QUANTITATIVE DATA COMPARISONS: APPLICATIONS AND EXPERIENCES IN AUTOMOTIVE EMC

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Abstract: The nature of most vehicle level EMC measurements is such that the opportunities for employing quantitative data comparisons in analysing manufacturers' test data are somewhat limited. However, there is a need for quantitative comparison in a number of applications relating to automotive EMC where more complete datasets are likely to be available. This paper outlines some of these potential applications, as well as MIRA's practical experiences of attempting to quantify comparisons between such datasets.

1. Introduction

Vehicle electromagnetic emissions performance is assessed in terms of a measured quantity (ie. the electric field strength interpreted from the voltage measured at the terminals of an antenna). However, as the permitted ambient levels can be as high as 10 dB below the limit level [1], it is often the case that the emissions are hidden below the noise over large portions of the frequency band. Furthermore, since such measurements are commonly carried out using an open area test site (OATS), the measurements are subject to further confusion due to strong signals that are present in the environment.

Immunity is judged in terms of a more subjective perception of functional performance, with the vehicle or subsystem exposed to a field up to some maximum level [1]. If a fault is detected then the frequency and the threshold field at which the fault manifests is recorded. This again means that the available data is normally limited to relatively small portions of the test frequency band.

In addition to this, vehicle level measurements for EMC certification purposes are limited to a small subset of different vehicles (which aims to give representative, but not comprehensive, coverage of the production variants), and there is no culture of regular sampling to establish conformity of production. Thus, the opportunities for employing quantitative data comparisons in manufacturers' vehicle EMC measurements are somewhat limited.

Nonetheless there is a need for quantitative comparison in a number of applications relating to automotive EMC where more complete datasets are likely to be available, such as:

- validation of vehicle electromagnetic models;
- investigation of comparability between test methods;
- evaluation of design options (eg. chamber design, cable routing, module and antenna placement);
- quality control (eg. production verification of sub-system performance, chamber calibrations).

This paper outlines experiences in attempting to quantify comparisons between datasets arising from these applications.

2. Model validation studies

There is increasing industrial interest in the development of whole vehicle electromagnetic models in order to allow automotive EMC [2-4] and antenna engineering issues [5-6] to be analysed during the design stages of vehicle development. In order to take full advantage of these techniques it is necessary to have sufficient confidence in the models to use them as a basis for making design decisions. However, as the use of computational electromagnetics (CEM) for automotive applications is still an emerging technology, there is a need for experimental validation of numerical models for both building user confidence in vehicle CEM models and to support the development of strategies for approximating vehicle geometry.

As part of this activity there may also be interest in comparing vehicle results obtained using different numerical techniques. For comparison between numerical techniques complete datasets will be available, although one must ensure that they are directly comparable. In experimental validation, however, care is also needed in the design of the experiment to ensure that the parameter that is to be used for comparison can be measured reliably.

2.1 Presentation of results

A convenient approach to addressing both of these issues in comparing field distribution is to use the relative field strength between two points as the measure for comparison [7]. 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 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.

2.2 Antenna model validation example

The results that can be obtained using this approach are illustrated in Figs. 1-2, for a biconilog antenna that was used in a large semi-anechoic chamber for vehicle model validation purposes in the GEMCAR project [8]. This antenna was modelled using a variety of numerical techniques, and the results compared with measurements in the chamber.

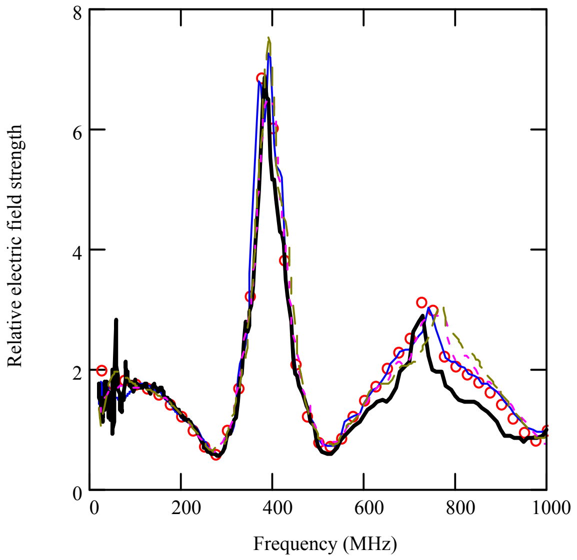

Fig. 1: Electric field at a point relative to that at reference point for horizontal biconilog antenna above a ground plane (heavy line is measured, others are modelled)

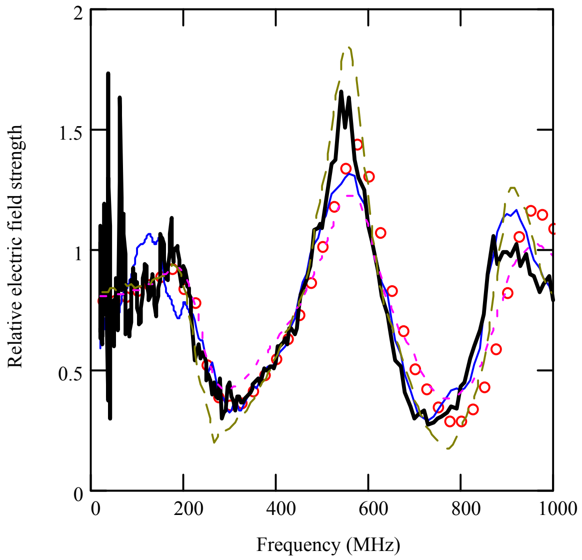

Fig. 2: Electric field at a point relative to that at reference point for vertical biconilog antenna above a ground plane (heavy line is measured, others are modelled)

As a result of comparing normalized responses, the remaining discrepancies between models and measurements (apart from random noise) can 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 very difficult to identify the impact of the other possible error sources.

In order to quantify the “quality” of these results both FSV [9] “global difference measures” (GDM) and correlation coefficients were derived. These are shown for all possible pairs of measured and computed results in Tables 1-2, for a single field measurement configuration. The interpretation of the correlation coefficient is that a value of unity corresponds to a perfect match, while for the FSV approach a value of zero represents the perfect comparison. The relative rankings of the results by the two methods are broadly similar. However, the correlation coefficient results seem to be overly optimistic, while the FSV GDM results appear rather pessimistic when compared with visual inspection of the graphical results.

Table 1: Biconilog antenna, horizontal polarization (Fig. 1)

FSV GDM values					
DATA	TLM	BEM	FDTD	MoM(1)	MoM(2)
Measured	0.16	0.15	0.24	0.20	0.28
TLM		0.12	0.17	0.14	0.17
BE			0.19	0.16	0.21
FDTD				0.12	0.13
MoM(1)					0.13
Correlation coefficients (CC)					
DATA	TLM	BEM	FDTD	MoM(1)	MoM(2)
Measured	0.97	0.97	0.95	0.97	0.88
TLM		0.99	0.97	0.98	0.91
BE			0.96	0.97	0.88
FDTD				0.99	0.94
MoM(1)					0.94

Table 2: Biconilog antenna, vertical polarization (Fig. 2)

FSV GDM values					
DATA	TLM	BEM	FDTD	MoM(1)	MoM(2)
Measured	0.29	0.50	0.42	0.48	0.46
TLM		0.40	0.29	0.42	0.30
BE			0.43	0.28	0.28
FDTD				0.40	0.41
MoM(1)					0.34
Correlation coefficients (CC)					
DATA	TLM	BEM	FDTD	MoM(1)	MoM(2)
Measured	0.91	0.76	0.88	0.80	0.79
TLM		0.86	0.96	0.91	0.91
BE			0.77	0.96	0.87
FDTD				0.84	0.84
MoM(1)					0.89

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, CC: 0.88-0.97
Vertical polarization - GDM: 0.29-0.5, CC: 0.76-0.91

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

Horizontal polarization - GDM: 0.12-0.21, CC: 0.88-0.99
Vertical polarization - GDM: 0.28-0.43, CC: 0.77-0.96

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 poorer.

A significant resonant feature that arises from interference with the ground image, which is in anti-phase, dominates the response for horizontal polarization. The vertical results, by contrast, exhibit much weaker resonant features, since the ground image is in phase in this orientation. This suggests that the measures of model quality are not absolute, but reflect the nature of the results that are being compared. Although resonant features are present in the vertical results, they are relatively modest compared to the horizontal case. The greater dynamic range of the horizontal data seems to result in enhanced measures of the correlation between the different calibration data sets.

The antenna calibration results for the horizontal biconilog antenna demonstrate that FSV GDM values better than 0.15 can be achieved between models, while the comparison with measurements provides GDM values better than 0.3 for this case. However, the results for vertical polarization produce much poorer measures than the horizontal case, despite the fact that the measurement process and the numerical models are identical except for the orientation of the antenna relative to the conducting ground. Nonetheless, the disparities between the various modelled results are only slightly better than those between the measured and computed data for both polarizations, despite the fact that the quantitative levels of these disparities are markedly different for the two cases. It would be difficult to identify the measured results from the ensemble of measured and computed data based on this data.

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 systems that will 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 in isolation because of the need to include the system that the antenna is illuminating.

3. Practical considerations

The ability to quantify, and hence objectively rank, comparisons between large numbers of datasets is particularly attractive in applications where the volume of data is such that simple manual inspection is no longer viable. However, such techniques must aim to reduce that volume of data that the analyst needs to absorb if they are to be of benefit in avoiding information overload.

3.1 Data reduction

Methods that reduce the comparison of complex frequency responses to a few numerical values are of benefit in this respect. The FSV method is based on the derivation of frequency dependent measures representing both amplitude and frequency differences between two frequency responses. The derivation of additional curves from the pair that are being compared may have merit in some specific cases, but are more likely to be a hindrance than a benefit in most applications. The amplitude difference measure (ADM) and frequency difference measure (FDM) can also be combined (with weightings id so desired) into a single global difference measure (GDM). In the results presented in section 2 the GDM is averaged over the frequency band to obtain a single quantity that describes the comparison.

Attempts have been made to link a subjective classification with the quantitative measures provided by the FSV method, as indicated in Table 3 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.

Table 3: Proposed subjective interpretation of 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

The association of a subjective classification scheme with the quantitative values, whilst appealing in principle, is not really a practicable approach in many applications. For example, it seems pointless to classify a comparison that results from the experimental validation of a numerical model as "fair" if the repeatability of the measurements is only "good", as has been found in vehicle model validation studies [10]. If the measures that are chosen to quantify the comparison are found to be identical then this actually represents as good as result as can reasonably be expected. So in this case it is perhaps more realistic to regard such a comparison as a very good result.

3.2 Source of results

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, models may differ more significantly than expected in order to make the modelling of large and complex systems practicable.

The example outlined in section 2 notionally compares results for the same antenna. In practice 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 solid metal bars, while in the FDTD and BEM models the bars are solid but the dipole elements are thin wires. There are also results for two slightly different MoM models, 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 mechanism 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 of section 2 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.

3. Investigation of emissions test methods

Use has also been made of FSV values in theoretical and experimental investigations of automotive emissions test methods. This work involved comparing the results of emissions measurements carried out in different test environments and for different test configurations, as well as comparing simulated measurements and raw field predictions obtained from numerical models for these test configurations. The measurements were carried out at 3 m and 10 m distances from a vehicle using a large semi-aenchoic chamber (SAC) and an open area test site (OATS). In addition, measurements at 3 m range were also carried out in a fully anechoic room (FAR). In the numerical models, the OATS and SAC were represented by a semi-anechoic environment, while the FAR was represented using an anechoic environment.

The same vehicle and the same excitation scheme were used to ensure that measurable and repeatable emissions could be generated in each of the test configurations and environments. The measured data sets were then compared to assess the relationships between them [11]. This project also included a theoretical study of the impact of the receiving antenna on the measured field [12], but the models used for this work were only representative of the real system and there was no requirement for comparison between the modelled and measured results. Thus, the remaining comparisons were made purely between electric field predictions and simulated measurements in which the model was augmented with a representative log-periodic dipole array antenna structure. Simulated antenna calibrations were also carried out under plane wave illumination to provide antenna factors for the simulated measurements.

In this application, therefore, the use of the subjective classification scheme was much more reasonable, since the data that was compared was of the same type. Nonetheless, in comparing measurements the ideal comparison is still an unachievable goal, since the presence of random noise represents a fundamental limitation to the quality that can be expected from comparisons of measurements. For automotive emissions measurements, differences due to positioning errors are also unavoidable

Sample results obtained from this work are shown in Figs. 3-4, which illustrate the similarities between predicted fields and simulated measurements under semi-anechoic conditions for the 3 m and 10 m measurement configurations.

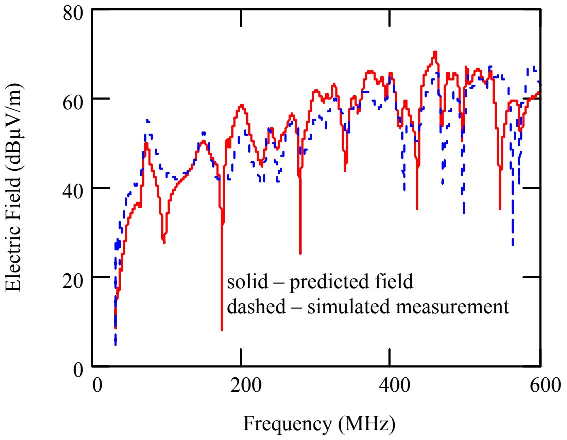

Fig. 3: Vertical electric field at 10 m range for semi-anechoic environment (a "fair" GDM comparison)

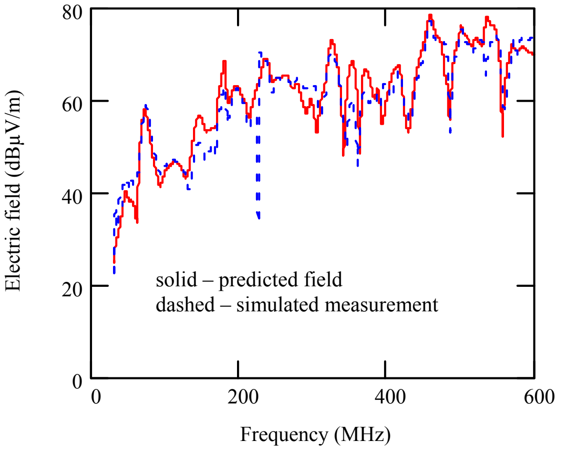

Fig. 4: Vertical electric field at 3 m range for semi-anechoic environment (a "good" GDM comparison)

The FSV classifications obtained from the computed electric fields and simulated measurements are detailed in Table 4, showing that at the 3 m distance the simulated measurements gives a "good" indication of the predicted electric field strength. At 10 m, however, the simulated measurement only gives a "fair" indication of the predicted electric field.

Table 4: FSV classifications for comparisons of predicted fields and simulated measurements at 3 m and 10 m

Configuration	ADM	FDM	GDM
3 m, anechoic	good	good	good
3 m, semi-anechoic	good	very good	good
10 m, semi-anechoic	fair	fair	fair

Numerical results for the field distribution at 3 m from a model vehicle indicate that the presence of a ground plane introduces differences in the details of the frequency characteristics as well as the amplitudes of the fields. Thus, although the two fields are similar, they are not identical and the relationship between the data sets is frequency dependent.

Simulated measurements using a model antenna at the 3 m range are found to provide a good representation of the reference fields. Thus, the correspondence between the field predictions at the 3 m range is carried over into the simulated field measurements.

The results of practical measurements also show a good degree of similarity between the measurements at 3 m from a vehicle in the FAR and SAC. The comparisons obtained from measurements at various points alongside the vehicle, as well as from simulated measurements and field predictions at a point aligned with the front axle, have also been assessed using the FSV method, are indicated in Table 5 below.

Table 5: FSV classifications for semi-anechoic and anechoic emissions at 3 m (from models and measurements)

Configuration	ADM	FDM	GDM
Measured, aligned with front axle, horizontal polarization	good	good	fair
Measured, aligned with front axle, vertical polarization	good	good	fair
Measured, 1 m back from axle, horizontal polarization	good	fair	fair
Measured, 1 m back from axle, vertical polarization	good	fair	fair
Measured, 2 m back from axle, horizontal polarization	good	good	fair
Measured, 2 m back from axle, vertical polarization	good	fair	fair
Predicted field, front axle, horizontal polarization	good	good	good
Predicted field, front axle, vertical polarization	good	good	good
Simulated measurement, front axle, vertical polarization	good	good	good

The results shown in Table 5 indicate a “good” correlation between both predicted fields and simulated measurements at the 3 m measurement distance under both anechoic and semi-anechoic conditions. The comparison is not “ideal” as the antenna and its calibration affect the result of the simulated measurement. The simulated measurement could only be expected to give a perfect indication of the predicted field if the field over the volume sampled by the antenna was a plane wave. However, since the observation point is relatively close to the source the antenna measurement is really an interpretation of the received voltage as if it were excited with a co-polarised plane wave. This is unavoidable, since for other field distributions the antenna response cannot be uniquely defined. These effects appear to be a greater problem at 10 m than at 3 m, which is rather more surprising. This probably indicates that the ground plane has a greater impact on the field distribution over the antenna at 10 m than at 3 m.

The corresponding measurements also show “good” correlations in terms of amplitude, but there are frequency differences which lead to a “fair” classification overall. It is not surprising, however, to find that the measured results are not quite as good as those obtained from numerical models, since the vehicle had to be relocated to different chambers for the two groups of measurements, so both random noise and positioning errors were unavoidable. Considering these measurement limitations, it can be seen that the test results effectively confirm the findings of the numerical models.

4. Other potential applications

The applications considered above, whilst important, cannot really be regarded as mainstream engineering activities. The main purpose of model validation studies is to gain sufficient confidence in numerical techniques to be able to make use them to support design decisions when no other data is available. Consequently, there are greater opportunities for exploiting quantitative data comparisons in areas such as EMC design and optimisation, as well as for some applications relating to quality control.

4.1 Design and optimisation

In vehicle design, electromagnetic performance has much lower status than styling considerations and mechanical issues. Thus, vehicle packaging aspects such as module and antenna placement or harness routing are largely dictated by other considerations. Consequently, there may be opportunities for relocating modules or antennas, or rerouting some parts of the wiring harness, but the options are likely to be rather limited. However, the complexity of the data is such that even with very few options the selection of the optimum may be far from easy.

For example, in choosing between two possible module locations, the electric field at these locations could be computed using an electromagnetic model of the vehicle. For physically large modules the field distribution over the volume of the module might be of interest. However, immunity testing would typically involve illuminating the vehicle with horizontally and vertically polarized sources from the front and side of the vehicle. So for the analysis, the results of four frequency responses (representing the four test illumination configurations) would characterize the performance of each of the possible module locations.

If the four frequency responses for each position are significantly different then the choice of location is simple. It is quite possible, however, that the frequency responses for both of the available locations are associated with similar field levels but different patterns of resonances for each location. The results are also likely to differ between each of the four illumination configurations. Thus, in this case the use of quantitative data comparison techniques would be extremely valuable in assessing whether one of the options does in fact offer any advantages of the other.

The optimisation of antenna placement and harness routing options are likely to be more complicated problems, since the volume of data to be considered is much greater than for specific module locations. For antennas, the input impedance, bandwidth and radiation pattern can be influenced by the vehicle geometry [6], and coupling to other antennas and vehicle systems may also need to be considered in assessing the relative merits of different location options. In considering possible harness options, the extended structure and uncertainties relating to its exact location, construction and termination are also likely to give rise to very large volumes of data that would almost certainly require preliminary statistical processing in order to reduce the quantity of results to a level where quantitative data comparison methods could begin to be applied. In practice only parts of the complete harness may have routing options, but the volume of data will still be large.

Activities such as design and performance verification for EMC test equipment, such as specialised antennas, test cells and even chambers, offers further opportunities for exploiting quantitative data comparison techniques.

4.2 Quality control

Repeat EMC testing to establish conformity of production at whole vehicle level is not currently common practice amongst vehicle manufacturers. However, this type of quality control activity does occur at the sub-system level. The samples that are selected for testing will inevitably exhibit some variability in terms of their emissions as measured using sub-system test methods. However, modifications may be made during the lifecycle of the product that may result in more significant deviations from the anticipated performance characteristics.

A further area where quantitative data comparisons could be useful is in monitoring the chamber calibrations that are carried out in immunity test facilities. These calibrations are influenced by various elements, including:

- signal generator and amplifier;
- measurement equipment (including spectrum analyser, cables, couplers etc.);
- test antennas;
- chamber performance.

These measurements are carried out on a regular basis and therefore provide a body of data that could be analysed in order to identify possible anomalies and ageing effects that may result in more gradual degradation.

5. Conclusions

Tools and techniques for quantifying and objectively ranking comparisons between data sets are essential to overcome the problems of information overload that arise in trying to analyse the results of the complexity that is found in EMC engineering. A number of attempts to quantify comparisons between data obtained in a number of automotive EMC engineering applications have been described here. These include the validation of numerical models against both measured data and different modelling techniques, and the assessment of comparability between different emissions test methods based on both measured and computed results.

The results obtained from these examples suggest that FSV values are perhaps overly pessimistic, while correlation coefficients are certainly too optimistic. It is also considered that the association of quantitative measures with subjective classifications based on an absolute scale is only really successful when the data sources are essentially the same. A number of other possible automotive applications for quantitative data comparisons have also been presented, in areas such as design and optimisation, as well as quality control for measurements and sub-system manufacturing. Thus, although the available methods remain weak in many respects, they are of considerable potential benefit in many areas of EMC engineering. Consequently, further work in this area could be very valuable for the automotive industry, and for many others with similar analysis problems.

6. Acknowledgements

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