EEVC/CEVE

European Experimental Vehicles Committee

EEVC Report on the Viability of Component Tests used with Mathematical Models as a basis for a Legislative Side Impact Test Procedure

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VIABILITY OF SUB-SYSTEMS OR COMPONENT TESTS USED WITH MATHEMATICAL MODELS AS A BASIS FOR A LEGISLATIVE SIDE IMPACT TEST

EXECUTIVE SUMMARY

One of the tasks with which EEVC WG9 was charged was to consider the viability of sub-system or component tests used as a basis for mathematical models for legislation, in comparison with full scale tests for this purpose.

The use of alternative methods for evaluating vehicles for side impact protection appear at first inspection to offer attractive advantages. However, closer inspection leads WG9 to the conclusion that technical difficulties preclude the use of these procedures within the foreseeable future.

One prominent example, the Composite Test Procedure (CTP), is claimed to allow approval of a vehicle design earlier in the design time frame as it can take place once the bodyshell is ready. This advantage to the manufacturer would not be valid if a bodyshell test were acceptable for the full scale test procedure.

The CTP is claimed to be less expensive than the full scale test procedure, but a careful estimation of the costs by WG9 suggests that the difference in costs is small.

The specific conclusions of WG9 are:-

1. The use of a mathematical model/ subsystem test approach to vehicle side impact legislative testing could have the advantage of being able to approve a vehicle earlier in the design stage than current whole vehicle tests on a completed vehicle. The time advantage gained depends on the complexity of the mathematical model and on the proportion of the vehicle necessary for the sub-system or component test.

2. A mathematical model approach would allow the performance of a vehicle to be assessed under a wider range of conditions than the single test condition of a full scale test.

3. The use of mathematical models is not straightforward and their ability to reproduce adequately the dynamics and reactions of a barrier impacting a car containing an occupant have yet to be demonstrated.

4. The model of the occupant must be sufficiently detailed to be able to predict likely modes of injury in lateral impacts and to give the correct load transfer between vehicle and occupant and between the major body parts of the occupant.

5. The sub-systems test procedure must be closely specified and must adequately represent the collapse of the vehicle under dynamic conditions.

6. The procedure for deriving the input data and for operating the model, including any necessary use of dynamic correction factors, must be uniquely defined and must not rely on expert interpretation.

7. The procedure must be fully validated over a wide range of conditions which differ from those for which the model was calibrated.

8. The difference in the costs of testing a vehicle for final approval between full scale vehicle impacts and a mathematical model/subsystems test approach is not likely to be as great as might be supposed, although testing for development purposes could prove to be much less by using the latter approach.

9. Taking into account the present status of mathematical modelling and the time required to develop, validate and evaluate test procedures, WG9 considers that it will be at least 4 years before a mathematical model/ sub-systems test approach could be considered seriously for legislative testing. It might prove practical for it to be used earlier for supplementary testing or Conformity of Production testing.

VIABILITY OF SUB-SYSTEMS OR COMPONENT TESTS USED WITH MATHEMATICAL MODELS AS A BASIS FOR A LEGISLATIVE SIDE IMPACT TEST

REPORT PREPARED BY EEVC WORKING GROUP 9

PREFACE

EEVC Working Group 9 was created with the overall task of coordinating the progress of the EEVC Side Impact Test Procedure. One of the tasks with which WG9 was charged was to consider the viability of sub-system or component tests used as a basis for mathematical models for legislation, in comparison with full scale tests for this purpose. There is a wide range of possibilities for the use of mathematical models for simulation of side impact from procedures that are almost entirely theoretical to procedures that use mainly hardware tests together with some mathematics to a limited and straightforward extent.

This paper reports the views of WG9 members based on experience both of mathematical simulation and of full scale testing at several European Institutions. Although the report is written in general terms, an appendix has been added in which the considerations of WG9 are applied specifically to the CTP (Composite Test Procedure). As the CTP is subject to development and revision, it should be emphasised that this Appendix is related to the June 1989 version of the CCMC CTP. However, the considerations of the CTP are presented alongside summaries of the WG9 views so that proposed modifications to the CTP can be readily evaluated.

1 INTRODUCTION

The real test of the impact performance of vehicles is how they perform in actual accidents on the road. However the effect of vehicle design is very difficult to isolate from other factors and is clearly not available early enough to use as a basis for approval for production and marketing. Instead, a reproduction of the circumstances that can cause injury in an accident is made on an example of the vehicle model and measurements are made that determine whether the vehicle meets certain criteria associated with particular injury mechanisms.

Currently, these simulations take the form of component tests, such as ECE Regulation 21 headform impacts, or whole vehicle impacts, such as ECE Regulation 12 steering wheel tests or US FMVSS 208 occupant protection tests. These tests form a common target for manufacturers to meet to achieve at least a minimum safety level and such tests have resulted in a reduction in injuries in road accidents (see for example Refs 1,2,3). Whole vehicle tests can only take place at a late stage in the design and development process. It would clearly be advantageous for a vehicle manufacturer to be able to obtain information on performance at an earlier stage in the development of the vehicle in order to avoid expensive design changes late in the development of a model.

An alternative to whole vehicle impact testing that is being suggested as a means of assessing the occupant safety of a vehicle is to use mathematical models, usually supplemented by component tests to provide the input data (4,5,6,7). If the impact performance of the whole vehicle could be modelled using finite element techniques, for instance, this could in principle take place at a fairly early stage in the design process, though in practice most published examples have been carried out on cars already in production. It is important to distinguish the type of *dynamic* finite element program used for impact modelling (e.g. DYNA3D) from the type of *quasi-static* program used as a normal design tool for the structural analysis of cars (e.g. NASTRAN): some problems of applying finite element techniques are described in Section 3.1.1 . The advantage would be somewhat less if component tests were required to provide input data, since whole vehicle structures would be required. The mathematical modelling approach also has the potential advantage that the evaluation of the vehicle for a range of occupant sizes, seat positions and impact speeds would be more practical than if whole vehicle tests were required each time. Depending on the technique used, a range of impacting objects such as trucks, rigid poles and rigid walls could, in principle, be simulated in addition to simulating car to car impacts. Results obtained from the mathematical simulation part will, of course, be exactly repeatable every time the simulation is performed. Results from any repeated sub-systems testing would, however, still show variability (8,9), though this might be less than for a full scale dynamic test. Testing for legislative purposes requires a straightforward and methodical approach, in which there is no scope for individual "value judgements" or modifications by manufacturers. This could present difficulties, as the use of mathematical models is far from straightforward, and the ability of such models to reproduce adequately the dynamics and reactions of a barrier impacting a car containing a dummy has yet to be demonstrated. However, this approach might prove to be suitable for evaluating small design changes to approved models or for extending approval to a wider range of vehicle trim levels and specifications without the need for further dynamic tests.

The use of modelling by manufacturers to evaluate the safety performance of new car designs is of great value and indeed is already used by manufacturers to develop new vehicle models. It gives direction to the design (10,11,12,13,14,15). In this respect it is an objective method compared with engineering judgment and experience (9). In some circumstances it can partly replace test work (13,16). Currently, models appear to be better at predicting trends than absolute values (17). These absolute values are best established by tests which are the final proof that design objectives have been met (10).

Models are also useful for giving a basic understanding of the influence of certain parameters, such as impact speed, vehicle weight, padding characteristics or occupant-door spacing (18). Model studies can identify countermeasures and vehicle modifications to give improved performance.

It has been suggested that, if a manufacturer has sufficient confidence in a mathematical modelling technique, he would be able to develop the new model to the production stage without the concern that a legislative impact test would fail.

This paper presents the views of EEVC Working Group 9 members on the viability of the use of sub-system or component tests, together with mathematical models in their current state of development, as a basis for a legislative side impact test. The comments are supported where appropriate by references. An appendix, in which the views of the Working Group are applied specifically to the CCMC CTP (Composite Test Procedure) proposals (4,5,6,7), is attached.

2 LEGISLATIVE ASPECTS

2.1 Influence of Type Approval

It is generally agreed that, because the use of motor vehicles can result in death or serious injury to the occupants, it is in the public interest to minimise these dangers by vehicle safety legislation. However the way in which the legislation is applied in the U.S. and Europe differs.

An EC Directive requires manufacturers to undergo testing of new models in order to get type approval from the competent authority which enables them to start production. Further testing to ensure conformity of production may be performed and the type approval may be withdrawn for non-compliance. The EC therefore has to have confidence that the test procedure will result in safer vehicles and would need evidence that alternatives are as effective as the full scale test. If, for instance, approval were granted for a vehicle based on early mathematical model evaluations and it was subsequently shown to be unacceptable in a full scale test, the approval could not be withdrawn. Product liability is in the early stages of development in Europe.

In the US, the Federal Government through NHTSA sets safety targets and establishes FMVS Standards published in the Federal Register. The manufacturer operates under a scheme of self certification such that every car carries a label that states, "This vehicle conforms to all applicable US Federal Motor Vehicle Standards in effect on the date of manufacture above". The manufacturer may choose any method to satisfy himself that his product complies with the FMVSS. NHTSA performs standard tests on a random basis to ensure compliance with the Standard. In addition product liability, which is well developed in the US, ensures that public pressure can also influence the safety performance of vehicles.

2.2 Existing Regulations

Some existing regulations permit the use of calculation as alternative methods to practical tests provided equivalence can be demonstrated.

For instance;

EEC Directive 70/387 - Door Latches, allows the strength and inertial activation requirements to be demonstrated by an alternative test method, assisted if necessary by calculations.

EEC Directive 74/408 - Seat Strength, allows the strength of seat backs and their resistance to inertial loading to be demonstrated by calculation.

ECE Regulation 58 - Underrun Protection, allows the strength requirement of rear underrun guards to be demonstrated by theoretical analysis.

However, these are relatively straightforward calculations, concerned in the main only with static strength requirements, since the inertial loadings involved can be estimated adequately by making simple assumptions about the applied accelerations. The response of a car to side impact is, in contrast, a very complex dynamic process, which involves the relative motion of the deformable barrier, several different parts of the car structure, and a fully anthropometric occupant. Simulation of a lateral dynamic impact should take full account of the inertial forces generated by these relative motions, if it is to be compared at all closely to "real world" events.

3 TECHNICAL REQUIREMENTS

3.1 Simulation Methods

The objective of developing a dynamic simulation model is to produce a representation of the various components of a structure (or set of structures) which will move in the "correct" way during an impact between different parts of the system, or between the system and some external object. This requires that each part of the model structure must follow Newton's laws relating acceleration, applied force, and mass. Real structures are mostly formed of components such as shells and beams in which the mass is distributed continuously across the structure; but for dynamic modelling purposes it is necessary to break such structures down into a finite number of "lumped" masses, connected by suitable energy absorbing components such as (non-linear) springs and dampers. Clearly, a model with a large number of masses provides a much closer approximation to the real (continuous) structure than a simpler model, but it also requires much more development effort, and greater running time on the computer.

Practical models can be divided into two main families: finite element models, and lumped parameter models (e.g. Ref 19). These involve very different kinds of programming, and in practice have little in common.

3.1.1 Finite Element Models. The finite element method of modelling attempts to provide an accurate representation of all the details of a real structure by dividing the structure up into a very large number of elements. The "mesh" has to be sufficiently small to include all relevant structural detail, both in the undeformed and the deformed state. This requires an especially fine mesh, for example, in areas where large or complex distortions are expected, and in particular where there is significant buckling. The properties of the connecting elements are obtained directly (within the program) from the mesh geometry and the engineering properties of the structural material. Modern finite element program packages can provide accurate modelling of the inter-element forces, including effects such as non-linear material properties (e.g. plastic deformation), very large deformations, correct modelling of contact forces between buckling surfaces, etc., subject only to limitations imposed by the finite mesh.

It would be desirable to be able to use the same mesh for dynamic modelling as the one that (in current practice) would have been used for static stress and vibration analysis during development of the car body design. This is not practicable for several reasons: the number of elements has to be significantly smaller if the model is to run on the computer in a reasonable time, but, as described above, it is necessary to use a particularly fine mesh in the dynamic model at various key areas. The effort required to generate a suitable mesh for the dynamic model is considerable, even with all the help that can be provided by computer, and it still needs a significant amount of engineering judgement. The method has recently been used successfully as a design tool for investigating frontal impact problems, but does not yet appear to be at a stage where it could be used for legislative purposes relating to side impact. It has been suggested that, at the present state of development of the art, it would be desirable to validate a finite element model by a full scale impact test *before* using such a model even for detailed investigation of the effect of structural changes in the vehicle body.

At the present state of the art, Finite Element modelling must also be considered impracticable for legislative testing because of the time and effort necessary to set up the model, and the computer time required to run it, typically several hours on a super computer. However, research experience with F.E. models demonstrates some of the possible problems with lumped parameter models.

3.1.2 Lumped Parameter Models. The alternative lumped parameter model uses a small number of lumped masses, which are connected by "springs" (and/or dampers). The method does not attempt to describe the detailed behaviour of the structure at a local level, but is only intended to show the motion of a few major components. The force/deflection characteristics of the spring/damper elements are usually obtained from quasi-static crush experiments, though they could in principle be derived theoretically from a (quasi-static) finite element model.

This method of calibration assumes that the structural connections between the masses show similar characteristics under dynamic impact to those seen under the very slow loading conditions implied by a quasi-static crush. This is not always justified in practice, particularly when a very small number of lumped masses are used. In this case the connecting structure between the lumped masses can itself contain significant mass, which will affect its dynamic behaviour. The problem of "dynamic corrections" is described in more detail in Section 3.4

3.1.3 Hybrid models. A recent development in Finite Element modelling is the provision of lumped parameter elements which can interface directly with the beam, shell, or solid elements of a 'traditional' Finite Element model. Using such elements it is possible to reproduce a wholly lumped mass model within a dynamic F. E. program. Critical elements in which the effects of distributed mass are significant (such as a buckling floorpan), can then be remodelled by the use of an adequate number of F. E. elements, while retaining lumped parameter elements for the less critical parts of the structure. This could considerably improve the accuracy of the dynamic response of the model, without the very large increase in complexity (and hence run time) required for a full finite element model. It would, for example, be possible to use relatively simple lumped parameter models of the occupant and barrier, within a car structure model composed largely of F. E. elements.

At present the use of such hybrid models is being proposed for research purposes, in which a simplified 'generic' model need not conform exactly to a particular car type, provided its impact response is realistic. However, models using these principles could in the future have a place in legislative testing.

3.2 Model Structure

At the current stage of development, lumped mass models of the vehicle structure are essentially one-dimensional, being concerned only with motion in the direction of the initial impact. The occupant is usually modelled by lumped mass models (20), or alternatively by one of the specialised Crash Victim Simulation models (21,22). With the lumped mass models parts of the body of the occupant are represented by one or more mass/spring/damper units. Sometimes the units for different parts of the body are interconnected in a defined way. The CVS models describe the occupant by a chain of rigid body elements connected to each other by joints. The elements represent the masses, dimensions and stiffnesses of the body parts. These models are two or three dimensional. More recently, distributed mass models (23) of body parts or finite element models of the occupant have been used.

It is important that the model is sufficiently detailed to be able to predict correctly the motion of parts of the structure adjacent to the occupant, and to be able to detect the likely causes of injury to an occupant. However, it is very difficult to derive all the input data required for a complex simulation. In practice, a complex simulation usually contains data which has been guessed or is based on engineering judgement. In this respect, the model should be simple, commensurate with the requirement to reproduce accurately the important events of the impact. The amount of detail in the simulation model can be considered in three areas: the car structure model, the occupant model, and the interface between the two. The requirements for the interface partially define the requirements of the other areas.

3.2.1 Interface. As more experience is gained from full scale vehicle impacts, the more complex appear the requirements for the interface. Most current simulation models consider inputs to the occupant either through a single load path or through two load paths: one to the pelvis and one to the thorax or ribs. However, in the development of side-impact dummies it was decided that measurement of injury parameters at a larger number of points would provide a better indication of the safety of an occupant during an accident. Consequently at least as many load paths should be provided in the simulation as in the dummy. It may also be necessary for the model to allow the interface to the thorax to tilt during the impact to allow different intrusions at different levels (24).

3.2.2 Occupant. These considerations lead to the requirements for the occupant simulation. This should have at least as many elements to interact with the various load paths as are provided in an instrumented dummy. It should also be able to provide a reasonable representation of the bending/shear properties of the lumbar spine (between pelvis and thorax). It is possible that the requirement for measuring head injuries may be met, in the legislative requirements, by supplementary component tests. In this case, a head and neck should still be included in the occupant simulation to provide appropriate loading to the top of the thorax.

It is clearly desirable to be able to represent a human occupant in the simulation, but in practice there is insufficient data on the impact dynamics of live people to be able to provide a representation which is much better than that of a dummy. The mathematical representation of the occupant should be evaluated against the same criteria as are the mechanical representations, such as the ISO biofidelity requirements, for instance (25).

3.2.3 Car and MDB. The simulation of the car and MDB (mobile deformable barrier) is also likely to require some degree of complexity if it is to be able to represent a wide range of car designs and impact speeds (17,26,27). The mass/spring system should contain sufficient elements to reproduce all the aspects of vehicle behaviour which are likely to influence occupant injury.

The MDB requires separate consideration for the separate elements contacting different parts of the vehicle's structure. In a dynamic impact there is considerable relative movement of different parts of the side structure which can only be modelled satisfactorily by considering them as separate elements. For instance, the relative movement of the door and the rest of the vehicle structure will depend, inter alia, on the relative stiffness of the door to the sill, A and B-posts and seat, the effective masses of the door and other parts of the car and on the various load paths between the MDB face and the target car. The most accurate representation of the impact dynamics would be to regard the car structure as a continuum through which stress waves are transmitted; a dynamic finite element model can provide a close approximation to this ideal. In practice the high frequency waves are not important for determining injuries and can be virtually ignored, but the finite transmission times of the lower frequency distortion waves can be produce significant effects. For most purposes a lumped mass model is a reasonable approximation, provided it has sufficient detail.

For this straightforward approach it is assumed that the occupant impacts only the door. In some cars the B-post may contact the occupant directly and the seat/occupant interaction may be significant.

3.3 Specification of the Sub-system Tests

The method of determining the input (calibration) data for the vehicle model is clearly important. The stiffness of the vehicle structure is described by force/deflection characteristics. In research work accelerations measured in full scale impact tests are sometimes used to define these characteristics(17,26,28), but this would not be applicable for a simulation which replaced the dynamic test.

The main sub-systems test necessary to obtain data for the simulation model is a quasi-static crush test on a complete body (9,10,11). Current studies suggest that it may not be possible to obtain all the required data from a single test using a representative deformable barrier face but that several tests with different loading conditions will be necessary. It is very important that the collapse mode of the structures in the test is similar to that in dynamic tests (10,11,29,30).

In a simulation for legislative purposes it is essential that the procedure used to obtain the data sets should be independent of the user, although it has been stated that, for research purposes, a fully automatic process for determining complete data sets will never be available and the procedure will therefore not be independent of the user (31).

There are some important features that must be included in the specification of the test procedure:

a) The method of holding down the vehicle must be designed so that the main mass is fixed without the fixtures modifying the stiffness of the structure being tested (32). The requirements are likely to be individual for each model tested and will require some individual engineering judgement.

b) The properties of the loading face must be specified. For tests using the MDB face this will be straightforward since this will be identical to the specification for the full scale test procedure (33). However, it will generally be necessary to carry out crush tests in which individual loads are applied to different parts of the structure. The procedure must ensure that these loads are applied in a way which avoids local and unrealistic stress concentrations and buckling.

c) The positions at which the deflections of the structure are measured should be specified. As with the specification of the loading points, the precise locations for measurement will vary between different cars.

d) Details of the procedure for analysing the results to obtain load/deflection characteristics for the model springs and for interaction coefficients. Considerable experience of the difficulties in applying this to a range of vehicle models will be necessary before any general specification can be written. For instance, in quasi-static tests on one type of car,an attempt was made to measure the load/compression characteristics of the door by differencing the displacements of the inner and outer doors. Due to the way in which the door deformed relative to the rest of the car structure, the load/compression characteristic showed multiple values of load at the same value of compression.

e) It is desirable to include several unload/reload cycles within the overall crush test, in order to determine the "unloading" force/deflection characteristics that are important when different parts of the structure are oscillating with respect to one another. (e.g. "bounce" of the door against the barrier face.)

3.4 The use of Quasi-static Tests as the Basis for a Dynamic Simulation

There are two obvious problems in using the data from quasi-static tests in a dynamic model. It is necessary to estimate the effective mass of the various components in order to allow for the inertia effects of the lumped masses in the model, and the effects of the change in force/deflection characteristics with strain rate must be determined (9,10,11,15,26,29,30). There are however also potentially more serious problems in a lumped mass model due to the inertial effects of distributed masses, such as the floor pan, under dynamic loading, as described below (34). A further aspect of this effect is in the difference between the physical positions in space of interfaces such as the barrier face - door interface,due to the need to represent inertial forces by crush of the barrier face or vehicle structure (Section 3.4.3).

3.4.1 Effective Component Masses. The actual mass of some components can be obtained by direct weighing but the effective mass to be used in the dynamic equations may be have to be somewhat different to get the best fit to reality. This is because the structures being represented in the model are continuous, without necessarily having well defined boundaries between different components but collapse progressively, and also because there may be some internal flexibility. For example, the "whole body" mass used in a simple side impact model has had to be reduced by about 20% to allow for the way in which the ends of the car are initially left behind when the centre is impacted (34). The factor is actually time dependant, but the use of an average value has proved good enough for the whole initial period of impact within which the injuries would have occurred. For cars which have been crash tested it is possible to estimate effective masses by a process of trial and error, matching actual motion to predicted motion. For new and untested cars it would be necessary to use engineering judgement. Fortunately, some experience to date suggests that the precise estimation of mass values within the car structure may be less critical for the determination of injury parameters than for the correct determination of details of vehicle motion (4).

3.4.2 Strain Rate Dependence of Force/Deflection Characteristics. As stated above, the force deflection characteristics of vehicle structures change with increasing speed of impact. One cause is the effect of strain rate on the properties of the structural materials; dependant on the material considered, the strain rate can influence the elastic and plastic moduli, and the yield stress. Much more significant is the effect of the inertia of substructures within the main structure, which can effectively stiffen the structure against buckling failure. This effect could be correctly simulated by a finite element model, provided the mesh were sufficiently fine. It should be noted that this "inertial stiffness" mainly influences buckling failure, and has much less effect on bending failure.

For a simple lumped parameter model to be effective, it is necessary to postulate a stable relationship between the stress/strain characteristics measured under quasi-static conditions and those for high speed deformations under impact conditions. Current models use empirical correction (dynamic magnification) factors based on past experiences (9,10,26,29). They vary from 1.3 to 2.5 (9,26,29,30). Sometimes a certain percentage increase per unit impact speed is used (10,30). These correction factors are not necessarily constant but may depend on material, geometry and crush mode (9,30). They might not be valid for novel materials or novel types of structure.

If the use of empirical correction factors is to be meaningful, it is desirable to be able to separate those parts of the structure which deform primarily by bending (whether elastic or plastic) from those that deform primarily by buckling, and apply appropriate (different) dynamic magnification factors. It also appears important that the sequence of failure should be the same in the quasi-static test as that which would be expected in a dynamic impact. This does not necessarily occur in practice. Tests have been observed in which an increase in speed had a major effect on the way in which the structure collapsed, with apparent beneficial effects on the thoracic injury criteria (35).

3.4.3 Dynamic Effects on the Position of Interfaces between Structures. The effect of mass distribution within a structure is exemplified in the floor pan. Under *quasi-static loading* a floor pan will tend to buckle equally on both sides of the central tunnel. Under a *dynamic input* most of the buckling occurs between the struck side of the car and the tunnel, since the tunnel is constrained by its inertia so that the compression load is higher on the struck-side than on the non-struck side of the floor (34). Such an effect can, in principle, be allowed for in terms of the overall force/deflection characteristic by the use of a suitable dynamic magnification factor.

A more serious problem occurs at the interface between structures in methods in which the loading of the structure in the quasi-static test are computer controlled to try to provide an exact reproduction of the movement of each lumped component represented in the simulation of the dynamic impact (5,6,7). The problem arises at the "door" mass, which provides the interface between the Mobile Deformable Barrier and the car side structure. In the quasi-static crush the compression forces on the two sides of the door must be equal, otherwise the door would accelerate rapidly, and so cannot exceed the maximum strength of the side of the car. However, in the dynamic input the forces on the two sides of the door are very different, as the door *is* rapidly accelerated. In full scale impact tests peak loads in the barrier face can be as much as three times the value obtained in quasi-static tests (35,36). There is no way in which such inertial effects could be reproduced in quasi-static testing to produce a force equal to the full dynamic load in the barrier face. In practice it will be necessary for the simulation model to use a force/deflection characteristic for the barrier face which is derived from other tests, and so does not exactly reproduce the forces and deflections obtained in the "computer controlled" quasi-static test.

3.5 Accuracy and sensitivity

It needs to be established how closely the simulation model should predict actual crash results. In principle, the only output that is necessary is a single figure which gives the probability of injury to a given body area for a particular type of car subjected to a particular impact. However, even if such a model were produced and validated by comparison with a crash test, this would not give much confidence that the model would be able to give a correct prediction for a different set of conditions. In practice it is necessary to demonstrate that the simulation behaves in the same way as reality for a number of parameters. It is important that these parameters correspond fairly closely to quantities which are believed to relate to occupant injury. In particular it is important that the time history of such parameters should be similar for the simulation and the actual test, as this improves confidence that the simulation incorporates the correct structural collapse and energy transfer between bullet and target vehicles and between the vehicle structure and occupant. It is not, however, sensible to try to match the output from a simulation to the results of a test with better accuracy than the repeat accuracy of a crash test. There are numerous reasons for variability between supposedly identical crash tests, some of which will apply equally to sub-system tests used to give input for simulations.

These include:-

a) Differences in the exact lateral and vertical position of the impact point.
b) Differences in the crush characteristics of the deformable barrier face due to manufacturing tolerances.
c) Differences in the occupant positions.
d) Real variations in the collapse characteristics of supposedly identical vehicles due to manufacturing tolerances and variations in actual construction (e.g. position and quality of spot welds).

The observed coefficient of variation in results from nominally identical tests due to these and other factors is about 10 per cent. It may be noted that, where large differences have been observed, careful examination of the vehicles after the crash has usually shown some differences in the vehicle state which has affected the collapse pattern..

It is suggested therefore that a simulation which produced values for injury parameters which did not differ by more than 10 per cent from values observed in the crash test that was being simulated could be regarded as adequate, provided the time histories of the parameters were similar and, in particular, that the peak values occurred at approximately similar times after impact. (Typically within about 5 msec)

It is also important that the sensitivity of the simulation to changes in barrier speed or mass is similar to that observed in full scale tests.

4 METHOD OF APPLICATION

Full scale impact tests can be performed by national approval authorities or by manufacturers supervised by the approval authority. The approval authorities are familiar with impact testing techniques and will be able to detect errors or malfunctions. If necessary, data can be cross checked for verification. For instance, accelerometer results can be integrated to give velocity change which can be compared with film records. It would be more difficult to verify simulation input data, particularly if variable correction factors have to be used, and there is likely to be a lengthy learning period before the method could be applied with confidence.

It may be advisable, at least for the first few years of application, for all parts of the approval procedure to be performed by the approval authority. In order to ensure that the procedure was fair and realistic, the procedure should involve a fully validated single mathematical model, with a carefully defined sub-systems or component test procedure to provide any necessary input for the model. If the model contains a choice of procedures to allow simulation of a range of vehicle types or construction methods, then there should be a carefully defined method for predetermining the procedure that would be used. Similarly, if factors for static to dynamic correction are required, then there must be a prescribed method for selecting these. They should not be arbitrary or left to the choice of the manufacturer seeking approval. There should be no requirement for expert interpretation of data.

It is common for alternative test procedures to be permitted provided equivalence has been demonstrated. This would probably be acceptable eventually provided the alternative procedure had been validated to the same extent as the prescribed procedure (see Section 5).

Conformity of production tests would be the responsibility of the approval authority, but would not necessarily be performed by that authority.

5. EVALUATION

Any mathematical simulation procedure that is proposed for use in place of full scale impact tests should be fully validated over as wide a range of conditions as are expected to be encountered in the approval system. The model should be calibrated by performing tests on a component level to determine the values of the individual model parameters. It should be noted that, if input parameters are based on estimates or engineering judgment and are adjusted after comparison with the test results, then this is "tuning" rather than validation (18). A true validation would predict the results of a dynamic test on a vehicle which has not been used to calibrate the simulation model and then these results would be compared with a subsequent full scale test on this vehicle. Validation with six vehicles of different sizes and weights and verification by 20 crash tests have been reported (26).

Satisfactory operation of computer simulation methods must be demonstrated over a range of well defined applications (benchmarks). The following variations should be included in the validation of a procedure:-

a) Mass of struck car.
b) Mass of impacting MDB.
c) Impact velocity of MDB.
d) Dimensions of struck car.
e) Type of car (2-door, 4-door, soft top etc.).
f) Manufacturing materials (steel, aluminium, composite plastic, etc.).
g) Similar size vehicles with known differences in performance *.
h) Standard and modified vehicles.
i) Side structure stiffness and geometry.

* For validation (g) the requirement to perform the simulation before the crash test clearly cannot be met since prior knowledge of a difference in performance is required.

Parameters should include inner door velocity and the dummy injury criteria. In order to be confident that the model is representing reality and can predict results accurately for conditions where there is no foreknowledge, it must be able to reproduce the correct values of all important parameters relating to the full scale test. Not only should peak values be compared but also the time histories of the parameters and, in particular, the time of peak values. (see Section 3.5)

6 COST

It is not possible to quantify the costs of a mathematical approach to vehicle evaluation for side impact protection without considering a specific case. For instance a full finite element approach would involve considerable computing time (12) and a very large effort in generating the model and the necessary properties of each model element. Some of the relevant work on model generation might well have been spent in the design processes of the vehicle, but as explained in Section 3.1.1, considerable effort would be required to translate this into a form suitable for a dynamic F.E. model.

The costs of a sub-system or component test procedure for a legislative side impact test are often considered to be less expensive than full scale test using a moving deformable barrier and a dummy. The difference in costs may not be as great as expected depending on the complexity of the subsystem tests necessary to produce the input data for a satisfactory simulation. The costs can be divided into three categories:

a) Investment and maintenance.
b) Labour costs.
c) Special costs, related to consumables used in the specific test procedure.

The cost of the vehicle or body shell could be included in this comparison but it is difficult to decide on the realistic cost of prototype vehicles or bodyshells.

7 TIMESCALE

It is difficult to be precise regarding the time before a mathematical or subsystems approach to legislative testing would be fully developed and validated. However WG9 considers that the current development is at about the same stage as the full scale side impact test procedure was 4 to 6 years ago and that it will be at least a further 4 years before it is in a state that could be considered for legislative use.

8 ALTERNATIVE USES FOR SIMULATION

The use of a mathematical modelling approach to legislative testing of side impacts is clearly complex, particularly if the procedure has to cover a very wide range of vehicles and test conditions. There is a more limited use which could be more easily validated. That is in the evaluation of small design changes or in the evaluation of a range of vehicles which are basically the same design but have very different trim levels (37). In this case, the simulation technique could be demonstrated to predict the actual test results and could then be used to predict the effect of relatively small changes. Perhaps the technique could also be used at an early stage for conformity of production if it were validated for that vehicle at approval stage.

9 EXPERIENCES WITH MATHEMATICAL MODELS

9.1 General

Early models for the simulation of side impacts were simple one-dimensional models using lumped spring/mass systems similar to those developed for frontal impacts (19,38). Subsequently the models have been improved by adding a deformable front element to the barrier used as the impactor and by using a representative model of the dummy thorax which has enabled occupant injury parameters to be calculated.

9.2 Experience at TRRL

This type of model has given useful insight into some of the phenomena occurring in side impacts but the quantitative agreement with full scale tests has been poor. Also the model was fundamentally unable to describe some aspects of side impact which are important for determining the injury levels measured by anthropometric dummies in experimental impact tests.

With the benefit of hindsight, it has become clear that the simple adaptation of a frontal impact model for the side impact problem was an oversimplification and neglected various important factors. The main problem is that the coupling between the car and occupant dynamics is much stronger in side impact due both to the proximity of the occupant to the impacting vehicle and to the relatively low mass of the parts of the target car structure that actually contact the occupant. A further problem is that when a deformable barrier (or car front) is the impactor, there can be considerable differential motion of different parts of the target vehicle side structure which must be represented in the model. The angle of tilt of the intruding door about a longitudinal axis, caused in part by such differential motion, can have a large effect on the occupant injury parameters. With a rigid impactor, the whole of the car side is constrained to move inwards at the more or less the same speed and this differential motion is less likely.

When experimentally derived stiffness data for the car structure were used in the simple model, it was found necessary both to assume a large increase in dynamic stiffness compared with the quasi-static results and to make the thorax much stiffer than that of the dummy ribcage in order to duplicate the experimental results. Also the determination of the barrier stiffness from deformation at the centre of the door proved to be ineffective. A better estimate for the barrier face stiffness was derived from an average of the specification for the EEVC MDB face

Further modifications have been made to the model to improve agreement with experimental results. An important modification has been to separate the load paths from the upper and lower halves of the MDB face so that load paths through the door and the sill are considered separately. The A and B-pillars are also treated separately. These changes have improved the simulation considerably, but the dummy injury parameters are still higher than in actual tests. This appears to be due to an oversimplification of the dummy model which is still not fully two-dimensional and does not include a load path through the abdomen. Once the abdomen load path has been included, the connections along the spine between thorax, abdomen and pelvis become important. The occupant model will then need to incorporate a more comprehensive multi-body representation (similar to the Crash Victim Simulation models (21, 22)) while retaining the realistic spring/damper rib model of the present simulation.

9.3 Experience at TNO

Simulation of side-impact collisions, or at least the effect of them on the occupant, requires models of bullet and target vehicles, and an occupant model. In general , the two types of model use different techniques for describing the geometrical and physical properties. In the last few years considerable knowledge has been gained in the development and evaluation of numerical databases for standardised anthropomorphic dummies. At this time very reliable databases of the Hybrid II and III dummies exist (39,40). These databases are used to simulate an occupant in frontal impact. However, due to the direct interaction between dummy and vehicle in side impact collisions, different phenomena are involved, resulting in a much more complicated dummy. Consequently, a model which would react to these phenomena would be correspondingly complicated. To describe occupant behaviour during side impact realistically, a 3D model would be required, which would cover the gross motion and which would at the same time record the prescribed injury parameters. Experience teaches that such a model demands thorough investigation for measuring and defining the geometry and contact interactions, and for determining internal load paths. Currently, only a single 2D EUROSID model is available; work is still in progress to develop a 3D model database, but this is understood to be a very complicated matter.

It must be clear that the development of a model of a human being will be several orders more complicated.

Since the first publication about the Composite Test Procedure (4), this method has been improved through the years. At this moment a more or less definitive version has been developed which consists of a fully computerised test. However only a prototype is available yet and it will take at least another year before a complete procedure with the specifications of hardware and software will be available in the public domain.

A number of tests have been done by TNO since the first presentation, each according to the state of the art at the time. The results were compared with the results of full-scale side-impact tests,using the same test configuration, with an identical vehicle and barrier front. The conclusions from these tests can be split int general and specific remarks, and into recommendations:

i) General - comparison of costs. It was found that at TNO the composite test was roughly as expensive as the full scale test. For both tests considerable preparation had to be done. Additionally, the quantity of information obtained with the composite test was less than that which is normally obtained from a full scale test, while the effect of interactions can only be determined in a dynamic test with a full vehicle. However, to study the influence of one single parameter, the composite test can be put to excellent use, once the characteristic curves are known.

ii) Specific remarks. These apply to the preparation, test performance, data processing, and simulation results. Though guidelines are given for vehicle preparation and installation, additional decisions have had to be made based on good engineering practice. Also, the method of execution of the test is not quite clear and unambiguous, so it is possible for different characteristics to be obtained by different operators carrying out the same test. Furthermore, the characteristic curves which provide an input to the simulation have to be interpreted and processed from the test data. This presents another opportunity for data manipulation to occur.

Finally, the CTP reflects trends rather than providing an exact copy of the full-scale test results. It has been noticed that a variable such as displacement is reproduced well. The time histories of the higher order variables, such as the accelerations, often show poor agreement. Peak values, their time of occurrence, and oscillations, mostly differ from the results of a full scale test. Moreover, the computer dummy only produces a limited number of injury parameters; the safety of the vehicle should be assessed on the basis of a more extended set of injury criteria, whose values cannot be calculated with the present model. For that purpose a comprehensive dummy model will be required, which would present the same difficulties as were mentioned in the previous section.

iii) Recommendations Use of the CTP can be recommended in cases where changes in the design of a vehicle would demand a new approval test. By using the CTP the effect of a variation in design parameters can be evaluated. For that purpose a complete and fully described test procedure, including the state, preparation and positioning of vehicle and loading devices, the method of carrying out the test, and the method of evaluation, is necessary to obtain unbiased and comparable results between tests conducted by different operators.

9.4 Experience at Ford of Europe

Ford are currently investigating and using several computer codes to assist in the development of vehicles to meet specific legal and corporate requirements for side impact. These codes include;

- One dimensional lumped mass/spring models for general guidance and macro parametric studies
- Quasi static beam codes (stick models) where empirical data is used to represent non-linear springs in the system,
- Dynamic beam codes for structure and occupant simulation (e.g. Madymo and Calspan CVS), which again depend on empirical data,
- Large three dimensional Finite Element models which simulate the structure, occupants and the deformable face of the barrier and are run on a super computer.

It is considered that two or three of the codes would be used during the development programme for a vehicle; the lumped mass-spring model, the Madymo or Calspan CVS type of model and the large FE model. This is due to the necessity to provide guidance at an early stage of the development cycle when there is insufficient detailed structural data to use a large FE model. The advantage of the large FE model is that micro parametric studies can be conducted to fine tune the design but clearly this can only be achieved at a late stage in the development when the required detailed structural data is available.

Sufficient studies and validation exercises have not yet been conducted on a variety of vehicles to validate completely the programs although the work to date with the Madymo and Radioss FE model is encouraging. Both codes include a model of the US DoT SID developed by Ford and a validated model of the US barrier face but the overall validation is restricted to two cars only.

The quasi static models have proved deficient in terms of their ability to represent the dynamic response of the structure and their interaction with the occupant model. Only the resulting door velocity is used as input to the occupant model. The models at this stage, therefore, are only being used to establish the trends of specific proposals rather than to obtain absolute numbers from the analysis. This application is ideal as the effects of a modification can be established without any influence of test variation.

The actual recommendations resulting from the analysis work are eventually supported by an actual test to confirm the design. The use of simulation models at this time is to reduce the number of crash tests but not to eliminate them completely. With respect to side impact at this time, there is the added benefit of using simulations to understand more fully the side impact phenomenon in a time scale that is acceptable.

In terms of analysis time, running costs and data availability, the ideal program will be a FE model incorporating a beam code, for instance Dyna3D, Pamcrash or Radioss. The occupants and most of the structure would be modelled by beams and joints with the more critical areas, the door and the B-pillar, represented by a FE mesh , as would the deformable barrier face. This approach is being progressed at present.

Summary. The use by vehicle manufacturers of computer simulations will increase as improved codes and computers become available and as analytical experience improves. The use of such programs to *replace* crash tests is, however, debatable and is obviously long term as the necessary validation exercise would be both time consuming and costly.

9.5 Experiences of CTP Reported in the Literature.

CCMC have not provided results of testing with CTP to WG9 but have reported some experimental results obtained by CTP at a conference(6). These were obtained using the original version, before implementation of computer control for the quasi-static crush, but incorporating a dummy with a separate pelvis. Comparative results are presented for a set of full scale impact tests and corresponding simulation results, using the CCMC implementation of the CTP. The tests were carried out by MVMA in the USA, using Ford LTD cars and the US SID (Side Impact Dummy). No comparisons have been reported from the further tests carried out by MVMA using the EUROSID dummy. Cars were tested in the following configurations:

HN - unpadded door,no space between dummy and door.
HF - unpadded door,space between dummy and door.
PN - padded door, no space between dummy and door.
PF - padded door, space between dummy and door.

Acceleration/time plots were presented for the barrier, main car body, door, and dummy ribs, spine and pelvis, with the test car in the HN (unpadded door, dummy in contact with door) configuration. The comments on the published results given here are those of WG9 and not those of CCMC.

The results for the barrier and car components show poor agreement between full scale and simulation, after about the first ten milliseconds, and cannot be regarded as providing any confirmation for the accuracy of the CTP simulation. The results appear to demonstrate the discrepancies between dynamic and quasi-static testing that might be expected from a simulation model with too few lumped masses (see Section 3.4).

The results for the dummy components, on the other hand, appear to show quite reasonable agreement between the CTP and full scale test results. It should, however, be noted that when the dummy is initially in direct contact with an unpadded door, the dummy motion will be largely determined by the door motion in the first 10-15 msecs after the initial impact. This is influenced largely by the inertial effects of the initial

impact conditions between the barrier face and the door, while the rest of the car structure plays relatively little part. Beyond this time the relative motions of the sill and the A and B posts have a much greater effect on the door motion. When the door is padded or the dummy is not initially in contact with the door, the door motion in the period after 15 msec becomes a significant factor in determining the dummy behaviour. No plots have been published relating to CTP simulations of dummy motion for the configurations HF, PN, PF.

Results from the other three configurations are only presented in terms of the peak values for acceleration of ribs, spine ,and pelvis, and the corresponding values of TTI. These results are reproduced in Table 1, in which are also shown the percentage changes (in each column) from the values recorded in the HN "base" configuration.

Table 1
Comparison of Full Scale Test and CTP Simulation Results

	Rib "g"		Spine "g"		Pelvis "g"		TTI	
Type	Full scale	CTP	Full scale	CTP	Full scale	CTP	Full scale	CTP
HN	98	105	106	100	143	155	105	104
HF	66 67%	61 58%	92 87%	59 59%	150 105%	109 70%	92 87%	61 59%
PN	45 46%	45 43%	62 59%	59 59%	57 40%	56 36%	56 53%	52 50%
PF	51 52%	33.5 32%	58 55%	44 44%	61 43%	44 28%	61 58%	38 37%

These show some major discrepancies, and can hardly be regarded as confirming the accuracy of CTP. For example, peak rib acceleration for the PF configuration shows a full scale test value 60% higher than the CTP prediction. In practice it is most unlikely that there will be no initial gap between the occupant and the door in a real crash, and there will usually be some padding on the door. The configuration PF is therefore the one most likely to be relevant to "real world" crashes. The CTP predicts a reduction in rib acceleration, TTI and pelvis acceleration when changing from configuration PN to PF whereas these were observed to increase in the full scale tests. Similarly, pelvis acceleration shows a wrong sign change when going from the HN to the

HF configuration. These discrepancies are concerned only with the effects of padding and different dummy seating positions; no data have been published by CCMC on the effect of structural changes in the car body.

10 CONCLUSIONS

1. The use of a mathematical model/ subsystem test approach to vehicle side impact legislative testing would have the advantage of being able to approve a vehicle earlier in the design stage than current whole vehicle tests on a completed vehicle. The time advantage gained depends on the complexity of the mathematical model and on the proportion of the vehicle necessary for the sub-system or component test.

2. A mathematical model approach would allow the performance of a vehicle to be assessed under a wider range of conditions than the single test condition of a full scale test.

3. The use of mathematical models is not straightforward and their ability to reproduce adequately the dynamics and reactions of a barrier impacting a car containing an occupant have yet to be demonstrated.

4. The model of the occupant must be sufficiently detailed to be able to predict likely modes of injury in lateral impacts and to give the correct load transfer between vehicle and occupant and between the major body parts of the occupant.

5. The sub-systems test procedure must be closely specified and must adequately represent the collapse of the vehicle under dynamic conditions.

6. The procedure for deriving the input data and for operating the model, including any necessary use of dynamic correction factors, must be uniquely defined and must not rely on expert interpretation.

7. The procedure must be fully validated over a wide range of conditions which differ from those for which the model was calibrated.

8. The difference in the costs of testing a vehicle for final approval between full scale vehicle impacts and a mathematical model/subsystems test approach is not likely to be as great as might be supposed, although testing for development purposes could prove to be much less by using the latter approach.

9. Taking into account the present status of mathematical modelling and the time required to develop, validate and evaluate test procedures, WG9 considers that it will be at least 4 years before a mathematical model/ sub-systems test approach could be considered seriously for legislative testing. It might prove practical for it to be used earlier for supplementary testing or Conformity of Production testing.

11 MEMBERSHIP OF WORKING GROUP 9

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APPENDIX
ANNEX 1. VALIDITY OF CTP.

Validity of the June 89 version of the Composite Test Procedure proposed by CCMC, judged by EEVC WG9 Requirements

The Final Report has described various requirements which WG9 consider should be satisfied by a mathematical modelling approach supplemented by component tests before such a procedure could be regarded as a satisfactory alternative to a full scale test procedure. These requirements are summarised in this Annex together with comments on how far they could be regarded as being satisfactorily met by the CCMC proposals (June 1989 version (1)). This differs from the earlier (April 1988) version in the use of on-line computer control for the quasi-static crush, and in the use of a more complicated dummy with separate thorax, abdomen, and pelvis segments. These changes still do not meet many of the criticisms levelled at the earlier version, while the use of on-line computer control appears to add some additional problems.

REQUIREMENTS	COMMENTS ON CCMC CTP PROPOSALS
Complexity of Simulation Model	
General. The model should be as simple as possible, within the constraints that it must give reliable results that adequately represent the effects of a full scale test. (Section 3.2)	The model is too simple to meet the requirements.
Dummy/Occupant. This should have provision for separate load inputs through several ribs, the abdomen and the pelvis. (Sections 3.2.1 and 3.2.2)	The later version of CTP models a thorax (including an abdomen) and a separate pelvis, but only has a single rib.
It must have a suitable connection between the different parts of the body, particularly in representing shear and bending of the spine. (Section 3.2.2)	The CTP model now includes a shear connection between the thorax and the pelvis, but does not give a proper representation of bending of the spine.
It must have a biofidelic representation of the rib structure. For validation, it must be able to provide an accurate representation of a relevant dummy. (Section 3.2.2)	The adequacy of the CCMC simulation of the occupant has not yet been demonstrated. It has been suggested that the simulation should use data derived directly from cadaver tests. As the cadaver test conditions were generally unlike those in a lateral car impact, this approach would be insufficient. In order to generalise the cadaver results for use in car "impacts" it is necessary to postulate a mechanism for the relevant body part (eg

	thorax) that will reproduce the relevant biomechanical outputs. This is the basis for dummy design and should be adopted for the mathematical simulation also.
Car Structure. This should model the identifiably different parts of the car structure with separate lumped masses. (Section 3.2.3)	As currently presented, the model has only two masses : the "side structure"- which includes the door - and the rest of the car structure. There appears to be no specific provision in the model for relative motion between the sill, pillars and door. Such relative motion is normally different under the conditions of dynamic impact compared with those of the quasi-static test.
Car door tilt. The model must represent the effects of door tilt to give different intrusions at the levels of top and bottom ribs, abdomen and pelvis. (Section 3.2.3)	This is not included in the CCMC model which only simulates one-dimensional motion of the door. In the current version the deformation of the door is measured at rib and pelvis levels. However these separate motions are only related to a single overall motion of the interface between the barrier face and the vehicle, and the model has no representation of the effects which contribute to door tilt.
Deformable Barrier. The model should contain separate load paths with appropriate stiffnesses to identifiable -parts of the car structure such as the sill, A-post, B-post and the door. (Section 3.2.3)	As currently presented, the model has only a single load path from the barrier face to the car.
Sub-system test. The method of holding down the body shell must ensure that it does not influence the measured stiffness. (Section 3.3(a))	This is not a trivial problem. The current CCMC proposals give a reasonable general definition of the method for holding the vehicle down, but the specification concerning the support of the body side above sill level is vague. There are potential difficulties in some vehicles with the use of the suspension attachment points, and some engineering judgement is likely to be required. This conflicts with the requirement for the procedure to be user independent.
The properties of the loading should be specified. (Section 3.3(b)).	This requirement is met in the CTP face in that, while it is not actually specified, it is implicit that the specification for the EEVC MDB face could be used.

The position of the measurement points requires precise definition so that tests carried out in different establishments will be compatible. (Section 3.3(c))	This was not adequately defined in the earlier CCMC proposals. In particular, there was uncertainty about the measurement of the compression of the barrier face. It could variously be interpreted as compression at a single point opposite the point for door deflection measurement and also as an "average" deflection across the barrier face. The results would not be the same. The difficulty has been "overcome" in the current proposal by only measuring displacement at the exterior and interior loading rams, with no measurement at all being made at the interface between the barrier front and the door. The method by which this limited information is used in the computer model has not yet been clearly explained in the literature.
Details of the procedure for deriving the force/deflection characteristics for the model must be described. (Section 3.3(d))	It is claimed that this requirement is circumvented by the use of "on-line" computer control for the loading devices. The logical background to the computer program is not described in the CCMC proposal, and in its absence it is not possible to level specific criticisms at the concept. In practice there could be some serious problems, since without the ability to control the position of *all* parts of the car structure, it is not possible to run a quasi-static test which provides an exact reproduction of all the stages of a dynamic impact.
It must be possible to "correct" the quasi-static stiffnesses for use in the dynamic model. (Section 3.4.2)	This area has not been addressed in detail in the CTP proposals. The "dynamic magnification" of stiffness is likely to be different for different materials and for different types of structural component. The use of these magnifiers appears to require engineering judgement which conflicts with the requirement in section 3.3.
The collapse of the sub-structure should be the same in the static test as for dynamic impact. (Section 3.4.3)	This difficult area has not been adequately discussed by CCMC. If the collapse modes differ, then the static test results will not predict the correct dynamic result. There is a major problem concerning the relative collapse of the barrier face and the door. (Section 3.4.3)

It should be possible to relate the sequence of collapse of sub-structures in the quasi-static test to the sequence observed in the dynamic test. (Section 3.4.3)	The CTP procedure does not consider this aspect. CCMC do not appear to have discussed this problem to date. A particular point is the relative movement of the door, pillars and sill. The model used in the CTP cannot reproduce the "bounce" motion of the door which occurs in impact tests and which may be significant in determining the injury risk.
Validation. The model must be fully validated using carefully chosen parameters over the full duration of impact and over a wide range of test conditions and vehicle types. (Section 5)	The CTP has not been fully validated. The problem of validation, and of how good the model should be, have not been adequately discussed. The published results are not convincing nor are they necessarily relevant. CCMC have suggested that it is adequate to give correct predictions only for peak values of the injury parameters even if the time history of those parameters do not agree with actual results, but this conflicts with the requirement to get a mechanistic or causal relationship into the model in order to have confidence in its use other than for the validated conditions. It also appears to be assumed by CCMC that consistency is more important than accuracy.

REFERENCE FOR APPENDIX

1. CCMC., *Proposal for a Council Directive on the Approximation of the Laws of the Member States Relating to the Protection of the Occupants of Passenger Cars in the Event of Lateral Collisions.* (Directive 89/x/EEC) June 1989. Ref: 249/89.

ANNEX 2. COSTS

Cost of CTP in comparison with FST

The cost of the CCMC Composite Test Procedure (1988 version) has been estimated and compared with the costs of a full scale test. A request has been made to CCMC to suggest costs for the 'computer-in-the-loop' system but these have not been forthcoming. The costs can be divided into three categories:

a) Investment and maintenance
b) Labour costs
c) Special costs

The cost of the vehicle or body shell could be included in this comparison

a) Investment and Maintenance costs

(i) CTP

For the quasi static crush tests, the vehicle has to be fixed to the laboratory floor or to a heavy support mechanism. The hydraulic loading cylinders used for the external and internal intrusion tests should also be fixed to the laboratory floor or to this support frame.

Estimated costs for the fixation and support system:- 5-10k ECUs

To obtain the force-deflection characteristics of the inside and outside of the vehicle, quasi-static loading tests are performed. This requires at least two long stroke hydraulic cylinders, each activating a loading device which represents the dummy or the striking barrier face.

Estimated costs for the hydraulic loading system:- 12-17k ECUs

The forces and displacements generated during the quasi-static loading tests must be measured. This requires one large load cell (150kN) for the outside force deflection characteristic and at least one smaller load cell (50kN) for the inside characteristic. The deformation of the individual blocks of the barrier face, the overall displacement of the barrier impactor and the vehicle and the displacement of the dummy representation must be measured some of which require relatively large displacements measuring capability, up to 0.5m..

Estimated costs of instrumentation:- 12-15k ECUs

The mathematical simulations included in the CTP use a small personal computer.

Estimated costs for hardware (assuming free software) :- 1300 ECUs

The estimated total costs for investment appear to be 30000 to 43000 ECUs. It is intended to extend the performance of the CTP by incorporating the computer into a continuous on line control system for the integration of the mathematical simulation and crush tests. To meet some of the requirements given in section 3 of the report extra loading and measuring facilities will have to be provided. These two changes will increase the costs considerably to the same order as the full scale test.

The initial capital investment costs will have to be met only in the first year. In subsequent years calibration, maintenance and replacement costs will apply. These are difficult to estimate but a yearly budget of 10 per cent of the investment costs seems appropriate:- 3000 - 4000 ECUs

It should be noted that some of the required equipment (e.g. hydraulic equipment, long-stroke cylinders etc.) may already be available in some test laboratories, which could affect the estimates of capital investment required, but this cannot be assumed for the purposes of this calculation.

(ii) FST

The investment and maintenance for the full scale test procedure requires the following:-

Side Impact Dummies. At least two are considered to be necessary with an expected useful life of four years.

Estimated cost of Side Impact Dummies:- 80k ECUs

The dummies will require to be Certified at regular intervals, requiring special equipment and software. The expected life of this is ten years.

Estimated cost for Certification apparatus and software:- 25k ECUs
Mobile barrier with expected life of ten years. Estimated cost of mobile barrier:- 15k ECUs

Standard equipment, which is used for a range of testing carried out at the test facility, part of whose investment can be attributed to the Full Scale Test Procedure.15-20 years expected life. Estimated partial cost for test equipment:- 100k ECUs

The total investment and maintenance costs per year for the FST are approximately 29 - 31k ECUs

b) Labour costs

(i) CTP

The vehicle or bodyshell has to be prepared for test. For instance the wheels and suspension and the opposite door need to be removed, the body must be fixed to the loading structure. Three quasi static tests are performed and the force deflection characteristics are determined. Other computer input data, such as the effective door mass, are established and a simulation performed. The test report has to be written.

Estimated labour costs for the CTP:- 5-7k ECUs. (But this could drop to 4k ECUs with experience under routine test conditions)

If the CTP is extended, as suggested in section (a) above, more data would be required resulting in more labour costs.

(ii)FST

Similar costs may be estimated for the Full Scale Test to include the costs of preparing the vehicle, Mobile Deformable Barrier and dummy, analysing the results and preparing the report

Estimated labour costs for the FST:- 8.3k -9.5k ECUs

c) Special costs

(i)CTP

A deformable barrier face from the full scale test procedure is used to determine vehicle and barrier crush characteristics. This could be a rigid foam or an aluminium honeycomb front.

Estimated cost, MDB face:- 1-2k ECUs

Special fixtures for each vehicle type would have to me made in order to mount the vehicle rigidly to the floor or to the support frame.

Estimated cost:- 1-2k ECUs

(ii)FST

The FST requires the same barrier face as the CTP. Consequently this cost will be the same for both procedures.

Estimated cost, MDB face:- 1-2k ECUs

There is likely to be some equipment that is specific to the particular vehicle model under test, such as camera mounts. It is thought that the cost of these would be similar to those for the CTP Estimated cost, special equipment:- 1-2k ECUs

Total estimated special costs for both the CTP and the FST are 2-4k ECUs

Vehicle costs

For prototype development tests a vehicle body without engine, drive chain and, perhaps, suspension can be used, whether the type approval Test is a Full Scale test or the CTP. However, most of the costs will be in the development rather than the actual test hardware. It is possible that for legislative tests (Type Approval), only some parts of the whole vehicle would not be necessary, in which case the vehicle costs could be considerably lower than those of a full scale test. However, if complete vehicles are necessary, no reduction in vehicle cost is expected.

Summary of costs.

The cost of the April 1988 CTP procedure can be estimated from experience with tests actually performed and from the estimates given in the previous sections. Tests to the more recent proposal incorporating the computer in the loop would be considerably more.

If 25 per cent of the investment costs are considered as yearly costs, including interest charges on capital, and assuming that 10 tests are performed per year, then the total estimated costs per test are:-

	Cost Item	Composite Test Procedure(April 88) ECU	Full Scale Test Procedure ECU
a)	Investment/maintenance	1050 - 1500	2900 - 3100
b)	Labour	5000 - 7000	8300 - 9500
c)	Special costs	2000 - 4000	2000 - 4000
	Total	8050 -12500 ECUs	13200 -16600 ECUs

These costs appear to be slightly lower than the costs of a full scale side impact test. However, extensions or improvements such as a complete dummy representation, extension of loading and measurements to meet the minimum requirements of section 3 of the report or the integration of the computer simulation and the crush tests will considerably increase the costs of the CTP procedure proposed by CCMC. This applies to investment and maintenance costs and to labour costs. If the test procedure becomes fully routine, it can be assumed that the labour costs for the CTP would reduce by about 1000 ECUs Therefore cost differences between a full scale test and an equivalent sub-systems and simulation test will be marginal.

APPENDIX CONCLUSIONS

1. The CCMC CTP proposal (April 1988) represents an interesting approach to legislative testing through sub-system tests supplemented by mathematical modelling.

2. The model is currently oversimplified and cannot simulate some of the phenomena observed in experimental tests that are known to affect the injury parameters.

3. The procedure is not yet fully specified.

4. Some aspects appear to require engineering judgement (e.g. vehicle fixation, multiplying factors).

5. The procedure has not been fully validated over a wide range of conditions (benchmark tests).

6. The cost of the CCMC CTP is expected to be slightly less than the cost of a full scale test (perhaps 30%). The cost of a fully equivalent CTP may not be very different from a full scale test.