10 UNDERSTANDING THE COST OF DESIGN EVALUATION USING VIRTUAL CRASH TESTING

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The automotive safety-testing environment currently deploys virtual methods and physical crash testing for new product development and validation in safety testing legislation. Cost benefit analysis of crash testing as a design evaluation method is considered here by estimating the cost of virtual crash testing. This has been achieved via the compilation of detailed process maps and AS-IS analyses of the current virtual testing procedures. This leads on to detailed work and cost breakdown structures used in the comparative analysis of cost drivers. The research considers cost drivers at the final stages of the virtual crash testing process only which potentially can evaluate legislation requirements with minimum physical crash testing. This research considers front and side impact only.

Keywords: Cost Estimate, Virtual Crash Test, Cost Benefit.

1. INTRODUCTION

Crash testing, or the study of crashworthiness, is a field that considers how vehicles withstand a crash or sudden impact. European legislation requirements include physical testing for final safety analysis. Due to the high number of iterations and repetitions involved in the overall testing procedure, from design to final approval, even a partial conversion to the virtual simulation testing domain has potential significant cost reduction opportunities. It also raises car safety standards by increasing safety integrity through more complex parametric testing that is not possible in physical testing. The virtual design evaluation methodology is becoming more popular with the increase in computing power.

This research is part of the Integrated European Framework 6 Project, Aprosys, "Advanced Protection Systems", which is concerned with developing technology to lessen the fatalities and injuries on the road. An investigation has taken place into the potential of introducing wider virtual impact testing within the vehicle development process, assessing the cost and benefits to legislation, society and car manufacturers. The study has produced detailed process maps, cost breakdown structures, cost estimates and cost analyses of the three areas of physical crash testing, virtual crash testing and cost of a crash in society. Data and information has been collected via communication with a number of external parties, including private car manufacturers, academics, public services and other interested parties. This paper reports on the results of investigating virtual crash testing through a cost design evaluation method.

The aim of the research is to investigate the costs and benefits attributed to virtual crash testing. This is developed using cost estimates and a cost analysis of virtual crash testing as a measure of design evaluation. Front and side impact of virtual crash testing is considered only. The objectives of the research are to:

- Identify cost breakdown structures for virtual crash testing.
- Identify cost drivers and some of their behaviour for final virtual crash testing only.
- Validate the above using industry experts.

2. LITERATURE BACKGROUND

The process of physical crash testing has evolved dramatically since the first official test took place in 1969, both as a result of increased emphasis in society on vehicle safety and the utilisation of new technology. It remains the primary measure of vehicle crashworthiness, and indeed the only compulsory method accounted for in official legislation.

By law, all new car models must pass certain safety tests before they are sold. These specific safety requisites vary worldwide and are defined by the legislation of the country in which the car is to be licensed. In the UK and other countries in the European Union, legislation controlling vehicle safety and crashworthiness is defined by[1] the United Nations Economic Commission for Europe (UNECE) Working Party of the Construction of Vehicles (WP29). This legislation largely evolved in complexity throughout the 20th Century as road travel increased, in line with harsher controls on vehicle safety and the increasing introduction of safety features such as seatbelts and airbags.

Cost Engineering is a multi-disciplinary profession for which one of the main outputs is a cost estimate.[2,3] Cost estimating is a potentially labour intensive activity which involves significant collection of a large quantity of data. Cost modeling is the development of mathematical models enabling efficient cost estimating for a range of product parameters. For example the development of cost model equations for estimating costs of design from a dataset.[4]

Cost estimating of vehicle crash testing activities is an infrequent one in research. This research has already established a cost estimate of physical vehicle crash testing.[5]

Virtual models, as well as simulations, are built on assumptions and simplifications.[6] Despite these uncertainties in computer simulation, regulating bodies are considering making some virtual testing mandatory for manufacturers,[7] and with the computational power and software available today things can be taken much further. In order to explore this introduction the WG22 Mandate was created and debates available technology and its availability for virtual testing. Although there are variations within virtual testing, the results are widely trusted as a good guideline to the behavioural characteristics of a vehicle.[8] This research considers virtual testing versus physical testing as a new field.

3. METHODOLOGY

Seven companies, three academics, two consultants, and 30 hours of interviews were used to collect qualitative and quantitative data about the structure and behaviour of the costs involved in the three domains of virtual test, physical test and cost to society. Overall 56 experts were contacted via a questionnaire, however not all were able to take part. Types of questions used in the research were categorised as quantitative and qualitative. An example of a quantitative question is: "In your opinion, what would be the cost drivers involved in Virtual Testing and their weight?" An example of a qualitative question is: "What are the examples of successful applications of Virtual Testing replacing the PT?" The development of domains other than Virtual Crash testing was not considered in this paper.

A demonstration of the Virtual Testing process was provided by an expert practitioner of ten years experience using an industrial Crash Test modeling software. Further information was gathered from competitor software product specifications, a literature review, access to an expert of 25 years in Computer Aided Engineering and crash testing, and access to a Framework 6 Integrated European Project focusing on crash testing.

An IDEF0 process map of the virtual test domain was produced from the resulting information. The process mapping exercise enabled understanding of the target domain and the identification of cost elements with their associated cost drivers. The IDEF0 diagram was validated as described in Section 4. This resulted in deduction of a Cost Breakdown structure shown in Figure 1. A cost estimate was developed based on a number of assumptions and significant information gathering from the public domain. Information included wage rates and hardware costs available on public web sites. The cost estimate included the use of a Computer Science expert from Cranfield University Information

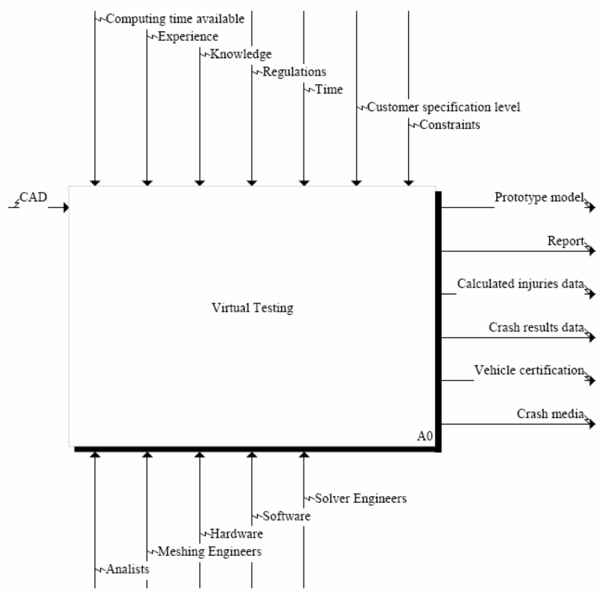

Figure 1. Top level IDEF0 for running a virtual test.

Technology expert whom had recently identified and installed a main frame computer similar to clusters used in industrial Virtual Testing. The estimate facilitated a cost analysis with Rough Order of Magnitude results at general industry level.

4. DESCRIPTION OF THE VIRTUAL TESTING PROCESS

The questionnaires and the literature review provided the following description. The Virtual Testing process begins with the meshing of the Computer Aided Design (CAD) model of the vehicle. The meshing task is enabled by processes such as partitioning and is a potentially outsourced task to cheaper wage economies. Meshing is more versatile than conventional physical testing where the points of reference are limited to the number of sensors and where these sensors are placed.

With this in place, material properties and test parameters, such as constraints and forces, can be applied to the models. The test scenario includes the placement of barriers or other vehicles at specific velocities. The scenario is then sent from a workstation to a solver usually run on a mainframe cluster for analysis. This involves thousands of equations needing to be solved and takes many hours to produce useable results.

In the post-processing stage, these simulations display stress distributions and where deformation occurs. Results are considered as pass or fail with set figures for forces and acceptable deformation. A bad result with Virtual Testing is not such a problem as with physical testing, and retesting is very common until the required results are achieved: models under going various iterations at little extra expense.

Analysis of the resulting data must be correlated to the results of physical testing and comply with customer and regulatory standards and requirements. Figure 1 shows the top level of an IDEF0 diagram developed for virtual testing. Arrows from the left form inputs to the process, and arrows to the right form outputs. The arrows from the top form constraints to the process and the arrows from the bottom form mechanisms. The initial diagram was developed from the literature and an interview with a virtual testing expert. The overall IDEF0 was validated by Expert A from the automotive sector with experience within an OEM and academia; Expert B with 10 years crash testing experience; and Expert C with 30 years virtual crash testing experience.

		Structure of Virtual Testing in Cost Element (Cost Driver) format	Overhead Elements are Shaded	
Labour	IT Infrastructure	Software	Facilities	Consumables
Meshing the Model Vehicle (Man Hours)	Work Stations (Type, Spec)	PrePost Processing Suite (Type, Years Licence)	Office Furniture	Lighting (kwhs)
Validating the Integrity of Virtual Model (Man Hours)	Computer Nodes (Type, Spec)	Solver Software (Type, Years Licence)	Cooling System (Time, Power)	Heating (kwhs)
Setup Simulation (Man Hours)	Other Equipment (Type, Spec) including Head Node, Failover Head Node, Storage Server, Failover Storage Server, Network Equipment.	Meshing Software (Type, Years Licence)	Building (Location, Square Metres)	Computational Power Consumption (kwh)
Solving (Man Hours)		Models (Type, Years Licence) including Barrier and Dummy including Operating Systems, Cluster Job Scheduler, Models and Other	Other Facilities	Other Consumables
Intepretation of the Results (Man Hours)				
Reporting (Man Hours)				
Adminstration (Man Hours)				
Management (Man Hours)				

Figure 2. Cost breakdown structure of virtual testing

5. COST BREAKDOWN STRUCTURE

The identification of the different activities required to perform Virtual Testing enabled the definition of a Cost Breakdown Structure (CBS) as shown in Figure 2. The identified structure has five major cost components: Labour, IT Infrastructure, Software, Facilities and Consumables. The highlighted cost elements have been included as overheads in the cost estimation due to the difficulty of calculating the cost per hour. Overheads are calculated as a percentage of direct costs in this research. Other methods, for example, Activity Based Costing, were not practical.

6. COST ESTIMATION

A cost estimate was developed for Virtual Testing using the Cost Breakdown Structure, information collected from experts and an assumption list. For example IT experts and virtual crash test experts provided IT configurations required for computing clusters and their associated costs. Examples of the total of 49 assumptions made for the estimate are:

- Each model requires an equal amount of time to process.
- Results take an equal amount of time to be analysed.
- Models are run overnight, when the cluster can be dedicated.
- The cluster results are trusted irrespective of how many processors have been used.
- Experience levels of labour are consistent between projects and tests.
- The same dummy model is used in all virtual testing.

Part of the cost estimate is the estimate of Labour costs. This estimate is described in Section 8. Because of potential variation in data and the assumptions made, the estimate is used as the basis of a visualisation of the proportions of cost elements in a Virtual Test.

7. LABOUR COST ESTIMATE

In order to calculate the Labour cost, the time required to perform the different tasks involved in virtual testing (meshing the CAD model, validation of the model, setup of the simulation, solving, interpreting and reporting the results) has been multiplied number of people involved and corresponding wage rates. Today's car manufacturers outsource certain tasks within the virtual testing process to low cost

Table 1. Cost of meshing in UK.

CONCEPT	ROLE	Quantity	Annual Wage	Cost of Employment	Wage (£/h)	TIME (Days)	COST
Meshing the Model	CAD Engineer	3	£35.647	£48.123	£28	40	£27.064
TOTAL Meshing							**£27.064**

Table 2. Cost of outsourcing the meshing

CONCEPT	ROLE	Quantity	Annual Wage	Cost of Employing	Wage per Hour	TIME (Days)	COST
Meshing the Model	CAD Engineer	3	£8.911	£12.030	£7	40	£6.766
Labour Subtotal							£6.766
Overhead (100%)							£6.766
Subtotal							£13.531
Profit (10%)							£1.353
TOTAL							**£14.884**

labour economies like India or China. For this reason both scenarios, meshing in-house in the UK and outsourcing the meshing to countries like India, have been considered. Table 1 illustrates the cost of meshing in-house in the UK, while Table 2 defines the cost of outsourcing the meshing activity to India. The number of CAD engineers, in this case three, and the number of days required to carry out the activity, 40 days, have been provided by experts. Salaries for both CAD engineers in the UK and in India have been collected from salary statistics on the web. To an employee's annual wage a figure of 35% tax, which companies are required to pay as part of the concept of the cost of employment, has been added. In order to calculate the wage per hour, the cost of employment has been divided by the number of hours an engineer works a year. It has been assumed that the average in the UK is 1707 working hours. Finally, the cost has been calculated by a multiplication of Time in days, by eight working hours a day and by the wage (£/h).

When calculating the cost of outsourcing the meshing the overhead (100%) and the profit (10%) which subcontracted companies charge to the car manufacturer have been included.

Once the model has been meshed, the car manufacturer has to validate the model, setup the simulation, submit to the solver, interpret the results and produce the report. Table 3 includes the costs of these activities required to perform a virtual test and the total cost of the analysis of the virtual crash. These calculations have been carried out with the same basis as the calculation of the cost of the meshing.

8. COST ANALYSIS

A full cost estimate of virtual testing has been completed building on Section 8. Figure 3 shows the contribution to the virtual cost estimate of each cost element. The cost analysis of a full virtual crash test has revealed that Overhead is the most significant cost element. However, focusing on the direct costs, it can be observed that the Labour cost, which includes meshing of the model and the analysis tasks, i.e. the validation of the model, the setup of the simulation, solving, interpretation of results and reporting, is the main cost element. The cost analysis demonstrates the importance of the meshing task in comparison with the rest of the labour costs. Finally, one can see that the software and IT infrastructure costs are not comparable to Labour cost.

Figure 4 shows the decomposition of the Labour involved in virtual testing. It is confirmed that meshing is the activity which has the largest cost contribution, followed by the validation and the interpretation of results activities.

9. DISCUSSION AND CONCLUSIONS

Virtual Testing facilitates design optimisation of the car which would be prohibitive in real testing due to time and budget constraints. This optimisation reduces the number of physical crash tests, subsequently decreasing the cost of the development of a car.

Table 3. Cost of crash analysis.

CONCEPT	ROLE	Quantity	Annual Wage	Cost of Employing	Wage per Hour	TIME (Days)	COST
Meshing the Model	CAD Engineer	3	£8.911	£12.030	£7	40	£6.766
Labour Subtotal							£6.766
Overhead (100%)							£6.766
Subtotal							£13.531
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TOTAL							**£14.884**

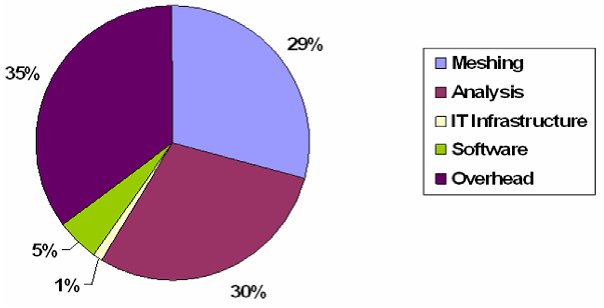

Figure 3. Cost components of virtual testing.

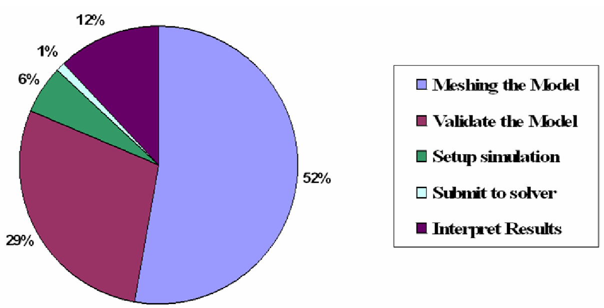

Figure 4. Cost of labour in virtual testing.

Figure 5 shows the cost effectiveness of Virtual Testing. While in Physical Testing the cost of a full crash test does not vary depending on the quantity of planned tests, the first virtual test's cost is high due to the meshing activity; but once the model has been meshed, the cost of re-running the crash test decreases substantially. For instance, car manufacturers usually run stochastic simulations where the car is crashed in different scenarios or environment conditions, so that the cost per test is considerably lower than the first virtual test or physical crash test.

Virtual Testing also covers more impact scenarios, occupants or conditions that the physical and legislative tests exclude. An improved insight of the crash is allowed, providing details that are not normally visible in real world conditions.

Virtual Testing has no standards or legislation that car manufacturers are required to follow. The results of Virtual Testing are dependent on the model, so if the model quality is low, the results will be inaccurate. Virtual Testing simulates an ideal world that cannot consider all the variables and possibilities of true reality. This results in less accuracy than real tests.

For these reasons there is a lack of confidence from society and car manufacturers in Virtual Testing. If the results of Virtual Testing do not match the results of a physical test it is assumed that the virtual model is wrong. Virtual Testing technology is still evolving and in the early future, the advances in

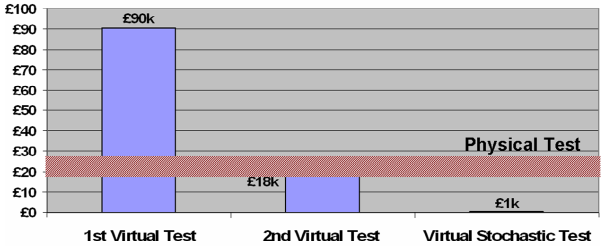

Figure 5. Cost of a full scale crash test (in miles).

hardware and software will allow models of greater complexity, increasing the correlation between Virtual Testing and Physical Testing.

A cost estimate and analysis of virtual vehicle crash testing has been completed for rear and side impact crash test. The research was required in the context of a market requirement for safer cars and a manufacturers' requirement for less costly and faster product development.

This research assumes that the digital model is ready to input into the virtual crash testing process (as shown in Figure 1). The scenario being considered is that of consultancy on a pre-developed Computer Aided Design model. There is some conjecture that multi-skilled Computer Aided Engineers could benefit OEM's in product development effectiveness. Potential scenarios in which the development of the digital model is performed by multi-skilled labour and is integrated into the virtual crash testing process should be the subject of further work. The potential time compression of the product development cycle afforded by this conjecture does not affect the cost of physical crash testing. Physical crash testing can be thought of as an independent activity with a constant cost per test. Virtual crash testing is expected to decrease the number of physical crash tests in future years.

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REFERENCES

[1] United Nation Economic Commission for Europe-http://www.unece.org/, first accessed 15/02/2008.

[2] Grant, I.C., Baguley, P. and Roy, R. (2007). Development of a Cost Engineering Knowledge Audit Tool, the 4^{th} *International Conference on Digital Enterprise Technology (DET 07).* Bath University, 19–21 September.

[3] Roy, R. and Sackett, P. (2003). Cost Engineering: The Practice and Future Computer and Automated Systems Association of the Society of Manufacturing Engineers Blue Book Series.

[4] Roy, R. Kelvesjo, S. Forsberg, S., and Rush, C. (2001). Quantitative and Qualitative Cost Estimating for Engineering Design. Journal of Engineering Design, Vol. 12, No. 2, pp. 147–162.

[5] Baguley, P., Roy, R., and Watson, J. (2008). Cost of Physical Vehicle Crash Testing, *International Society of Productivity Enhancement (ISPE) Concurrent Engineering*, Queens University, Belfast, 18^{th}–22^{nd} August.

[6] Cipra, B. (2000). Revealing Uncertainties in Computer Models, Volume 287, Science Magazine.

[7] EEVC Working Group 22 Virtual Testing, (2007). European enhanced vehicle-safety Committee, First mandate final report.

[8] Kushfeldt, S. Ertl, T. and Holzner, M. (1997). Efficient visualization of physical and structural properties in crash-worthiness simulations, *Proceedings of the Eighth IEEE Visualization Conference, ISBN 0818682620.*