-length was as close to 500 mm as possible, see table 9.1.

<table>
<thead>
<tr>
<th>Cell size [mm]</th>
<th>No of cells</th>
<th>FDTD-length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>24</td>
<td>490</td>
</tr>
<tr>
<td>40</td>
<td>12</td>
<td>500</td>
</tr>
<tr>
<td>80</td>
<td>6</td>
<td>520</td>
</tr>
</tbody>
</table>

Table 9.1. Number of cells to give an FDTD-length close to 500 mm.
Figure 9.10. In the upper left corner is a simplified CAD-model, of a truck cabin, which is used as a basis in the FD-meshing. The following three models are meshed with a cell size of 20, 40 and 80 mm, respectively.

In Fig. 9.11 the coupling between the two antennas expressed as $I_{\text{ref/boresc}}$ is shown. For frequencies up to 250 MHz the amplitude difference is less than 3 dB which in some cases could be acceptable. However, with a cell size of 80 mm there is a big amplitude difference although the shape of the amplitude is similar. This could be explained by the stair-case approximation but also that the frequency is close to $\frac{\lambda_{\text{min}}}{10}$, see chapter 3.1.
Figure 9.11. Comparison between different cell size of the truck cabin for the coupling between two antennas mounted on top of the roof.
10 Results truck Scania CR19

Comparison of measurements and simulations have been made on three types of problems. These have been probing of the E-field in a circle around the truck, coupling between two antennas and field-mapping inside the truck.

An FDTD model of the set-up was made with a problem space of 8.4x8.4x3.9 m using a cell size of 20 mm giving a total of 38 million cells. The outer boundary was ABC set to Fang-Mei.

![Image of a Scania truck in a semi-anechoic chamber.]

Figure 10.1. Measurement on a Scania truck in the semi-anechoic chamber.

10.1 E-field around the truck

Measurements and simulations of the E-field due to excitation of an antenna around the truck have been performed. The truck was placed in one end of the problem space/turn-table with a 100, 450 or 900 MHz-antenna mounted on top of the roof. The total E-field was evaluated with a 3° resolution in a circle 4 m from the centre of the problem space/turn-table and 1.8 m over the ground plane. For all measurements the front of the truck was in the 180 degrees direction.

The 100 MHz-antenna, modelled as a thin wire with a radius of 1.5 mm and an FDTD-length of 750 was mounted on the right side of the roof, see Fig. 10.2. A comparison between the measurement and simulation gives an amplitude difference less than 4 dB in all directions. The shape of the probed E-field for the measurement has a more complex shape than the simulation but there is an acceptable agreement. Notice that the shortest distance from the antenna to the E-field probes was in the 160° direction (1.6 m) and the longest in the 340° direction (6.4 m). This of course influence the shape of the probed E-field.
Figure 10.2. Comparison between measured and simulated E-field from an antenna mounted on the right part of the roof at 100 MHz.

The 450 MHz antenna, modelled as a thin wire with a radius of 1.0 mm and an FDTD-length of 170 mm was mounted on the back part of the roof. Although the shapes of the probed E-fields are complex there is an acceptable agreement between the measurement and simulation. The difference in amplitude is less than 4 dB.

Figure 10.3. Comparison between measured and simulated E-field from an antenna mounted on the back part of the roof at 450 MHz.
10.2 Coupling

In order to study the coupling between antennas mounted on a vehicle a number of different test cases have been studied.

The coupling shown in Fig. 10.4 is between a 100 MHz-antenna on the back part and a 450 MHz-antenna on the right part on the roof. Both antennas have been modelled as thin wires with an FDTD-length of 750 and 170 mm and with a radius of 1.5 and 1 mm, respectively. As can be seen an acceptable agreement between measurement and simulation up to 295 MHz with a difference less than 3 dB was achieved. At 310 MHz the difference is 9 dB and at 490 MHz the measurement, but not the simulation, has a deep null. This have no other explanation than a possible bad connection in the measurements.

![Graph](image)

*Figure 10.4. Comparison between simulation and measurement of the coupling between two antennas mounted on the roof, one at the back (450MHz) and the other one (100MHz) at the right side of the roof.*

The coupling shown in Fig. 10.5 is between a 100 MHz-dipole inside the cabin, horizontally polarized, and a 450 MHz-antenna on the right part on the roof. Both antennas were modelled as thin wires with an FDTD-length of 760 and 170 mm and with a radius of 1.5 and 1 mm, respectively. As can be seen the coupling is very low and there is a poor agreement between measurement and simulation under 100 MHz, between 150 and 240 MHz.
10.3 Field-mapping

In order to create a model that is similar to a real truck, chairs and steering wheel have been added to the CAD-model, see Fig. 10.6. On the outside of the vehicle a 900 MHz-antenna was placed on the left rear back mirror. The antenna, modelled as a thin wire with a radius of 1.0 mm and an FDTD-length of 90 mm, was fed by a voltage source at the base of the antenna. The E-field was mapped, at 900 MHz, 80 mm above each chair. The spatial resolution of the E-field mapping was 20 mm for the simulation and 100 mm for the measurement.

We had no CAD-model for the rear back mirror and therefore it was modelled afterwards, from photos, by hand in CADfix. This could be one reason for the big difference in E-field pattern and amplitude between the measurement and simulation.

Figure 10.5. Comparison between simulation and measurement of the coupling between two antennas. One mounted on the front right side of the roof (450 MHz) and the other a dipole (100 MHz) inside the cabin.
Figure 10.6. Comparison between simulation (upper) and measurement (lower) of E-field inside a truck from a 900 MHz-antenna at the rear back mirror.
11 Conclusion

It has been shown that simulations on complex vehicles, using simplified CAD-data, are possible to perform. Parameters have been probing of the E-field around a vehicle, E-field-mapping inside a vehicle and coupling between antennas on vehicles. The agreement between simulations and measurements performed in a semi-anechoic chamber have, for most tested configurations, been satisfactorily.

When comparing the measurements and the simulations a lot of questions arise. For example, which gives the most correct result, the measurement or the simulation. Are the problem set-up for the measurement and simulation different and because of that give different result?

We have spent a lot of time in finding a method to import CAD-models to the pre-processor CADfix in an efficient way. Finally we found a method described in chapter 3. However, we have done some simplifications on the CAD-models which could affect the simulation result.

1. The CAD-models used as a basis for creating CAD-models for EM simulations does only include metal parts no (lossy) dielectric media.
2. Surfaces (metal parts) with a complex curvature are simplified to large simple flat quad and triangular surfaces.
3. Small holes have been filled and metal parts close to each other have been stitched together.
4. The Finite Difference (FD) meshing of the CAD-model gives rise to a cubical structure. We are bounded to cubical cells with the same size in the whole problem space (in this project 20x20x20mm cells).

Comments:
1. There are three reasons why dielectric media with or without losses have not been included in the CAD-model. The first is that for most cases it does not affect the result much. The second is that a lot of time is needed to include the extra CAD-data for the dielectric media. The third is that the simulation time step is decreased and thereby the simulation time is increased.
2. By using simple surfaces we minimize the problems when exchanging CAD-data between different CAD-systems. It wouldn’t be possible to work in CADfix with too many surfaces. However the accuracy of the CAD-model is decreased but for most cases it does not make a big difference because later on in (4) the model is approximated by a cubical structure.
3. In real vehicles there is a gap or slot between many metal parts as e.g. the front door and rear door. A typical value of the gap or slot is between 2-4 mm. This could affect the simulation result, at certain frequencies, when we are close to the gap or slot. See [15] where a simple conducting box with and without a narrow slot has been simulated.
4. The FD meshing makes it impossible on a whole vehicle model, with todays computer, to resolve e.g. slots between doors and to model rounded objects.

The measurements also give errors like:
1. Cables radiating
2. Measurement uncertainty
3. Uncertainty for the placement of probes.
What do we need to start with the simulations described in this report? For EM simulations on vehicles using CAD-data using the method described in chapter 3.7 the following programs and CAD-data are needed.

- Simplified finite element (FE) meshed CAD-models describing chassis, doors, hood etc. These models are used at each automotive company at a department doing structural dynamics analysis.
- The pre-processor program ANSA [3] where the simplified finite element (FE) meshed CAD-models described above are further simplified to a CAD-model for EM simulations.
- The pre-processor program CADfix [4] where smaller adjustments to the CAD-model for EM simulations, like adding chairs, steering wheel etc are made. Finally the CAD-model is finite difference (FD) meshed in CADfix.
- The computational program EMA3D [5] where the EM simulation on the FD meshed model are made.

What is possible to simulate for a complex vehicle with EMA3D?

- Different antennas like monopoles, dipoles and loops but also other types of antennas as long as they are along the cubical structure determined by the cells in the computation domain, see chapter 3.
- EM fields inside and outside the vehicle like radiation pattern outside the vehicle and field-mapping inside the vehicle.
- Coupling between antennas mounted on the vehicle or in free space.

What is not possible to simulate with EMA3D?

- Antennas with a shape that is not aligned along the cubical structure.
- Antennas closer than one cell.
- Shaped surfaces with a small curvature like front fenders because of the cubical structure of the meshed model.
- Slots and gaps smaller than one cell.

For all the computational methods (Finite Difference in Time Domain FDTD, Finite Element Methods FEM, Method of Moments MoM) there are built-in limitations specific for each method. That’s why a lot of research is directed towards the area of hybrid methods which is a mixture of two or more methods such as FDTD/FEM. In this way the finite difference (FD) cells could be used in areas with the same media as e.g. the air surrounding a vehicle. Then the finite elements (FE) elements (tetrahedron that can be of different size) are used to describe the fine structure of the vehicle. In this way the hybrid code comes closer to the reality.
References


[6] Jan Carlsson, Computer code Wire-MoM (can be obtained free of charge from jan.carlsson@sp.se).


Appendix A  Influence on results when using different distance from top of monopole to absorbing boundary condition

What distance from antenna to absorbing boundary condition (ABC) is appropriate?

In the vicinity of an antenna is a reactive field. If an object is placed in this region the electrical properties of the antenna changes. That’s why it’s best to place the ABC outside the reactive area. However, it is difficult to know where the reactive region ends because it depends on the type of antenna, frequency, the surrounding media etc. To avoid this problem the boundaries should be kept far away from the antenna. A coarse estimation is to use a distance larger than $\lambda/2$. However, when we are doing vehicle simulation we are on the limit of what the computer can handle and also the simulation time should be kept at a reasonable length. That’s why we want to minimize the distance from the antenna/object.

If the worst simulation case appears to work then the other should also work. The worst case would be to put the 100 MHz-antenna on top of the roof. In this project where the problem space has been 8.4x8x2.5 m, for the cars, the distance would then be 350 mm from top of the antenna to the boundary. At 100 MHz $\lambda/2$ is 1.5 m. Consequently, we moved the upper boundary 1.5 m which gives a problem space of 8.4x8x4.0 m, see Fig. A.1.

For the quality of the simulation result the distance from the antenna to the ABC plays a major role. Furthermore the type of ABC is also important to minimize reflections from the antenna. For the vehicle simulations, in this project, an ABC called Fang-Mei has been used. To test if this Fang-Mei is good enough for our simulations an ABC, with less reflections, Perfectly Matched Layer (PML) was used. This ABC is put outside the original problem space and consequently the computer memory space and simulation time increases. We used a 8-layer PML.

The E-field was probed with a 3° resolution at a distance of 4 m from the centre of the problem space and 1 m over the ground plane. The antenna, modelled as a thin wire with a radius of 1.5 mm and an FDTD-length of 750 mm was mounted on top of the roof. For all simulations the front of the car was in the 180 degrees direction.

The three simulations, see Fig. A.2.

A. Problem space 8.4x8x2.5 m and ABC set to Fang-Mei
B. Problem space 8.4x8x4.0 m and ABC set to Fang-Mei
C. Problem space 8.4x8x2.5 m and ABC outside the problem space set to 8-layer PML
Figure A.1. Two problem spaces including a car is shown. The lower problem space is 8.4x8.4x2.5 m and the higher is 8.4x8.4x4.0 m.

A comparison of the simulation result for the problem space used in this project and a problem space where the height has been increased 1.5 m. This extra height in B, 1.85 m instead of 0.35 m, from the top of antenna to the ABC gives a difference less than 1.5 dB in amplitude which is good enough for our simulations.

Another comparison using PML instead of Fang-Mei shows a difference in amplitude of less than 1 dB which also is good enough for our simulations.

These comparisons show that a distance of 0.35 m from antenna top to the ABC, when measuring the E-field 4 m away (far-field) from the antenna, is good enough for our vehicle simulations.

Figure A.2. Comparison of the of the probed E-field when using different problem space and absorbing boundary conditions. The antenna is a 100 MHz-antenna mounted on top of the roof.
The agreement between the antenna impedance for the three simulations, see Fig. A.3, is good.

Figure A.3. Comparison of the impedance for an antenna when using different problem space and absorbing boundary conditions. The antenna is a 100 MHz-antenna mounted on top of the roof. Lower diagram is a close up of the upper diagram.
Appendix B  Comparison of the probed E-field inside problem space to the far field outside problem space

In the car simulations, in this project, we have used a problem space of 8.4x8.4x2.5 m. Inside the problem space a car and E-field probes are put. However, it is possible to make the problem space smaller and put so-called far field probes outside the problem space, see Fig. B.1. From an equivalent surface surrounding the object the field can be calculated outside the problem space. Two methods exist, the simplest and fastest assume a plane wave formalism while the other method uses a full wave formalism.

The smaller problem space of 5.6x2.8x2.8 m gives with a cell size of 20 mm a total of 5.5 million cells. This is approximately four times less cells than the problem space used in this project.

The E-field was probed with a 3° resolution at a distance of 4 m from the centre of the problem space and 1 m over the ground plane. The antenna, modelled as a thin wire with a radius of 1.5 mm and an FDTD-length of 750 mm was mounted on top of the roof. For all simulations the front of the car was in the 180 degrees direction.

The four simulations.
A. Problem space 8.4x8.4x2.5 m, ABC=Fang-Mei.
B. Problem space 5.6x2.8x2.8 m, ABC=Fang-Mei, Plane wave formalism.
C. Problem space 5.6x2.8x2.8 m, ABC=PML, Full wave formalism.
D. Problem space 5.6x2.8x2.8 m, ABC=PML, Plane wave formalism.

A 100 MHz-antenna, with an FDTD-length of 750 mm, was put on top of the roof.

Figure B.1. The vehicle is inside and the E-field probes, so-called far field probes, are outside the problem space.

As can be seen from Fig. B.2 using PML with far field probes (C and D) gives approximately the same result. Using Fang-Mei with far field probes (B) results in a amplitude difference of at most 2 dB compared to the PML with far field probes.

The problem set-up A gives a maximum difference of 4 dB to problem set-up D at the angles 35 and 325 degrees. The difference could be due to the fact that the far field probes in D are in an exact position while in A the positions of the near field probes are discretized and could be positioned up to 20 mm from the wanted position?
The problem space when using the far field probes is 4 times smaller and we could expect a shorter simulation time. In spite of this using the problem space including the probes (A) the simulation time is approx. 18 hours. For the plane wave formalism it is 70 hours and the full wave formalism takes 110 hours. Neither 110 nor 70 hours is an acceptable time. That's why we have used the large problem space 8.4x8.4x2.5 in the vehicle simulations.

Figure B.2. Probed E-field around a car with 4 different problem set-ups.
Appendix C  Simulation of the impedance for a 450 MHz monopole on an infinite ground plane

The impedance of a monopole antenna is affected by the length, radius of the rod and size of the ground plane. For the simulations in FDTD the length of the antenna (FDTD-length) and the size of the voltage feed gap is affected by the cell size.

Simulations of a monopole consisting of a thin wire, with a radius of 1 mm, mounted on an infinite PEC-plane, see Fig.C.1, have been performed. A problem space of 1x1x1 m, giving different number of cells in the problem space depending on the cell size. The outer boundary was a 8-layer PML simulating free space. The effects of the cell size on the antenna impedance, and by that the reflection coefficient, has been studied.

![Figure C.1. Monopole consisting of a thin wire mounted on an infinite ground plane (PEC).](image)

The length of the antenna is modelled, in CADfix, to have a length of 160 mm. However, the FDTD method adds a half cell at the end, which means that the electrical length (FDTD-length) of the thin wire in the simulations vary with the cell size, see table C.1. The size of the voltage feed gap is also proportional to the cell size.

<table>
<thead>
<tr>
<th>Cell size [mm]</th>
<th>No of cells</th>
<th>Cells/wave length</th>
<th>FDTD-length</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>2</td>
<td>8</td>
<td>200</td>
</tr>
<tr>
<td>40</td>
<td>4</td>
<td>16</td>
<td>180</td>
</tr>
<tr>
<td>20</td>
<td>8</td>
<td>33</td>
<td>170</td>
</tr>
<tr>
<td>10</td>
<td>16</td>
<td>66</td>
<td>16.5</td>
</tr>
<tr>
<td>5</td>
<td>32</td>
<td>133</td>
<td>16.25</td>
</tr>
</tbody>
</table>

*Table C.1. The effect on the FDTD-length on a monopole when using different cell size.*
Figure C.2. Impedance related to the size of the cell size. Lower diagram is a close up of the upper diagram.

From the impedance the reflection coefficient is calculated. The resonance frequency for the simulated monopole is slightly lower than the frequency corresponding to an FDTD-length/4, see Fig. C.3.
Figure C.3. The resonance frequency of the monopole is shifted to lower frequencies the larger the cell size is.

For a monopole with a small radius the impedance is approx. 36.5 + j22 ohm. By shorten the monopole a little the reactance (imaginary part) will be “zero” and the resistance will only decrease some percent (the antenna becomes pure resistive).

In Fig. C4. we see that at 468 MHz corresponding to a (CADfix length of 160 mm)/4 for the monopole the impedance depends on the cell size and number of cells. A ‘better’ value is achieved by taking the FDTD-length into account, see Fig. C.5.

Figure C.4. Impedance at 468 MHz related to a CADfix length of 160 mm for the antenna.
Figure C.5. Impedance at frequencies related to the FDTD-length/4 of the antenna.

If the radius is larger the reactance will change less when the frequency is changed. As can be seen the thicker the wire is the more broad banded the monopole becomes. This is because the reactance changes less when the radius is larger. At the same time the resonance frequency is shifted to a lower frequency, see Fig. C.7.

Figure C.6. The impedance change due to a change in the thin wire radius.

Figure C.7. A monopole with a large radius becomes more broad banded and the resonance frequency becomes shifted to lower frequencies.
At 450 MHz 400 mm orthogonal to the antenna and 100 mm over the ground plane the wave impedance was calculated, see Fig. C.8. As can be seen the electric field is dominating over the magnetic field for frequencies under 120 MHz. Another more detailed study with Wire-MoM is made in App. D.

Figure C.8. Wave impedance 100 mm over ground plane and 400 mm from a 450MHz-antenna.
Appendix D  Simulation of the induced current in a monopole mounted on an infinite ground plane

Below is shown some of the simulations that have been done to investigate the coupling to a monopole mounted on an infinite ground plane.

Two different cases have been investigated, the coupling between two monopoles placed on the same ground plane and the induced current in a monopole caused by an incident plane wave. All simulations have been done with the Method of Moments program WireMoM developed at SP[6].

![Induced current at the base](Image)

Figure D.1. Two monopoles mounted on an infinite ground plane.

![Induced current at the base](Image)

Figure D.2. Induced current at the base of a 0.5 m high monopole caused by coupling from 0.5 m high monopole fed by a voltage source of 1 V. The distance from the antennas are 2 m. Geometry according to Fig D.1.
In Fig. D.2 we see that for low frequencies the coupling is increased linearly, i.e. the coupling increases with 20 dB per decade. This can be explained by that the antennas are situated in the near field, to each other, and the coupling can be described as pure capacitive. For higher frequencies we see that the coupling increases with approx. 60 dB per decade. To explain this we have to consider both the transmitting and the receiving antenna. The transmitting antenna is fed by a constant voltage of 1V, which means that if the antenna impedance can be regarded as pure capacitive (the resistance can be neglected at these frequencies) the current in the antenna will increase linearly with increasing frequency, i.e. 20 dB per decade. It can also be shown that the field at this distance and in this frequency range increases with 20 dB per decade if the current is assumed to be constant. All together the field at the receiving antenna increases with 20+20=40 dB per decade. If we have a look at Fig. D.4, we see that if a monopole is excited with a constant field the induced current in this frequency band will increase by 20 dB per decade. Consequently, the total induced current increases with 40+20=60 dB per decade. For even higher frequencies we will be in the resonance area.

![Figure D.3. Induced current at the base in a 0.5 m high monopole caused by the coupling from an adjacent antenna 0.5 m high monopole fed by a voltage source of 1V. The distance between the monopoles are 2 m (dashed line) and 10 m (solid line), respectively. Geometry according to Fig D.1.](image)

Fig D.3. further illustrates the fact that the coupling is pure capacitive for low frequencies. We also see that the break point between the 20 and 60 dB slope of the coupling is moved towards lower frequencies if the distance between the antennas is increased. The explanation is that the near field limit is proportional to the frequency (or equivalently inversely proportional to the wavelength).
Figure D.4. The induced current in a 0.5 m high monopole caused by an incident plane wave with a field strength of 1 V/m. The incident field is polarized along the monopole and the incident direction is along the ground plane (i.e. Theta=90 degrees)

As can be seen in Fig. D.4 the induced current in the monopole increases with 20 dB per decade if it is excited with a constant field strength, at least up to the resonance frequencies.

Figure D.5. The relation between electric and magnetic field strength from a 0.5 m high monopole fed by 1V. The relation is valid at a distance of 2 m and a height of 0.25 m over the ground plane.

In Fig D.5 we see that the electric field from a monopole dominates over the magnetic for low frequencies. It once again illustrates that the capacitive coupling is dominating for low frequencies.
Appendix E  Simulation of the coupling between two loop antennas

The coupling between two loop antennas was measured by a network analyser and simulated in the programs EMA3D and Wire-MoM. A loop antenna consisting of a square loop (60x60 mm) with a 260 mm long shielded conductor was made, see Fig. E.1. The radius of the wire was 0.5 mm. In both the simulation programs a model of a square loop without the connected shielded conductor was made, see Fig. E.2. The purpose was to see if a model of a loop antenna could be used in the verification measurement/simulation of a vehicle.

![Image](image1)

Figure E.1. A loop antenna consisting of a square loop 60x60 mm connected to a 260 mm long shielded conductor.

![Image](image2)

Figure E.2. Simulation set-up for a loop antenna in Wire-MoM and EMA3D.

As a first test of the simulation models the currents in the antenna were probed. The loop was excited by a voltage source of 1V. For low frequencies the impedance of the loop is pure resistive which gives a current \( I = \frac{U}{R} = \frac{1}{50} = 0.02\,A \). There is a good agreement between the currents of the two models.
Figure E.3. Current in loop over a frequency band.

Before any measurements of the coupling a calibration of the network analyser to the N-contact, see Fig. E.1 was done. This means the 260 mm long shielded conductor was not included. The set-up was made on a wooden table with two identical loops faced upward and separated 75 mm.

In Wire-MoM a model with two loops separated 75 mm in free space was made, see Fig. E.2. A comparison between measurement and simulation of the coupling for frequencies up to 30 MHz shows a good agreement. However, over 30 MHz the agreement is bad. The reason is believed to be measurement difficulties for higher frequencies.

Figure E.4. Comparison between measurement and simulation of the coupling between two loops separated 75 mm.
A new simulation set-up in Wire-MoM and EMA3D now with two identical loops faced upward separated 3 m and over a ground plane was modelled. From Fig. E.5 it can be seen that the agreement between the computed coupling with the two simulation programs is quite good.

Figure E.5. Comparison of coupling between two loops separated 3 m and 1 m over an infinite ground plane.