FINAL TECHNICAL REPORT

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(FORMERLY THE MOTOR INDUSTRY RESEARCH ASSOCIATION)

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EXECUTIVE SUMMARY

The GEMCAR project was a collaborative research project supported by the European Commission under the Competitive and Sustainable Growth Programme of Framework V (Key Action 3: Land and Marine Transport). The project was active from the beginning of January 2000 to the end of March 2003.

The project aimed to develop the experience necessary for the practical exploitation of existing electromagnetic (EM) modelling tools and techniques in automotive applications such as EMC and vehicle antenna engineering. Although considerable research activity has been focused on the enabling technology that is required to support practical vehicle-scale EM modelling, relatively little research has been devoted to the practical modelling of large scale systems. Thus, many practical modelling questions remain un-answered, with the result that electromagnetic modelling has not yet been widely adopted in industry.

The primary objective of the project was to develop a guidance document (the "GEMCAR Guidelines") for the practical application of EM modelling in the automotive industry, based on the processes and methodology developed by the partners in the course of the project. The GEMCAR Guidelines aim to address:

- various possible application areas (eg. in design, specification, certification, standards);
- relevant electromagnetic issues (eg. immunity, emissions, intra-system EMC, antennas);
- efficient strategies for generating and exploiting simulation results;
- how best to use different techniques in order to develop practical industrial solutions.

Although the project was focused on automotive applications, the guidelines will nonetheless be equally applicable in all other transport sectors (rail, aerospace and marine) and will be of value in other industries where the EMC characteristics of large systems must be considered.

The work carried out included:

- analysis of potential user requirements;
- investigation of approaches to maximise the efficiency of vehicle simulations;
- measurement and simulation activity aimed at developing validation data for vehicle models;
- investigation of practical aspects of building whole vehicle electromagnetic models;
- assessment of industrial exploitation issues and opportunities;
- practical case studies based on the guidelines.

The model validation studies were based on a range of numerical modelling techniques and different test environments, and demonstrate that good agreement can be achieved between models developed using different numerical techniques, as well as between models and measurements at realistic levels of complexity.

Dissemination of the project objectives and results has been via personal contacts, the project website (*www.gemcar.org*), a two project workshops at leading European EMC conferences (EuroEMC 2000 and EMC Zurich 2003), and the publication of papers. To date 29 papers have been published describing work carried out in the course of the GEMCAR project, and it is expected that more publications will follow after the end of the project. Copies of these papers and presentations are available from the project website. The GEMCAR Guidelines can also be requested via the project website.

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1 Summary

This report provides a summary of the work carried out by the GEMCAR consortium in the course of this collaborative research project, which was supported by the European Commission under the Competitive and Sustainable Growth Programme of Framework V (EC contract G3RD-CT-1999-00024). The contract ran from January 2000 to April 2003, including a three-month extension to the original term of the project. The areas addressed in this final technical report include the following:

- project objectives;
- description of the scientific and technical results;
- deliverables;
- comparison of planned and actual activities;
- management and coordination aspects;
- conferences and papers;
- co-operation with other projects;
- conclusions;
- acknowledgements.

The primary objective of the project was to develop generic "best practice" guidelines concerning the deployment of numerical modelling in support of automotive EMC engineering. All of the work carried out within the project was therefore intended to contribute to the GEMCAR Guidelines. The achievements of the project include the following:

- potential user requirements assessed
- realistic vehicle EM models demonstrated
- several methods, different levels of complexity
- efficient simulation strategies proposed
- model validation evidence developed
- integration into vehicle engineering investigated
- practical pilot studies carried out
- research distilled into "GEMCAR Guidelines"
- two project workshops held at major European EMC conferences (EuroEMC 200 and EMC Zurich 2003)
- results widely disseminated (29 papers presented at 7 European and 2 US conferences).

The quantitative targets that were identified in the proposal, concerning the correlation between measurements and likely cost benefits of using modelling, were also demonstrated.

In the course of the work it was found necessary to introduce some work that was not foreseen when the proposal was written. This resulted in a number of "unplanned" achievements, including:

- optimisation and parallelisation of NEC2 code (EPFL)
- tools for translating a TLM mesh into a NEC model (EPFL)
- hybridisation of FVTD and FDTD codes (ONERA)
- time-domain variant of BEM solver (EADS)
- measurements to establish impact of vehicle seat frames, cushions and glazing (MIRA, Hevrox, CETIM)
- simulations to establish impact of window heater arrays, sunroof and steering gear (MIRA)
- development of "test wire" approach to "measure" internal field distribution (ONERA)
- FSV analysis of composite datasets derived from groups of simulation and measurement results (QinetiQ).

The adaptations to existing 3D field solvers were necessary in order to allow realistic models of a vehicle illuminated by a nearby EMC test antenna to be developed using numerical methods based on unstructured, surface-meshing techniques. The experimental and numerical investigations of the impact of vehicle features were prompted by the need to identify the geometrical requirements for the final validation test case, but this work was extended as it was realised that this information is of considerable significance for the development of practical vehicle models.

In order to define the geometrical requirements for the final validation test case, in which a "complex" model would be compared with a real vehicle, it was necessary to establish the electromagnetic impact of many structures that are present in vehicles. This information was also recognized as being of considerable benefit for the Guidelines. Consequently, additional simulations carried out at MIRA on medium complexity TLM models, and measurements carried out by MIRA, Hevrox and CETIM on the complete vehicle with various parts removed. This work allowed the significance of components such as vehicle glazing, rear window and windscreen heater arrays, a sun roof, seat frames, seat cushions and other interior components (composed of foam, fabric and plastic), to be quantified. The use of a simple "test wire" as a distributed electric field sensor was investigated by ONERA, in both the complete vehicle and the medium complexity test case. The results of this work confirmed the findings of the additional measurements on the complete vehicle, in that the interior components have only a modest impact on the coupling of fields onto cables located close to the bodyshell.

The analysis of composite measurement and simulation datasets was investigated by QinetiQ, as a way of reducing the volume of data to be compared and to take account of the uncertainties that are present in both measurements and simulations.

Some of the activities that were originally planned were ultimately found to be unworkable, and therefore abandoned. These were primarily related to the idea of working on the harness in isolation from the vehicle. In practice it was not possible to make a successful translation from the 3D harness in the vehicle to a meaningful 2D configuration for bench testing. Although this work was carried out for the simplest validation test case, this approach was not pursued in the more complex test cases. In addition, as the complex test case was provided by a complete vehicle, it was also impossible to reproduce the measurement locations used in the preceding validation examples (on account of the large numbers of additional components). Consequently, the scope of the final measurements was modified to accommodate comparative measurements that could be used to assess the impact of common components that could be readily removed from the vehicle.

Although the project start date was 1st January 2000, the decision to approve the project was too close to this date to allow consortium resources to be allocated for this project on that date. It was not possible to hold the initial project meeting until 20th January 2000, with the result that technical work began more than a month later than the official start date. The consequences were most significant for DERA, which had no internal budget available until the following financial year (April), and EPFL, who had difficulty recruiting PhD students. In addition, the loss of staff members at EADS CCR, DERA, and Ford during the initial months of the first year, and subsequently at MIRA and CETIM, resulted in some additional disruptions for the project.

The most significant delays to the programme were associated with the acquisition of CAD data for the test case vehicle, and subsequent processing of the geometrical model, since this impacted on the validation activities at various stages of the project. Preliminary simulations demonstrated that the effects of the harness on the internal field distribution due to external illumination are not generally significant. It was decided, therefore, that the validation of models for the bodyshell without the harness present would not be necessary after the simple test case.

By the end of the project manpower reached just over 96% of the effort anticipated at the beginning of the project, while expenditure was similar at about 97% of that originally planned.

2 Objectives and strategic aspects

2.1 Project objectives

Automotive EMC engineering has traditionally been an experimental activity, carried out towards the end of development programmes. Unfortunately, the correction of defects at such a late stage can be very costly and difficult, and in the future EMC testing is expected to become a much more significant burden for vehicle manufacturers. The most likely solution to these problems is to use electromagnetic modelling in design, to both identify problems at an early stage and to make better use of more limited physical testing. Much research effort has been devoted to the development of numerical techniques and software tools, but their use has largely been confined to very simple examples. Consequently, numerous practical modelling issues remain unresolved, with the result that these techniques have not yet been widely adopted in automotive engineering processes.

The consortium aims to accelerate the adoption of electromagnetic modelling in the transportation sector by jointly developing a much more detailed understanding of practical modelling issues. This knowledge will be distilled into a set of modelling guidelines, which will be widely distributed. The Guidelines aim to address a variety of possible applications of modelling results, in areas such as:

- the design of vehicles and their subsystems;
- the specification of EMC requirements;
- supporting vehicle certification and approval activities (eg. better targeted testing);
- the development of standards, for both experimental and numerical assessment methods.

The Guidelines also consider a wide range of issues that could be addressed using electromagnetic modelling, including vehicle emissions and immunity, intra-vehicle EMC issues and the installed performance of antennas.

2.2 Anticipated impact

Future vehicle electronic systems will provide many more safety related functions to aid the driver and advanced telematics facilities to support activities such as traffic management. In addition, more sophisticated control systems will be used to optimise vehicle performance and emissions. Thus, electromagnetic compatibility (EMC) represents a significant threat to the function, safety and reliability of vehicles. Furthermore, the advent of electric and hybrid-electric vehicles and the increasingly wide range of systems and frequencies that are used in vehicles will add further to the EMC threat. Thus, the success of future vehicle technologies that aim to improve transport and to minimise its environmental impact will be critically dependent on the efficient and successful handling of automotive EMC issues.

European companies currently lead the other main vehicle manufacturing regions (USA and Japan) in the development of electromagnetic modelling, particularly for large-scale systems such as vehicles. This project will maintain that lead by developing the detailed understanding of modelling techniques which is required in order to exploit this technology in practical vehicle applications. This information will also be of relevance to other transport sectors, particularly the rail and aerospace industries, and in other industries where EMC must be considered for large-scale systems.

The results of this project will be disseminated primarily in the form of practical user guidelines. Although the guidelines will principally be of use to the automotive industry, the generic EMC problem being considered is also relevant to other areas of land transport and the aerospace sector.

Thus, the prospects for the guidelines being used as the basis of further development for other industries will be high, particularly in the aerospace industry where three of the partners are active. Reliable avionics systems are essential for passenger aircraft, and the development of efficient EMC design processes will be an important asset for the European economy.

2.3 Economic gains

It is considered that savings of 40% on automotive immunity test costs should be achievable by using simulation to identify “worst case” configurations for automotive immunity testing, and hence reduce reliance on physical measurements. This is a particularly significant issue in the automotive industry, where tests must be repeated for each system on the vehicle. Industry sources also suggest that relaxing the immunity specification of an electronic sub-system may reduce the cost by around €10 per unit, which could represent savings of more than €1 million for manufacturers of large volume products such as passenger cars.

The benefits to be gained from exploiting electromagnetic modelling in design studies are less easy to quantify, since the range and extent of potential problems is unlimited. Savings can be made through the avoidance of rework and repeat testing, which become increasingly costly towards the end of a vehicle development programme. An analogous situation exists in the aerospace industry, where it is reported that potentially enormous product recall costs have been avoided through the identification of completely unexpected aircraft construction problems during electromagnetic modelling of lightning strikes. Estimates suggest that if modelling can be used to optimise the design of aircraft such that the cost of EMC protection is reduced by 20%, saving for the European civil aviation industry could amount to €7 million per year. It is also considered that savings of up to €1 million could be achieved in the development of each aircraft by using modelling to reduce reliance on physical EMC testing.

3 Scientific and technical performance

The project consortium comprised nine organisations drawn from five different European countries, as detailed in Table 3.0 below. As EMC modelling techniques are most mature in the aerospace industry, the consortium included aerospace organizations in order to exploit this existing expertise and to further develop practical vehicle modelling strategies in collaboration with automotive companies.

Table 3.0: GEMCAR consortium

Partner	Role	Country
MIRA	Coordinator	UK
CETIM	Principal contractor (industry)	France
EADS	Principal contractor (industry)	France
EPFL	Principal contractor (academic)	Switzerland
Hevrox	Principal contractor (industry)	Belgium
ONERA	Principal contractor (industry)	France
QinetiQ	Principal contractor (industry)	UK
Volvo	Principal contractor (industry)	Sweden
Ford	Assistant contractor (to MIRA)	UK

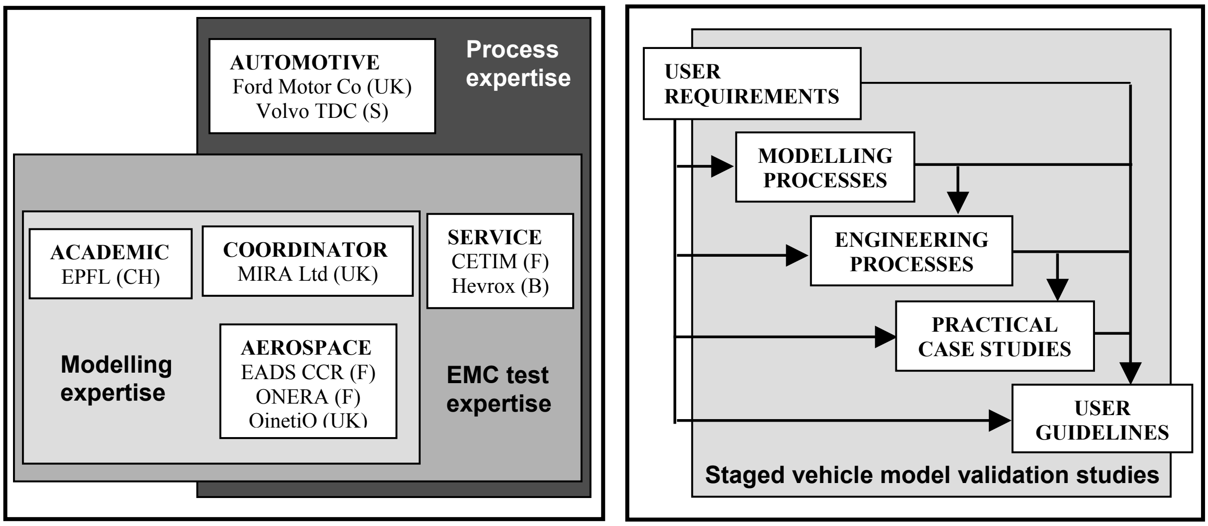
This consortium was selected in order to bring together the various skills and experience that were considered necessary to achieve the goals of the project. These included electromagnetic modelling, EMC measurement and vehicle system integration expertise from both automotive and aerospace backgrounds, as well as representing both industrial and academic viewpoints (see Fig. 3.0a below).

The main elements of the project workplan comprised five main “foreground” activities:

- analysis of user requirements;
- investigation of modelling processes;
- assessment of vehicle engineering processes;
- practical case studies;
- development of the GEMCAR Guidelines.

The tasks were carried out against a “background” activity of staged model validation studies, which was based on vehicle modelling using a variety of established numerical techniques together with measurements obtained from several different test environments. These measurements were carried out using a semi-anechoic chamber, a fully anechoic room and an electromagnetic pulse simulator. The latter is not normally used for automotive measurements, but was of interest as an emulation of plane wave illumination.

The combination of the foreground investigations and background model validation activity (see Fig. 3.0b) allowed the consortium to generate and progressively refine the material needed to define and populate GEMCAR Guidelines. The difficulties that were encountered in the course of this work also made important and unforeseen contributions to the Guidelines in themselves.



(a) Consortium members, skills and experience *(b) Main elements of the workplan*

Fig. 3.0: Pictorial overview of the GEMCAR project

Although the GEMCAR project aimed to provide guidelines to support practical EMC modelling, resource constraints limited the scope of the project to electromagnetic (EM) modelling, for frequencies up to 1 GHz. An EM model only describes the interaction between a structure and an applied field. Consequently, an EM model is not the same as an EMC model, which must also represent the functional performance of the electronic systems that are housed within the structure. Nonetheless, accounting for the 3D electromagnetic interactions that determine the coupling from or to cables and equipment within their housing (a geometrically complicated vehicle bodyshell for automotive applications) is the fundamental element of the wider analysis that is needed in order to predict functional EMC effects.

The sections that follow detail the work carried out in the course of the project, following the structure of the GEMCAR Guidelines into which the results are distilled.

3.1 User Requirements Analysis

The initial task of the GEMCAR project was an investigation of user requirements for modelling in support of automotive EMC engineering. This work was carried out primarily by Hevrox and MIRA, with support from other members of the consortium. Electromagnetic modelling (EM) for automotive EMC and related applications remains an emerging technology at present. Consequently, the issue of user requirements could only be investigated by developing a series of draft requirements, based on the existing experience of the consortium members, and then discussing these draft requirements with selected representatives from European vehicle manufacturers, test houses, sub-system and component suppliers, as well as appropriate standardization and certification bodies. The user requirements were investigated with regard to a variety of possible applications of EM modelling, such as:

- vehicle and sub-system design and development;
- development of EMC standards and test methods;
- supporting testing for vehicle development and certification purposes.

The aim of this analysis was to enable the consortium to define the following:

- scope of models needed for different purposes (including CAD requirements);
- parameters that would be required from simulations;
- accuracy of model results required for particular applications.

The requirements of interest therefore fall into two basic groups: those that are associated with model development, and those that are associated with the exploitation of model results. However, both of these groups of requirements need to be satisfied in order for electromagnetic modelling to achieve commercial, rather than purely technical, viability.

3.1.1 Potential users and applications

All groups that are involved in automotive EMC must be prepared to accept electromagnetic modelling if it is to become an integral part of automotive EMC engineering. The vehicle EMC engineering process can be considered in terms of five main user groups with an interest in EM performance issues:

- system integrator;
- sub-system suppliers;
- test houses;
- standardization bodies;
- certification authorities.

The system integrator is responsible for the overall vehicle system, including defining the performance requirements for systems that are to be provided by the sub-system suppliers. Although the system integrator has traditionally been the manufacturer of the chassis and major mechanical components, it is possible that this may change as the electronic and software content of the vehicle increases. Nonetheless, the bodyshell and wiring harness can have a significant impact on the EM performance of the vehicle system as a whole, and the ability to model such effects is potentially of significant benefit to the automotive industry. Numerical modelling offers considerable promise in the design and specification stages, where little objective information is currently available.

EM modelling is no less valuable in the support of EMC testing activities. As the number of systems and operating frequencies that are used in modern vehicles increases, the EMC testing burden is becoming increasingly onerous. In the later stages of the vehicle or system development lifecycle, modelling techniques could be used to support better targeted testing, by reducing reliance on physical EMC testing.

In addition, modelling can also be applied in the design and development of improved test facilities and equipment as well as developing basic understanding of EMC phenomena and measurements.

The requirements for immunity and emissions performance are defined by international standardization bodies, as are the tests that are to be performed in order to demonstrate compliance with the performance requirements [1-3]. These are very difficult tasks, given the complexity of the systems of interest. Consequently, modelling techniques are potentially of benefit to the standardization community in applications such as the investigation of measurement methods [4], or the definition of emissions and immunity limits. Finally, the evidence to support manufacturers' claims that their products conform to the relevant legislation is reviewed by certification authorities. The latter will therefore become indirect users of modelling results as the other user groups begin to exploit electromagnetic modelling techniques.

Thus, modelling techniques could be used in a wide range of roles in automotive EMC and antenna engineering. However, the details of the model, as well as the requirements in terms of input data and the quality of the results, will depend on the user and the nature of their particular application. Techniques for identifying and classifying the requirements are therefore vital, both for constructing the initial proposals and for presenting them to potential users in a readily understandable form in order to promote dialogue and feedback.

3.1.2 Requirements for model building

Electromagnetic modelling of real-world equipment and test configurations is not normally possible without introducing many approximations. The aim of this process is generally to minimize the computational requirements, but the resulting model is of no practical value if the results become so poor that they are no longer suitable for the intended purpose. The objective of the analyst, therefore, is to reduce the model to the simplest system representation that can provide results of the desired "quality".

Identifying the nature of the models required for particular analysis tasks is a key issue in determining requirements for geometry and the quality of the results. The quality that is required from modelling results is likely to be very varied, ranging from order of magnitude estimates through to precise predictions, depending on the nature of the modelling task. Moreover, the quality of the geometry that is available when the results are required is also likely to be very variable. Thus, the identification of model requirements can be difficult, and the conclusions may not be obvious.

3.1.2.1 Quality issues

Given the inherent uncertainty and repeatability problems of EMC measurements, as well as the wide variations in model fidelity and modelling tasks that can be expected, it is not easy to quantify the accuracy of simulation results. Presupposing that the basic numerical analysis techniques are sound, and that they are correctly implemented in the simulation software, the factors that determine the "quality" of the results, in terms of how well they represent the real world, are:

- fidelity of the geometry used to build the model;
- accuracy of the electrical properties that are assigned to different materials;
- nature of the discretization that is applied when the geometry is meshed.

An immunity model that is based on plane wave excitation cannot be expected to produce identical results to a measurement carried out using a finite source antenna. Similarly, results that are generated using "intermediate" vehicle geometry cannot be expected to be identical to models or measurements based on the final product. Nonetheless, even imperfect results may be of sufficient quality to make decisions about design options or "worst-case" test configurations. In some cases, information regarding relative performance may be sufficient, while in others confidence that the absolute values are likely to be within a few dB of actual levels may be acceptable.

3.1.2.2 Model fidelity

The scope of GEMCAR addresses four main areas: vehicle immunity, vehicle emissions, intra-vehicle EMC and installed antenna performance. Models of all of these phenomena can be considered in terms of two basic elements: the "test object" and the "antenna" (which may be transmitting or receiving). In this context, the "system under test" may in fact be a controlled environment, such as a semi-anechoic chamber or a reverberant room, or another antenna.

The nature of these model elements may range from the "abstract" (eg. for plane wave illumination) to the "detailed" (as required for model validation purposes). It is not possible to describe these aspects in quantitative terms, so a scheme for classifying the model fidelity requirements in qualitative, natural language terms has been used (see Table 1 below).

Table 3.1: Model fidelity classifications

Fidelity class	Interpretation
Detailed	Detailed geometric models of particular antennas and/or test objects (usually vehicles and harnesses in the GEMCAR context)
Intermediate	Approximate geometry for particular test objects and/or antennas
Representative	Geometric models which reflect the main features of the structures of interest (eg. simple log-periodic antennas, synthetic geometry for "vehicle like" objects, real geometry for similar sized vehicles)
Abstract	Notional representations, such as plane wave illumination, that are difficult or impossible to implement in physical experiments

Although only four fidelity classes are defined in Table 1, the class for the "antenna" and "test object" elements of a model may differ for a particular application, thus giving rise to a much richer spectrum of fidelity classifications.

3.1.3 Requirements for exploitation

The primary motivation factors for the introduction of electromagnetic modelling techniques into the vehicle development process are:

- reduced costs;
- fewer design iterations;
- shorter development time;
- more efficient use of physical test time;
- greater confidence in system reliability and performance.

The requirements associated with exploitation of model data that result from these goals could be considered as falling into three basic groups concerned with:

- simulation output;
- quality and accuracy of the results;
- timing and duration of the modelling activity.

The technical ability to carry out electromagnetic modelling is of limited practical engineering benefit if it is not also possible to satisfy these exploitation requirements.

3.1.3.1 Simulation output

The output data that can be obtained from electromagnetic models ranges from directly computed parameters, including fields, currents and voltages, to derived quantities such as scattering parameters and far-field characteristics of antennas. The nature of the output that is required will vary between modelling tasks, and presentation requirements may include qualitative visualisation of spatial field distributions or radiation patterns as well as more localised and quantitative frequency response information.

It is anticipated that even directly computed quantities will need to be further processed in order for the user to exploit this information for practical engineering purposes. Although the computing effort associated with such tasks is likely to be much smaller than for the electromagnetic simulation, the effort required in processing and analysing the results may be significant. Consequently, these issues may well impact on the commercial viability of particular modelling tasks.

3.1.3.2 Quality and accuracy

Identification of the “quality” requirements of model results is difficult, partly because the limits of usefulness are difficult to define and partly because the nature of model results is such that quality is not easy to describe. Validation results for EMC models encompass a very wide range of frequencies, and the quality of correlation often fluctuates across the frequency band. The nature of the differences may range from simple amplitude differences to more complex shift and stretch of features in the frequency response. These problems are further compounded by the complexity of the experimental reference: measurement uncertainty is relatively large for these kinds of measurements. Thus, it is unreasonable to expect validation results to be better than experimental repeatability.

A simple amplitude error is not a satisfactory measure for this type of application. The “feature selective validation” (FSV) method [5-7] provides a quantitative and objective mechanism for describing the similarity of results such as model validation data, and is proposed as a tool for describing the “quality” of model results in GEMCAR. The nature of the method is such that a perfect match provides a measure of zero, while a value greater than unity represents a very poor result. The repeatability of electric field measurements for a test object in a semi-anechoic chamber, for example, is found to provide a global difference measure (GDM) of 0.2-0.3 [6].

3.1.3.3 Scheduling

Scheduling is an issue for the vehicle integrator and system supplier, where the intention is to integrate electromagnetic modelling into the development of specific products. These considerations include both the time needed to build models and complete the necessary simulations, and the integration of modelling activities into the design, development and certification processes. Such work can probably be carried out in parallel with other tasks, but the availability of suitable data and the development programme deadlines will place important constraints on the acceptable timing and duration of electromagnetic modelling tasks.

In a typical vehicle development programme (see Fig. 3.1) there may be a period of around 18 months between vehicle CAD data becoming available and the cut-off point for changes. The EMC test activity is then perhaps scheduled to begin about 12 months after the preliminary CAD data becomes available. However, the CAD data may need to be finalised within perhaps 8 months of the preliminary data being issued. This programme is representative of those of passenger cars for volume production. The timing constraints for other types of vehicle, particularly more specialized vehicles for freight transport, construction and other industrial and agricultural applications may be quite different. However, the time to market for passenger vehicles probably represents the worst case, and is therefore considered to be the most useful example for illustration here.

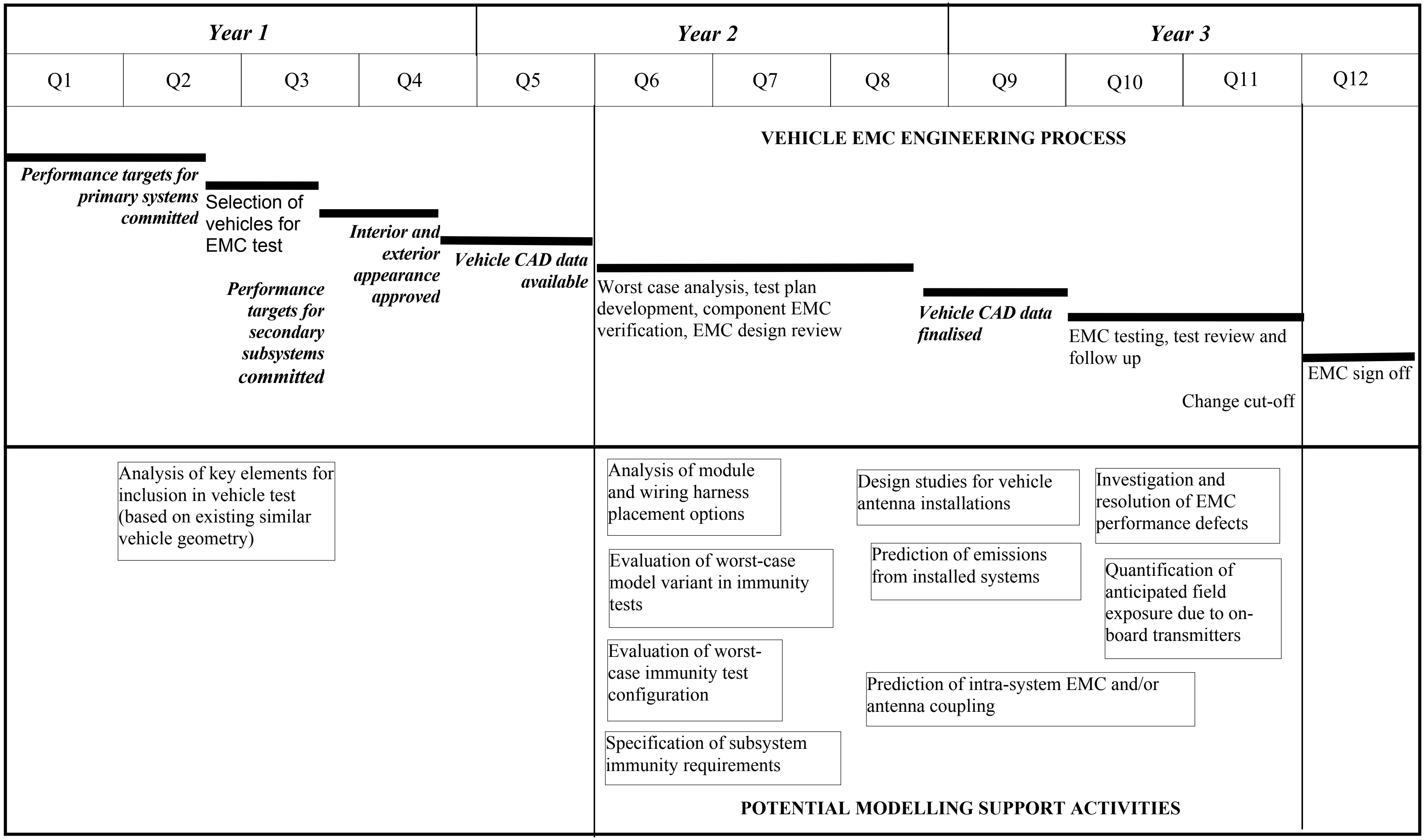


Fig. 3.1: Representative vehicle development lifecycle and opportunities for introducing electromagnetic modelling

Thus, for this example, any modelling tasks that could impact on the vehicle CAD must be completed within the available eight-month window. However, a further four months are available for the evaluation of test configurations and selection of vehicle variants. The duration of large scale, broadband electromagnetic simulations can be significant, perhaps taking 50 hours to compute results for some 10^4 frequencies (the exact details will depend on the nature of the model). Consequently, these timescales suggest that modelling is commercially viable, and will become even more so as more powerful computing resources become available, particularly if parallel processing is employed to increase model throughput.

In some applications, the aim may be to exploit modelling in a more strategic role. Possible examples include support for standards development (test methods and limits) and the investigation of basic EMC phenomena. Although these applications are primarily associated with the standardization bodies, vehicle integrators and system suppliers may have an interest in improving their understanding of the EMC impact of generic features of their products (non-metallic body panels, for example). In these applications, scheduling issues are unlikely to be critical for success, since the modelling effort is not required to fit into a development lifecycle.

Similarly, in applications such as the development of new test facilities, or specialised equipment such as antennas, scheduling is an issue but is unlikely to be as restrictive as in the vehicle development process. Projects such as the design and construction of an EMC test chamber could be scheduled around the necessary modelling activities, which would be core to the process as a whole. This is quite different to the use of electromagnetic modelling as part of the vehicle development process, where electromagnetic performance is not the pre-eminent driving force in the project timing plan.

3.1.4 Definition of user requirements

Modelling requirements for the different classes of user were summarised in a “requirements matrix”, which reflects the requirements and objectives for different types of modelling task that may be relevant to the particular class of user.

The rows in the requirements matrix for each user group were determined by proposing a number of possible modelling tasks. These tasks have differing requirements, depending on the nature of the input data that is needed and the quality of the results that are required. The proposed entries for the columns were then based on practical considerations, such as:

- intended use of the results;
- when the results are required and the time available to generate the results;
- availability and quality of geometrical data;
- availability and quality of data concerning electrical properties of materials.

For example, in trying to identify a “worst case” vehicle variant or illumination configuration for an immunity test, it is probably sufficient to look at relative performance under arbitrary illumination conditions. However, it must be possible to differentiate between the model variants or illumination directions. The implications of this are that while a good representation of the test object is required, and this should be feasible in the later stages of a vehicle development programme, the excitation could reasonably be a simple plane wave. The latter limits both the complexity of the model and the number of configurations that must be simulated. However, if the parameter of interest is the coupling between some portion of the vehicle harness and an on-board antenna, it will probably be necessary to build a detailed model of all elements in order to obtain satisfactory coupling results.

Furthermore, some possible tasks may only be reasonably carried out at stages of development, when detailed information is unavailable. Examples include the assessment of vehicle module and harness placement, or the definition of immunity specifications for the vehicle systems.

For these tasks, it may be necessary to use representative geometry based on existing models or early design details. The results that can be obtained from such models will inevitably differ from what might be obtained using the final geometry or a more complete model. Nonetheless, inaccurate information is probably more useful than none at all, and may be sufficient to guide early design decisions.

Sample requirements for users including vehicle manufacturers and test houses are illustrated in Tables 3.2-3.3, using the FSV GDM value as a measure of the "quality" of the results. The tasks concerned with "worst-case" evaluations are assigned to the test house requirements matrix for convenience, since they are intended to support better targeted testing. However, these tasks could also be carried out by the vehicle manufacturer, either in house or under sub-contract to a third party. Similar investigations could also be appropriate to some system suppliers. No matrix was proposed for system suppliers, as it will be similar in form but narrower in scope than that of the vehicle manufacturer. The certification authorities have a need for overall confidence, rather than specific task requirements, so no matrix was proposed for this class of user either.

Table 3.2: Sample user requirements for vehicle manufacturers

Modelling task	Objectives	Antenna model fidelity	Test object model fidelity	Output data	Quality of results	Timing and duration	Comments
Preliminary evaluation of likely immunity characteristics	Early identification of possible problems, basis for harness and module placement decisions	Abstract	Intermediate	Interior field at selected points, spatial fields for selected areas	Relative performance	Within 8 months of 1st issue of CAD data	Final, detailed geometry will not be available, plane wave illumination is probably adequate
Design studies for vehicle antennas	Evaluation of antenna placement options	Intermediate	Intermediate	Impedance mismatch, far field gain and patterns	Relative performance	Within 6 months of 2nd issue of CAD data	General trend assessment is probably feasible without detailed geometry
Prediction of intra-system EMC and/or antenna coupling	Identification of performance defects and EMC protection requirements	Detailed	Detailed	Scattering parameters, wire current and voltage	FSV value GDM≤0.5 relative to experiment	Within 6 months of 2nd issue of CAD data	Accurate prediction of coupling is likely to be highly dependent on geometry, placement and termination characteristics
Identification of structural features impacting on test vehicle selection	Maximize quality of vehicle sample used for certification testing	Abstract or representative	Representative /intermediate	Interior and exterior field at key points	Relative performance	Within 8 months of project start	General trend assessment is probably feasible without detailed geometry

Table 3.3: Sample user requirements for test houses

Modelling task	Objectives	Antenna model fidelity	Test object model fidelity	Output data	Quality of results	Timing and duration	Comments
Evaluation of worst case model variant in immunity tests	Reduce physical test requirements, saving test time and costs	Abstract	Detailed	Fields, wire current and voltage	Relative performance	Within 12 months of 1st issue of CAD data *	Selection based on relative performance under plane wave illumination is feasible and probably adequate
Evaluation of worst case immunity test configuration	Reduce physical test requirements, saving test time and costs	Abstract	Detailed	Fields, wire current and voltage	Relative performance	Within 12 months of 1st issue of CAD data *	Selection based on relative performance for plane waves of different direction and polarization is feasible and probably adequate
Design of low frequency test antennas	Design optimisation to meet field strength and uniformity requirements	Detailed	Intermediate	Field distribution, scattering parameters	FSV value GDM≤0.4 relative to experiment	Project specific	Chamber size and lining properties need to be adequately represented
Design and optimisation of anechoic chambers	Optimise cost and performance of chambers	Abstract or representative	Intermediate	Normalised site attenuation, antenna characteristics	FSV value GDM≤0.4 relative to experiment	Project specific	Antenna models can be avoided in TLM/FDTD, but chamber size and lining properties need to be adequately represented

3.1.5 Feasibility assessment

The requirements matrices described in section 5 were used to develop a set of questionnaires to support the elicitation of feedback from selected individuals through interviews. This information, together with input from the consortium, has been used to assess the feasibility of the proposed tasks and the importance of the results to potential users.

Conclusions regarding the viability and desirability of a number of the modelling tasks that were proposed are summarized in Tables 3.4-3.5 (corresponding to the vehicle manufacturer and test house groups). In this context, the term “viability” represents the ability to satisfy both the technical and commercial requirements for the particular tasks. The “desirability” reflects the views of potential users as to their interest in the proposed task and its perceived benefits. In some cases, such as chamber design, the anticipated demand for modelling support may be relatively small. Nonetheless, the potential benefits may be significant, in terms of reduced cost or better performance of the chamber, and the resulting impact on subsequent business. Both of these attributes are rated on a scale of 0-10, where “10” would be completely viable or highly desirable while “0” would be totally unviable or of no interest. A value of “5” therefore represents the mid-point of this scale.

Table 3.4: Feasibility assessment for vehicle manufacturers

Modelling task	Viability	Desirability	Comments
Preliminary evaluation of likely immunity characteristics	8	9	Highly feasible since vehicle geometry is likely to be available in sufficient time. Results are highly valued, as potential problems can be identified prior to physical testing of prototypes.
Specification of system immunity requirements	8	7	
Prediction of emissions from installed systems	5	9	Moderate feasibility because of detail required in module characteristics and harness geometry. Highly desirable, especially in the railway industry where emissions are a greater problem than immunity.
Prediction of intra-system EMC and/or antenna coupling	6	8	
Design studies for vehicle antennas	7	8	Feasible, but requires details of both the vehicle and the antenna geometry. Increasingly important as the number of antennas and radio based systems deployed in vehicles is expected to rise rapidly.
Quantification of anticipated field exposure due to on-board transmitters	6	7	
Identification of key structural features for vehicle test selection	7	9	Feasible for many structures. Highly desirable to improve test sample.

Table 3.5: Feasibility assessment for test houses

Modelling task	Viability	Desirability	Comments
Evaluation of worst case model variant in immunity tests	8	9	Highly feasible since vehicle geometry is likely to be available some months before testing is required and detailed modelling of antennas can be avoided. Cost savings are easily identified in terms of reduced reliance on physical tests. Savings of >40% have been reported.
Evaluation of worst case immunity test configuration	8	9	
Design of low frequency test antennas	8	7	Highly feasible, since model size is relatively small at low frequency. Demand is unlikely to be great.
Design and optimisation of reverberant rooms	8	8	Highly feasible, since low frequency performance is the problem area, where models are relatively small. Reasonable prospects as reverberation chambers are increasingly popular.
Design and optimisation of anechoic chambers	7	7	Feasible, but most significant problems are model size and determining materials properties for absorbers (chambers) and finite ground (OATS). Demand for designing new facilities may be small, but there is also potential for assessing problems and designing upgrades (eg. high frequency performance).
Analysis and design of open area test sites (OATS)	7	7	

3.1.6 Conclusions

The analysis of user requirements that was used to initiate and direct the GEMCAR project showed that the requirements are highly dependent on the nature of particular modelling task and the anticipated use of the model results. The results of this analysis also confirmed that electromagnetic modelling is commercially viable for most of the possible tasks that were identified. Nonetheless, even those applications that do not appear feasible for the passenger car market (perhaps because there is not sufficient time available in the development programme) may be viable in the development of more specialized types of vehicles. Consultation with selected representatives from the range of potential user groups has confirmed that the use of modelling is perceived to be desirable and of potential benefit.

3.2 CEM Techniques Investigated

There is no single numerical method that meets all of the requirements for EMC modelling, with the result that it is necessary to deploy a range of tools to address specific aspects. Furthermore, there is no single technique from any specific class of tools that is uniquely suited to the solution of EMC related problems. Consequently, the purpose of this section is to give a brief review of the types of numerical techniques that have been applied by the GEMCAR partners engaged in model validation (ie. EADS, EPFL, MIRA, QinietiQ and ONERA), the ways in which they can be used, and the relative merits and disadvantages of the different methods. Specific adaptations to make GEMCAR simulations practicable included the development of a parallel implementation of the freely available NEC2 “method of moments” code by EPFL, and the hybridisation of finite difference and finite volume methods by ONERA.

Details of the formulation of particular numerical techniques are not considered to be necessary in this document, as this information is readily available in the technical literature and is not of direct relevance to the issues considered here.

3.2.1 BEM coupled with cable network code – EADS

ASERIS/BE solves Maxwell’s equations in the frequency domain by a finite boundary element method (BEM) based on a surface mesh of triangular elements (see Fig. 3.2). This code is widely used for EMC and antenna applications for complex geometries [8, 9]. The quality of the expected results depends on the quality of meshing that is used. The size of the mesh elements should not be too large with respect to wavelength: one generally uses a rule of one-fifth of the wavelength λ (on average, the size of each edge of the meshing triangle will be $h = \lambda/5$). This solver does not handle directly SDRC Universal format files. A pre-processor analyses the electromagnetic complexity of the structure, and assigns to each of the element edges the number of degrees of freedom that are needed for the unknowns that are required to solve Maxwell’s equations.

For surface elements, these unknowns are the electric and magnetic current fluxes of induced currents across the mesh edges. They are located at the middle of the sides of triangles. For a given frequency, the code assembles one matrix, factorizes it, and then solves a linear system with the right hand side containing the illumination distribution. A frequency value or a frequency range and a step are set for the calculation. The main limitation of these techniques is in the memory requirement, because a dense matrix describing the interactions between the different cells has to be stored.

Electromagnetic fields are calculated in the vicinity of the structures at particular points defined by the user. Calculation of the scattered field is obtained by subtracting the incident field from the total field. The scattered field at any point in a homogeneous domain is expressed by a surface integral on the boundary of that domain. For a perfectly conducting object, this expression depends on the surface electric currents through an integral-differential operator.

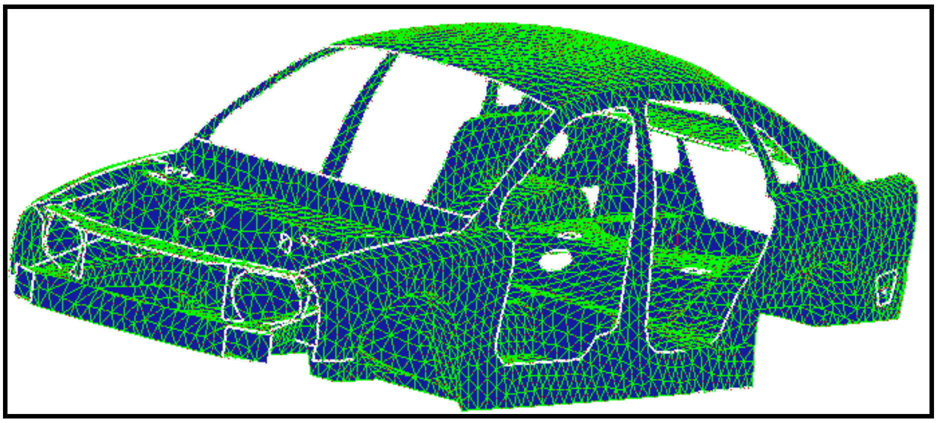


Fig. 3.2: BEM mesh for simplified bodyshell

3.2.1.2 Cable network code (ASERIS/NET)

The 3D Finite Boundary Element code can be used to compute the incident field on a wiring, the response of the wiring being solved with a cable network code. The method theoretically comes form the “field-to-transmission-line” model. In this model, the incident field is transformed into equivalent generators, driving currents on the wiring. In this approach, it is important to understand that “incident” field means the field in the absence of the wiring. Therefore, the 3D incident field calculation does not require the wires to be meshed, which may be seen as a great advantage.

Three equivalent field-to-transmission line models are available (Taylor et al. [10], Agrawal et al. [11], and Rachidi [12]). ASERIS/NET is based on Taylor’s model, in which the coupling of an incident field on a cable is equivalent to applying a set of distributed current and voltage generators, expressed in terms of the incident electric and magnetic fields [10]. ASERIS-NET simulates the interference on an electrical or electronic network, resulting from local injections and distributed sources, due to natural or artificial external ambient fields or electromagnetic disturbances. The distributed field sources are computed by the 3D code and are coupled on the cables by solving the transmission line equations in the frequency range of interest.

Multiconductor transmission lines are convenient models to describe at the same time EM coupling and propagation on cable bundles. We refer to the BLT equation formulated on cable networks [13], and also on study the transmission line models at high frequencies using a rough, non-uniform description [14]. Input parameters for the simulations described above include the bundle construction (single conductor wire), electrical characterization (RLCG matrices), the various geometrical shapes of the bundles, shield or non-shield and integration of dielectrics in the wires, the loads or devices: linear circuits (R, L and C). Outputs from the simulations are frequency domain currents and voltages at any point of the network. Scattering parameters between the network ports can also be computed from these currents and voltages. The scattering matrices “*S*”, referenced to the characteristic impedance of the tubes connected in the network, have a physical significance in terms of the network transmission and reflection coefficients [15].

3.2.2 Method of moments (MoM) – EPFL

In the framework of the GEMCAR project, EPFL uses the Numerical Electromagnetics Code (NEC), a freely distributed incarnation of the MoM. The NEC code is a user-oriented software tool for analyzing the electromagnetic response of antennas and other metal structures [16]. In the last 20 years, NEC has been widely and successfully applied to radio communications testing as well as antenna design. As the code is written in FORTRAN, it is readily compiled and run on a variety of platforms featuring all kinds of operating systems, an advantage of the portability of the language.

Since NEC uses models represented by means of wires, the numerical core allows the simulation of very complex 3D structures, limited only by the capacity of the environment in which it runs, with memory as the main constraint. The NEC code produces an interaction matrix representing the system of integral equations that leads to the calculation of the currents and consequently the fields. The dimension of this matrix depends on the number of segments that are needed in the model to represent the structure to be evaluated. The matrix is then reduced using LU factorization and, with the aid of the excitation vector, the final solution to the integral equations is obtained [17].

For a model consisting of N segments, the amount of memory required by NEC is proportional to N^2. As a consequence of the square growth in the expression, the amount of memory required becomes important on many current computers at around 3000 segments. An 'out-of-core' routine is embedded into NEC to allow the use of the hard disk as swap memory in case of bigger models. The matrix is cut in pieces that are stored on the hard disk, following a special pattern. The operating system can then use all available RAM and NEC manages the disk swapping. The out-of-core routine requires about four times the normal RAM and, as a consequence, enormous swap files are created. Even more important is the fact that the use of the hard disk, through the swap file, will slow down the execution of NEC to unpredictable values.

In order to overcome this problem, the only solution seems to be more memory. Having as much memory as needed is the best way to assure an optimal execution. However operating systems are not capable of managing all the memory one would be prepared to buy. There are limits imposed by the operating systems to the size of an executable application. Thus, a version of NEC compiled for a very large number of segments will fail to start, because operating systems are unable to allocate enough memory for the declared matrix sizes.

3.2.2.1 Parallel NEC [18, 19]

The original NEC code can be globally divided in two parts:

(1) The input section, which reads geometrical information about the model and stores the "cards" that dictate additional model information, program commands and execution requirements.

(2) The calculation section, which computes the coefficients of [$\boldsymbol{G}$] for the matrix equation [$\boldsymbol{G}$][$\boldsymbol{I}$]=[$\boldsymbol{E}$] and solves this equation by means of the Gauss-Doolittle numerical method. This method solves the system by first calculating the LU decomposition of [$\boldsymbol{G}$] into [$\boldsymbol{L}$] and [$\boldsymbol{U}$] so that the matrix equation becomes [$\boldsymbol{L}$][$\boldsymbol{U}$][$\boldsymbol{I}$]=[$\boldsymbol{E}$]. The equation is solved by forward substitution in [$\boldsymbol{L}$][$\boldsymbol{F}$]=[$\boldsymbol{E}$] and backward substitution in [$\boldsymbol{U}$][$\boldsymbol{I}$]=[$\boldsymbol{F}$] so that the [$\boldsymbol{I}$] vector containing the currents for every single segment is obtained.

The major computational effort is factoring [$\boldsymbol{G}$] into [$\boldsymbol{L}$] and [$\boldsymbol{U}$]. In fact, computation of the elements of the matrix [$\boldsymbol{G}$] and the solution of the matrix equation are the two most time-consuming steps in computing the response of a structure, often accounting for over 90% of the computation time [16]

Since the NEC code is open and freely available, we have been able to modify it and include a certain number of routines so that the program can also be executed in parallel supercomputing architectures. The idea behind this technique is to share the interaction matrix among a number of processor (P) so that the memory requirements can be fulfilled and the total computing power help produce faster results.

The routine that computes the elements of the interaction matrix was substituted by algorithms that partition the matrix assign to each processor the task of calculating only those elements that belong to its local sub-matrix. In this way, we reduce the per-processor memory requirements by nearly a factor of P, for a machine with P processors. The factorization and solution routines were substituted by highly optimized scalable parallel solvers that deliver dramatic improvements in execution times, particularly for cases where disk swapping is unavoidable on single processor machines.

Representative timing and memory results (based on a test model) are shown in Table 3.6 below. These results compare both the both original version of NEC on a single PC and the modified version on a parallel supercomputer.

Table 3.6: Timing and memory as a function of the number of processors for a 6753 segments test case.

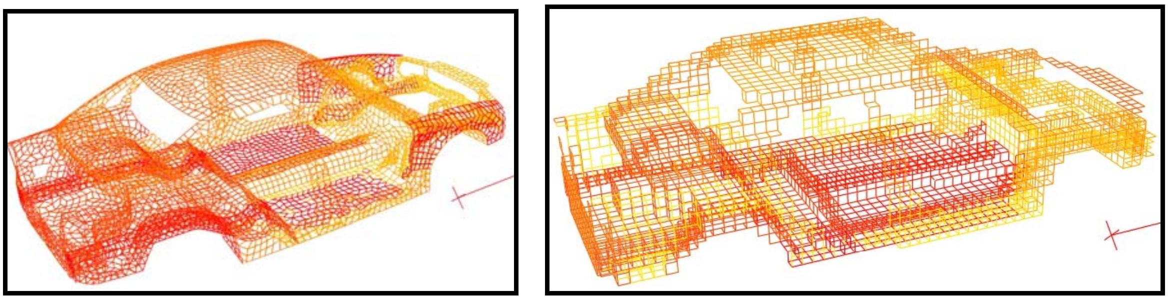
Number of Processors	Matrix Filling Time	Matrix Factorization Time	Run Time (for 2 frequencies)	Memory per processor (MB)	Total Memory (MB)
1 – PC	10 min	6 h 47 min	14 h 6 min	62*	2790
4 – T1	2 min 56 sec	5 min 24 sec	16 min 7 sec	193.9	769.34
8 – T1	2 min 42 sec	2 min 45 sec	11 min 37 sec	104.4	816.04
16 – T1	2 min 34 sec	1 min 31 sec	8 min 52 sec	57.28	883.76
24 – T1	2 min 50 sec	1 min 39 sec	8 min 29 sec	39.55	905.81
32 – T1	2 min 33 sec	1 min 27 sec	8 min 16 sec	33.72	1019.45
36 – T1	3 min	1 min 3 sec	8 min 34 sec	28.45	988.57

***Approximation based on core storage of 2000 segments.**

3.2.2.2 MoM meshing issues

Special care must be taken when building a complex NEC model. In addition to a series of basic guidelines for the simulation of antennas and other single structures [16], other considerations, derived primarily from empirical observations, are of considerable importance for surface simulations. In particular, a model of very high geometrical complexity, from the visual point of view, does not necessarily guarantee better results than can be obtained from a model based on a much simpler representation of the geometry.

Two different approaches for the meshing of the GEMCAR simple test case model are shown in Fig. 3.3, for example, both converted into NEC input files. It was observed that the more accurate body-fitted model (a) produced satisfactory results of a very narrow frequency interval. However, the stair-cased approximation (b) produced a very good agreement for a wide interval and for different configurations of the experiment.



(a) Body fitted mesh (from BEM mesh) *(b) Stair-cased approximation (from TLM mesh)*

Fig. 3.3: Two different approaches for the NEC mesh

The most important parameter that determines the accuracy of the results appears to be the wire radius. The guidelines stated in [16] for the representation of segment lengths and radius do not apply in an identical manner in the case of wire-grid surface simulations. The so-called "equal area rule" [19], has been shown to give the best results when it comes to perfectly square and homogeneous meshes.

In fact, the application of the rule is also a guarantee that some of the other guidelines regarding the use of NEC are respected. For example, a completely square and homogeneous mesh will ensure that all segments have the same length and radius, a condition that is highly desirable for successfully modeling complex 3D surfaces with NEC. On the other hand, the extension of the application of the equal area rule to more complex, body-fitted meshing techniques (i.e. with a triangular mesh) does not provide the same degree of accuracy, possibly due to the fact that significant variations in segment length and radius result.

3.2.3 Transmission line matrix (TLM) – MIRA

The transmission line matrix (TLM) method [20, 21] is a full-wave, 3D electromagnetic field modelling technique. In this approach, the entire volume is discretized using structured hexahedral cells (usually rectangular, but sometimes cylindrical) that are occupied by a “node” connecting 12 transmission lines, representing two orthogonal polarizations at each of the cell faces. Boundary conditions are applied by appropriate termination of the transmission lines, while materials are represented by adding stubs to the node to modify the propagation characteristics. Like FDTD, TLM is attractive for EMC applications because it is normally formulated in the time-domain, thus permitting broadband frequency-domain results to be obtained from Fourier transformation of a single time-domain response. As TLM employs a structured mesh, very large models can be accommodated within relatively modest computing resources. Furthermore, sub-cell models are available for long, thin features, thus ensuring that common elements such as wires [22] (including multi-conductor bundles [23]) and slots [24] can also be efficiently represented in models of large structures. Frequency dependent materials [25, 26] and features such as arrays of apertures [27] can also be accommodated using special models.

In common with other finite methods, such as FDTD and finite elements, the modeled volume must be truncated with an artificial absorbing boundary. In TLM this can be achieved by using simple matched (ie. 377 Ω) terminations at free space boundaries that are sufficiently far from the radiating or scattering structures, or with more sophisticated PML schemes. The main disadvantages of TLM, like FDTD, are its inability to provide a body-fitted mesh for arbitrary geometries (with the result that curves are normally represented by a staircased approximation) and the fact that the duration of simulations for highly resonant structures can be very long. However, these issues are not found to be serious limitations in most automotive EMC modeling applications. A sample vehicle TLM mesh is illustrated in Fig. 3.4, for a bodyshell containing a simple wiring harness and illuminated by a nearby antenna. Thus, the harness model in this case is fully integrated with the 3D electromagnetic model.

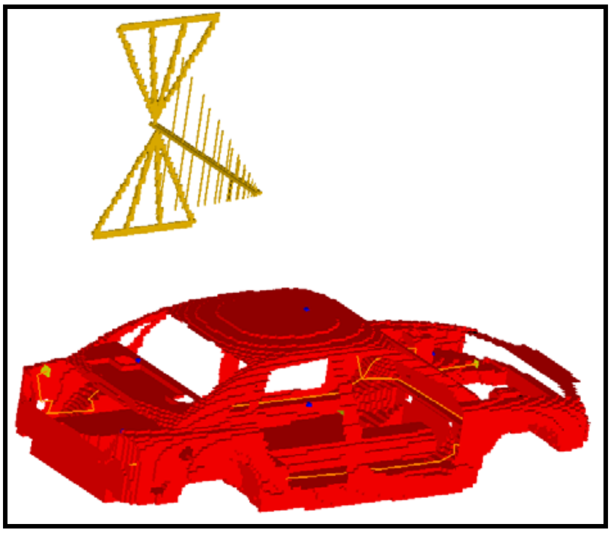


Fig. 3.4: TLM mesh for simplified bodyshell, with integrated harness model and vertical biconilog antenna at side

This capability is needed for areas where the cables are a significant distance from the bodyshell (typically in the dashboard area and engine bay). However, for those parts of the harness that are close to the bodyshell a separated method would avoid the the need to allow for the long "ringing" times that result from adding additional resonances associated with the cables to the 3D model.

3.2.4 FDTD – ONERA and QINETIQ

The method used is based on the well-known Yee scheme [28], where the Maxwell equations are solved in time domain and in a bounded computational space domain. The boundaries of the computational domain taken into account, permit to simulate the infinite space with Berenger's PML formalism [29] or a special condition such as a conducting plane to simulate, for example, the ground plane in the MIRA and EPFL measurements for the GEMCAR project.

In the Yee scheme, the computational domain is split into a grid of parallelepipedic cells where different spatial steps are given in the three directions (x, y and z). The unknowns of the method are the electric and magnetic field components. The electric field components (E_X, E_Y and E_Z) are located in space at the edges of the cells of the grid. For the magnetic fields a second grid ("dual grid") is defined, the vertices of which are located at the centres of the cells of the first grid. The magnetic field components (H_X, H_Y and H_Z) are then located at the edges of this dual grid (see Fig. 3.5 below).

The magnetic and electric fields are not located at the same position in space: the numerical scheme is described as "leap-frogged" in space. In this method, the electric and magnetic fields are evaluated with a delay of $dt/2$ where dt represents time step. The scheme is also leap-frogged in time. This leap-frog approach permits an explicit second-order numerical method with a Courant Frederich Levy (CFL) condition of:

$$dt < \frac{1}{c}\left(\frac{1}{dx^2}+\frac{1}{dy^2}+\frac{1}{dz^2}\right)^{-1/2}$$

where c, dt, dx, dy and dz define respectively the speed of light, the time step and the spatial step size along the three orthogonal axes.

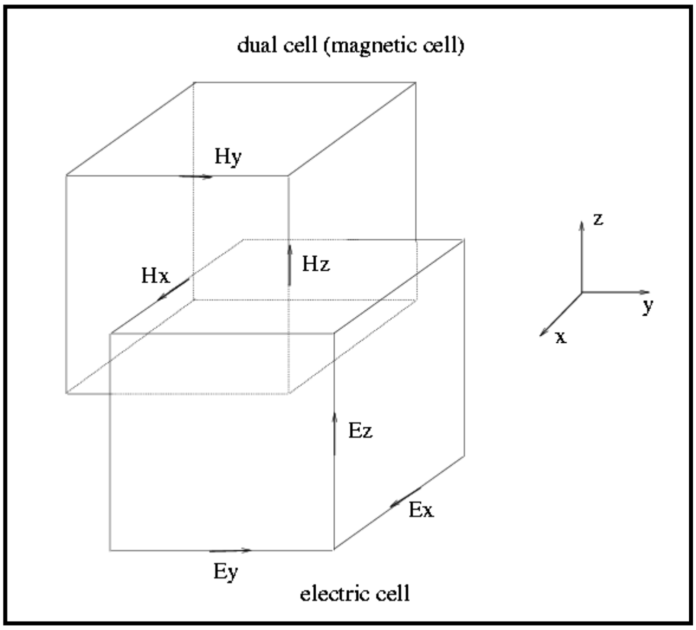


Fig. 3.5: Locations of unknowns in the FDTD method

The choice of this numerical approach results in a stair-cased representation of objects with surfaces that are not aligned with the mesh. An example of an FDTD mesh is illustrated in Fig. 3.6, for the MIRA test case simulation.

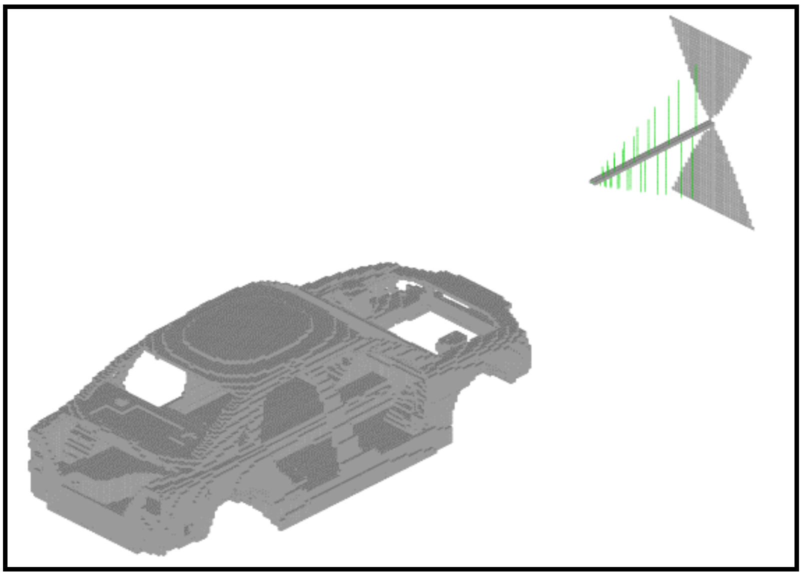


Fig. 3.6: ONERA FDTD mesh for a MIRA test configuration

A special wire model formalism due to Holland and Simpson [30] can be used to take account of thin wires in FDTD models without meshing them in fine detail, which adversely impact on both the memory requirements and runtime of FDTD models. The wire is represented using a sequence of broken lines that follow the edges of the electric grid with appropriate boundary conditions at its two terminations (eg. wire open circuit or connected to metal).

In conclusion, the method is robust and very attractive in term of CPU time. However, in order to compute a field at a given position, the field components along the cell edges must be interpolated in order to obtain the field at specific points inside the cells. This can be a disadvantage when the fields along a path close to an object are required.

3.2.5 Hybrid FDTD/FVTD method – ONERA

The hybrid technique used by ONERA combines the finite difference (FDTD) and finite volume (FVTD) methods to solve the Maxwell's equations in the time domain. This method, developed at ONERA and implemented in the code EIVE, combines two kinds of meshes and two different numerical schemes:

(1) The first is the well-known FDTD method based on the Yee scheme [28]. This scheme is applied only on a structured Cartesian mesh where the size of the cells can be different on each axis and along a given axis. In this case a perfectly matched layer (PML, [29, 31] is used to truncate the computational domain.

(2) The second is a cell-centered finite volume scheme that solves a conservative form of Maxwell's equations [32]. In this method the computational domain is split into a set of non-structured cells, which can be cubic, pyramidal, tetrahedral, prism, etc. The magnetic and electric fields are located at the center of the cells. The computational domain is bounded by a Silver Muller condition to simulate infinite space.

The code EIVE offers the possibility to use only the FDTD method, only the FVTD method, or both methods simultaneously. In the latter possibility, the mesh over the computational domain is composed of a structured zone, where the FDTD scheme is applied, and an unstructured zone where the FVTD scheme is applied. The hybridization between the two schemes is achieved using one ore more overlapping cells, where the fields at the time *t+dt* are computed for each method by using the fields at the time *t* evaluated by the other method [33]. The CFL number for the two methods is not the same and the CFL number for FVTD generally implies a much smaller time step than for FDTD. This is due in part to the numerical scheme but also to the size of the cells that are used, which are generally smaller in the unstructured part than in the structured part of the mesh. To avoid the situation where the smallest cells in the unstructured part impose the overall time step for the hybrid method, a local time step is used to evaluate the fields inside these cells. Fields in the others cells are computed with time steps corresponding to the FDTD CFL number for the structured part and to the FVTD CFL number for the unstructured part. In the GEMCAR model, the antennas and the computational domain is defined using a structured mesh except in the vicinity of the car where an unstructured, body-fitted mesh is used (see Fig. 3.7).

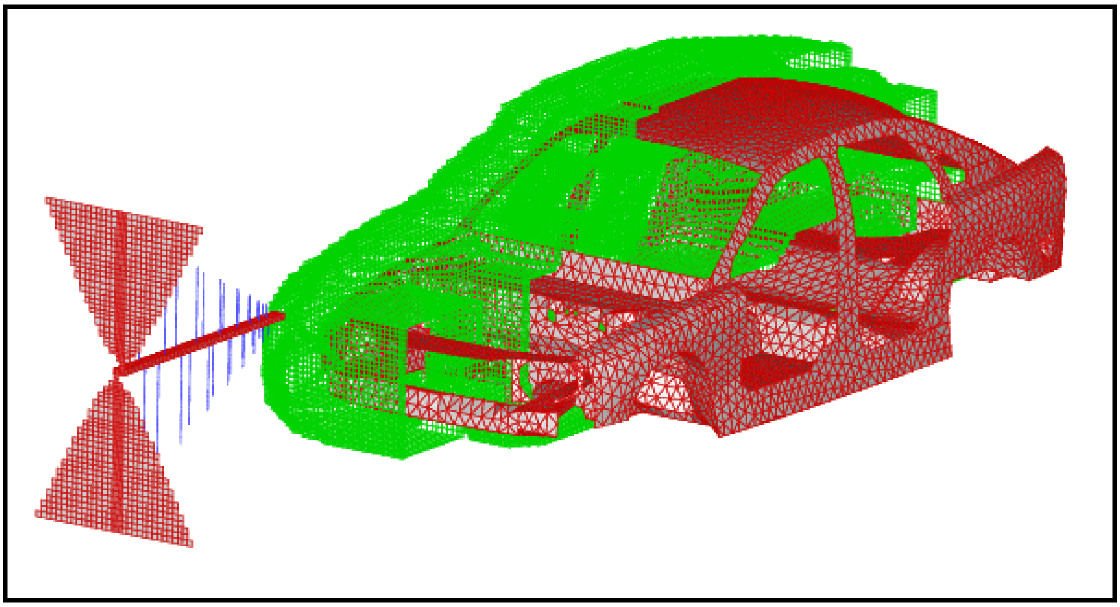


Fig. 3.7: Hybrid FV/FDTD mesh, showing the boundary between structured and unstructured parts.

We consider that the antenna is sufficiently Cartesian to be meshed with a structured mesh. Near the bodyshell, however, the mesh is composed of unstructured tetrahedral cells derived from a body-fitted surface mesh based on triangular elements. In particular, this condition is important to evaluate the electric fields tangential to the path of the harness inside the car. The hybrid method offers a compromise between a fast method based on a stair-cased model (FDTD), which needs a very fine mesh to correctly capture the path of the harness, and an entirely conformal method (FVTD) which implies too large a number of unstructured cells in order to correctly model the antenna geometry, resulting in requirements for much greater memory and CPU time than FDTD.

3.2.6 Conclusions

The range of different numerical techniques that are represented in the GEMCAR project is representative of the currently available electromagnetic modelling techniques, but not complete. Nonetheless, the techniques that are described here are probably the most widely used techniques for EMC applications, particularly for modelling electrically large structures.

3.3 Efficient Simulation Strategies

The objective of this task was to identify strategies for improving the efficiency of vehicle level EMC simulations. This work was carried out by ONERA and MIRA, with contributions from other partners engaged in numerical modelling. The scope of this work is limited to the calculation element only: no consideration is given here to the equally important model building aspects of the problem (eg. geometric descriptions, mesh generation, identification of material properties) or the engineering processes that are required to integrate EMC modeling with wider vehicle engineering tasks. These elements are addressed in other parts of the GEMCAR project.

In the context of this activity, the notion of improved “efficiency” includes:

- the capability to perform a calculation that is perhaps not achievable with a single tool or technique;
- improvements in the accuracy of the results;
- approaches allowing easy modification of parameters associated with the model;
- reductions in the duration, scope and number of models that are required.

These goals can be achieved by working on three main areas:

- optimizing the algorithms used in the simulation software;
- combining numerical techniques to exploit the strengths of different approaches;
- improving the modeling methodology to obtain the maximum benefit from each simulation.

Within the GEMCAR project, it was not possible to investigate all possible types of improvements. Nevertheless, the main ones that were applied in the project will be described in detail as illustrations of the enhancements that can be achieved. Other ideas are also mentioned, even if not specifically addressed in the project.

3.3.1 Modelling methodology

The approach that is used in building and exploiting EMC models can have a significant impact on the computer resources that are required, and hence the efficiency of the modelling activity. This is particularly true where full 3D field computations are to be carried out, as these calculations are extremely demanding in terms of computer time and resources. Nonetheless, there are opportunities for reducing these requirements, depending on the exact purpose of the modelling activity.

For 3D simulations, the complexity of the model determines the required memory and run-time to complete the necessary calculations. Such models should therefore be made as simple as possible in order to ensure their computational tractability. For validation purposes, it is generally essential to include a realistic representation of the antenna that is used to illuminate the real system in order to replicate the test conditions effectively. This requires the geometry of the antenna, which may be quite intricate in itself, to be added to the model at the correct position relative to the test object. This inevitably adds considerably to the size of the model and the resources required for the simulation. However, it is not anticipated that model validation will be a mainstream modelling activity. The primary aims of adopting numerical modelling are to:

- reduce reliance on physical testing;
- improve understanding of physical tests;
- facilitate the analysis of “un-testable” scenarios;
- provide a source of objective information that can be used to guide design choices, even before any physical hardware is available for test.

Thus, although model validation is without doubt an extremely important activity, the true benefits of modelling only become available when the simulation results are trusted without reference to practical measurements. In addition, direct simulation of physical test conditions is unlikely to provide the most efficient route for generating useful simulation data. However it is likely that EM modeling may have a strong impact on the definition of the test conditions of the following domains of interest:

- radiated immunity,
- illumination antenna,
- optimization of on-board antenna,
- radiated emissions;
- intra-system EMC.

3.3.2 Modelling functional EMC performance

An electromagnetic (EM) model is not the same as an electromagnetic compatibility (EMC) model. Nonetheless, accounting for the 3D electromagnetic interactions that determine the coupling from or to cables and equipment within their housing (ie. a geometrically complicated vehicle body-shell for GEMCAR) is an essential element of the wider analysis that is needed in order to predict functional EMC effects. A single monolithic simulation for such purposes is not a practicable proposition, so a combination of appropriate modelling techniques represents the most viable approach to developing a functional EMC model. There are, however, a number of points at which hybridization can be considered.

For building an EMC model, we can consider a range of modelling techniques operating at a number of different levels as outlined in Table 3.7 below.

Table 3.7: Classification of model types required to predict functional EMC performance for vehicles

Model class	Model order	Model nature	Objectives
A	3D + time or frequency	Electromagnetic - volume or surface meshing	3D electromagnetic field distribution and related parameters (eg. antenna characteristics)
B	2D static	Electrostatic - planar or peripheral meshing	Lumped circuit models of transmission line segments (valid for small spacing)
C	1D + time or frequency	Transmission line - linear meshing	Accounting for wave propagation effects on transmission lines (length and load dependent)
D	0D + time or frequency	Circuit simulation – lumped element behavioural models	Device physics in circuit models, but no account of physical layout

The clearest requirement for combining models of different types is the integration of circuit behaviour (a “class D” model) with the electromagnetic performance of the vehicle installation (a class A model). It is possible to include cable models within some 3D field modelling schemes (the “self-consistent” approach), which should provide a more rigorous solution, but an approximation that treats the behaviour of the cables separately (the “separated” method) may offer some advantages in terms of computational efficiency. The latter approach, however, requires the introduction of class B (2D) and class C (1D) models in order to determine the transmission line parameters for the various elements of the network and the propagation characteristics of its branches. The separated approach is only valid for those cases where the harness is located close to the vehicle structure. However, in some areas, such as the engine bay and dashboard regions, the harness may not meet these requirements.

The most computationally expensive elements of such models (in time and computing resources) are the full 3D electromagnetic field computations. Thus, there may also be advantages in linking different class A models in order to maximize the efficiency of the 3D field calculation, particularly for electrically large systems such as vehicles at high frequencies. A representative scheme for modeling functional performance using the separated method is illustrated in Fig. 3.8, which outlines the necessary interactions between various model types.

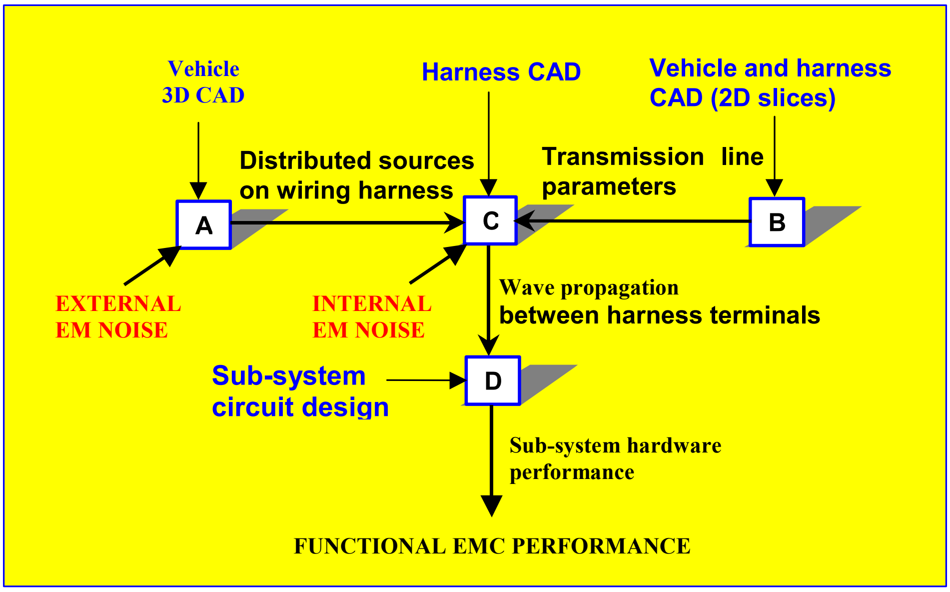


Fig. 3.8: Strategy for functional EMC performance prediction using separated methods

At present, all of the model types outlined in Table 1 are possible, and the integration of some of these techniques has been demonstrated to some degree. However, comprehensive modelling for systems of realistic complexity is still relatively untried.

3.3.3 Capabilities of numerical techniques

The purpose of this section is to provide an overview of the main capabilities of the numerical techniques that can be employed in the analysis of vehicle level EMC. As it is not possible to exploit a class C model without input from a class B model (using the designations illustrated in Fig.1), the combination of these two can be described more conveniently as "cable network" simulation [34].

To avoid describing each technique in detail the methods are classified in terms of the following criteria:

- the operational domain of the simulation (ie. time or frequency);
- the nature of the simulation (3D field, cable network and electrical circuit codes).

3.3.3.1 Time and frequency domain techniques

The relative merits of simulations in the time and frequency domains are summarized in Table 3.8 below. It can be seen that both time and frequency domain techniques offer advantages, and that neither provides an ideal approach for all types of problems.

Table 3.8: Relative merits of simulation techniques

Operating domain	Advantages	Disadvantages
Time	Good description of transients and non-linear problems (eg. sparks, non-linear components) Entire frequency spectrum from a single simulation Calculation time depending on the size of the mesh	Difficult to account for frequency dependence of materials (cables, absorbers, soils) Difficult to have a multiple excitation problem Accommodating multiple-domain approaches (signal processing requirements) Calculation time for resonant structures
Frequency	Accounting for frequency dependent materials Simultaneous application of multiple sources Analysis of restricted frequency ranges	Calculations made at single frequencies Frequency step required to generate a detailed frequency response

3.3.3.2 Types of simulations

(a) Three-dimension numerical codes

These are numerical codes that solve some form of Maxwell's equations for an approximate representation of the scattering geometry. This geometry is represented in a discrete form, generally described as a "mesh". Numerous methods have been developed to solve Maxwell's equations, in both time and frequency domains. In principle, they can solve any kind of problem since Maxwell's equations account for the overall coupling within the geometry in a global sense. For classification purposes, a useful distinction can be drawn between volume and surface meshing techniques.

- Volume meshing techniques such as FDTD, TLM, FEM or FVTD are based on computing fields over the entire object and its surrounding environment (in theory, the entire universe). The advantage of these methods is that they easily account for complex spatial variations in the electrical properties (permittivity, conductivity etc.) of the modeled volume. However, special techniques (absorbing boundary conditions) are required to truncate the workspace to ensure computational tractability. In the past ten years the "perfectly matched layer", introduced by J.P. Berenger, has demonstrated considerable promise. Nevertheless, this approach still presents instabilities in specific conditions that could perhaps be overcome with more sophisticated schemes.

- Surface meshing techniques such as BEM and MoM are based on computing parameters only over the surfaces of the objects of interest. They are very well suited to the solution of integral equations, in either the frequency or time domains, and automatically take into account radiation effects. The main limitation of these techniques is in the memory requirement, because a dense matrix containing the interactions between the different cells has to be stored. Modeling dielectric materials is also a greater challenge in surface meshing techniques than is the case for volume meshing techniques. Recently, the fast multipole method (FMM), which is based on optimizing the product of matrices and vectors, has shown dramatic improvements for Radar Cross Section (RCS) calculations [35, 36]. However, the application of this method for EMC applications at high frequencies is not obvious with the current forms of integral equations that are used (EFIE - Electric, MFIE - Magnetic, CFIE – Combined Field Integral equations).

(b) Cable network codes

Cable network codes are numerical codes that determine the response of a network under different excitation and termination conditions. Versions are available that operate in both the time and frequency domains. Substantial efficiency gains can be obtained when the branches can be approximated as multiconductor transmission lines. The gain compared to 3D codes mainly comes from the avoidance of time-consuming field computations.

In this case, the calculation is made not on the geometry but on equivalent electrical models of cables (per-unit-length impedance and admittance parameters), connections (electrical circuits) and sources (equivalent voltage and current generators). The field distribution local to the cable is determined from an electrostatic model and the subsequent calculations are then essentially limited to longitudinal propagation and reflection effects.

(c) Electrical circuit codes

Electrical circuit codes are computer codes able to calculate the response of an electric circuit. Such codes operate both in time and frequency domain. Public domain versions like the famous SPICE software developed at Berkeley University and commercial products are available throughout the world.

3.3.4 Improving efficiency of simulation techniques

In this section we propose several enhancements to either the implementation or use of EM simulation techniques.

3.3.4.1 Mesh optimization

Mesh optimization is concerned with more efficient spatial sampling of the geometry in 3D codes. In current techniques, the cell must be small compared to the wavelength λ. In free space, a widely accepted criterion is that the size of the cell must be smaller than $\lambda/10$. However, even if this criterion is respected, the discretized model is often a coarse representation of the real geometry, which may lead to errors in the field calculation in key areas.

In GEMCAR, this is the case for the illuminating antenna when modeled using a structured mesh (Fig. 3.9). As the antenna is a broadband device (operating up to 1 GHz in GEMCAR) all of the details of the geometry are important. For methods based on a structured mesh it is important to define a grid parallel to the main directions of the antenna in order to avoid “staircases” in the feeder bars.

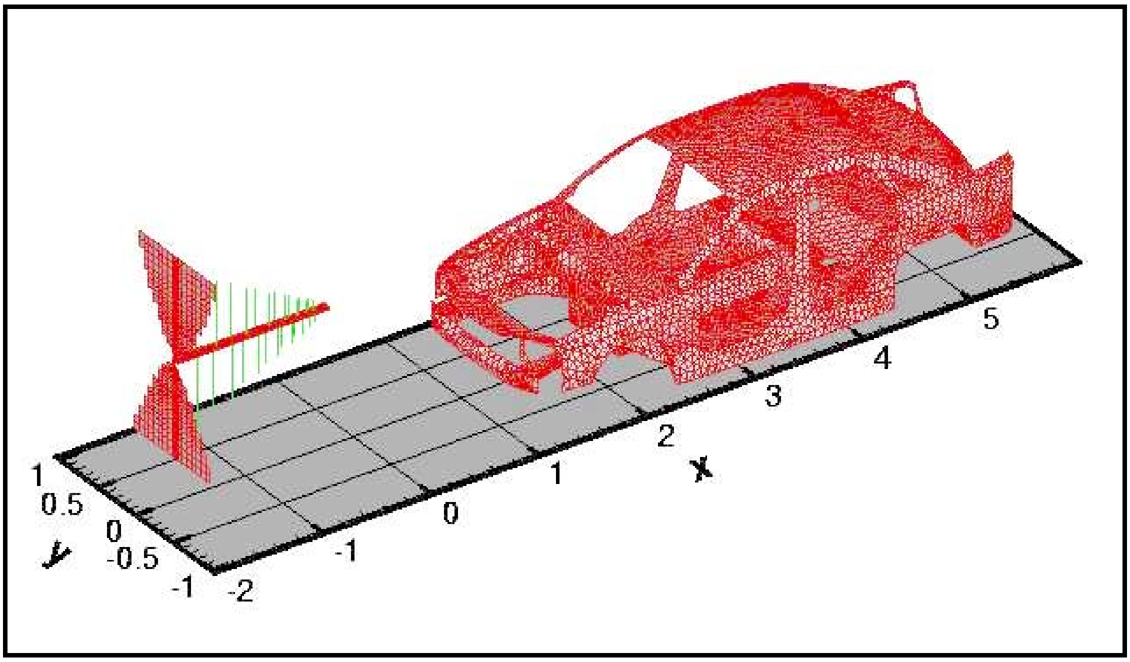


Fig. 3.9: Unstructured mesh of Volvo S80 car (simple test case geometry) with biconilog antenna

The use of high performance absorbing boundary conditions may also help in reducing the size of the workspace in 3D codes. As an example, Fig. 3.10 shows the big calculation volume required in FVTD to treat the GEMCAR plane-wave excitation problem (note the two different layers required).

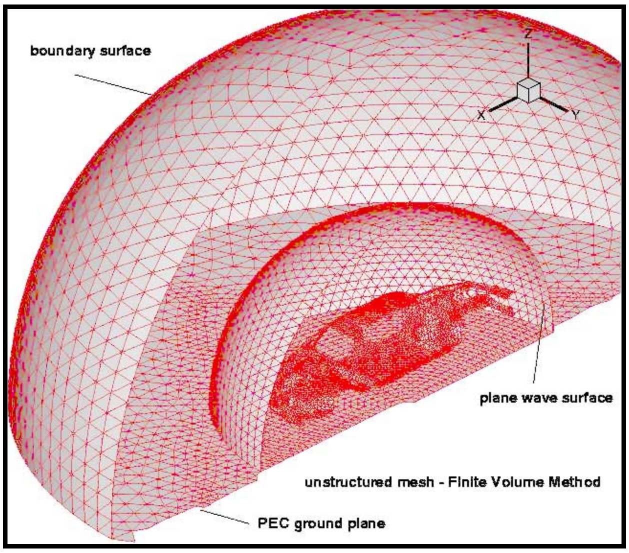


Fig. 3.10: Example of the calculation volume required in FVTD to treat the GEMCAR plane wave excitation problem

3.3.4.2 Accounting for geometry sensitivity

The objective is to use an implementation of the source code in such a way that it may account for geometrical variations during the calculation, thus allowing for limitations in our knowledge of the real geometry in 3D codes. This technique is based on the computation of a Taylor polynomial used to approximate and optimize a solution.

From an initial design made with a CAD system (for example I-DEAS from SDRC), one or a small number of polynomials are built and integrated back into the CAD representation in order to allow the EMC specialist to manipulate the design and determine the optimal solution. The automatic computation of the Taylor polynomial is based on the inversion of a complex matrix and on higher order differentiation of the same matrix.

3.3.4.3 Different EM-states formulation

The idea is to structure a calculation in order to account for different EM-states configurations (different source excitations, different materials) within the same calculation, whereas a direct approach would require several runs to obtain the response of the system under different conditions. The linear equation can be written under the form:

$$[A]\cdot[X_1, X_2, \ldots, X_n] = [S_1, S_2, \ldots, S_n]$$

Generally, this kind of approach is well suited for methods based on the resolution of linear systems. This capability is particularly suited for numerical techniques working in frequency domains, such as integral equation codes, cable network codes and electric circuit codes.

A typical application of this kind of technique is the BLT equation used in EM Topology [37] for network resolutions [13, 38]:

$$([1]-[S])\cdot\left[W_1^u, W_2^u, \ldots, W_n^u, W\right] = [S]\cdot\left[Ws_1^u, Ws_2^u, \ldots, Ws_n^u, Ws\right]$$

3.3.4.4 Exploiting reciprocal formulations of problems

A further approach is based on the application of the reciprocity theorem. Therefore, two EM states must be defined judiciously. The choice of the two problems is made in order to make possible a calculation that would not be possible in a single step. Two applications have been investigated:

- Calculation of the response of a wiring system in an EM field environment. Particularly, let us mention that the approach is appreciable when the incident EM field is decomposed in a series of plane waves [39]: in this case, the response of the cable may be obtained by a projection of analytical plane waves on numerically-calculated currents in an emission state [40].
- Calculation of the field in an enclosure. This is useful when the inner field is close to the noise level. In this case, reciprocal formulations allow one to solve the outer and inner problems separately.

3.3.5 Combining different methods

In this section, two approaches will be discussed:

- the multiple-domain approach;
- the hybridization approach.

3.3.5.1 Multiple-domain approach

The term "multiple-domain" describes techniques where different tools are applied to different parts of the problem. With the multiple-domain approach, the calculation of each part can be achieved separately at different times. In order to re-create the entire problem, the link is made through data files calculated by the elementary tools. The interest of the approach is in the parametric analysis that it permits. In the following sections, two main types of linking techniques have been identified.

3.3.5.2 Link through scattering matrices

Each part of the problem is characterized by S, Z or Y matrices. A network formulation is then used to describe the full wave interactions between the different parts. This technique leads to a network resolution such as the BLT equation. The technique may be applied to decompose a 3D geometry as illustrated in Fig.3.11 below for a simple cavity with an aperture and internal wire.

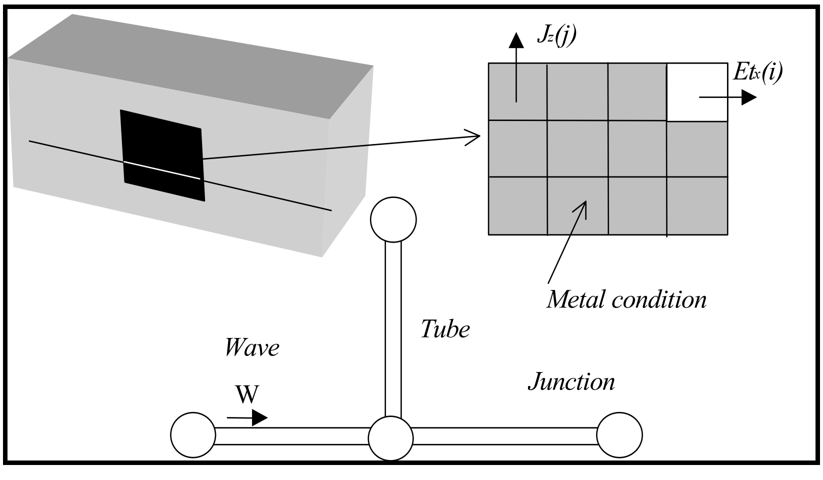


Fig 3.11: Example of a multiple domain decomposition to treat the coupling on a wire in an enclosure

The problem in that case is that large files have to be stored. Interpolation in space, time or frequency is needed to make the different files compatible with each other and with the specifications of the global calculation. All these considerations may explain why this approach has not been serriously developed in the operational context. However, the network approach may also be applied to describe very complex cable bundles topologies. Applications in the past 10 years have fully demonstrated the value of this technique [14, 41].

3.3.5.3 Link through incident fields

The link through incident fields is based on the field-to-transmission-lines formalism [42, 11, 12]). Its interest is for calculating the response of a complex wiring system illuminated by an incident field (the field in the absence of the wiring). This technique has been successfully applied in different applications [43] and in GEMCAR [44].

3.3.5.4 Hybridization approach

The word “hybridization” is used to describe different numerical techniques that are merged within a single source code. This technique is currently applied in 3D codes, as for example in GEMCAR between FDTD and FVTD [44] (see Fig. 3.12). In these techniques the calculations must be made at the same time. Compared to the multiple-domain technique approach, the advantage is that no large files have to be stored in order to exchange data. Nevertheless, the entire calculation has to be repeated for any local modification to the geometry, which is not the case with a multiple-domain approach.

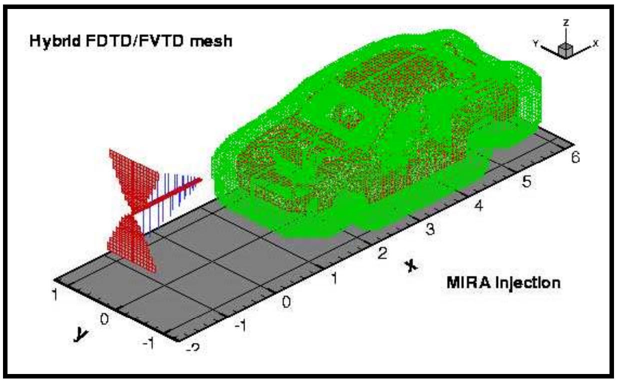


Fig. 3.12: Example of hybrid FV/FDTD mesh for the illumination configuration used in measurements at MIRA

3.3.6 Suggestions of an operational strategy

3.3.6.1 Topological decomposition

The suggested strategy is based on a good understanding of the topology of the problem. This topological approach will certainly not guarantee that the system is perfectly designed, but it will at least ensure that it is possible to analyze the system in the future [45, 46, 47]). To make this analysis possible, one has to design the system in such a way that the frontiers between different domains are well defined. The boundaries of these domains correspond essentially with the points of entry of EM interference. In EM Topology, depending on the hierarchy of coupling, the problem is decomposed in terms of “shielding levels” defining several volumes. The coupling from one shielding level to the other is oriented, which means it goes from an upper level to a lower level, but no retroaction is taken into account. Within a given shielding level, a full EM interaction analysis is required. This means that a modification within a particular shielding level always has an influence on all the other components at that shielding level. The three shielding levels that we suggest for automotive and similar applications are the following (Fig.3.13):

- Source and structure of the vehicle. At this level, the source and structure are in close interaction. Of course, the antenna illuminates the car, but the car also interacts with the antenna. The source comprises the whole antenna system, including the generator and if possible the driving cable. The structure comprises the body shell and all parts other than cabling and electronic equipment within the vehicle (ie. the data from the CAD model).
- Wiring harness. The cable paths must be designed in order to reduce EM coupling, which generally requires the cables to be close to the structure (hence allowing the use of network methods based on transmission lines).
- Electronic modules. The design of the equipment should not allow direct coupling from the field to the circuit paths or radiation from these circuits. Thus the coupling path for interference to and from the equipment is limited to the wiring alone.

Associated to this decomposition is of course the nature of the calculations that are to be performed with the available codes. Indeed, if large and fast enough computer codes were available, direct calculations could be performed on the entire model, without any decomposition. However, even if feasible, this approach would still remain poorer than a decomposed one in that sense that it would be very difficult to identify the sub-system that is "responsible" for the problem.

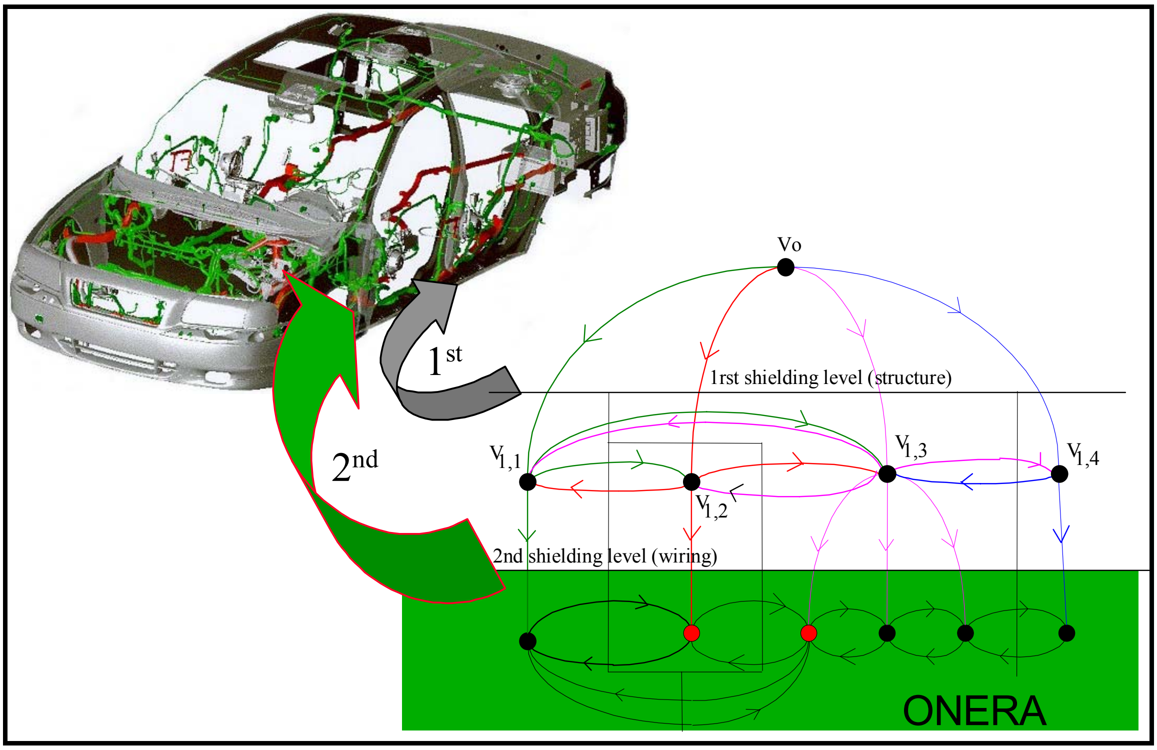


Fig. 3.13: Identification of topological shielding levels on the Volvo S8O car

Let us emphasize that this design approach is equally useful for experimental analysis. Without this approach the identification of the origin of a problem remains difficult, and sometimes impossible. The statement of such design principles may sound straightforward. Nevertheless, it is very easy to break these rules, thus producing a system decomposition that is not amenable to any form of EM analysis, either numerical or experimental.

3.3.6.2 The link between the topological levels

From the analysis of the topology leading to shielding levels, the link between each level is achievable through equivalent generators allowing the calculation of the response of the shielding level directly below it in the hierarchy (see Fig.3.14).

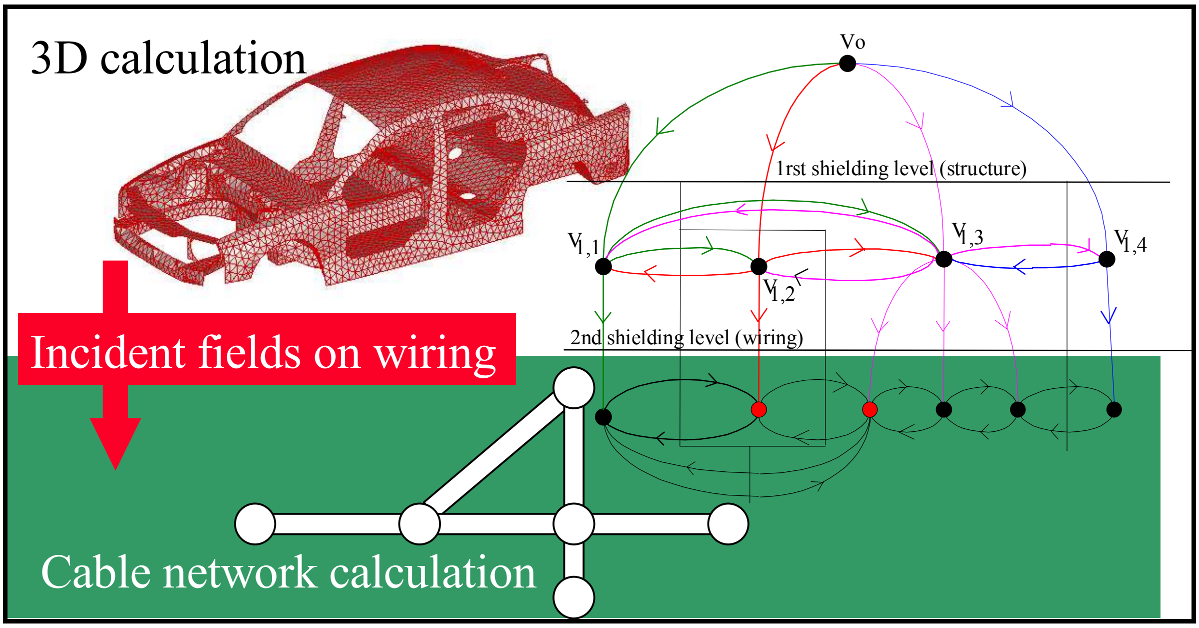


Fig. 3.14: Calculation strategy as related to the topological level decomposition

First shielding level

If the penetration points in the structure are small compared with the wavelength (e.g. small apertures), it is possible to separate the external problem (outside the structure from the internal problem (inside the structure). Equivalent sources may therefore be applied at aperture levels. These may be derived by short-circuiting the apertures, which provides complete separation between external and internal volumes. This kind of decomposed approach is generally well suited for EM hardened military systems. Nevertheless, it cannot be applied on a car because the openings are too large. So both external and internal volumes must be calculated at the same time using a 3D code, solving Maxwell's equations [46, 47]. This calculation must provide the equivalent generators distributed along the wiring, which are obtained by collecting the incident fields on the wiring path. It should be noted that the wiring is not present in this calculation.

Second shielding level

With the distributed generators, the response of the wiring may be derived using a cable network code. The calculation provides currents and voltages everywhere on the network, along each wire and particularly at the wiring terminals. If a precise linear description of the terminal circuit is available, this may also be included in the model. Otherwise, or if the circuit is non-linear, it is worth connecting a reference load at the terminals (typically 50 Ω) since the voltages on this load enable the derivation of Thévenin equivalent generators. For this the input impedance matrix of the wiring is required. This is obtained by an additional calculation resulting from compaction of the cable network to provide its equivalent S, Z or Y parameters. It should be noted that both the equivalent parameters and the Thévenin generators can be obtained from a single calculation on the network [38, 48].

In practice it is found that, the greater the complexity of the network, the higher the quality of the simulations. This is because modelling a single wire is more demanding than a whole multiconductor network, in terms of precision. Moreover, even if the local incident fields that are used to excite the cable network model are not perfect, the coupling onto the wiring provides a summation of the incident fields and so reduces the significance of the field errors in the computed network response.

Third shielding level

In GEMCAR, the third shielding level is associated with the circuitry at the wiring terminations. Thanks to the Thévenin equivalents calculated in the previous step with the cable network code, it is possible to calculate the response of each termination independently.

If the termination is a linear circuit, the calculation may be directly performed with the cable network tool, using its network modelling capability. If the circuit is non-linear, a convolution approach is generally required because of the wideband analysis. In all cases, the method suggested is to use electrical circuit codes with the Thévenin equivalents as inputs (see Fig. 3.13).

3.3.6.3 Approximations made

Except for the approximations made within the numerical models, no approximation is made in this methodology. In particular, the retroaction between shielding levels is implicitly taken into account in the equivalent generators. The retroaction could be calculated if necessary, but the order of magnitude of this retroaction is small compared to the direct excitation. For instance, once the response at the terminal is determined, it is possible to calculate the distribution of currents on the network and make them radiate in the 3D geometry to obtain the total field (ie. incident plus scattered) inside the vehicle.

This kind of approach must not be compared with the "good shielding approximation" which is suggested in the theory of EM Topology [31]. In this approximation, the retroaction is neglected, which makes the approach more suited for norm determinations than for precise calculations.

3.3.7 Conclusion

In this document, we have presented a number of strategies for maximizing the efficiency of electromagnetic simulations, and we have emphasized the value of combining different numerical methods. After having presented specific aspects of modelling the EMC performance of a system, we have also outlined the capabilities of currently available numerical techniques.
This led us to analyze how to improve the efficiency of the calculations made by one technique and how to combine those techniques. Consequently, a modelling methodology and a strategy of EM simulation of the coupling on a system have been suggested.

Nowadays, we can say that many numerical tools are mature enough to treat complex local problems, but they are still limited in their ability to treat large systems. In this case, one must consider combining different tools that are particularly well adapted to the resolution of specific problems. Typically, three types of numerical codes suitable for three types of problems have been identified. Firstly, 3D codes allow the calculation of 3D fields everywhere in a complex 3D structure. Secondly, the cable network codes calculate the response of a complex network, including the incident field along its paths. Thirdly, the electrical circuit codes allow calculation of the response at complex circuit terminations, including those with non-linear characteristics.

The strategy that we suggest for automotive and similar problems is based on the determination of equivalent generators at each shielding level (with respect to an EM topology terminology). It is important to note that different ways may lead to the determination of those generators. Some come from direct methods, but it can be also interesting to use indirect methods (based on reciprocity, for example).

The value of a decomposed approach is also that it is well suited for parametric analysis, since each level is calculated independently from the other. This also means that different partners in different companies can carry out the calculations. This may be of great interest if confidential information is needed concerning the vehicle geometry or the detailed design of an electronic system. The calculation may also be carried out on different computers. Concerning this point, only the 3D calculations require access to a high performance computer, whereas the cable network calculation and the electrical circuit calculation may be performed on more modest computers.

3.4 Practical Aspects of Vehicle EM Model Development

Even when suitable CAD data, modelling tools and computing resources are available, many practical difficulties and limitations remain for engineers attempting to build electromagnetic models of complex systems such as vehicles. This section discusses various practical issues concerned with the development of whole vehicle electromagnetic models, including the acquisition and processing of CAD data, identification of vehicle components that could be neglected from numerical models, and computational issues. The results presented here derive primarily from simulations carried out at MIRA on medium complexity TLM models, and measurements carried out by MIRA, Hevrox and CETIM (both which were initially directed towards identifying the geometrical requirements for the complex test case models). In addition the experience developed by MIRA and Ford in building vehicle models for Ford's pilot studies, and by EADS in simplifying the Volvo CAD data for the model validation studies, also contribute to this practical knowledge.

There is a considerable gulf between the availability of a 3D field modelling tool and the ability to build successful electromagnetic models of vehicles. In fact the detailed geometrical models of vehicles that are needed in order to build an acceptable discretized representation of the vehicle are only now becoming widely available. Furthermore, the computing resources that are needed to solve such models over the frequency ranges of interest, and in a time that is acceptable for industrial purposes, have only recently become affordable for more than a handful of potential users.

However, even when suitable CAD data, modelling tools and computing resources are available, many practical difficulties and limitations remain for those attempting to undertake computational electromagnetics (CEM) for complex systems such as vehicles. The process for CEM modelling, using any technique, comprises three main phases:

- pre-processing – in which a description of the geometry of interest is prepared for the specific simulation technique;
- simulation – in which the response to a specified excitation is computed;
- post-processing – in which the simulation output is worked into a form that is amenable to analysis.

Many of the practical difficulties that are encountered are generic, but some are also specific to particular types of modelling techniques. Consequently, the range of numerical methods that were used in the GEMCAR project was selected to be representative of the full range of techniques that are currently available.

3.4.1 Vehicle CAD import and meshing

There are modelling applications for which detailed representation of a specific vehicle is not necessary. For the investigation of particular vehicles, however, it is essential to have access to CAD geometry in order to develop an adequate electromagnetic model. Although many of the issues relating to CAD import and meshing are common to all numerical methods, some aspects are inevitably specific to particular techniques or groups of techniques. Both of these types of issue are outlined below.

3.4.1.1 Common issues

The first problem to be resolved in building electromagnetic models is to acquire geometrical data for parts that are of interest. A typical geometrical model for a vehicle is constructed from many thousands of sub-assemblies and lower order parts, most of which will not be of interest for electromagnetic models because they are either too small to be important or the materials from which they are formed are unlikely to be significant.

A preliminary filtering scheme that allows the unwanted parts to be rejected is desirable, and probably practicable, but would require the CAD database to be structured in a manner that would support the needs of this process. At present, however, this preliminary filtering normally requires manual inspection to identify parts that can be discarded (such as nuts, bolts, screws etc.).

A second stage of filtering is then required to identify which of the remaining parts can be neglected, perhaps because their surfaces are either coincident with or contained within other parts, or because they are not expected to be significant for the model application. An example of the latter could be a model intended for examining the fields inside the passenger compartment, for which the components inside the engine bay and underneath the bodyshell are not likely to be significant. It is not easy to see how this type of filtering could be automated, as it depends on the intended purpose of the model and the judgement of the analyst. Some aspects of the rationale for including or rejecting some of the larger components are discussed further in section 3 below.

After the geometrical data has been collated it is necessary to define a suitable meshing strategy, which meets the requirements of the selected numerical technique and the modelling application, and then impose this scheme on the geometrical model in order to obtain the discretized model needed to carry out simulations using the desired 3D field modelling technique.

An automated meshing algorithm generally requires coherent and unambiguous 3D geometry in order to generate a mesh successfully. This requirement, however, is not always easily satisfied. The main causes of problems with geometry include:

- poorly constructed geometrical models (3D models may that appear correct when drawn, but are not properly connected, contain duplicate entities etc.)
- defects introduced through translation (an intermediate file format is often needed where different tools are used for meshing and drawing), which may occur during both export and import
- geometrically complex features that the meshing algorithm cannot cope with

Poorly constructed models and overly complex features can be corrected, and many CAD products provide geometry repair tools to assist with this. The potential for corruption and incompatibility in data interchange can only be resolved through the use of intermediate geometry repair tools that can provide geometry that is acceptable for the meshing algorithm. These problems also afflict the more established automotive modelling disciplines, but are perhaps more acute for computational electromagnetics because much more of the vehicle geometry is required for these purposes. Thus, it is not currently possible to obtain all of the required geometry in a suitable state of topological integrity, and it is often found that CAD is not available for all of the parts that are required.

The ideal situation would be a unified process in which the CAD data is repaired to the point where it can be used as source material for any kind of numerical modelling, thus allowing suitable meshes to be derived directly from CAD with minimal manual intervention. In practice, the complexity of the problem is such that this is often not practicable, and considerable effort, often requiring several different software tools, remains necessary.

Although CAD is in many ways the most satisfactory starting point for mesh generation, it is also possible to use mesh data intended for other modelling disciplines (such as crash or aerodynamics models). It is not uncommon to find that, while there may not be CAD data for all vehicle parts, there are finite element meshes that have been manually generated for other purposes. It is possible to regenerate geometry from such meshes that can be used for further meshing. It is also possible to re-mesh the available mesh directly. The latter approach can be quicker than meshing directly from CAD, since the surfaces are already considerably simplified and the topological integrity of the existing mesh is guaranteed. It is expected that this type of approach will become more common in the future as re-use offers vehicle manufacturer the opportunity to extract the maximum value possible from their existing investments in CAD processing and mesh generation activities

These problems are not usually apparent in the simple examples that are normally demonstrated by software vendors. For a real vehicle, however, the number of surfaces to be processed will be ~10^5, which can take a considerable amount of time to process (perhaps even days) if the model is required for use at the low microwave frequencies that are now becoming of interest. Robust meshing algorithms, which will not fail as soon as they encounter the first topological ambiguity, are essential to treat CAD data of real-world complexity. The problem areas in the geometry may in fact only affect a very small proportion of the total mesh, and small spurious holes and missing parts can probably be tolerated without adding greatly to the existing model errors. Much greater approximations will almost certainly have already been introduced in order to make the development of the model practicable.

Where CAD data is available for the wiring harness, it is likely to be in the form of a 3D tube representing the path and diameter of the bundle, as well as associated features such as branches, connectors and mountings. However, this data is not sufficient for CEM models. The path data is useful for both integrated and separated cable models (for the latter the field along the harness path is obtained from 3D field models for use as input data for cable network models). Modelling the cable response requires further information, concerning the position of wires in the bundle, as well as their dimensions, material properties and termination impedances. This type of information is currently less readily available, and is subject to much more uncertainty than the vehicle geometry.

3.4.1.2 Particular issues

The numerical methods that were represented in the GEMCAR project included:

- boundary elements (BEM) in frequency domain;
- finite differences in time domain (FDTD);
- finite volumes in time domain (FVTD);
- method of moments (MoM) in frequency domain;
- transmission line matrix (TLM) in time domain.

In terms of the field modelling methods that are currently available, this list is fairly comprehensive but is by no means complete. However, the problems with these methods can be considered in terms of whether a body fitted mesh is used.

For surface meshing techniques, such as BEM, MoM and FVTD (which, like finite elements, requires a surface mesh to "seed" the unstructured volume mesh), the mesh reflects the topology of the surface, as illustrated in Fig. 3.15 below.

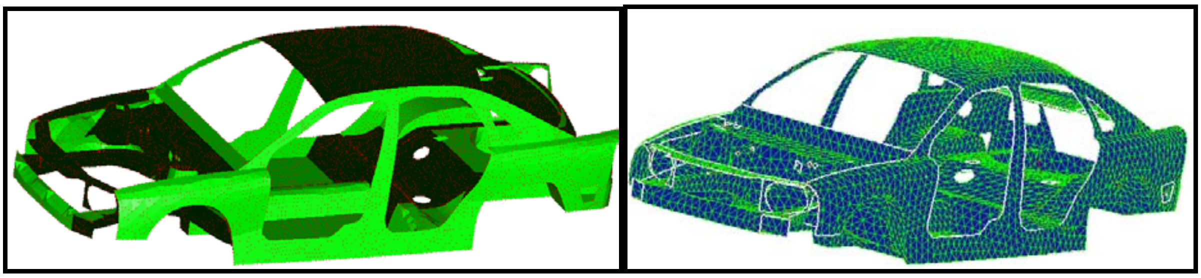


Fig. 3.15: Surface mesh for vehicle bodyshell derived from simplified CAD data (by EADS)

However, the computing requirements for the model increase very rapidly with the number of elements (and hence the number of surfaces) that are included in the model. Thus there are significant advantages in pre-processing the geometry to minimize both the number of surfaces and their complexity.

For volume meshing techniques based on a structured mesh (such as TLM and FDTD) the number of surfaces to be meshed has no impact on the computing requirements for the model, which are determined essentially by the cell size and the volume of space that is to be modelled (ie. by the total number of cells in the model). Thus, while there may be some merit in simplifying the surfaces (depending on the capabilities of the meshing algorithm) there is no advantage in limiting the number of surfaces. The main disadvantages of this type of approach is that the resulting model employs a "stair-cased" approximation to curved surfaces (see Fig. 3.16) and the finite volume of the model has to be truncated using some form absorbing boundary condition (which in practice will generally give rise to spurious boundary reflections).

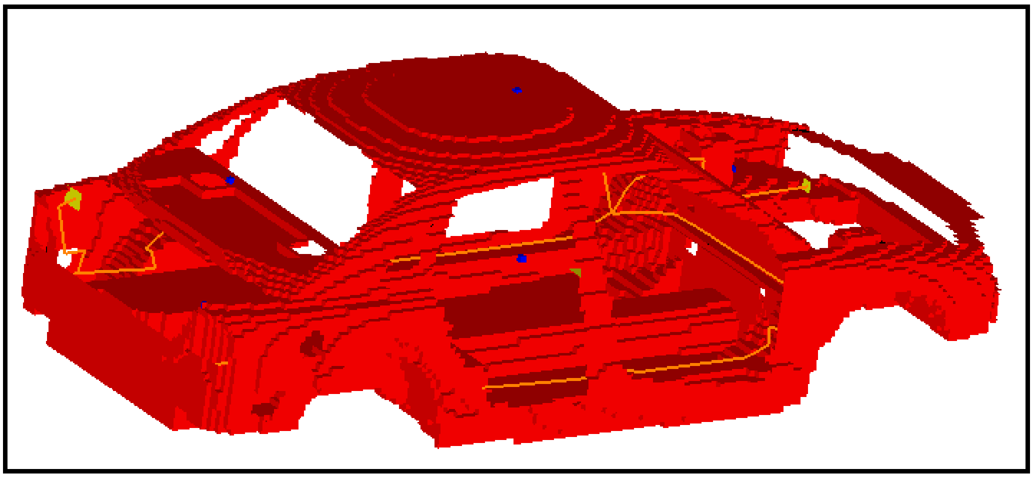


Fig. 3.16: TLM mesh for simplified bodyshell (with integrated harness model)

Thus, the surface meshing techniques are able to provide a body fitted mesh, but their ability to represent both the exterior surfaces (which determine the scattering from the vehicle) and the interior surfaces (which determine the internal resonances) is more limited. By contrast, the volume meshing techniques based on structured meshes can accommodate both the interior and exterior surfaces at negligible additional computing cost, but do not provide a smooth representation of these surfaces.

3.4.2 Vehicle model content

A complete model containing all parts of a vehicle is unlikely to be practicable for the foreseeable future due to the resulting model complexity and computing requirements. In addition, in many cases it may not be possible because the detailed geometry may not be available at the time that the model is required. Consequently, it is necessary to establish which parts of the vehicle must be present in the model in order to ensure that an adequate representation of the characteristics of the real vehicle can be obtained.

It seems reasonable to assume that many of the smaller items that are found in a complete vehicle, such as brackets and fixings, will have negligible impact on the electromagnetic characteristics. The vehicle can then be considered in terms of the following major groups of components, as follows:

- bodyshell (ie. chassis and metallic body panels);
- window glazing and associated parts;
- seats (largely metal frames with foam mouldings and leather or textile coverings);
- interior trim (carpets, instrument housing, plastic parts) and composite elements (eg. body panels);
- mechanical parts (engine, powertrain, suspension, brakes, tyres, brake pipes, exhaust etc.);
- electrical parts (ie. harness, modules and antennas).

The likely significance of these types of components for electromagnetic models of vehicles is discussed below.

3.4.2.1 Bodyshell

The main bulk of the body shell is the most fundamental element of the model. The outer surfaces will determine the scattering characteristics of the vehicle under external illumination, but the interior surfaces, which can be significantly displaced from the outer surfaces ($\Delta x \sim 0.1$ m for vehicle doors), will determine the internal resonances of the structure. Consequently, both the inner and outer surfaces are required in areas where their separation is significant.

For some applications (eg. installed performance of antennas [49]) it may be necessary to include thin slots around the periphery of vehicle doors. Vehicle body variants (hatchback, estate, convertible etc.) and optional structural features, such as a sunroof, also need to be taken into account in identifying the requirements for the model. Numerical studies [50] indicate that a sunroof may modify the field coupled into the interior of a vehicle by up to around 5 dB, while changes of 10-15 dB are likely in the fields radiated from internal sources.

3.4.2.2 Window glazing

Vehicles contain a large number of windows to ensure good driver visibility, but these features also provide significant field coupling paths between the interior and the environment. Moreover, it is increasingly common to add components such as heaters, antennas and solar screening to vehicle glazing.

(a) Simple glass windows

Although glazing materials have a relatively high dielectric constant ($\varepsilon_r \sim 7$ for typical glasses), the thickness of vehicle windows is sufficiently small to suggest that their effects will be minimal at frequencies up to 1 GHz. Comparative field measurements carried out with the side windows up and down show little difference between these two conditions [51], except in the upper part of the frequency band. However, at frequencies above 1 GHz even simple glazing may become significant for electromagnetic coupling. Theoretical estimates of the reflectance for a dielectric slab under plane wave at normal incidence are illustrated in Fig. 3.17, for representative single layer and laminated arrangements.

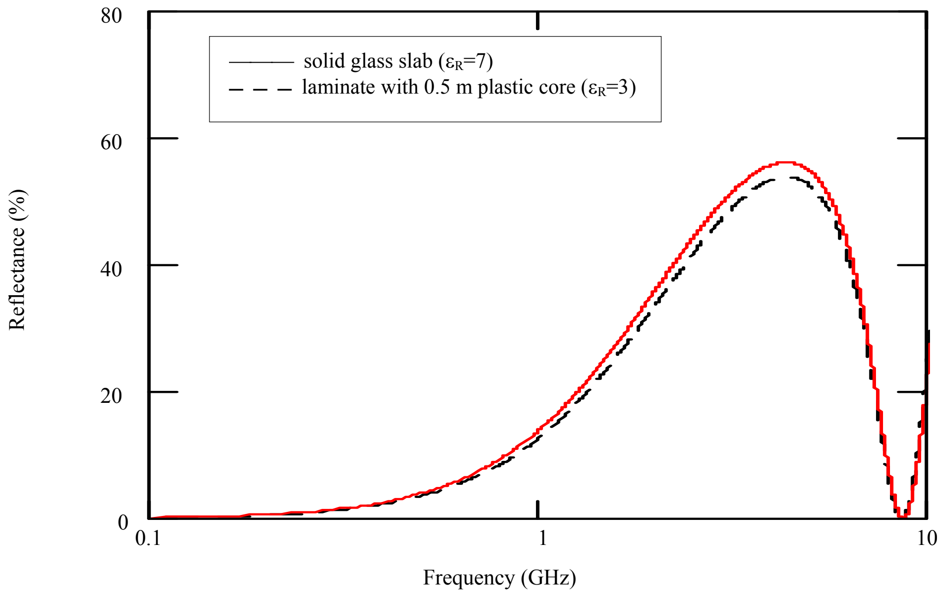


Fig. 3.17: Reflectance of 6.5 mm thick infinite dielectric slab under plane wave illumination at normal incidence

In general, therefore, it seems reasonable to ignore the vehicle glazing for frequencies up to 1 GHz where simple glass panels (including laminated structures) are present. However, not all windows are of such simple construction, as conductive materials and structures are commonly embedded in the glass.

(b) Heaters embedded in glazing

Embedded heating elements are commonly used in vehicle windows, usually in the form of simple arrays of conductors, to provide a demisting or de-icing function. Almost all vehicles are equipped with a heater for the rear window, usually in the form of an array of horizontal conductors, although more complex arrangements can also be found. A more recent development is the introduction of heating elements into the front windscreens of some vehicles, where a much denser array of fine vertical conductors is often used, which minimizes visual disruption for the driver.

At frequencies for which such arrays are relatively dense, field components that are co-linear with the conductors will be reflected while the orthogonal components will be transmitted. Measuring such effects is also not easy, because of the need to remove fixed glazing, but a representative numerical model can be used to assess the potential impact of such structures on vehicle emissions and immunity performance. However, numerical results [52] for typical heater geometries indicate that a windscreen heater has a more significant impact that a rear window heater and that the impact on emissions is greater than for immunity. It is also found that under illumination from the front of the vehicle, the field in the interior is predominantly vertical for both horizontally and vertically polarized sources. The effect of the rear window heater is therefore likely to be greater for horizontal illumination from the rear of the vehicle.

(c) Antennas embedded in glazing

Security and styling considerations, as well as the increasing numbers of antennas deployed on vehicles, make conformal designs increasingly attractive for automotive applications. These are often embedded in the window glazing, and are commonly integrated with the rear window heater array. Another location that is sometimes used is behind composite bumpers. At high frequencies the local dielectric material be significant for the performance of such antennas, but even at low frequencies (f ~ 100 MHz) where the material is electrically thin the effective dielectric constant is sufficient to modify the electrical length, and hence the performance characteristics, of the antenna. This effect has been shown by experimental methods [53] at VHF frequencies and in numerical models of an antenna at DAB (digital audio broadcast) frequencies [54]. Thus, the presence of the dielectric cannot be simply neglected in attempting to predict the installed performance characteristics of such antennas.

(d) Solar screening

In some cases conductive material is added to the glass in order to reduce the transmission of solar radiation (infra-red and ultra-violet) into the vehicle interior. Such schemes are implemented by doping the glass, by adding surface or embedded coatings, or by including a meshed structure. The latter is commonly used in sunroof glazing, while some laminated windscreens contain an embedded metallic layer. There is some anecdotal evidence to suggest that this type of solar screening may also influence the transmission properties of the glass at the lower frequencies of interest for EMC performance. However, it has not been possible to address these issues within the scope of the GEMCAR project.

3.4.3.3 Vehicle seats

Vehicle seats are normally constructed from a metal supporting frame, stiff plastic parts, shaped foam and a thin covering of some type of textile or leather. The rear seats are often of much simpler geometry than the front seats. The rear seats generally obtain their rigidity from the floor pan and a simple metal panel between the passenger cavity and the rear luggage space. The cushions are therefore largely shaped foam with very little metallic content (perhaps some wire stiffening adjacent to the metal panels). Their electromagnetic significance is therefore likely to be smaller than that of the front seats.

The front seats, by contrast, are much more complicated. The seat itself must provide rigidity for the user, including headrests, and numerous adjustment mechanisms are provided to maximize comfort. In addition, the seat may be fitted with heaters, motors, and even systems for assessing the mass of the user. Airbag modules are also found embedded in seat structures. The back of the seat is often constructed from a stiff but open frame, with thick wires running across the open central area to provide support. It would seem likely, therefore, that the front seats would have a very significant impact on the electromagnetic characteristics of a vehicle. Measurements of the field coupled into the region above the rear seat with and without the lower rear seat cushion in place indicate that this structure makes very little difference [51]. This suggests that all such foam and fabric structures within the vehicle can probably be neglected.

Although there are differences between the field and wire coupling results obtained with and without the seats, the impact of these structures is generally much smaller than expected. It appears that a model without the seats would give a good guide to the fields that would be seen above the seats and current levels that would be induced on harness elements running along floor pan adjacent to the doors. This suggests that even the front seats could be neglected in automotive CEM models for many applications. Nonetheless, they will be essential in models that aim to predict effects in areas that are either within or at least in very close proximity to the seat frames.

3.4.3.4 Interior trim and composite panels

The observations noted above concerning the impact of seats and window glass suggests that much of the interior trim of a vehicle can probably be neglected in vehicle models. Much of the plastic used inside vehicles is thinner than the window glass and is likely to have a smaller dielectric constant ($\varepsilon_r \sim 3$ for many such materials). Similar arguments probably apply composite body panels and bumpers, provided that antennas are not associated with such parts.

3.4.3.5 Mechanical components

Many major mechanical components represent large conductors, but their locations are such that their influence is likely to be rather limited in many modelling applications. The majority of the wiring harness and the electronic modules are located around the periphery of the passenger compartment, with some in the engine bay and rear luggage space.

There are often sensors and actuators, and therefore harness elements, associated with the braking system and perhaps even the suspension elements if the suspension system is active. Nonetheless, this represents a relatively small proportion of the total and the bodyshell and doors will provide some degree of isolation between the interior cavities and these under-body components.

The engine bay is packed with mechanical components of many kinds, including metal pipes, and also houses some of the key electrical components. The latter may include engine management systems in internal combustion vehicles, or electric motors and power conditioning electronics in electric vehicles. The associated wiring harness elements may also not meet the criteria for exploiting transmission line models in this area. The engine bay is therefore likely to present a significant challenge for electromagnetic models.

For models where the focus of interest is in the passenger compartment, most of the major mechanical components are probably of little importance except those associated with the steering column, which is inside the passenger cavity, and brackets and members that support the dashboard and instruments.

3.4.3.6 Electrical components

Including all of the electrical components in a single monolithic simulation is not practicable. It is possible to treat some elements separately, such as the harness and the modules, but this is unlikely to be the case for antennas, which can be significantly influenced by the vehicle geometry.

(a) Antennas

The installed performance of antennas can be profoundly influenced by the geometry of the vehicle. Such effects are very difficult to predict on the basis of simple arguments, but can significantly impact on system performance. Numerical models suggest that, even for very simple systems (ie. a monopole on the roof of a vehicle) the performance characteristics vary depending on where and how the antenna is mounted [56]. An electromagnetic model of the vehicle, augmented with representations of the vehicle antennas, is therefore needed in order to predict the installed performance characteristics of vehicle-mounted antennas. While this is relatively easy for traditional monopole antennas, there are considerable practical difficulties in developing suitable models for more sophisticated designs.

(b) Wiring harness

The wiring harness provides an important coupling path between the electronic modules on the vehicle, and between these modules and the external environment. Most automotive EMC problems are found to result from coupling via cables rather than direct field coupling to, or radiated emissions from, the modules.

Although it is possible to use thin wire models to produce an integrated model of the wiring harness in the structure (as illustrated in Fig. 2), there are a number of disadvantages in such models:

- additional mesh refinement may be required in order to place the wire in the desired position;
- there is likely to be considerable uncertainty about the geometry of the harness and its terminating impedances (which may well be frequency dependent);
- for time domain simulations, the presence of additional resonant structures may lead to a significant increase in the time required for the system response to decay.

The impact of uncertainties in the geometrical configuration and termination impedances can be investigated much more easily using transmission line network formalism. As much of the wiring harness is normally routed in close proximity to the conducting shell of a vehicle it meets the criteria for approximation as a transmission line structure, thus allowing separated methods [42] to be used. Using these methods, the results of a limited number of CEM simulations of the structure without the harness are combined with many smaller and faster network simulations [49, 55], thereby offering a much more efficient approach to the treatment of wiring harnesses.

This approach can be combined with any CEM technique, but depends upon the harness being sufficiently close to the vehicle shell for the transmission line approximation to be valid. In cases where these criteria are not met, which is likely to be found in areas such as the dashboard region and engine bay, it may be necessary to treat the harness element as an unintentional antenna, which will then require the harness element to be represented in the 3D field model.

(c) Electronic modules

The functional EMC performance of electronic modules is beyond the scope of the GEMCAR project. A separated modelling approach, with behavioural and circuit simulators exchanging data with electromagnetic models [49], is the most practicable approach for modelling functional EMC performance issues. However, some electronic modules may also modify the field distribution and these effects could be significant in some cases.

Including detailed models of electronic modules within whole vehicle electromagnetic models is not currently practicable because of the resulting computing requirements. Modules that are equipped with a screened enclosure could perhaps be represented using a simple conducting block. However, this is not characteristic of automotive modules. Most are without significant shielding structures, often comprising a single board in a dielectric enclosure, although some may have a substantial heat-sink that could also be approximated using a simple conducting block.

3.4.3 Computing issues

This section gives a brief overview of computing issues associated with the simulation and post-processing phases of the CEM process. The exact details of the type work that is involved, and the time that is needed to complete it, depend in detail on the modelling approach that is employed, the nature and scale of the system under investigation, and the capabilities of the hardware and software that are used to support these activities.

Possible generic schemes for undertaking CEM modelling of vehicle immunity issues are illustrated in Fig. 3.18 below. The basic options to obtain a frequency response are to use either a single time-domain 3D field simulation followed by a Fourier transform step (which normally has negligible computing cost), or to carry out many 3D field simulations at different frequencies. The 3D field models could include integrated cable models and/or field output along the harness path to allow transmission-line network codes to be used. The network calculations will also need to be carried out for many frequencies, and may include multiple runs to investigate the impact of uncertainties and variability in parameter such as termination impedance and cable geometry. Finally, the data from the field models and or network models will need to be collated and prepared for presentation in a format that best meets the requirements of the analysis task.

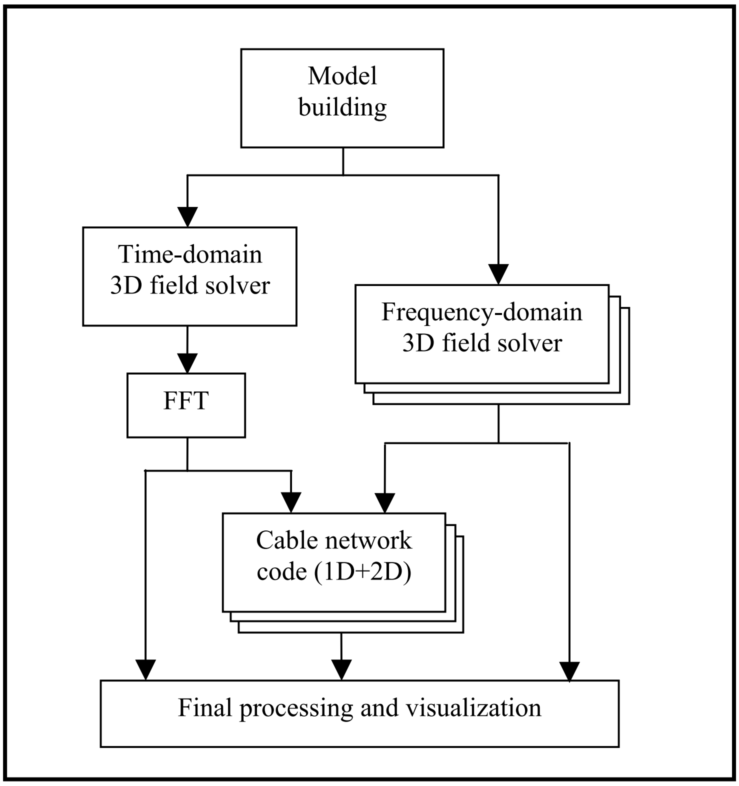


Fig. 3.18: Options for CEM analysis of immunity

Of the various tasks indicated in Fig. 4, the 3D field modelling stages will have the longest computing times, greatest memory requirements and produce the largest amount of output data (requiring Gigabytes of disk space if spatial field distributions are requested). Even using high performance computing resources (ie. running in parallel on several processors) such calculations are likely to take hours to complete and require in excess of 1 Gigabytes of memory for frequencies up to 1 GHz. Both the computing time and memory requirements will also increase rapidly with the maximum frequency of interest. In addition, these models would typically need to be repeated under several illumination configurations, representing those commonly used in physical tests (eg. horizontal and vertical polarizations from front and side).

The network models, by contract, require only modest amounts of memory (Megabytes), run in seconds or minutes and produce output files of negligible size. However, if many models are to be run (eg. to derive statistics relating to the variability of harness geometry and termination impedance) then the duration of this activity is likely to become comparable to that for the 3D field simulations. The volume of data that can result from such calculations is such that information overload is a potential problem that should not be underestimated. Thus, the time that is required to process the results of the simulations into a form that can be absorbed by the analyst and explained to non-specialists can also become a very significant part of the overall computing time.

3.4.5. Conclusions

Although an electromagnetic model is not the same as an EMC model, it is an essential element of EMC models. Such a model may also be useful in itself, for assessing EMC risk and installed antenna performance issues during the design stages of vehicle development. In the past, the availability of detailed CAD data, software tools and adequate computing resources severely limited the exploitation of CEM in automotive applications. However, as a result of recent developments in these areas, whole vehicle electromagnetic modelling is now a practicable proposition.

Nonetheless, even when suitable CAD data, modelling tools and computing resources are available, many practical difficulties and limitations remain for engineers attempting to build and interpret electromagnetic models of complex systems such as vehicles. Furthermore, the computing requirements for CEM models at this scale are not insignificant. There are no simple solutions to these problems, but an understanding of model requirements and limitations is essential to enable potential users to build and exploit vehicle CEM models with reasonable confidence in their results.

3.5 Model Validation Activities

The GEMCAR model validation activity was a long-term, background activity that was ongoing throughout the project. The validation of numerical electromagnetic models against experimental measurements represents an extremely important tool for establishing:

- the reliability of modelling tools and techniques;
- strategies for approximating real geometries;
- shortcomings in measurement methods.

In the context of the GEMCAR project, the emphasis was on the first two of these items, and the second one in particular. This required the combined simulation and measurement skills of EADS, EPFL, Hevrox, MIRA, ONERA and QinietiQ, with Volvo acting as a local interface with Volvo Cars.

This activity provided an important opportunity to investigate the practical issues associated with building electromagnetic models of vehicles and their wiring harnesses using a variety of well-established numerical techniques, as well as some more recent derivatives (see section 3.2). Furthermore, the measurements that were carried out in support of this activity also encompassed a wide range of typical test environments that are used for EMC measurements. This experience therefore provided an important source of material for the GEMCAR Guidelines, which are intended to address generic issues, rather than relating to specific tools and techniques. It should be noted that the motivation for this work was not to rank the various numerical and experimental methods that were investigated in the course of the project. There is no single numerical method that meets all of the requirements for EMC modelling, and all test methods similarly exhibit different merits and disadvantages. The objective of this work was to develop and share experience in the simulation of systems at realistic levels of complexity using a representative selection of established experimental and numerical methods.

3.5.1 Model validation strategy

The GEMCAR validation models were chosen to represent various levels of model complexity and physical test conditions, as outlined below.

3.5.1.1 Validation test cases

An important issue that the project attempted to address was how detailed a numerical model needs to be in order to be useful. A complete model containing all parts of a vehicle is unlikely to be practicable for the foreseeable future due to the computing resources needed for such models. In practice, for many applications it may not be possible to build a fully detailed model, as the final geometry may not be available at the time that the model results are required. Furthermore, the capability of different types of model to cope with fully detailed geometry also depends on the nature of the method.

The approach that was adopted in GEMCAR was to consider a range of validation test cases of increasing complexity based on a radiated immunity measurement scenario. These test cases included:

- the antennas used to illuminate the vehicle models, in a variety of environments;
- a “simple test case” (STC) comprising a vehicle bodyshell without doors containing a single conductor cable network together with a 2D arrangement of the cable on a ground plane;
- a “medium complexity test case” (MTC) comprising a vehicle bodyshell with doors containing a simple multi-conductor cable network;
- a complete vehicle (the “complex test case” – CTC).

3.5.1.2 Geometrical models

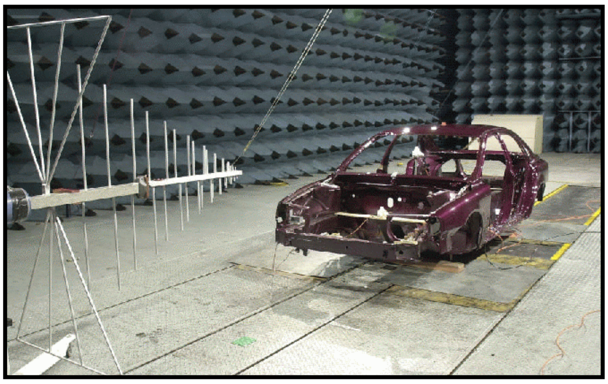
The test cases were based on a production vehicle for which CAD data and physical hardware were available. However, in order to ensure that vehicle models could be developed using all of the numerical methods the basis of the numerical models was a heavily simplified representation of the real vehicle geometry. This was carried out in order to remove some of the complexity of the real car, and thus reduce meshing problems. The full CAD data of the vehicle is many hundreds of megabytes, and some of the information contained in it is not required for electromagnetic modelling purposes (see section 3.4). The STC model was derived from the simplified geometry for the vehicle bodyshell without doors. Models for the more complex cases were generated by augmenting the STC geometry with further simplified geometry representing the doors (to produce the MTC) and the seats and steering gear (to produce the CTC). Consequently, it should be noted that the STC models are not particularly detailed, and the model fidelity declines further for the subsequent test cases. The selection of vehicle components to be included in the final model was based on experimental [57] and theoretical [58] investigations of the electromagnetic impact of vehicle components.

3.5.2 Measurement environments

3.5.2.1Fully anechoic chamber (Hevrox, CETIM)

A fully anechoic chamber (FAC) represents a free space environment. In this environment a log-periodic dipole array antenna (LPDA) was used to illuminate the vehicle for frequencies in the band 100-1000 MHz (see Fig. 319).

Fig. 3.19: Bodyshell in Hevrox FAC with horizontal LPDA



3.5.2.2 Semi-anechoic chamber (MIRA)

A semi-anechoic chamber (SAC) aims to represent the real environment in that the vehicle is placed on a conducting ground plane. In this case a biconilog antenna was used to illuminate the vehicle for the band 20-1000 MHz in the MIRA SAC (see Fig. 3.20), which has a working volume of 22x10x8 m^3.

Fig. 3.20: Bodyshell in MIRA SAC with vertical biconilog

3.5.2.3 EMP Simulator (EPFL)

The Swiss Defence Procurement Agency's EMP simulator *VERIFY* (Vertical EMP Radiating Indoor FacilitY, see Fig. 3.21), generates a vertically polarized electric field with a rise time of 0.9 ns and pulse-width of 24 ns. The working volume of the simulator is 4x4x2.5 m^3 and the maximum electric field amplitude is 100 kV/m. The uniformity of the field produced by the simulator was created by mapping the field at 1 m above the ground on a 1 m grid.

Fig. 3.21: Swiss *VERIFY* EMP simulation facility

35.2.4 Open area test site (QinetiQ)

Open area test sites (OATS) are not normally used for automotive immunity measurements. However, this type of test environment is still of interest, as it is routinely used for vehicle emissions testing.

Measurements on this site (see Fig. 3.22) employed the LPDA antenna (100-1000 MHz) that was used for the FAC measurements.

Fig. 3.22: QinetiQ open area test site (OATS)

3.5.3 Validation test configurations

Three types of tests, as well as corresponding numerical simulations, were carried out [59-60, 33, 61-62] for each of the validation test cases and selected test environments and their sources:

- Electric field coupling, in which the x, y and z components of the electric field were measured at various points inside the vehicle under external illumination.

- Cable coupling, in which induced currents and scattering parameters were measured at the terminals of the wiring under external illumination.
- Current injection, using an inductive injection probe to excite the network and measuring currents developed at the extremities of the harness when installed in the bodyshell (and at fixed height above a ground plane, for the STC single conductor network).

In automotive immunity measurements the antenna is placed very close to the vehicle [1] and the illuminating field is not a simple plane wave. For this reason, an appropriate antenna structure was also needed for the models representing the FAC, SAC and OATS measurement configurations. This, however, also required some additional preliminary validation activity in order to establish the quality of the antenna models that were needed for the vehicle models.

3.5.3.1 Antenna calibration

The preliminary antenna calibrations were carried out using a number of test points to provide samples over the volume that would be occupied by the vehicle (see Fig. 3.23 below).

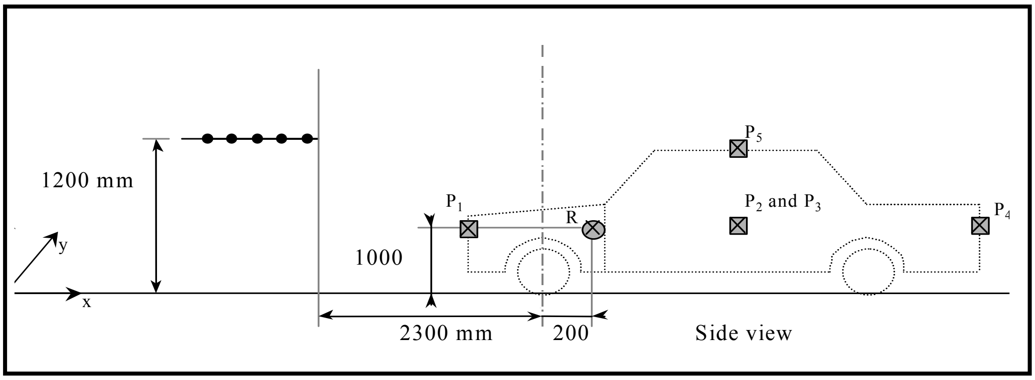


Fig. 3.23: Antenna calibration points over vehicle volume

In experimental validation, care is needed in the design of the experiment to ensure that the parameters that are to be used for comparison are directly comparable and can be measured reliably. A convenient approach for addressing both of these issues in comparing field distributions is to use the relative field strength between two points as the measure for comparison [63]. This effectively mirrors the approach that is used in automotive immunity measurements [1], where the fault level is described in terms of the field that would be generated in the empty chamber at a specific reference point with the same forward power delivered to the antenna. Normalizing the measured and computed fields to fields measured and computed at a common reference point in the empty environment (ie. a preliminary calibration of the antenna and environment) produces datasets that are directly comparable irrespective of the nature of the system excitation.

Thus, the simulations can be based on any type of field source that is convenient for the particular numerical technique, and measurements can use a variable power that ensures that the field is large enough to be measured reliably. A further benefit of this approach for measurement accuracy is that the normalization process will effectively remove any systematic errors, other than non-linearities, if the same probe (or a very similar one) is used for both measurement and calibration.

3.5.3.2 External illumination tests

For this type of test in the FAC and OATS, the antenna was placed in different positions and orientations relative to the vehicle. The SAC test configurations were based on standard requirements for automotive radiated immunity tests [1].

In the EMP simulator measurements, illumination from the front and side of the vehicle was used (vertical polarization only in these measurements).

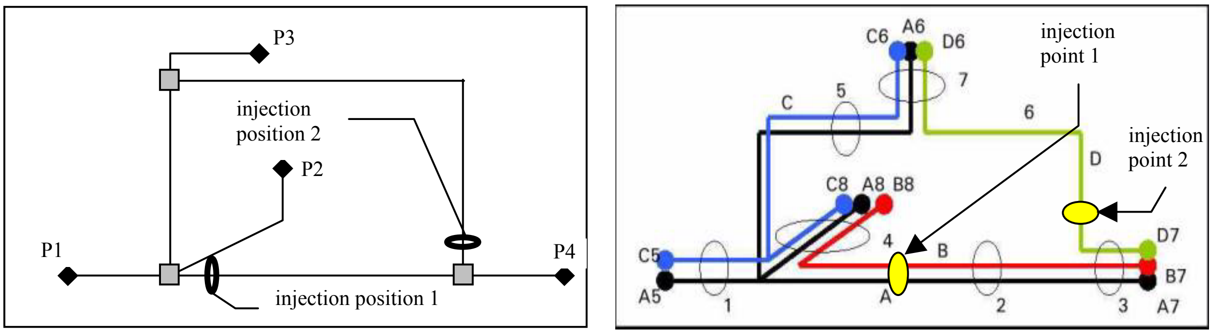
The points at which the field was monitored were located in the engine bay, passenger compartment and rear luggage space, as well as adjacent to the front and rear window apertures. The same points were used in the measurements carried out on the simple and medium complexity test cases. For the complex case, however, the presence of window glazing, interior trim and the engine resulted in the need to use a completely different set of measurement points, which were located in the passenger compartment only.

Induced currents and scattering parameters were measured at the terminations of the harness, and the same harness path and measurement locations were used for both the simple and medium complexity test cases. The network was terminated with 50 Ω coaxial connectors to allow measurements to be made and known loads to be applied. However, for the complex case a simple branched wire (again with coaxial terminations) was added to the real vehicle harness in order to allow measurements of cable coupling to be made.

3.5.3.3 Current injection tests

For these measurements, signals are coupled into the cable network by means of injection probe (FISHER F130 clamp). The measurements were carried out in the frequency range 0.1–400 MHz at 0 dBm incident power (CW). The cables and current clamp were calibrated using a vector network analyser and a calibration fixture (for the current clamp).

The topology for the STC harness is illustrated in Fig. 3.24(a), and the network was tested both in the vehicle and in a 2D configuration at fixed height above a ground plane. The MTC harness followed the same path in the vehicle as for the STC, but was augmented with additional cables to produce a simple multi-conductor network (see Fig. 3.24(b)). For each test configuration currents, voltages, and scattering parameters were measured with 50 Ω loads on all ports.



(a) STC, single conductor *(b) MTC, multiconductor*

Fig. 3.24: GEMCAR harness topology and current injection points

The simulation of such a test requires data concerning the current injection clamp, the wiring network and the loads. This information is used in multi-conductor transmission-line network codes such as ASERIS-NET and CRIPTE, which can simulate uniform transmission lines (LC matrix computation and solution of “Telegrapher’s Equations” in the frequency domain). For the computations it was assumed that the harness is at a constant height above a real ground plane. However, this was not achievable for the network installed in the car.

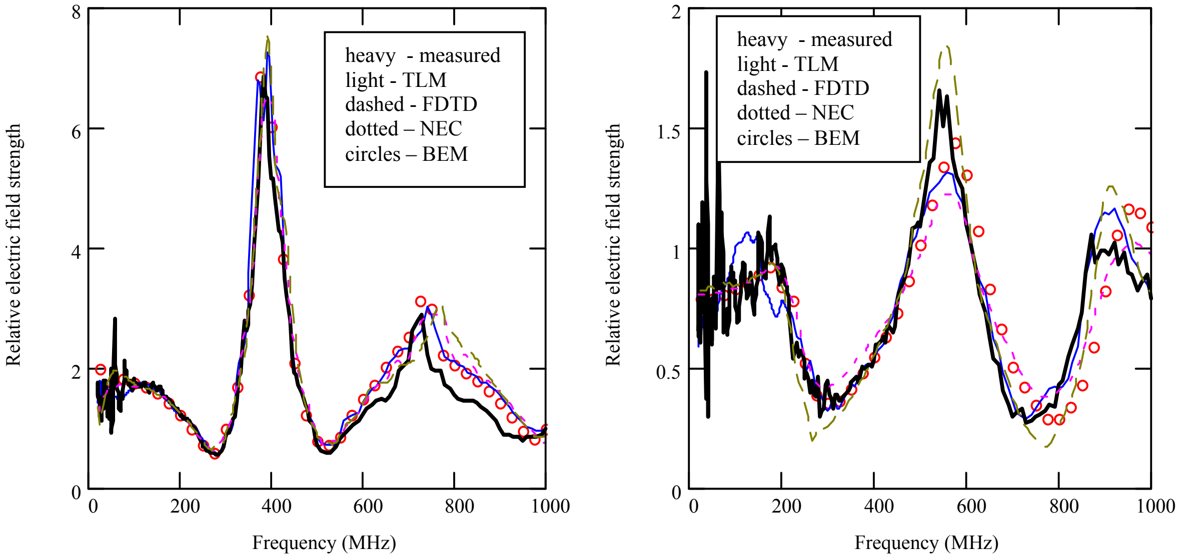
3.5.4 Model validation results

3.5.4.1 Antenna calibration

The results shown in Fig. 3.25 below compare simulations of the biconilog antenna in a semi-anechoic environment with corresponding measurements carried out in MIRA's SAC [59]. As a result of comparing normalized responses, the remaining discrepancies between models and measurements (apart from random noise) can probably be ascribed to the following sources:

- approximations in the antenna models;
- geometrical positioning errors in the models;
- field averaging in models (ie. FDTD and TLM);
- finite extent of the measurement probe;
- positioning errors during measurements;
- finite chamber wall reflections in measurements.

Evidence of the latter is clearly evident in the form of chamber resonances in the measurements below 100 MHz, where the absorber (1.8 m twisted pyramidal carbon-loaded foam) is too short to fully effective. The ripple that can be seen at frequencies of 100-300 MHz is probably a similar effect, but at a lower level as the absorber becomes more effective. However, it is not so easy to identify the impact of the other possible error sources.



(a) Horizontal polarization *(b) Vertical polarization*

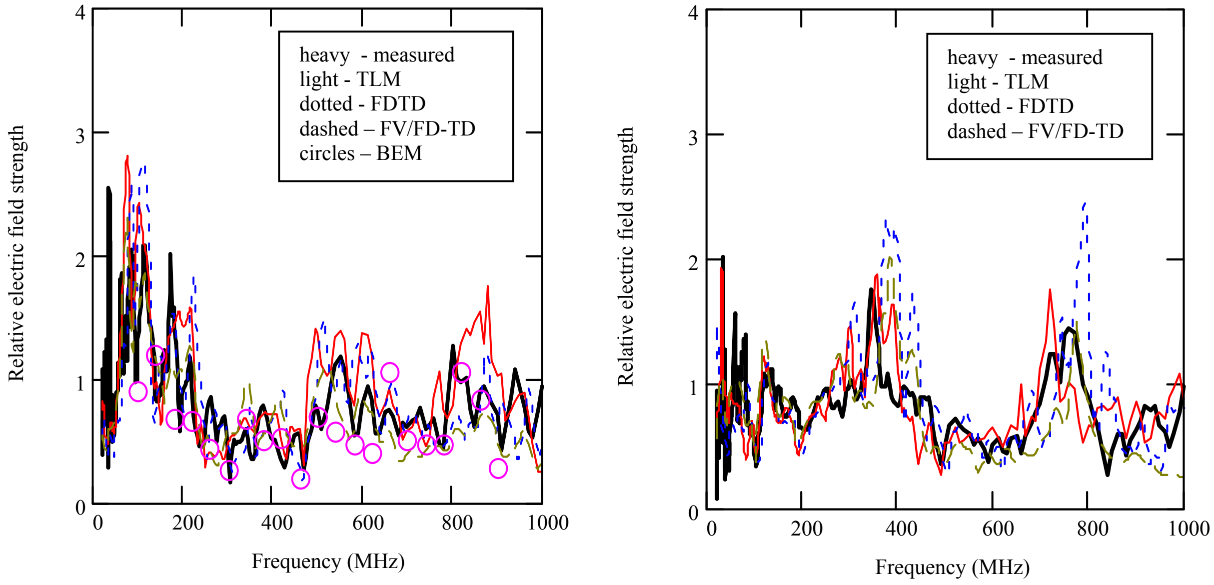
Fig. 3.25: Electric field at a point relative to that at reference point: for biconilog antenna above ground

It should be noted that the degree of correlation that can be obtained between the antenna models and the corresponding measurements represents a limitation to what can be expected for the more complex simulations that result from adding a vehicle to the model. Such investigations are therefore more about validating the antenna model than the system model that is actually of interest. In these models, however, the antenna model is likely to be poorer than could be achieved for the antenna alone because of the need to include the vehicle.

3.5.4.2 *External illumination*

(a) Field coupling

Sample results for two of the validation test configurations from several sources are illustrated in Fig. 3.26, for the STC vehicle. The underlying topology seen in the measurements is reflected in the models, although the fine details vary between the models as well as between the models and the simulations.



(a) Vertically polarized source at front *(b) Horizontally polarized source at side*

Fig. 3.26: Electric field at an internal point relative to that at reference point (SAC configuration)

Results obtained using NEC for the MTC vehicle are illustrated in Fig. 3.27, using a square wire-grid representation of the vehicle geometry derived from the TLM mesh, which is found to give better results over a wider frequency band than a body fitted mesh based on surface triangles.

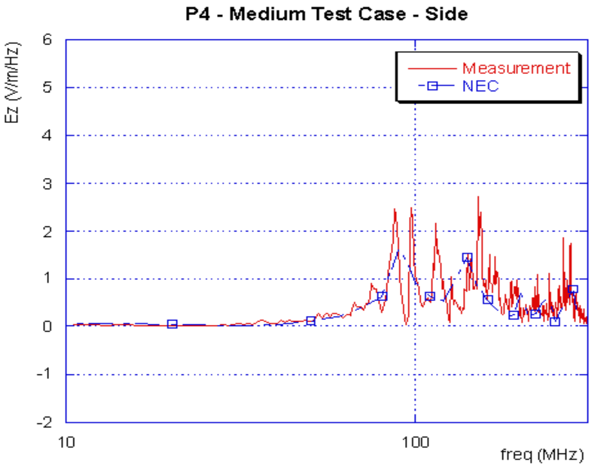
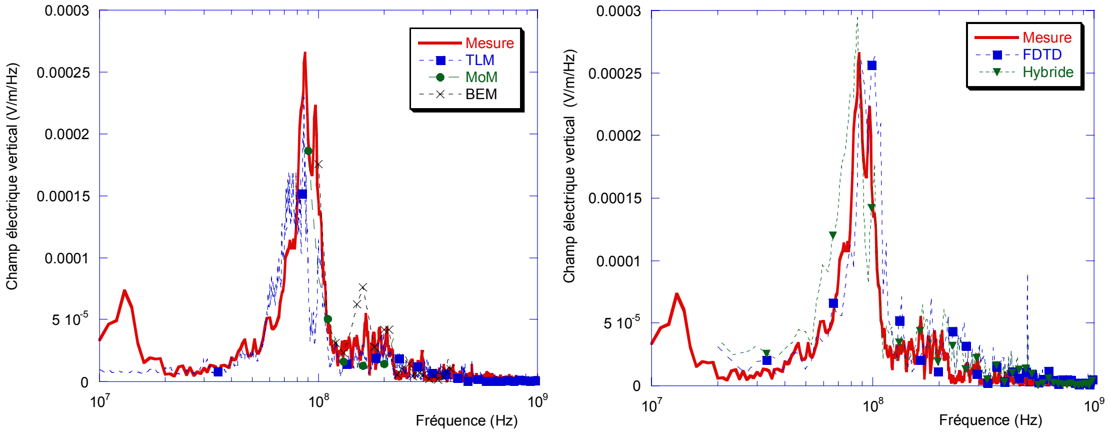


Fig. 3.27: Electric field at an internal point relative to that at reference point in MTC vehicle: NEC results

The EMP simulator was used to obtain measurements that could be compared with models using simple plane wave illumination, rather than needing an additional antenna model to act as the source. The results shown in Fig. 3.28 were obtained for the STC vehicle for vertical polarization incident from the front.



(a) TLM, MoM and BEM methods *(b) FDTD and FV/FD-TD hybrid methods*

Fig. 3.28: Coupling between biconilog antenna and sample port on multi-conductor harness in MTC vehicle: hybrid FV/FD-TD and cable network code

(b) Harness coupling

Sample results for the transmission coefficient between the biconilog antenna and ports on the harnesses installed in the vehicle are illustrated in Fig. 3.29, for the STC vehicle with single conductor network. The model results provide a reasonable indication of the levels and envelope of the response, although there are again differences in the fine detail.

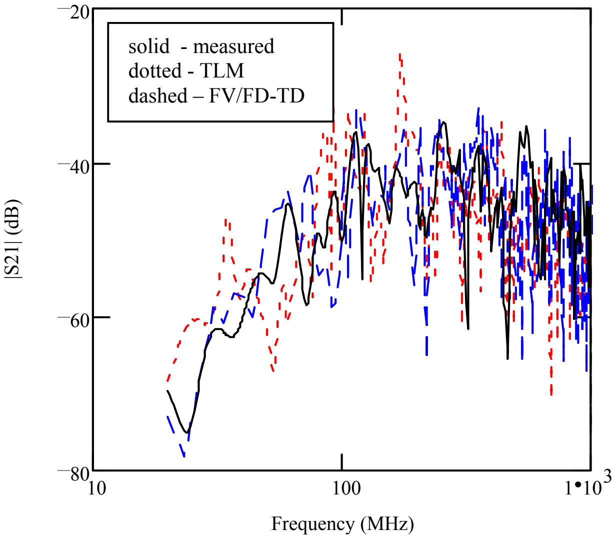


Fig. 3.29: Electric field at an internal point relative to that at reference point: horizontal source at side (SAC configuration)

The TLM results in Fig. 3.29 were derived using in integrated wire model in the full 3D simulation, while the FV/FD-TD results were obtained using a "separated" method [42]. In this approach, with respect to the simulation strategy proposed in GEMCAR (see section 3.3), the harness is not meshed and only the field distribution along the harness routes is calculated in the 3D simulation.

The incident fields are then used as voltage and current generators for the multiconductor transmission-line models that are used to determine the network response [33, 61-62]. Sample results obtained using the separated method are shown in Fig. 3.30, for the MTC vehicle with the multi-conductor cable network installed.

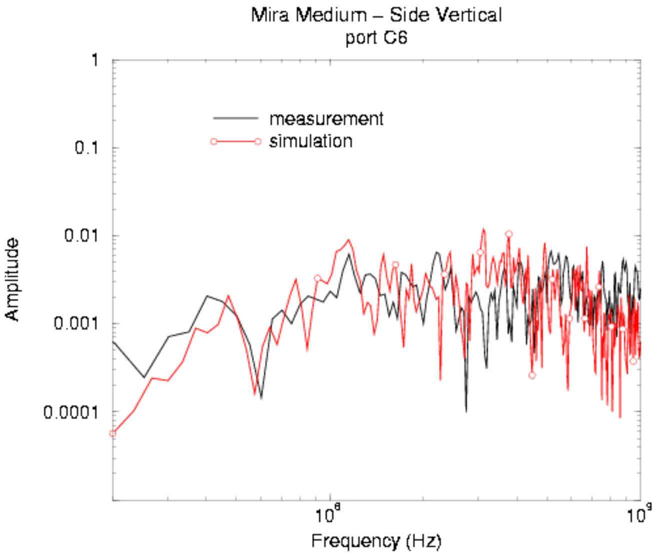
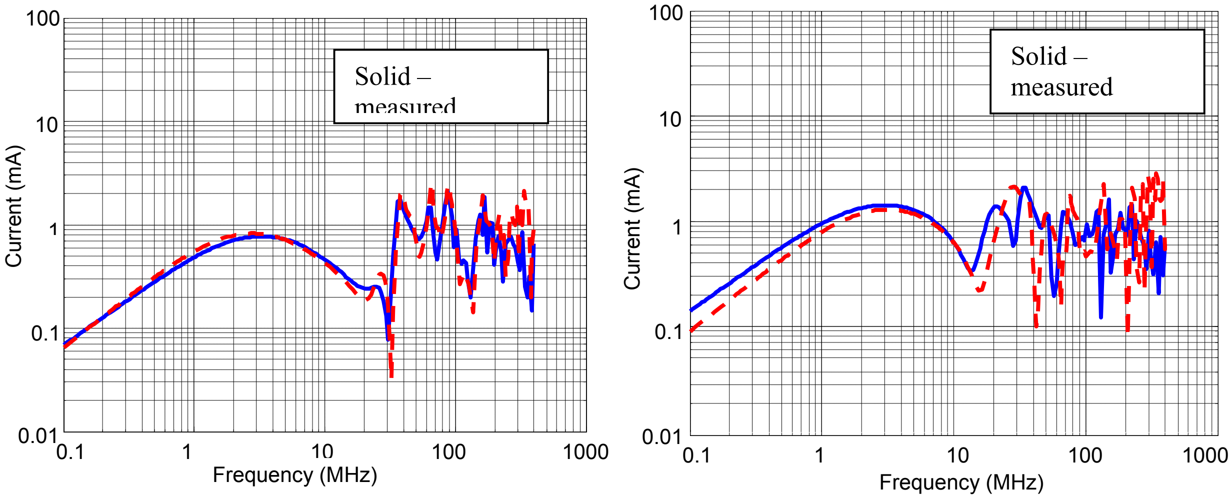


Fig. 3.30: Coupling between biconilog antenna and sample port on multi-conductor harness in MTC vehicle: hybrid FV/FD-TD and cable network code

(c) Current injection

In the case of current injection into cable networks it is not necessary to have a good model of the illuminating field or of its interaction with the vehicle structure. Network propagation effects dominate the coupling phenomena in this situation, so the impact of the structure is unlikely to be significant provided that the cable installation satisfies the requirements for the transmission line approximation. Thus, it would be expected that very good correlations should be possible between measurements and model results of this nature. This is illustrated in Fig. 3.31a below, which was derived for a 2D single conductor network at a fixed height of 3.5 cm above a conducting ground plane. Current injection results for the single conductor network in the STC vehicle are shown in Fig. 3.31b (this data is not for the same port injection/measurement configuration as Fig. 3.31a).



(a) Flat harness above ground plane (b) Harness in STC vehicle

Fig. 3.31: Current induced at a network port due to current injection for a 2D network at fixed height

3.5.5 Analysis of validation results

Detailed visual analysis of large volumes data is extremely difficult, resulting in a need for analytic techniques that can provide quantitative figures of merit to describe the degree of agreement between data that originate from different sources. The “feature selective validation” (FSV) technique [5] has therefore been used in GEMCAR in order to minimize the problems of information overload.

The FSV method is based on the derivation of two different measures based on amplitude differences (ADM) and feature differences (FDM) from each pair of datasets to be compared. These measures may also be combined (with appropriate weightings if so desired) to form an overall assessment of the comparison in question using a global difference measure (GDM). The FSV measures are actually frequency dependent parameters, but fewer values representing the overall quality of a comparison may also be derived with the aid of simple statistics. In this work simple average values for the FSV measures are used to reduce the volume of data to be considered.

3.5.5.1 Antenna model results

Values for the FSV GDM are shown for all possible pairs of measured and computed results in Table 1 [59], for one of the biconilog antenna calibration measurement configurations. The interpretation of the FSV measures is that zero represents a perfect match, while greater values indicate an increasingly poor match.

Table 3.9: GDM values for biconilog antenna in semi-anechoic environment

	FSV GDM values (averaged across the frequency band)									
	Horizontal polarization (Fig. 11)					**Vertical polarization (Fig. 12)**				
DATA	TLM	BEM	FDTD	MoM(1)	MoM(2)	TLM	BEM	FDTD	MoM(1)	MoM(2)
Measured	0.16	0.15	0.24	0.20	0.28	0.29	0.50	0.42	0.48	0.46
TLM		0.12	0.17	0.14	0.17		0.40	0.29	0.42	0.30
BE			0.19	0.16	0.21			0.43	0.28	0.28
FDTD				0.12	0.13				0.40	0.41
MoM(1)					0.13					0.34

In comparing numerical models one might reasonably expect that different models of the same system should produce nearly identical results. Slight differences might be expected, perhaps because of different meshing strategies, but since there are no experimental errors to contend with the results ought to be very similar. In practice, however, none of the models were able to capture the full geometry of the antenna, as the number of elements is large and their spacing is small to provide high frequency performance. Although all of the numerical models represented the same portion of the real antenna, there were also differences in the way that this was achieved.

In the TLM model both the dipole elements and the feeder bars are represented as bars, while in the BEM and FDTD and models the bars are solid bars but the dipoles are thin wires. There are also results for two slightly different MoM models, carried out by different groups (EPFL and MIRA) with each using different solvers. In the case denoted MoM(2) both the feeder bars and the elements are represented using thin wire models, but in MoM(1) the feeder bars are not represented at all and the dipole elements are in line rather than laterally displaced (in reality they are displaced to allow them to be connected to the feeder bars). In MoM(1), therefore, the real distributed feeding structure is not represented, while for the other methods it is present.

The TLM and FDTD meshes are truncated with absorbing boundary conditions, which is not necessary for the MoM and BEM models. Furthermore, the MoM and BEM models provide the field at an exact point, while for FDTD and TLM the field output is an average over the volume of the cell that most closely matches the location of the field output point. In practice therefore the results really represent a number of slightly different antennas, operating environments and measurement configurations, which explains the resulting spread that is observed in the results of the quantitative comparisons illustrated in Tables 1-2 above.

It is also notable that the correlation that is indicated between models and measurements is markedly poorer for vertical polarization than for horizontal polarization:

- Horizontal polarization - GDM: 0.15-0.28
- Vertical polarization - GDM: 0.29-0.5

However, the results are only slightly better between the various numerical models:

- Horizontal polarization - GDM: 0.12-0.21
- Vertical polarization - GDM: 0.28-0.43

The measured data could perhaps be affected by measurement difficulties, but the numerical models are identical except in the orientation of the antenna relative to the conducting plane. This therefore suggests that there is something in the nature of the results that makes the correlation measures differ between the two polarizations.

3.5.5.2 Vehicle model results

Sample FSV results derived from measured (SAC) and simulated data for the coupling of electric fields into the STC vehicle is summarized in Table 3 below.

Table 3.10: FSV data for field coupling results for STC vehicle

Reference Data	**Numerical Method**	**FSV values**		
		ADM	FDM	GDM
SAC	TLM	0.21	0.43	0.53
	FV/FDTD	0.26	0.47	0.59
	FDTD	0.23	0.49	0.58
TLM	FV/FDTD	0.15	0.33	0.43
	FDTD	0.19	0.32	0.43
FDTD	FV/FDTD	0.16	0.38	0.46

The results in Table 3 indicate that the amplitudes are in good agreement: the main differences between the various results are associated with details of the features. These results also show that the numerical results, whilst still divergent, are much closer to each other than to the measurements. This is almost certainly because the models are based on a common, but very heavily simplified, representation of the real vehicle geometry.

The FSV approach provides a considerable reduction in the volume of data to be considered in comparing large numbers of frequency responses. Nonetheless, it can be seen from Tables 3.9-3.10 that large numbers of FSV values still have to be assessed. Methods for achieving a more significant reduction in this data are therefore required.

An approach that has been adopted for this purpose in GEMCAR is to apply the FSV technique to composite results that can be obtained by averaging the modelled and measured results for a particular source polarization and field measurement point for example (see Figs. 3.32–3.33).

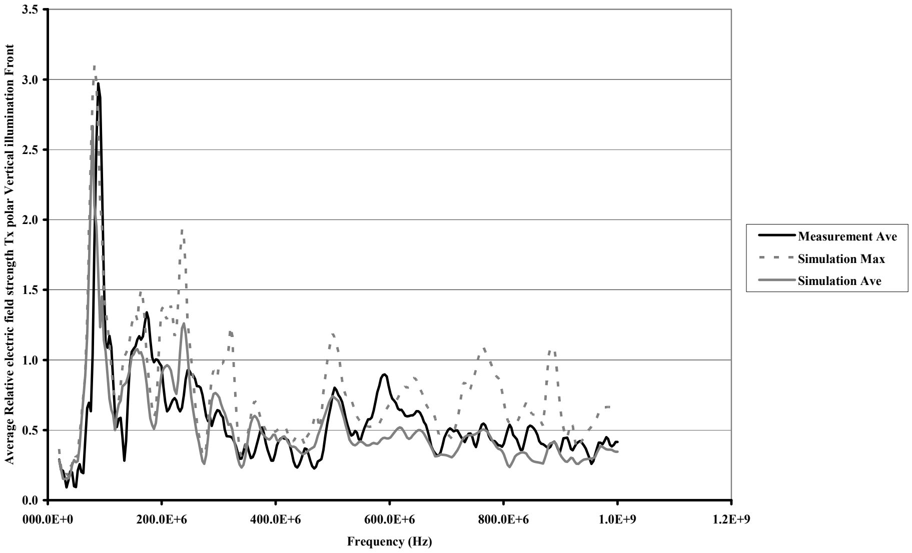


Fig. 3.32: Comparison of relative electric fields for vertical polarisation averaged over different semi-anechoic measurements and simulations: point TP4

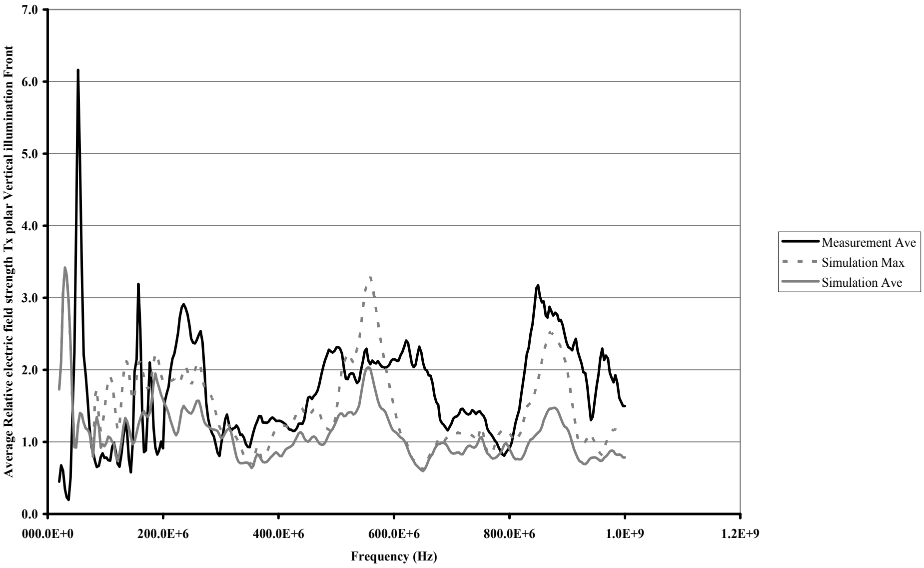


Fig. 3.33: Comparison of relative electric fields for vertical polarisation averaged over different semi-anechoic measurements and simulations: point TP8

Attempts have been made to link a subjective classification with the quantitative measures provided by the FSV method, as indicated in Table 3.11 below. The qualitative interpretation of the difference measures has been developed from a statistical analysis of the results of a series of selected visual assessments carried out by a group of experienced scientists and engineers. This is applied to any of the FSV measures.

It should be noted, however, that the experimental repeatability of measurements of this type is only "good" [64], and it would be unreasonable therefore to expect to obtain better levels of agreement than this. Thus, the subjective classifications that are proposed for the FSV measures do not provide an absolute scale.

Table 3.11: Subjective interpretation scale for FSV measures

Difference measure "x"	**"Quality" of comparison**
$0.000<x\leq0.025$	Ideal
$0.025<x\leq0.075$	Excellent
$0.075<x\leq0.15$	Very good
$0.15<x\leq0.30$	Good
$0.3<x\leq0.6$	Fair
$0.6<x\leq1.2$	Poor
$x>1.2$	Extremely poor

Sample results obtained from averaged results, including those illustrated in Figs. 3.32-3.33, as shown in Table 3.12 below. This data indicates a more optimistic view of the comparisons than that suggested by FSV results for individual test configurations and numerical methods. The results also confirm expectations of the accuracy of measurements in different locations. The test point TP4, for example, is located in the central region of the vehicle, while TP8 is located very close to the vehicle structure in the engine bay. The field gradients in the latter region will therefore be greater than in the former case.

Table 3.12: FSV results for vehicle models at various field monitoring points

Illumination configuration	**Electric field test point**	**Figures of merit (and classification)**		
		ADM	**FDM**	**GDM**
Front, vertical	TP4	0.11 (very good)	0.18 (good)	0.23 (good)
	TP7	0.19 (good)	0.24 (good)	0.32 (fair)
	TP8	0.26 (good)	0.39 (fair)	0.56 (fair)
Side, horizontal	TP3	0.27 (good)	0.36 (fair)	0.48 (fair)
	TP4	0.19 (good)	0.32 (fair)	0.41 (fair)
	TP7	0.21 (good)	0.28 (good)	0.39 (fair)
	TP8	0.31 (fair)	0.33 (fair)	0.58 (fair)
Side, vertical	TP7	0.17 (good)	0.40 (fair)	0.48 (fair)

As the field is likely to be less uniform over the finite volume of the measurement probe at point TP8 the “measured” field, which is interpreted in terms of an incident plane wave, will be less accurate than that measured at TP4, where the field distribution is likely to have greater uniformity over the volume sampled by the field probe. The point TP7 is located in the rear luggage space and is therefore closer to the vehicle structure. In this case, the FSV values lie between those obtained for points TP4 and TP8.

3.5.6 Conclusions

Sample results from the model validation activities carried out in connection with the GEMCAR project have been presented, including both direct comparisons between results and the results of analysis using the FSV approach. This work was primarily intended to support and inform the development of the GEMCAR Guidelines, which aim to be generic rather than targeted at a particular numerical method.

As a result of this, many compromises were necessary which limited the fidelity of the models to the real geometry of the systems on which the validation measurements were made. This inevitably impacted on the quality of the model validation results that were obtained. Nonetheless, the collective experience developed by the consortium in undertaking these validation exercises has proved to be extremely valuable for the development of the GEMCAR Guidelines.

Given the degree of simplification of the real vehicle geometry and the antenna construction, as the fact that the 3D harness path in the vehicle was extremely difficult to map with satisfactory accuracy, the quality of the validation results that have been obtained for the validation test cases based on external illumination conditions is considered to be reasonable. The results of the current injection test cases also indicate that the structure of the vehicle is of secondary importance in such cases. Thus, the results of the GEMCAR model validation activities have also proved to be of merit in establishing the capabilities of numerical methods in the analysis of vehicle-level EMC and related issues.

3.6 Exploitation of Simulation Data

The investigation of how best to adopt and exploit EM modelling in vehicle development processes was considered to be an important contribution to the Guidelines for many potential industrial users. This work as carried out primarily by Ford, Volvo and MIRA, with contributions from other members of the consortium.

Increasing competition in a global market is resulting in pressure on vehicle manufacturers to reduce the development time for new products in the automotive industry. In addition, more stringent legislation relating to vehicle emissions and operational safety, as well as demand for features to increase market appeal, are resulting in an enormous increase in the use of on-board electronic systems. This increased turnover of new vehicles, coupled with a greater number of product variants and higher electronic content, will result in a significant increase in demand for EMC testing unless alternative evaluation processes can be established.

Development cost and lead times in product development are two of the main factors that companies try to improve upon, resulting in a continuous enhancement of processes, practices, methods and tools is required. For this reason, modelling techniques are being used in the automotive industry for many different application areas, such as mechanical structures and aerodynamics. When introducing a modelling concept or tool, it is crucial to establish that the use of modelling can be shown to save time and/or money for the company, whilst providing verified sign off to the same level as traditional techniques.

3.6.1. The existing EMC process

The existing EMC process includes a number of tasks to ensure the compatibility of sub systems in the vehicles, as well as and compliance with legislative requirements for the compatibility of vehicles with their intended operating environment.

3.6.1.1 Specification

The EMC engineers set the EMC requirements specifications of the electronic parts. The requirements are set to at least follow the legal requirements but are most often more strictly set.

3.6.1.2 Testing

Testing is done to verify that the requirements are fulfilled. Emissions measurements are made on all components, whereas immunity is only tested if the component is considered to be safety critical, related to security or able to create customer dissatisfaction. Measurements on the complete vehicle are carried out to demonstrate compliance with legislative requirements and in order to identify possible performance defects in components/sub-systems.

3.6.1.3 Certification

Certification is carried out using pre-production vehicles, which are representative of the production vehicles. Vehicle certification bodies require a selection of vehicles covering all significant electronic control modules. This selection is based on 'worst-case' discussions but normally aims to test a permutation of engine types, transmissions and body shapes.

3.6.1.4 The status of EMC

EMC engineering has relatively low status in some companies, largely because it does not represent a functional “attribute” of the vehicle. EMC issues are mainly invisible to customers, provided that there are not any significant compatibility problems. Therefore, the development work relating to EMC can be slow due to lack of funding and relative priority for these activities.

3.6.2 The simulation process

Achieving full benefits of simulation processes is not trivial and it will inevitably take some time before the process is fully developed. The first simulations will be performed on simple structures with few components involved. Initially model building is likely to be time consuming and the results of the simulation might not be integrated in the design. Thus, potential cost savings are unlikely to be obtained from initial experiments.

3.6.2.1 Planning

A successful simulation activity starts with planning the integration of the simulation work within the vehicle development process. The necessary activities in the early stages of a project include:

- Allocate resources: human, software, hardware.
- Plan timing with CAD engineers.
- Plan feedback of results to CAD engineers.
- Identify necessary input data.
- Prepare model building.
- Plan exploitation of results.
- Plan interaction with system/sub-system supplier.
- Study earlier results.
- Study the existing development process.

3.6.2.2 Databases

CAD data are stored in different CAD databases. Simple CAD databases have no functionality and can thus not visualise the CAD drawings. More complex CAD databases with visualisation capabilities are linked to the different programs used for creating the CAD data. The use of different CAD tools will increase the time it takes to assemble a model but new intelligent databases that handle several types of CAD drawings are under development.

3.6.2.3 Validation and verification

When a simulation activity starts, the simulation engineer will interpret the simulation results together with EMC engineers. The experience of the EMC engineers and comparisons with tests will be useful tools in the verification of the simulation. When confidence in the simulation tools has been build up, the simulation engineer and the CAD engineers can handle the interpretation work together.

A mechanism for rapid feedback to CAD engineers, supplier and test engineers, through efficient information channels, is essential to make the simulation successful. The simulation results will inevitably be judged against other (often competing) requirements, with the result that priorities will have to be reassigned. The result of the simulations has to be documented in an easily accessible way. A data management system should be used for quickly documenting the results so that other departments in the development process can use it. A standardised simulation methodology will help since it will make the results in different projects easily comparable.

3.6.2.4 Testing

Simulations of full vehicles for improving tests are complex and will not be the first ones to be performed. Initially, the simulations will be used to compare with the tests to show the possibilities and the accuracy of the simulations. Therefore the simulations must take into account the full test rig with antenna and the possible reflections in the test chamber.

3.6.2.5 Certification

If full advantage of the simulation has to be realised, certification authorities and test houses must be part of the simulation process. Standardisation of simulation is one way of making the simulations accepted by authorities.

3.6.2.6 Timing

To be able to gain maximum impact with simulations, one should start the simulations as early in the development process as possible, when changes in the design are less costly. Since the design process (CAD data) will continue to evolve after the simulation engineer has received the CAD data, the simulation process has to be fast, otherwise the CAD design will be finished before the simulation results are available and the design that the simulation was set to affect has already settled.

3.6.3 Practical considerations

Among the main difficulties when introducing a new process that will involve people from different departments are differences in knowledge and attitude to the problem. As vehicle manufacturer have traditionally been mechanical companies the introduction of new processes related to electronics and computing can be a difficult and lengthy process. Engineers must develop a better understanding of both the benefits and limitations of simulations. Education is thus a key factor to moving from traditional methods, based on building prototypes, testing, correcting and then building new models, to new processes where many of the iterative loops are carried out using computer models.

In the automotive industry, new computational tools are judged in terms of two main aspects:

> *Capability*: It has to be shown that the proposed techniques are capable of solving the problems.
>
> *Maturity*: Use of the tools has to be considered as essential parts of the engineering process by both the users and their management.

In order to reach the stage of efficient use of modelling techniques it is necessary to:

- develop integrated design systems;
- introduce design processes in which the computational tools are integral parts;
- account for organisational and human aspects.

Since it is unlikely that the need for experimental verification will ever be completely removed, approaches are required that aim to improve the use and understanding of measured results, whilst minimising the overall volume of data that must be collected.

Based on past experience, the following key features are often regarded as crucial for successful product development:

- multi-disciplinary teams;
- cross-disciplinary communication and co-ordination;
- quality management methods;
- computer simulations of products and processes;
- integration of databases, application tools and user interfaces;
- education programs for employees at all levels;
- attitude from employees of ownership towards processes;
- commitment to continual improvement.

Thus, in addition to the purely technical issues, there are significant social and organisational aspects that must also be addressed in order to introduce new simulation techniques into the vehicle development process.

3.6.4 Who will perform the simulation?

A general trend in the automotive industry is for vehicle manufacturers to pass as much work as possible down to their suppliers. However, the EMC performance of a vehicle is dependent on the vehicle structure and the installation of the electronic systems, not just on the performance of the systems in isolation. Thus, it is unreasonable to place all responsibility for vehicle EMC performance onto the sub-system suppliers.

Building up a new competence in EM modelling might be considered costly, with the result that most work in this area has so far been carried out by specialist external partners. For such a consultant the flow of data has to be guaranteed in order to make the work smooth and fast. Even when the simulation is performed externally, the work has to be done in a close corporation with the vehicle EMC group so that they gain an understanding of how the simulation process works and what results can be obtained.

3.6.5 Applications and potential benefits

Because of the complexity of practical systems and the difficulty of obtaining theoretical models for such structures automotive EMC engineering has traditionally been a largely experimental activity. However, modern computing facilities are such that detailed modelling and simulation can now be considered for the analysis of EMC issues. This offers a variety of potential benefits to the industry, including:

- reduced reliance on experimental work;
- improved understanding of measurement techniques;
- faster evaluation of product variants;
- easier identification of potential problems in the early stages of design;
- the ability to investigate possible solutions to such problems;
- fewer programme scheduling difficulties if the need for testing can be minimised.

Numerical modelling techniques will also provide the ability to investigate issues relating to aspects such as sub-system immunity specifications, variations in harness design, and sensitivity to equipment location. Thus, it is anticipated that the increased use of EMC modelling by vehicle manufacturers will produce the following benefits for the customer:

- improved reliability of electronic systems (eg. engine management);
- enhanced confidence in safety related systems (eg. ABS, cruise control);
- fewer problems with the installation of after-market equipment;
- more competitive purchase price.

3.6.5.1 Cost savings

Potential cost savings are difficult to estimate in detail since many indirect factors influence the real cost for EMC. However, a number of areas can be identified where simulation is expected to result in a reduction of existing costs or the avoidance of additional costs.

(a) Improved specifications
Using simulation to develop more realistic requirement specifications at component and sub-system level could help to save costs by avoiding unnecessary materials, fabrication and development costs for those parts for which the installed environment is relatively benign.

In addition, requirements for late and costly alterations to parts that are subject to a more severe installed environment, which would not normally become known until prototype vehicles can be tested, may be avoided.

(b) Reduced test costs
It is not currently anticipated that numerical modelling could completely replace EMC testing in the automotive industry, due to the need to demonstrate compliance with legislative requirements. Nonetheless, it is expected that simulation will provide a cost effective replacement for at least some physical testing. This is a particularly important development, as the level of testing which is required is expected to grow significantly as a wider range of electronic systems, operating at ever higher frequencies and with increasing levels of integration, are expected to become standard equipment in future.

(c) Avoiding late changes
It is estimated that, in general terms, the cost for changes increases by a factor of ten for every milestone in the development phase that is passed. Thus, substantial savings can be made if the need for changes in the later stages of the development process can be avoided.

(d) Difficulties in quantifying cost savings
There are numerous difficulties in quantifying the costs savings that might be expected from EM modelling. These include:

- falling costs of computing resources;
- differences in the costing of computing between organisations;
- falling costs of model building activity, due to: increasing availability of CAD data;
- greater automation of the model building process;

- potential for reuse of results between different simulation disciplines;
- relative costs of different numerical methods (which may have significantly different computing requirements);
- differences in vehicle development programmes (particularly the number of variations on a basic vehicle);
- variability in test requirements (which depend on the number of systems on the vehicle).

For assessing a single system the overheads associated with the modelling approach are so high that testing is likely to represent a more acceptable alternative. In practice, however, manufacturers already need to assess several systems, and the level of electronic equipment fitted to vehicles continues to increase. Thus, the use of modelling could potentially lead to very significant cost savings, as well as easing the problems of matching test vehicles to the available chamber time.

3.6.5.2 Other benefits

There are other areas where simulation offers potential benefits that are not necessarily associated with direct cost savings. For example, simulation could be used to investigate and improve current immunity test methods. Simulation could also be used to investigate scenarios that are difficult or impossible to reproduce or emulate under laboratory conditions, as well as to provide data that it is not practicable to collect through physical testing. Installation of after-market components is a potential EMC problem since these products are not tested for functional safety and often have antennas, which can interfere with the standard components. Installations can be made safe if the vehicle manufacturer provides good recommendations for installation of these components. Simulations could thus be an important tool in finding out where and how additional antennas and electronic components should be installed.

3.6.6 Practical examples

This section of the paper discusses several practical examples of how simulation data is being exploited to assist vehicle development process. At this stage, these exercises are being conducted in parallel with normal processes in order to verify simulation tools and gain experience and confidence.

3.6.6.1 After-market radio transmitters & mobile phones

After-market radio transmitters and hand held mobile phones pose the largest risk of electromagnetic interference in modern vehicles. In particular, hand held mobile transmitters can be placed very close to vehicle electronics and could couple more energy to a victim system compared to strong fields emanating from outside the vehicle. Furthermore, the European Automotive EMC directive (95/54/EC) is currently under review and if the latest draft is adopted, vehicle manufacturers shall be obliged to publish information relating to on-board transmitters including frequency bands, power levels, antenna positions and installation provision. It is very difficult, if not impossible for a vehicle manufacturer to test for all possible combinations of equipment, frequencies, installation permutations and possible places where a user may place a phone. Typical radiated immunity tests for vehicles involve test with handheld mobiles, on-board transmitters and external (off-board) transmitters.

Simulations have been conducted to gain a better understanding of test coverage achieved by physical tests. The simulations focused on identifying module locations that would not be exposed to the maximum possible fields after all three types of tests compared to the worst-case conditions.

Sample results from these types of simulation are shown in Figs. 3.34-3.36, which compare field strength profile inside a vehicle when exposed to an external field, an onboard transmitter with external antenna and a hand held mobile phone. It can be seen that some parts of the vehicle are not exposed to the intended field strength but at the same time there are some parts which are in “hot-spots”. This increased understanding of field coverage will be used for determining which additional positions to test with mobile phones or where to install an on board antenna for actual tests.

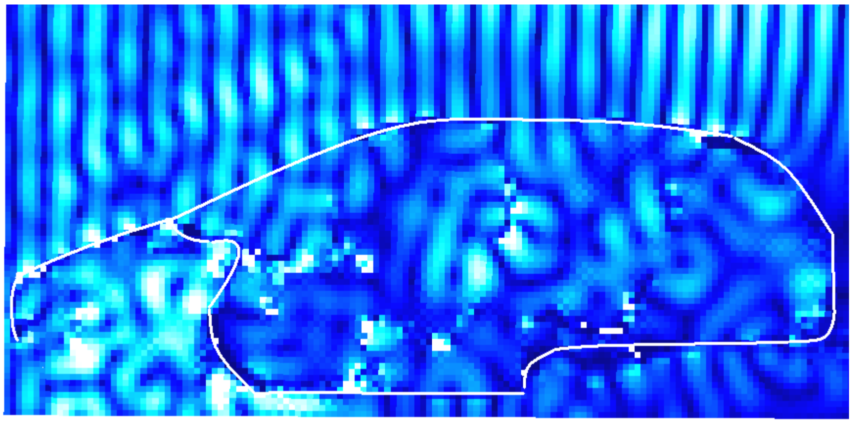


Fig. 3.34: Electric field distribution in a vehicle when exposed to a plane wave from a distant transmitter

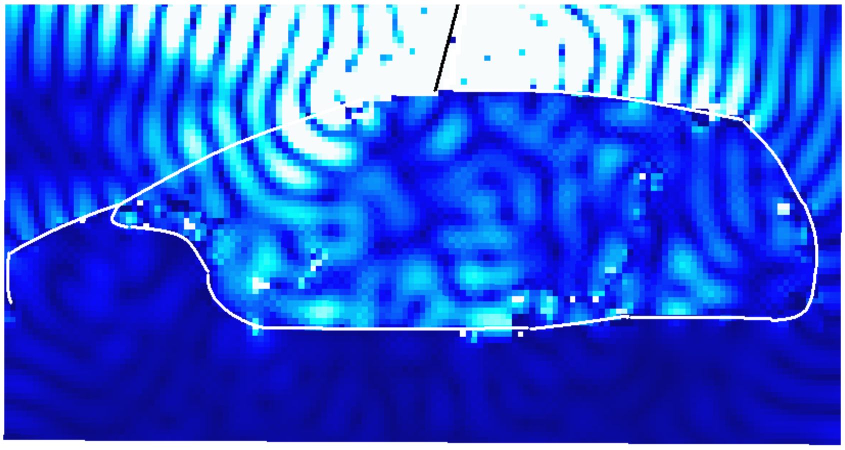


Fig. 3.35: Electric field strength profile in a vehicle when a transmitter installed on the roof is used

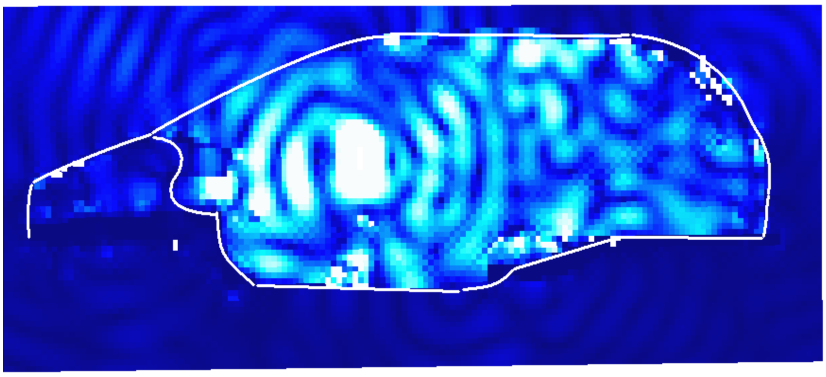


Fig. 3.36: Electric field strength profile in a vehicle when a handheld transmitter is used inside the vehicle

In summary, simulations will be used for:

- Identifying additional tests to be executed in order to ensure even coverage of all electronic systems.
- Eliminate tests that result in less severe conditions compared to other tests. For example if the combination of off-board and hand-held mobile phone test produces higher field intensity in all of the vehicle compared to an antenna located in the middle of the roof, this test can be eliminated.
- With respect to revised EMC directive, it may be possible to reduce on-board transmitter tests to few locations that will produce the worst case fields inside the vehicle cabin yet be able to issue a very detailed installation guide based on simulation data.

3.6.6.2 Vehicle packaging

Modern vehicles utilise highly complex body structures and the electromagnetic fields vary significantly around the vehicle. The simulation data provided by the analysis of the vehicle geometry early in the design cycle will be used for optimising locations of electronic components and harness routes.

One of the early targets for simulation is to support the robust packaging of electronic modules and sensors in addition to analysing the effects of potential harness routings. The position of relatively sensitive electronic components such as non-contact position sensors or radio receivers will be optimised wherever possible to utilise the natural distribution effects of the surrounding geometry.

Harness routings are normally defined solely by the mechanical criteria of the harness size, flexibility and the available package space. Simulation will drive a new set of harness routing guidelines that will encompass not only the mechanical limitations but also the coupling effects that the harness may experience. In some cases, it may not be possible to find alternative locations for parts predicted to be in EM hot spots. In these cases, additional steps such as higher levels of component immunity tests or preventative measures such as shielded cables or enclosures may be utilised.

3.6.6.3 Test Efficiency

Current practice for Radiated Immunity involves exposing vehicles to external interference from a few directions, roaming phones (mobile phones) in logical places and external antenna at 'typical' positions. This approach, combined with stringent tests at subsystem level, has been efficient in designing vehicles that are robust to external interference. However, increasing vehicle complexity, number of modules and more importantly vehicle shapes and variants mean that it is not economical to repeat traditional tests as listed above in all possible vehicle combinations. For example a modern mid-sized vehicle launched in 2003 will have in excess on 100 electronic components compared to 10-15 modules in the outgoing model.

Conducting EMC simulations to identify worst-case fields around the vehicle will help the development team to better direct tests. For example, it could be possible to use simulation data to compare test severity generated from different exposure directions for off-board immunity. It would be possible to establish if testing from a particular direction actually generates more stringent fields compared to the 'standard' exposure angle. Test can than be optimised for the worst case.

Another area where simulations will help is the test vehicle selection: current procedure for this test is merely based on engine type, transmission, body shape and vehicle trim level (base, high spec etc.). We are currently working to establish a better method of vehicle selection by using simulation.

3.6.6.4 Component tests

A further exploitation of simulation tools is envisaged in the area of component test methods for Radiated Immunity and Radiated Emissions. Vehicle manufacturers rely heavily on their suppliers to design and validate modules that are robust to external interference and do not produce excessive emissions. These parameters are communicated in EMC engineering specifications and verified through standard test procedures defined by international committees such as CISPR, SAE and ISO.

On close inspection, it can be seen that each test procedure attempts to "simulate" the vehicle environment. In some cases, test methods do not replicate vehicle environment very well, mainly due to fixed harness length and the presence of uniform ground plane specified in standards. As a result of this discrepancy, there are occasional cases where issues detected during a vehicle level test cannot be replicated at component level tests. Field strength data obtained by simulating component level radiated immunity test setup can be compared to vehicle simulations to establish compatibility to field strengths around proposed locations for modules. This information can enable vehicle manufacturers to better specify test severity levels for modules avoiding over or under testing.

Simulation tools can also be used very efficiently to better understand component level test. Simulation of component level tests are easier and require less computing resources compared to vehicles as these involve fixed geometries, such as a predefined size ground plane, 1m above the ground with few antenna types. For example, simulations have been conducted to identify the field distribution in the Triplate Line radiated immunity test fixture (as specified in SAE J1113-25). A plan view of the Triplate Line containing a device under test (DUT) is shown in Fig. 3.37 below. Simulation results shown in Fig. 3.38 indicated a large resonance in the noise induced to the wiring harness at around 25-30 MHz. This resonance was subsequently confirmed with measurements [65].

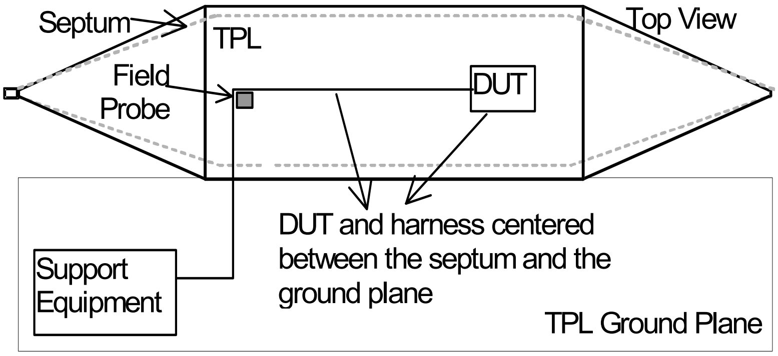


Fig. 3.37: Test configuration for component level radiated immunity using a Triplate line

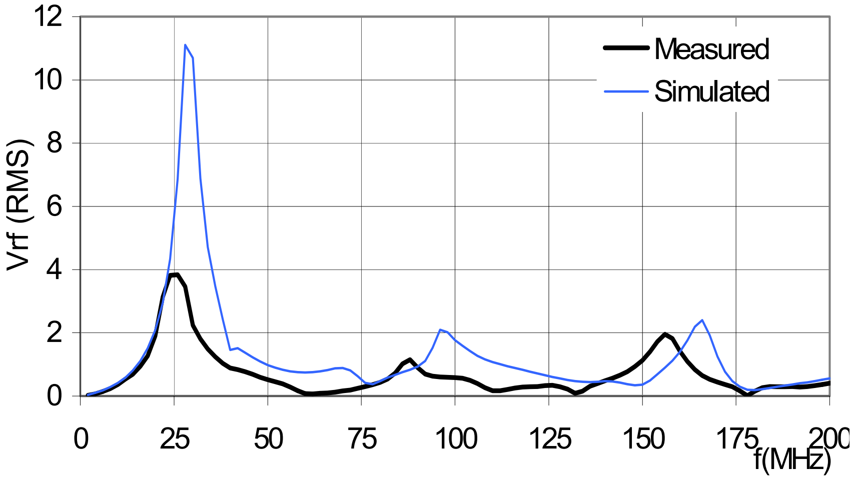


Fig. 3.38: Simulation and measurement of noise induced in wire during an immunity test sweep

This increased understanding is now being used when making decisions to rectify a problem observed during component tests at the resonance frequency of the test fixture. There is a big opportunity to simulate all tests with a view to improve test standards.

3.6.6.5 "Zonal" specifications

One of the most important parameters for automotive electronics is the operational environment at the component mounting location. Inadequate temperature rating could result in premature failure but over rating adds unnecessary cost so vehicle manufacturers carefully specify different ratings for modules based on where they are intended to be installed.

For example, a control module located inside the passenger cabin is not specified to meet the environmental conditions present in the engine compartment. However, this distinction is not currently used for EMC. There are many reasons for not doing so, including the need for the flexibility to move modules around the vehicle for packaging.

The technical limitation for not doing so is because vehicle manufacturers do not know enough about the EM environment of the vehicle. If it were possible to draw up a worst-case map of the vehicle EM environment, then it would be possible to specify several grades of immunity test levels. Vehicle manufacturers could optimise costs if the vehicle could reliably be divided in zones, as indicated in the Fig. 3.39 below, and produce requirements with varying severity.

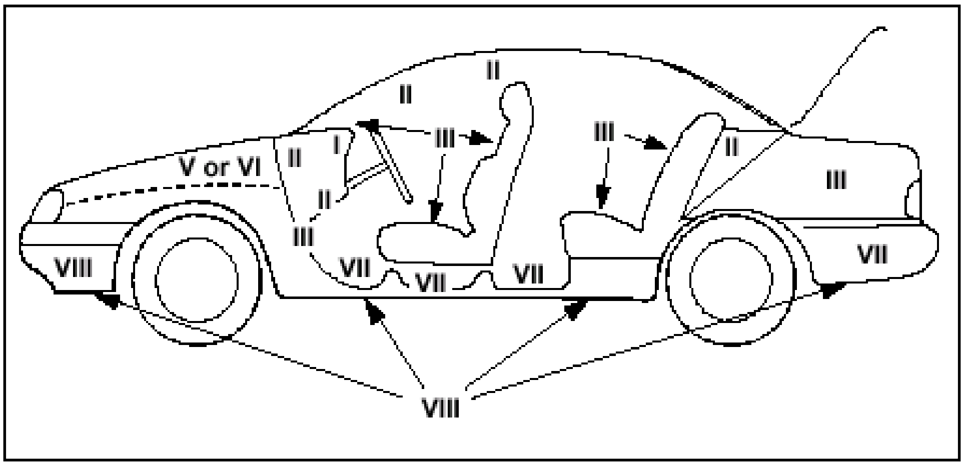


Fig. 3.39: Example of dividing vehicles into zones of varying EM field strength

Increased EMC robustness is not free; additional parts, development time and expertise in EMC design is required, all adding cost to final product. Optimising initial engineering specification can help manufacturers reduce costs without compromising safety.

The same argument can be applied to emissions; consider a module, which is intended to be positioned in the proximity of vehicle radio antenna (such as sun-roof control module in vehicle where the antenna is positioned in front of the sun-roof). Then consider an engine management module mounted in the engine compartment. Current approach is to specify that both modules meet the same radiated emission limit at component level. This approach results in either over engineering the engine control module or under engineering of the sun-roof module possibly resulting in radio interference when vehicle is tested.

If such zones are to be incorporated to vehicle development process, simulation is the only way to reliably achieve this. Testing and monitoring the whole volume of a vehicle for off-board and on-board sources to establish different EM zones is not possible as vehicles are not available when specifications are being written.

3.6.6.6 Education and communication.

One of the most difficult non-technical challenges faced by EMC engineers is the fact that not many people understand EM. It cannot be seen! It can be very difficult to convince other engineers and program managers who are focused on other targets to understand the consequences of certain actions. The visualisation of EM simulation results, such as vehicle body and colour field maps will go a long way to help other teams to identify and understand the potential risks posed by EM fields.

The benefits of well presented graphs and field plots showing the variation of EM fields both spatially and with frequency will also help EMC engineers themselves. Even the most experienced EMC engineer cannot claim to look at a vehicle and predict all hot spots and the level of coupling to harness.

In addition to the presentation of results to the engineers, the application of numerical methods and the modelling process itself can deliver a new level of understanding to those involved in this process. The ability for EMC engineers to sit with simulations engineers and review the model enables a deeper understanding of how the EM mechanisms interact and allows the true value of simulation to be explored.

3.6.6.7 Future opportunities

The long-term plan is to expand the use of simulation tools to component level development and to exchange information to optimise development. When the data exchange between vehicle manufacturer and module suppliers becomes formalised, consider this possibility:

Module suppliers are fully capable of simulating their test methods, including the level of emissions from a device and the level of interference induced during immunity tests. Vehicle manufacturers are also able to produce a detailed map of EM fields in their vehicle. When this data is exchanged the following possibilities become viable.

- Module suppliers provide models to the OEM which detail the emissions conducted into the harness of the module. The OEM can then simulate the potential coupling to a radio receiver.
- The OEM can provide the EM environment to supplier. The supplier can then adjust their tests to ensure the module would be robust in the vehicle specific environment, thus avoiding any surprises during vehicle level tests.
- Using the worst case EM field data provided by the OEM, the module supplier could simulate the response of their modules and correctly specify design severity during early development stages. This will assist in reducing the potential to "over engineer" the module for EMC performance.

3.6.7 Conclusions

Throughout this paper we have discussed the steps involved in the introduction of simulation tools into the vehicle development process. Many examples of opportunities to exploit simulation data to optimise and improve test coverage and to understand the weaknesses of test methods are discussed. A novel idea is also proposed to utilise simulation data to generate zonal specifications, with varying severity based on the expected EM environment in the vehicle packaging location.

3.7 Practical Evaluation of the Guidelines

CETIM (the Technical Centre for the Mechanical Engineering Industries) represents around 7000 French companies. Its main mission is to satisfy the research and development needs and associated technology transfer requirements of the French mechanical engineering industries. Since 1987 CETIM has developed knowledge to support French manufacturers in EMC design and compliance engineering. In particular, the manufacturers of mobile machine (agricultural, lifting and earth moving machinery) have expressed considerable interest in the use of simulation to support their EMC engineering activities. The main role of CETIM in GEMCAR was to undertake a practical evaluation of the Guidelines, as a “novice” user.

During the two first years of the project CETIM’s main role was to observe and understand the general GEMCAR activities. Since CETIM’s initial experience in EM modelling and simulation was very limited, this provided the opportunity to assess the available techniques. This observation and analysis of the partners’ activities permitted CETIM to anticipate potential problems and to identify the best people to work on the evaluation to be carried out at CETIM.

A further important effort has been to inform the French companies about the aims and objectives of the GEMCAR project, and to obtain the users requirement expression from some of them. A series of presentations were made to a number of relevant professional commissions in order to describe the progress and objectives of the project.

3.7.1 Application of the GEMCAR Guidelines

The user requirements expressed by a variety of organisations involved in EMC have been analysed and compared with the direct experience of our specialists. It was found that the immediate needs of mobile machine manufacturers are related to the requirements of the EMC and Machinery Directives. The expected contribution of EM modelling and simulation techniques is perceived to be in the development of knowledge concerning the distribution of EM fields in and around the machine. This information is expected to be of considerable benefit for the improvement of cabling strategies.

More efforts were necessary to convince French mobile machine manufacturers to participate in the GEMCAR project as suppliers of practical examples. Given the limited experience and lack of publications on EM modelling in the field of mobile machines the selection of a case study proved to be very difficult. Finally, two manufacturers accepted the invitation to collaborate and to provide real industrial examples.

The GEMCAR Guidelines enabled the CETIM engineers to increase their knowledge and understanding of existing EM modelling and simulation tools. The comparative tables provided for different EM modelling approaches (ie. volume or surface meshing, in time or frequency domain) provided an understanding of the relative merits and limitations of the different numerical techniques, as well as their computing requirements.

The experience of other partners had demonstrated that a crucial issue in EM modelling is in the exploitation of manufacturer's CAD data to develop the mesh representing the vehicle. The existing team EMC at CETIM has therefore been enhanced with an engineer with CAD skills. This engineer also had a significant role in the selection of suitable EM simulation software.

Meetings were organised with potential software suppliers from amongst the GEMCAR consortium. The capabilities and the match with the technical requirements were then analysed. The final choice of software for EM modelling was made with regard to following criteria:

- technical performance issues;
- match to existing CETIM CAD tools and skills;
- geographical factors (ie. language and location of software support staff).

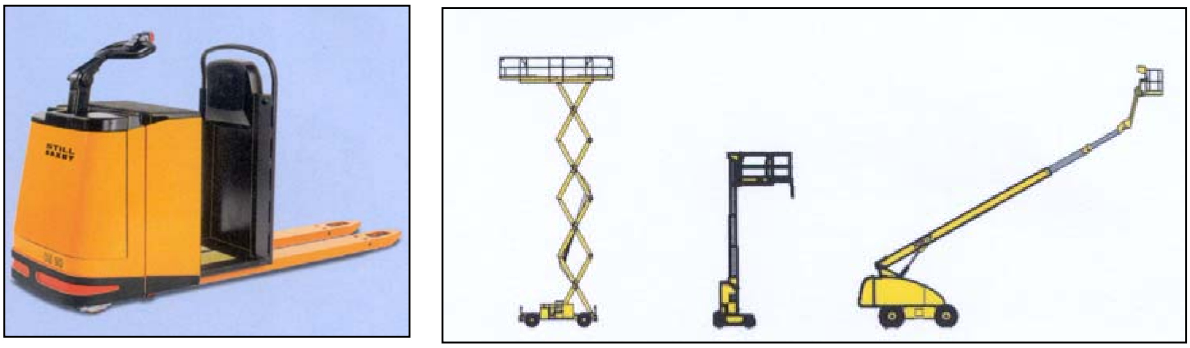
The offer of the consortium members to put EM modelling software at CETIM's disposal during the period of the evaluation tasks permitted us to delay the investment. The necessary training for the CETIM engineers, both EMC and CAD, was organized within the GEMCAR project.

A return on this experience was provided to the consortium in order to complete the guidelines with information about training aspects in terms of:

- minimum required skills;
- duration and cost;
- practical difficulties.

3.7.2 Practical case study

After consulting the members of consortium it was decided to begin with the modelling of a small industrial vehicle (a fork lift truck) rather than a large vehicle (the alternative was an aerial work platform with a 16 m vertical mast). These vehicles are illustrated in Fig. 3.40 Below.



(a) Lift truck : STILL *(b) Products of PINGUELLY HAULOTTE*

Fig. 3.40: Vehicle options for evaluation study

The use of STEP format CAD files from mobile machine manufacturer raised a number of problems:

- too many mechanical design details (eg. holes);
- how covert the STEP data to I-DEAS ".UNV" file format.

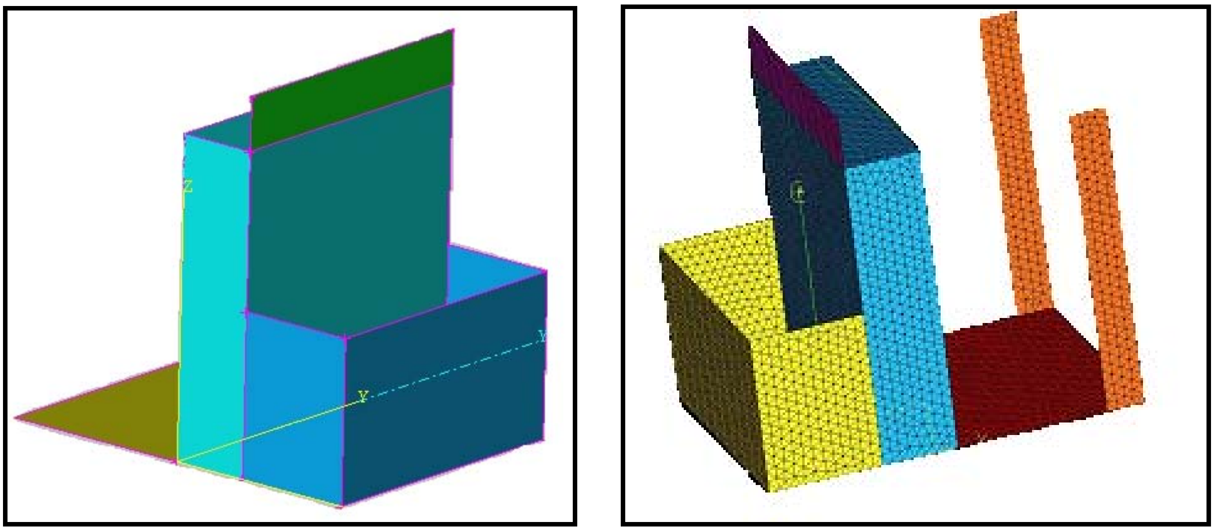
A two-stage approach was therefore adopted in the evaluation study, based on models of increasing complexity.

3.7.2.1 Simplified model

Inspired by the GEMCAR Guidelines, a simplified model was developed and meshed. It comprised:

- a ground plan representing the base of the machine
- a solid metallic parallelepiped (representing the battery compartment);
- an empty metallic compartment (containing supports for the electric motors);
- a central vertical metallic plate representing the support for the electrical and electronic parts;
- two vertical metallic plates for the rearward part of the machine (operator safety parts);
- the electrical harness between the steering gear and the electronics.

Both the synthetic geometry for the vehicle and the resulting surface mesh are illustrated in Fig. 3.41 below. The ASERIS–BE software was used to calculate the distribution of the EM field around the harness tube for two different positions. The illumination was implemented using both an ideal plane wave and the field produced by a model of the "EMCO 3109XP" antenna (operating over the frequency range 20-200 MHz). The ASERIS-NET software permitted the currents in the cable bundles to be estimated: for this purpose the output data obtained from ASERIS-BE were imported and used to excite the harness model.



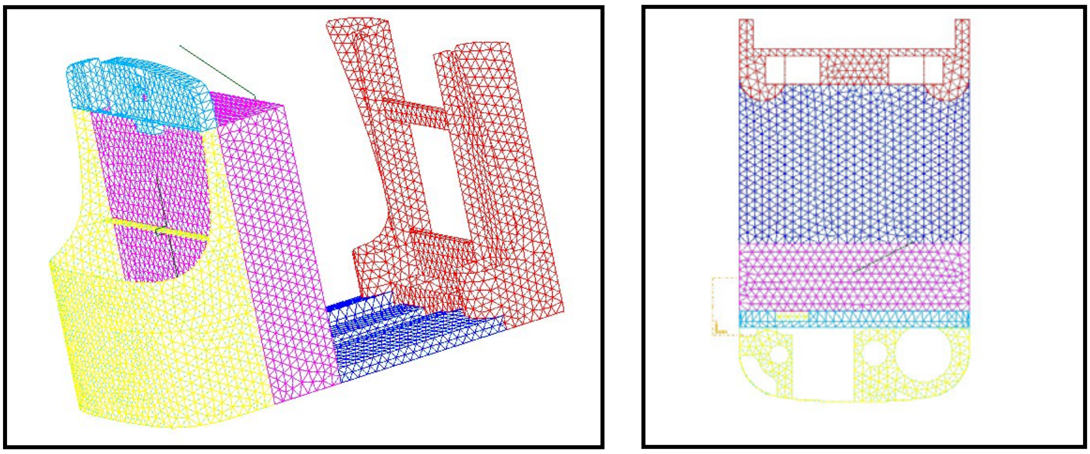
(a) Simplified surface description *(b) BEM mesh*

Fig. 3.41: Simplified model of fork-lift truck

3.7.2.2 Complex model

The STEP format CAD file, with small details removed, was used to build the more realistic "complex" model (see Fig. 3.42). The same calculations as in the simple case were also carried out for this model and the results compared. Computed surface currents for this model are illustrated in Fig. 3.43 below. Using the method indicated in the GEMCAR Guidelines, the global difference measure (GDM) reflecting the similarities between the simple and complex case results was estimated for predefined measurement points.

The influence of the rear metallic parts and of the electric motors (steering and traction) in the front compartment were estimated separately. In the frequency range under investigation in this work the screening effect of the vertical metallic parts behind the electric motors seemed to be more significant than the screening provided by the metallic parts of the motors themselves.



(a) View of complex model (without forks) *(b) Plan view of complex model*

Fig. 3.42: Complex model of fork-lift truck

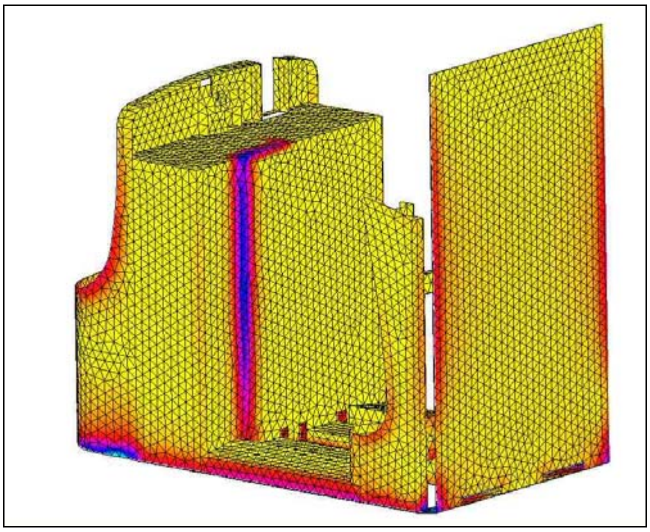


Fig. 3.43: Induced currents on complex model of fork-lift truck

3.7.2.3 Complete model

In a third stage and in a concern to take account of all the details of the lift truck likely to have an influence, we have added the forks, engine gearbox units and table to the average model, so as to generate the so-called "complete" model. It should be noted that we found that a table was included when STILL brought the truck prototype into CETIM's anechoic chamber. This is why the first-generation (simplified and average) models we made did not take the table into account. The prototype also allowed the model of the wiring route to be refined.

This model cannot be shown here for reasons of commercial confidentiality.

3.7.2.4 Complete model with antenna

A last model has been built that was the complete model including the modeling of the antenna used to make measurements in CETIM's anechoic chamber.

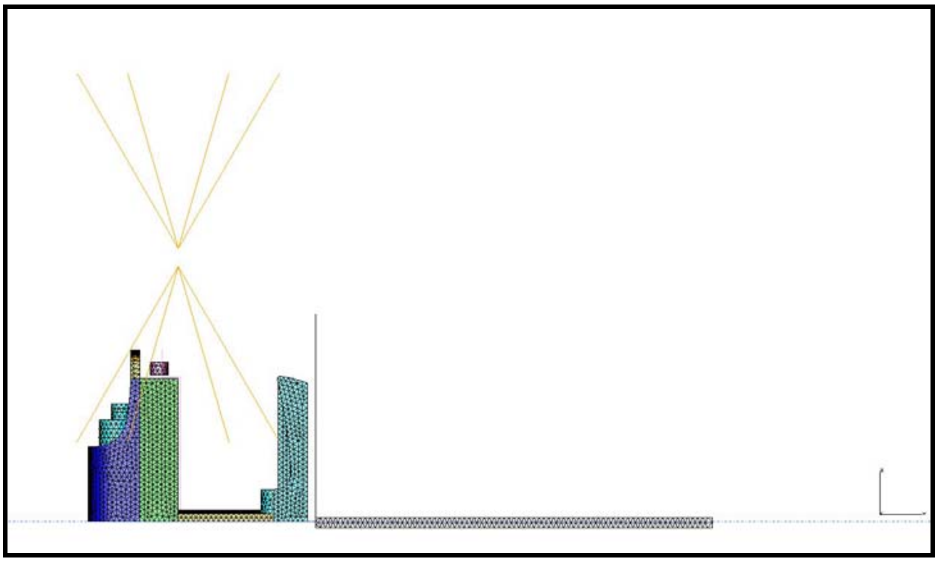


Fig. 3.44: Complete model with the antenna

3.7.2.5 Worst-case definition

The position and polarization of the illuminating antenna were varied in order to find the maximal values of the induced current in the harness. The highest induced currents were obtained under vertical illumination at particular frequencies.

3.7.2.6 Measurement of induced RF current

A prototype of the forklift truck was equipped with measurement wires terminated using three different load impedances: short circuit, 50 Ω and open circuit.

Measurements were made in a semi-anechoic chamber equipped with ferrite absorbers. The illumination conditions applied in the model were also applied in the measurements and currents were measured at positions on the wire corresponding with those used in the simulations.

3.7.3 Validation of the GEMCAR Guidelines

The criteria for the evaluation of the Guidelines were defined by CETIM after consulting various manufacturers of mobile machines:

- enhanced EMC performance;
- reduced development time and cost;
- avoidance of EMC problems.

All these criteria are satisfied and have been quantified.

The Guidelines have also been analysed by the manufacturers of mobile machines: they appreciated it and ask for more adapted information in accordance with their technical levels. The only criterion that is not addressed by the Guidelines is how one can correlate the simulation results with standard EMC test techniques and levels.

3.7.4 Conclusions

The general outlines proposed by the guideline have been observed and applied successfully. The main difference between CETIM's approach and the GEMCAR Guidelines consisted in the comparison of results between simple and complex cases and not systematically between measured and computed results.

The simulation permitted the manufacturer to define the optimal position of the harness and the type of cables to be used before having built the prototype. The definition of the "worst-case" also minimized the number of radiated immunity tests required, thus reducing certification costs, and consolidated the manufacturer's confidence in the safety and reliability of the vehicle.

CETIM's participation in this project created new skills for the company and permitted the dissemination of GEMCAR results to French manufacturers of mobile machines.

The Guidelines allow one to have a global view of the methods and techniques that are available for numerical modelling of EMC issues, and thus avoid many major obstacles.

4 Achievements and performance against plan

The achievements of the project, in terms of completed milestones, deliverables and the various dissemination activities that have been undertaken over the course of the project are outlined below. Deviations from the original project plan, resulting from both technical problems and various logistical difficulties, as well as in terms of manpower and budget consumed are also summarized.

4.1 Milestones and deliverables

Summaries of the milestones and deliverables that were identified in the project workplan are given in Tables 4.1-4.2 below. Some of the activities were modified and re-scheduled in the course of the project, as a result of various unforeseen difficulties that arose as the project progressed. However, the due dates shown in Tables 4.1-4.2 are those that were originally proposed in the workplan at the beginning of the project. In addition, the most recently updated version of the project plan is given in Annex 2 of this report.

TABLE 4.1: GEMCAR PROJECT MILESTONES

Milestone Nr.	Due date (delivered)	Brief description of milestone objectives	Decision criteria for assessment
1	month 4 (month 6)	Requirements defined	Requirements document agreed and issued
2	month 14 (month 20)	Simple test case successful	FSV difference measures ≤0.3 demonstrated for validation data (equivalent to experimental repeatability for field measurements) FSV difference measures ≤0.15 demonstrated for numerical results
3	month 18 (month 18)	Guidelines in progress	Preliminary guidelines available on internet
4	month 22 (month 30)	Medium complexity test case successful	FSV difference measures ≤0.6 demonstrated for validation data (equivalent to experimental repeatability for field measurements) FSV difference measures ≤0.3 demonstrated for numerical results
5	month 28 (month 31)	Routes for exploitation of simulation techniques identified and quantified	Potential for reduction in vehicle EMC immunity test costs of 30% demonstrated Methodology for integrating electromagnetic modelling into vehicle development defined
6	month 34 (month 39)	Guidelines complete	Final issue of guidelines available on internet

TABLE 4.2: SUMMARY OF FINAL STATUS OF DELIVERABLES

Nr.	Description	Due date	Expected/ actual date	Delay (months)	Comments
1	Requirements Specification (non-confidential)	1/5/00	7/7/00	2	Document made available via project web site
2	Geometry and hardware for simple test case	1/5/00	1/10/00	5	Vehicle hardware available on time, geometry release delayed
3	Definition of format for guidelines	1/7/00	1/7/00	0	Preliminary definition agreed at 2nd Steering Committee meeting
4	Test plans and test equipment models	1/7/00	1/8/00	1	Some effort postponed for changes in higher complexity test cases
5	Simple test case measurement data	1/9/00	1/10/00	1	Measurements completed at all sites
6	Hardware and geometry for medium complexity test cases	1/12/00	17/5/01	5	Vehicle hardware available on time, geometry release delayed
7	Report on efficient simulation strategies	1/12/00	1/5/01	5	Delayed with simulation activity
8	Report on simple test case validation	1/3/01	1/9/01	6	Delayed with availability of model geometry
9	First draft of Guidelines (non-confidential)	1/5/01	1/7/01	2	Delayed with model validation activity
10	Medium complexity test case measurement data	1/6/01	1/9/01	3	Measurements completed at all test sites
11	Technological Implementation Plan	1/6/01	1/6/01	0	Draft issued with Mid-Term review documents
12	Preliminary Guidelines (non-confidential)	1/7/01	1/7/01	0	First draft of Guidelines offered via GEMCAR website
13	Geometry and hardware for complex test case	1/9/01	1/4/02	7	Hardware already available, but geometrical data delayed
14	Report on MTC model validation	1/10/01	1/8/02	10	Delayed with earlier model validation activity
15	Second draft of Guidelines (non-confidential)	1/11/01	1/12/02	1	Delayed with model validation activity
16	Complex test case measurement data	1/3/02	1/6/02	3	Measurements completed at all sites
17	Report on exploitation of simulation data	1/5/02	1/8/02	3	Delay due to relative timing of Ford vehicle programme
18	Report on complex test case model validation	1/7/02	1/3/03	8	Delayed with earlier model validation activity
19	First issue of Guidelines	1/7/02	1/7/02	0	Chapters 1-7 populated
20	Report on evaluation study	1/11/02	1/3/03	4	Delayed due to problems agreeing case study with manufacturers
21	Final issue of guidelines	1/11/02	1/3/03	3	Delayed with case study
22	Final Guidelines available on internet (non-confidential)	1/11/02	1/3/03	3	Final issue of Guidelines offered via GEMCAR website

4.1.1 Progress to mid-term review

The first non-confidential deliverable, the User Requirements document (Milestone 1, Deliverable 1) was issued and the results presented during a project workshop that formed part of the programme for one of the main European EMC conferences ("4th European Symposium on EMC", Brugge, Belgium, September 2000).

The Volvo S80 bodyshell was obtained in good time, but acquisition and subsequent processing of the CAD data took longer than expected (Deliverable 2). An outline definition of the Guidelines (Deliverable 3) was discussed and agreed at the second project meeting. The test plans and equipment models (Deliverable 4) were originally intended to be complete within the first 6 months of the project, but it became apparent as work progressed that for various practical reasons these would need to be adapted to varying degrees during the course of the model validation activity.

The simple test case measurements were completed as planned (Deliverable 5), but the delays in defining the model geometry meant that the corresponding simulation activities were also delayed, with the result that the simple test case validation results were delayed by 6 months. Further delays affected the collation of CAD data for the medium complexity test case (Deliverable 6), including staff changes at Volvo Cars. Additional unplanned measurements (simulated lightning strikes) were carried out by EPFL while the test objects were in Switzerland.

The stated objectives for Milestone 2 were defined in terms of the level of agreement that can be achieved between models and measurements, and between models of different types, for the simple test case. The targets were:

- FSV difference measures ≤ 0.3 demonstrated for validation data (equivalent to experimental repeatability for field measurements);
- FSV difference measures ≤ 0.15 demonstrated for numerical results.

These targets have been shown to be achievable (see section 3.5 of this report) in the confidential report on Simple Test Case Validation (Deliverable 8). This work also revealed a number of problems in making measurements of this nature, and in comparing them with simulations, which informed subsequent work on the later test cases. Preliminary simulations showed that the effects of the harness on the internal field distribution in immunity models are not generally significant. It was therefore decided that the validation of models for the bodyshell without the harness present was not necessary. Although this did not significantly influence the effort required for model building and analysis, the change in computing time (~30%) helped mitigate the effects of the CAD acquisition and processing delays.

An assessment of strategies for maximising the efficiency of EMC simulations was carried out and the results documented in a confidential project report (Deliverable 7). A preliminary draft of the GEMCAR Guidelines (Deliverable 9) was assembled, drawing on the User Requirements document, as well as the Efficient Simulation Strategies and Simple Test Case Validation reports. This document was made available to interested parties via the project website (Milestone 2, Deliverable 12). It was decided that it would be useful to have some knowledge of the type of people who were interested in the GEMCAR Guidelines, so a scheme was implemented whereby the Guidelines could be requested via a form which requested some information regarding the location, activities and modelling interests of those people requesting the Guidelines.

The delays of 1-2 months in Deliverables 1, 4 and 5 were due primarily to delays in starting the project. The delays in Deliverables 2, 6 7 and 8 were due to technical difficulties, which have resulted in some re-planning by the Steering Committee. A draft of the Technology Implementation Plan (TIP, Deliverable 11) was made available for the mid-term review, which was held in month 18 of the project (hosted by Hevrox in Beringen, Belgium) as planned.

4.1.2 Progress to end of project

The medium complexity measurements (Deliverable 10) were delayed by about 3 months, due to limitations on the availability of the commercial test facilities used by some of the partners. However, delays in the geometrical definition for this test case (Deliverable 6) were primarily responsible for delays in the medium test case validation activity (Deliverable 14). Additional unplanned simulations were carried out by MIRA using the medium complexity models, in order to investigate model detail issues such as the impact of front and rear window heater arrays, as well as a sunroof

Further delays were also experienced in obtaining the geometrical information for the complex test case (Deliverable 13), due in large part to further staff changes at Volvo Cars. The complete vehicle that was used for the complex test case measurements (Deliverable 16) was obtained without any significant difficulties.

A second draft of the Guidelines (Deliverable 15) was achieved by updating the existing material and adding results from the model validation activities that had been completed by that time.

The stated objectives for Milestone 4 were defined in terms of the level of agreement that can be achieved between models and measurements, and between models of different types for the medium complexity test case. The targets were:

- FSV difference measures ≤ 0.6 demonstrated for validation data (equivalent to experimental repeatability for field measurements);
- FSV difference measures ≤ 0.3 demonstrated for numerical results.

These targets have been shown to be achievable (see section 3.5 of this report) in the confidential report on Medium Test Case Validation (Deliverable 14).

An extension to the contract end date was agreed, in order to allow the final project workshop to take place at the "15th International Zurich Symposium on EMC" in February 2003, and to accommodate some of the delays experienced during the project.

The report on exploitation of simulation data (Deliverable 17) was subject to a three-month delay associated with the relative timing of the project and Ford's vehicle development programmes (since some pilot modelling studies were to be carried out by Ford). The results of this activity included a methodology for integrating electromagnetic modelling into vehicle development processes, and demonstrated the potential for reductions in immunity test costs of 30% through the use of simulation, as required for Milestone 5. These results were also incorporated into the First Issue of the Guidelines (Deliverable 19), in which chapters 1-7 were populated.

It was not possible to make measurements on the complete vehicle in the same way as for the body shell, on account of the additional components that were present. The measurement strategy at this stage was therefore adapted to include further unplanned model detail investigations (by repeating measurements with the seats removed and the side windows retracted), as well as the primary aim of collecting data for comparison with simulation results. Experiments were also carried out in which a "test wire" was added to the complete vehicle to allow cable-coupling measurements to be made. This test wire was also installed in the body shell to assess how significant the additional components might be for coupling onto cables inside vehicles.

The complex test case measurements (Deliverable 16) were also delayed by three months, in line with the medium test case measurements. However, the difficulties in obtaining and processing the CAD data needed to complete the final models meant that the final simulations did not take place until the beginning of 2003. This delayed completion of the complex test case validation report (Deliverable 18) until the end of the project

The practical evaluation of the Guidelines carried out by CETIM was delayed, partly due to problems in identifying a manufacturer of a suitable vehicle for their investigation who would agree to participate. Consequently, the report on the evaluation case study (Deliverable 20), was not completed until March 2003. The final issue of the Guidelines (Deliverable 21) was therefore not completed or made available on the project website (Milestone 6, Deliverable 22) until the end of the project.

4.1.3 Manpower and budget

Comparisons between planned and actual manpower and budget are illustrated in Figs. 4.1-4.2 below, showing that the final figures were much as originally planned. Overall, achieved manpower was 96% of planned levels, while actual costs reached 97% of the planned budget.

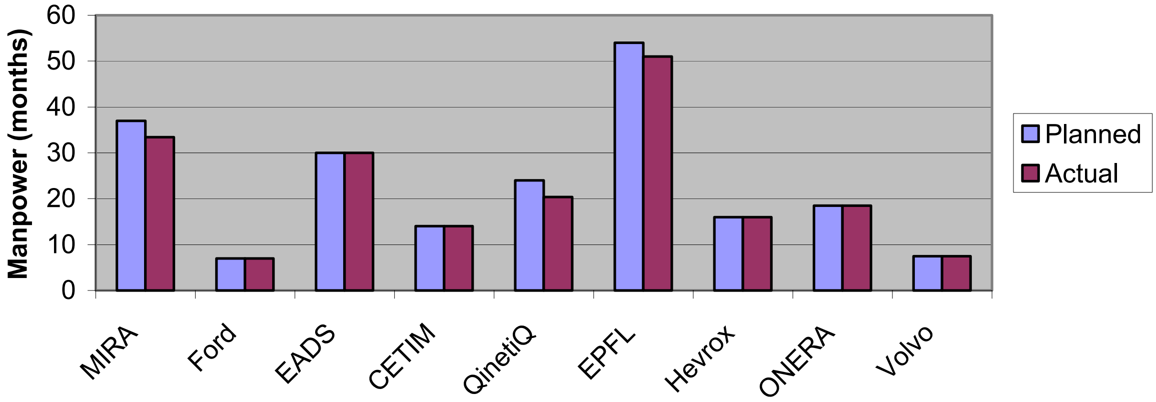


Fig. 4.1: Planned and achieved manpower, by partner

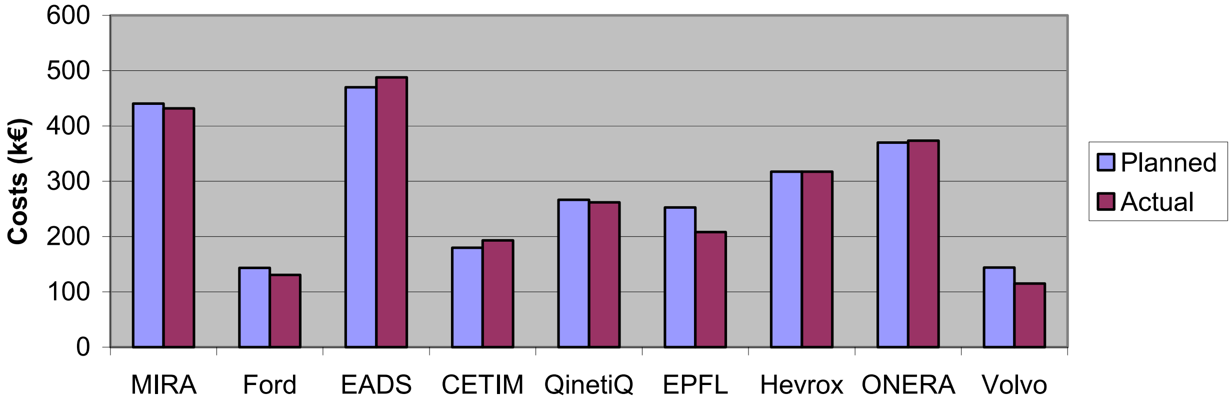


Fig. 4.2: Planned and achieved costs, by partner

4.2 Dissemination

Dissemination of the project objectives and results has been via personal contacts, the project website (*www.gemcar.org*), a two project workshops at leading European EMC conferences (EuroEMC 2000 and EMC Zurich 2003), and the publication of papers. To date 29 papers have been published describing work carried out in the course of the GEMCAR project, and it is expected that more publications based on GEMCAR results will follow after the end of the project. A full list of GEMCAR publications to date is given in Annex 3 of this report.

Although most of these papers were delivered at conferences in Europe, two were also given at conferences in the USA. These presentations were not limited to the automotive EMC community alone, but also included related research communities concerned with EMC, antennas, microwave and RF engineering, high power electromagnetics and computational electromagnetics. In particular, dedicated GEMCAR workshops were held as part of the programme for two of the leading biennial EMC conferences in Europe during the lifetime of the project:

- "4th European Symposium on EMC", Brugge, Belgium, September 2000
    - initial project workshop with four papers and about 30 attendees
- "15th International Zurich Symposium on EMC", Zurich, Switzerland, February 2003
    - final project workshop with 8 papers and about 60 attendees
    - 3 GEMCAR papers also presented in a mainstream session on automotive EMC.

The project was also represented at the EC conference on "Surface Transport Technologies for Sustainable Development" (Valencia, Spain, 4th–6th June 2002), which included a poster on the GEMCAR project. In addition, the project was the subject of a short news item that was recently broadcast on Flemish television, thus providing exposure to a much wider, non-technical audience for the project and the support provided by the Framework V programme.

Copies of the project papers and presentations can be obtained from the project website. In addition, copies of the GEMCAR Guidelines are available via the project website (Milestones 3 and 6, Deliverables 12 and 22). Around 40 requests for copies of the guidelines have been received to date, from potential users in Europe, Asia and the USA, including automotive users, academics and users from other industries. More than 3100 visits to the GEMCAR website have been recorded to date.

4.2 Unplanned activities

In the course of the work it was found necessary to introduce some work that was not foreseen when the proposal was written. This resulted in a number of "unplanned" achievements, including:

- optimisation and parallelisation of NEC2 code (EPFL)
- tools for translating a TLM mesh into a NEC model (EPFL)
- hybridisation of FVTD and FDTD codes (ONERA)
- time-domain variant of BEM solver (EADS)
- measurements to establish impact of vehicle components (MIRA, Hevrox, CETIM)
- simulations to establish impact of window heater arrays, sunroof and steering gear (MIRA)
- development of "test wire" approach to "measure" internal field distribution (ONERA)
- analysis of datasets derived from groups of simulation and measurement results (QinetiQ).

Although the project specifically did not aim to develop new simulation techniques or codes, as work progressed it became apparent that some partners would need to enhance their existing tools in order to make simulation of the model validation test cases practicable. This was partly because the GEMCAR model validation activity required the illuminating antenna, as well as the vehicle under test, to be simulated. Most electromagnetic modelling activities assume that large and complex systems are illuminated by ideal plane waves. For automotive measurements, however, this is not the case.

Consequently, EPFL have developed techniques for optimising and parallelising a freely available electromagnetic code (NEC2) and ONERA have demonstrated the hybridisation of two modelling techniques (finite volumes and finite differences in the time domain). Although the modelling capabilities of NEC 2 are limited to thin wire structures, and it normally becomes increasingly inefficient for large models, the adaptations that have been demonstrated by EPFL make NEC2 much more viable as a low-cost tool for carrying out electromagnetic simulation. It was also found that the triangular surface mesh produced in poor results, resulting in the need to obtain a model of the vehicle based on a square mesh. A tool to convert a TLM model into such a mesh was therefore developed by EPFL.

The hybrid approach demonstrated by ONERA permits a body-fitted mesh to be used efficiently in large-scale electromagnetic models, providing considerable benefits for the simulation of the coupling of fields onto wiring harnesses. In addition, it became apparent during the evaluation case study carried out by CETIM using the EADS BEM code that a time-domain variant of this tool was necessary in order to enable the necessary calculations to be carried out within the available timescales and computing resources.

In order to define the geometrical requirements for the final validation test case, in which a “complex” model would be compared with a real vehicle, it was necessary to establish the electromagnetic impact of many structures that are present in vehicles. This information was also recognized as being of considerable benefit for the Guidelines. Consequently, additional simulations carried out at MIRA on medium complexity TLM models, and measurements carried out by MIRA, Hevrox and CETIM on the complete vehicle with various parts removed. This work allowed the significance of components such as vehicle glazing, rear window and windscreen heater arrays, a sun roof, seat frames, seat cushions and other interior components (composed of foam, fabric and plastic), to be quantified. The use of a simple “test wire” as a distributed electric field sensor was investigated by ONERA, in both the complete vehicle and the medium complexity test case. The results of this work confirmed the findings of the additional measurements on the complete vehicle, in that the interior components have only a modest impact on the coupling of fields onto cables located close to the bodyshell.

The analysis of composite measurement and simulation datasets was investigated by QinetiQ, as a way of reducing the volume of data to be compared and to take account of the uncertainties that are present in both measurements and simulations.

5 Management and coordination aspects

5.1 Coordination aspects

5.1.1 Communications

Communication between the consortium members is conducted primarily through e-mail, the project website and occasional physical meetings. The use of e-mail allows individuals, small groups or the entire consortium to participate in discussions relating to project issues as appropriate to their interests with the maximum convenience. A secure area of the website, which is only accessible to the consortium members via a user name and password scheme, is used to deliver and record the current versions of documents generated for internal use by the project. Any new documents are made available on the secure part of the website and the consortium is then informed by e-mail that the document is available for review and comment. A formal mechanism for recording and registering discussion documents and deliverables that are generated in the project has been defined and implemented. Old versions of these documents are also archived to an associated secure ftp area, so that they are readily accessible to the consortium members.

5.1.2 Project meetings

Although e-mail is a very convenient tool for conducting project business, physical meetings have nonetheless remained invaluable in resolving misunderstandings and other difficult issues. In the last period there have been four formal meetings of the project Steering Committee and one informal meeting (with a more restricted attendance) to discuss measurement issues (see Table 5.1 below for details).

TABLE 5.1: SUMMARY OF PROJECT MEETINGS

Nature of meeting	Date	Location	Consortium attendance	Visitors
Steering Committee Meeting 1	20th–21st January 2000	MIRA, UK	All partners	Project officer
Steering Committee Meeting 2	3rd–4th May 2000	EADS, France	All partners except Ford	
Technical meeting on measurement issues	24th May 2000	Hevrox, Belgium	AM CCR, Hevrox and MIRA	Volvo Cars
Steering Committee Meeting 3 and EuroEMC 2000 Workshop	13th–14th September 2000	Brugge, Belgium	All partners except Ford	Volvo Cars
Steering Committee Meeting 4	11th–12th December 2000	Volvo, Sweden	All partners except Ford	Volvo Cars
Steering Committee Meeting 5	24th–25th April 2001	ONERA, France	All partners except Volvo	
Technical meeting on measurement issues	15th May 2001	Hevrox, Belgium	AM CCR and Hevrox	
Steering committee Meeting 6 and Mid-term Review	3rd–5th July 2001	Hevrox, Belgium	All partners except Ford	Project Officer
Technical meeting on exploitation of models	30th November 2001	Ford, UK	MIRA, Ford	
Technical meeting on exploitation of models	5th–6th December 2001	MIRA, UK	MIRA	Volvo Cars
Steering committee Meeting 7	10th–11th December 2001	EADS, France	All partners except Ford	
Steering Committee Meeting 8	4th-5th March 2002	EPFL, Switzerland		
Steering Committee Meeting 9	(26th-27th June 2002	CETIM, France	All partners except Volvo	
Steering Committee Meeting 10	8th–9th October 2002	QinetiQ, UK		
Steering Committee Meeting 11	16th–17th January 2003	EADS, France	All partners except Volvo	
EMC Zurich 2003 Workshop	17th–20th February 2003	Zurich, Switzerland	All partners except CETIM	
Final Review	8th April 2003	EC, Brussels, Belgium	All Partners except Ford	Project Officer

Volvo Cars provided the CAD data and vehicle hardware for the model validation test cases, and were therefore present at a number of these meetings to provide information and advice relating to the test case vehicles and CAD data. They also provided presentations regarding Volvo vehicle electrical systems as part of the 4th Steering Committee meeting in Sweden.

Although Volvo Cars were not members of the consortium, they are now part of Ford Motor Company's "Premier Automotive Group", which also includes Jaguar Cars, Land Rover and Aston Martin Cars, as well as retaining strong links with Volvo TDC.

5.1.3 Co-operation with other projects/programmes

Contacts were made with the AUTOEMC project during the EMC Symposium in Brugge in September. Representative from one of the AUTOEMC partners (ESI) have also visited MIRA to discuss the results of their project.

In the early part of the project contact was also been established with the ESCARV project through a meeting between the ESCARV project manager and Magnus Granstrom of Volvo TDC, as both are located in Sweden. More recently, contact has been made between MIRA and the coordinator of the COSIME project (BMW), and with other members of the COSIME consortium at EMC Zurich in February 2003.

In addition EPFL, MIRA and ONERA were active in the development of a Framework VI proposal for a "network of excellence" in the area of EMC and transport safety during the final stages of the project

5.2 Staffing and organisational issues

Turnover of staff amongst the consortium members was a problem for the project during the first year, as key members of the consortium from EADS CCR, Ford and DERA left their employers during the summer of 2000. As these individuals were involved in the proposal stage of the project their understanding of the plans and objectives was at a very high level when the project started, and working relationships with other partners were already well developed. The additional learning that was necessary for their replacements has inevitably had some impact on progress.

In addition, the effort available from EPFL in the early months of the project was limited due to problems in recruiting PhD students to work on the project. This situation was resolved with the recruitment of two students within the first half of the year. This has resulted in some shortfalls against anticipated EPFL effort. A member of the MIRA team also left the company shortly after the mid-term review, and it was not possible to obtain a replacement before the end of the project, with the result that the coordinator also undertook most of MIRA's technical work.

The timing of the project was such that DERA were not able to fully participate until internal budget became available with their new financial year in April 2000. Subsequently, DERA was partitioned by the UK government, with the larger part of the organisation ultimately privatised under the new name "Qinetiq". The GEMCAR project was allocated to the new private company, but the combination of these changes, staff turnover and the initial funding problems caused difficulties for DERA in supporting the project as originally planned.

Further organisational changes occurred at EADS CCR, which was Aerospatiale CCR at the proposal stage. The company merged with Matra to become Aerospatiale Matra CCR at the beginning of the project, and subsequently became EADS CCR as a result of further mergers within the European aerospace industry in the early months of 2000.

6 Conclusions

Although a number of technical difficulties were encountered during the project, these issues are exactly the kinds of practical problems, often unforeseen, that industrial users will face and that the GEMCAR Guidelines were intended to address.

The impact of the various delays that were encountered was most acute for the model validation activity. Nonetheless, opportunities for reducing the duration of the simulation tasks that dominated this work were identified and exploited.

A number of changes were made to the scheduling of various activities in the workplan, in order to accommodate the various delays and practical problems that arose during the course of the project. Nonetheless, the technical work that was undertaken was largely as envisaged at the beginning of the project. The main changes to the technical content of the workplan were in the following areas:

- the investigation of the wiring harness in isolation was not pursued beyond the simple test case
- additional work to quantify the impact of various vehicle features was carried out using both simulation and measurement techniques

Following the results of the simple test case work with the harness laid out flat, it was concluded by the Steering Committee that there was little merit in further investigations of this nature. The original objective was to test a conjecture that the vehicle geometry may not be too significant for coupling to the harness in some frequency bands. However, it was not possible, even for the harness used in the simple test case, to collapse this 3D structure on to a 2D plane in a manner that provides any meaningful representation of the 3D configuration. For a more complex harness the disparities would be even greater. Numerical studies also indicated that the presence of a harness within the vehicle structure does not have a significant impact on the spatial field distribution within the structure provided that the harness is terminated with finite loads (ie. not open or short circuited). This also eliminates the need to obtain separate results with and without the harness present. Consequently, all subsequent work was limited to the harness in the vehicle only.

The content of the “complex test case” models inevitably had to be limited to something considerably less than an entire vehicle. However, deciding exactly what is needed and what can be discarded is not possible without some objective information regarding the electromagnetic impact of the many components of the vehicle. Additional simulations and experiments were therefore carried out in order to quantify the impact of specific features, including vehicle glazing, heater arrays embedded in glazing, sun-roof, seats and seat cushions. This information also provides a very valuable contribution to the practical modelling advice given in the GEMCAR Guidelines.

The main purpose of the project was to develop and disseminate a body of knowledge concerning the use of electromagnetic modelling in automotive EMC engineering applications. The range of numerical methods used in this work was deliberately very wide, in order to develop knowledge that would be as generic as possible, and therefore of benefit to all potential users of these techniques. The consortium believe that the project has been extremely successful in this respect, having so far published 29 papers on the work (see Annex 3), delivered more than 40 copies of the draft GEMCAR Guidelines to potential users around the world and held project workshops as part of the programmes of two major international EMC conferences. It is envisaged that further dissemination will continue after end of the project.

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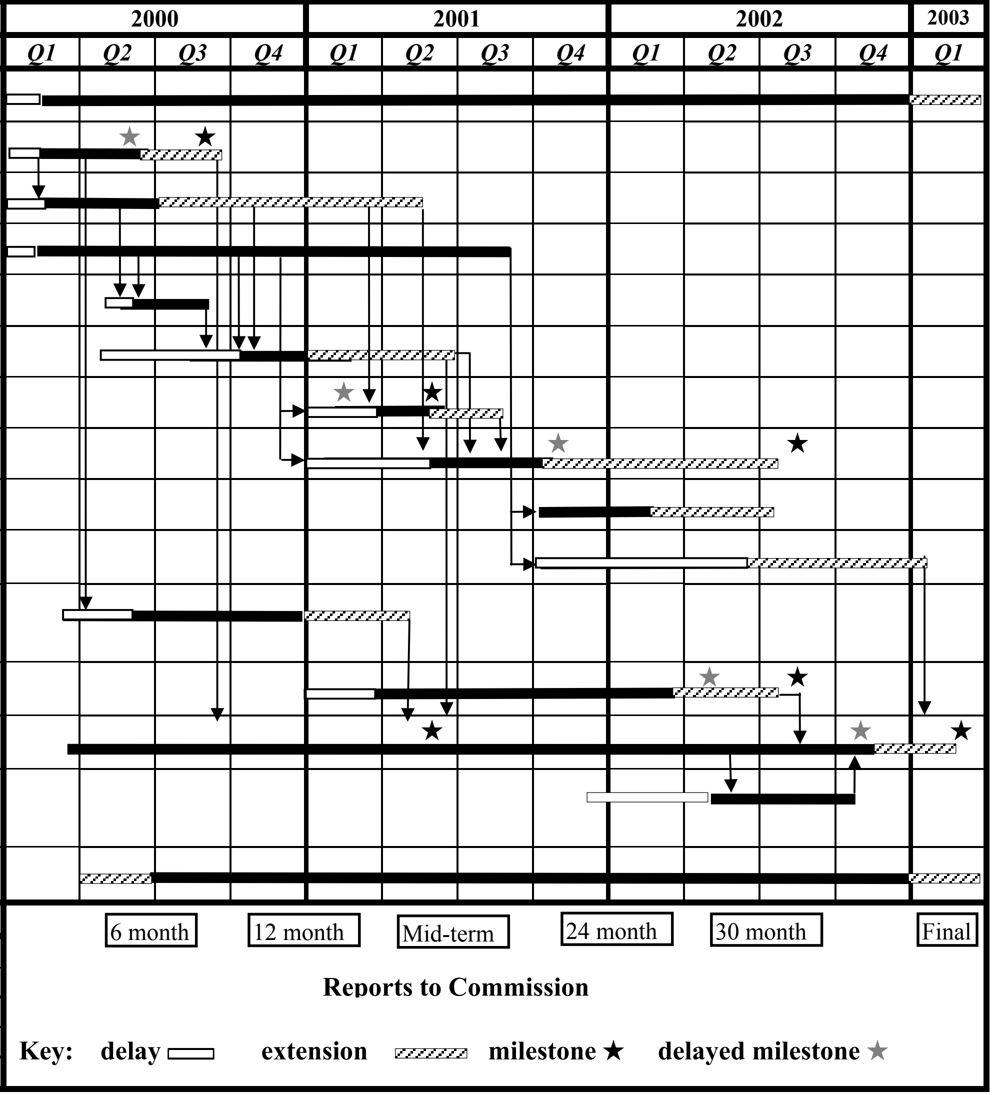
ANNEXE 1: GLOSSARY

A brief description of terms and abbreviations used in this report and other project documents is given below.

Term	Description
Aseris-NET	EMC tool based on network methods, developed and marketed by Aerospatiale
BEM	Boundary element method, a technique for solving field equations
BLT	Baum-Liu-Tesche equations, describing multiconductor transmission line networks
CATIA	A commercial CAD tool used extensively in the automotive industry
CONCERTO	UK commercial electromagnetic modelling tool based on the FDTD technique
CRIPTE	A network modelling tool developed by ONERA, based on the BLT equations
EIFFEL	EPFL tool for complex networks based on time-domain transmission line models
EM	Electromagnetic
EMA3D	US commercial electromagnetic simulation tool based on FDTD techniques
EMC	Electromagnetic compatibility
EMCP2	Field modelling tool developed by Aerospatiale, based on BEM techniques
EMP	Electromagnetic pulse
ESD	Electrostatic discharge
FAC	Fully anechoic chamber
FDTD	Finite differences in the time domain, a technique for solving field equations
FEM	Finite element method, a technique for solving field equations
FSV	Feature selective validation, a method for assessing correlation between signals
FV	Finite volumes, a technique for solving field equations developed by ONERA
GTD	Geometrical theory of diffraction, an asymptotic technique for field analysis
IGES	A neutral file transfer format for the exchange of CAD data
M-Harness	US commercial EMC analysis tool based on network methods and FDTD
Microstripes	UK commercial electromagnetic modelling tool based on the TLM technique
MoM	Method of moments, a technique for solving field equations
NEC	Numerical Electromagnetic Code, a US electromagnetic modelling tool (based on MoM techniques) developed for research and teaching
NEMP	Nuclear electromagnetic pulse
SAC	Semi-anechoic chamber (ie. conducting floor, anechoic walls and ceiling)
Spice	US network analysis tool developed for research and teaching
TLM	Transmission line matrix, a technique for solving field equations
UTD	Uniform theory of diffraction, an asymptotic technique for field analysis

ANNEX 2: WORKPACKAGE/MANPOWER BARCHART (UPDATED, JULY 2002)

Workpackage	Participant effort									
	M	*F*	*E*	*C*	*Q*	*EP*	*H*	*O*	*V*	*Total*
1. Project management	8									**8**
2. Requirements definition	1	1		0.5	1		4		1	**8.5**
3. Test definition and modelling	3		3.5		2	3	3	3		**17.5**
4. Definition of test cases			2						3	**5**
5. Simple test case measurements	1		1			3	2			**7**
6. Simple test case simulations	3		6.5		4	12.5		6		**32**
7. Med. oomplexity test case meas'mnts	1		1		2	0.5	2.5			**7**
8. Med. complexity test case sim'ltns	5		8.5		3.5	15		7		**39**
9. Complex test case measurements	2						3	1		**6**
10. Complex test case simulations	4		4		3	18		6		**35**
11. Efficient simulation strategies	2		1		1			4		**8**
12. Exploitation of simulation data	4	5	1		1				3	**14**
13. Modelling guidelines	1	1	1	1	6	1	1	1		**13**
14. Practical evaluation of guidelines				12						**12**
15. Dissemination	2		0.5	0.5	0.5	1	0.5	0.5	0.5	**6**
Total man-months	***37***	***7***	***30***	***14***	***24***	***54***	***16***	***28.5***	***7.5***	***218***
Plan effort at month 30	30.3	5.5	27.6	4.9	18.7	46.2	15.7	24.6	7.2	**180.7**
Actual effort month 30	25.1	5	21.9	3.4	15.6	33.4	15.9	20.1	7.2	**147.6**
Deviation (mm)	-5.2	-0.5	-5.7	-1.5	-3.1	-12.8	0.2	-4.4		**-33.1**
Deviation (%)	-14.1	-7.2	-19.0	-10.7	-19.6	-23.7	1.3	-15.4		**-15.2**
Forecast –to month 39	11.9	2.0	8.1	10.6	8.4	20.6	0.1	8.4	0.3	**70.4**



ANNEXE 3: LIST OF PROJECT PUBLICATIONS

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