NUMERICAL SIMULATION/ANALYSIS and COMPUTER AIDED ENGINEERING for VIRTUAL PROTOTYPING of HEAVY GROUND VEHICLES.

by

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Submitted to the graduate degree program in Mechanical Engineering and the Graduate Faculty of the University of Kansas School of Engineering in partial fulfillment of the requirements for the degree of Doctor of Engineering

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ABSTRACT

This doctoral project dissertation deals with the investigation of simulation/analysis in the product development process of specialized heavy ground vehicle engineering which posts some of the most challenging engineering problems. The focus of the project is to keep the process of simulation efficient by structuring and managing of models and the method, for usage early in product development cycle. Previous work in this area has focused on developing faster calculation algorithms, more specialized simulation software, and elegance.

For simulation/analysis, in today's competitive engineering environment in which engineers strive to develop designs with *high performance*, and *reduced time and cost*, there is also a growing demand to capture reality more accurately and efficiently when numerically modeling a problem in Computer Aided Engineering (CAE). Accurate simulation coupled with educated simplifications and other modeling techniques, allow for the concept of Virtual Prototyping (VP), upfront and in design-integrated manner for the product development which would reduce much of the status quo Specialized or Traditional CAE, and Physical Prototyping or Test, to ensure a problem free product launch, overall cost and time savings in the design work – essentially resulting in lean, economical and accelerated product development.

In line with increasingly popular new product development and project management paradigm, and also as trade studies, in this doctoral project design works are performed and managed, investigated on, and 'up or front loaded' using various contemporary CAE simulation software packages to Virtually Prototype and verify industrial design and wide variety of real world problems commonly came across in the design of Specialized Road and Rail Heavy Ground Vehicles. The numerical simulation technology capabilities are fully explored to specifically tackle the kinematics, dynamics, statics, and structural problems, some with the added realism of today's 3D high fidelity graphical environment of VP.

Adopting various modeling and VP strategies, the work for the doctoral project is performed with increasing complexity and some coupled with testing to compliment or validate simulation/analysis result as a show of accuracy providing high level of confidence in further design customization, synthesis, and iterations. The main purpose of the doctoral project is to arrive at a 'Virtual Prototyping driven' rather than a 'Virtual Prototyping verified' design, although much verifications are performed to confirm acceptable virtual prototype fidelity.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank *Universiti Malaya* and the *Malaysian government* for the support I received in completing the doctoral studies.

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My dearest thanks go to my wife, Intan Norliyana Ismail. She followed me in this challenging and exciting adventure, and over the years, her support allowed me to continue making progress, even though it often seemed that there were “more important things to do”. Also, my words go to my two sons, Akmal Hazim and Afzal Hariz. I want to thank them for putting a great deal of things about my life in perspective. The important things always come first, and the rest follow after - my family always comes first. I would like to dedicate this dissertation to all of my family and last but not least, to my parents, Mr. Abd. Rahim Yusoff and Mrs. Fuziah Ibrahim, and parents-in-law, Mr. Ismail Taib and Mrs. Aini Othman for their unfathomable love.

“Scientist investigate that which already is; Engineers create that which has never been.”
Albert Einstein

“Engineering is the center of all wealth creation”
Alan Mulally, CEO of Ford and former CEO of Boeing Commercial Airplane,
KU School of Engineering, Alumni

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1. INTRODUCTION

1.1 Computer Aided Engineering (CAE) – Simulation/Analysis for Heavy Ground Vehicle

In product development or engineering design process, 'keeping a design simple‟ philosophy seems plausible since the more complicated something is, the more risks there are for it to fail. However, the paradox to the philosophy is that, simple designs perform simple things with limited functionality - most modern designs today had evolved over time, and are complicated. These modern designs include not only purely mechanical but also biomechanical systems (emulating the human body as the nature intended it) and have combination of parts or bodies (solids and fluids) working together as they are expected to perform numerous functions. These bodies would entail mechanical (or biomechanical) assembly, and as they perform the intended functions, they would interface and/or be dynamically in motion, relative to each other.

In CAE, when numerically modeling mechanical designs and systems, industrial and market necessities and evolving modern design requirements on functionality of today's complicated machineries like Heavy Ground Vehicle (Road and Rail), bring about stringent demands to capture reality more accurately and timely. Not only the numerical simulation/analysis itself needs to be timely (quick), the timing in a design cycle can also be critical, to avoid expensive late design problem and surprises (as compared to untimely simulation/analysis or physical test for design validation further downstream in design cycle).

For Heavy Road and Rail Ground Vehicle, in managing the risks involved in its product development, the problems that need to be modeled not only timely but also accurately include kinematics, dynamics, and statics, with various level of complexity. In engineering context, kinematics is the study of motion in mechanisms without reference to the forces that act on the systems. Dynamics (including kinetics in addition to kinematics), is the study of the motion of individual bodies and system-level mechanisms under the influence of forces (lineal) and torques (rotational). While the study of forces and torques in stationary systems (and systems with negligible inertial effects) is called statics. Accuracy is especially important for the simulation/analysis of these problems, in its usually competing relation to physical test for design validation in the product development process.

Popular commercial simulation/analysis code or software, for instance, Finite Element Analysis (FEA) that has progressed greatly over the years (since the 1960s), predicts the effects of physical phenomena on stress or deformation of parts (structural) under static or quasi-static mechanical load and forces. Not only faster, FEA software today has also been complimented with capabilities to solve more advanced ground vehicle problems like non-linear applications, dynamic response, durability, and optimization (Figure 1.1).

In other growing number of ground vehicle applications, there are needs to model scenarios, which are inherently dynamic or varying with time, for example, fluid flow as modeled by Computational Fluid Dynamics (CFD), which also typically include heat transfer modeling capabilities. CFD greatly benefit the simulation/analysis work in specialized area of higher speed light ground vehicles (automotive aerodynamics) and power plant (heat and energy management) of ground vehicle. CFD also enjoys a pervasive use in aerospace industry, with good reputation over physical testing (59) (Figure 1.2).

When coupled with the effects of multiple physical phenomenon, like structural and fluid flow or with thermal or electromagnetic interactions, these simulation/analysis technologies are usually termed Multiphysics software (3),(5) (Figure 1.2). The multi capabilities software could also include virtual controls, hydraulics, and pneumatic system simulation capabilities (2).

Today's CAE technology that allows for simulation/analysis of ground vehicle dynamics phenomena of motion for its systems and component level mechanism is Multibody Simulation (MBS). The technology lags around a decade or so behind FEA (49) and simulates dynamic motions (kinematics) and forces (kinetics) of parts interconnected to one another via sets of constraints modeled as joints, which is analogous to boundary conditions in FEA. Its solution engine is faster than FEA and also solves an equilibrium system for static and quasi-static problems. Compared to FEA, MBS models are used to represent a wider variety of assemblies, and sub-assemblies, as well as higher level and complete systems such as vehicles and other machinery numerically on computer, as it does not consume the computer as much as FEA. MBS notably is used extensively in ground Vehicle Dynamics area (6), (7), (18), (28).

In the simulation, bodies can be modeled either as rigid and/or flexible bodies. When modeled flexibly, MBS is coupled with FEA, and it predicts a vast array of dynamic physical phenomenon of motion, vibration, and also stress and deformation /compliance of parts for realistic and elegant real world problem simulation. Relatively stiff parts can however be represented by rigid bodies when stress distributions and wave in such parts are not critical (3).

In MBS, ground vehicle rigid bodies can be connected via joint elements to flexible bodies to model hybrid, rigid-flexible body dynamics or to other rigid bodies on the vehicle. These joints are comparable to constraints (or boundary conditions) in problems encountered in FEA - the different being that solutions are computed at the joints for MBS versus primarily in the bodies for FEA (with higher degree of freedom (DOF)). Basically, joint elements provide kinematic pair or simply connectivity and interface between vehicle parts dynamically in motion. If modeled completely rigid, forces generated at these joints can then be exported and used as load cases separately in FEA environment, and ‘batch-processed’ to study deformability of these parts, albeit not in a lively interactive environment like of MBS (11).

Well known commercially available MBS software include MSC.ADAMS (MSC, Santa Ana, California, USA), LMS Virtual.Lab Motion (LMS, Leuven, Belgium), ANSYS Rigid Dynamics (ANSYS, Canonsburg, Pensylvania, USA), Dynamic Designer which is the 3D version and WorkingModel for the 2D version (Design Simulation Technologies, Canton, Michigan, USA). It should be noted that LMS.Virtual Lab has its roots from DADS (1), (2), (11), (22). Most of these software are also utilized and investigated on in this doctoral project and dissertation.

Majority of the companies that make MBS software have their own proprietary FEA codes that also provide flexible body simulation capabilities for MBS. On the other hand, there are companies that are well known for FEA capabilities that utilize popular MBS solver like ADAMS for MBS capabilities, as in the case for Structural Research & Analysis Corporation (SRAC, division of SolidWorks and subsidiary of Dassault Systémes, Vélizy-Villacoublay, France) which makes COSMOSWorks for FEA and COSMOSMotion for MBS (5). There are also Specialized CAE MBS software specifically catered for vehicle dynamics area like Car/Truck/Bike Sim or Vehicle Sim (Mechanical Simulation Corporation, Ann Arbor) and Vampire (DeltaRail, Derby, United Kingdom), for road and rail vehicles respectively (6), (7).

It should be mentioned that although they have rather celestial roots in aerospace engineering like CFD (49)(51), both MBS and FEA are the top two simulation tools in the industry and especially in ground vehicle engineering, allowing for the concept of Virtual Prototyping (Figure 1.4 and 1.5) (33) for design validation, covering a wide range of problem typically seen in the area .

Also, as a comparison to MBS and FEA, CFD simulation tools see a rather extensive application in aerospace engineering, to the extent that it plays a more pronounced role than physical tests in design validation process. MBS and FEA on the other hand, especially for vehicle engineering are still gaining credibility over status quo Physical Prototype/Test for design validation, indicating a potential of attaining greater role in validating designs for product development process (Figure 1.3) (57)(59).

Interested readers can refer to more discussions on the technical and theoretical aspects of MBS and FEA included in material referenced in the dissertation for more details.

Great majority of these software are now embedded or directly interfaced with CAD (Computer Aided Design, a subset of CAE programs), permitting their early use in a design process.

1.2 State of the Art – CAE for Ground Vehicle and Virtual Prototyping in the Doctoral Project

Today, MBS and FEA software have become the core components in CAE concept of VP (Virtual Prototyping) (Figure 1.5, surveyed in 2009) (33). FEA as a VP component is coupled or used separately from MBS, provides structural capabilities study. Together, these software could solve majority of real world problems typically encountered in the product development process of specialized and heavy ground vehicles.

Also currently, there are two major branches of CAE - traditional and upfront. Vis-à-vis Standalone/Specialized or Traditional CAE (which tends to be more involved, and typically allow customization or programming of the CAE software), the VP concept is basically a CAD and simulation/analysis-intensive design work, early and upfront in the design cycle.

Appropriately in this doctoral project dissertation, VP approach is then used to describe the process and tool entailing 'upfront or uploaded' CAE ground vehicle designs, with MBS and FEA numerical simulation/analysis functionalities, embedded or directly interfaced with CAD, allowing seamless simulation/analysis integrated and cohesively performed with early design work. Simulation/analysis also is proposed to be an integral part of a design process (normally through CAD; a subset of CAE), in the VP approach. This is in competition to status quo Specialized CAE and Physical Prototype/Test approach for design verification.

The ultimate goal of CAE design work is the production of high performing tangible artifacts with good industrial value. Respectively, CAE simulation/analysis is fast rising as the engineering practice of choice to assist in accelerated product development, thus improving productivity and time to market (8), (11), (24), (18). While the concept of using simulation early in the product development cycle initially emerged almost a decade ago, it was reported in 2006 that it has not been fully implemented yet (44). Further according to a late 2007 article, although there has been talk about the benefits of VP for years, the budget for the tools required to build and test a true digital prototype has been out of reach for most manufacturing companies - VP solutions are usually expensive, customized installations for large enterprises. Most out-of-the box 3D modeling applications provide only part of the functionality needed to create a complete digital prototype (26). There is also corporate culture/structure obstacles with lack of expertise and time cited as major impasses preventing full fledge successful VP implementation (44).

However, the fact taken advantage of in this doctoral project for Heavy Ground Vehicle engineering is that VP approach through MBS and FEA is becoming more accessible for design work with today's powerful and cost effective computers and because of its *integration with various CAD (or specifically MCAD – Mechanical Computer Aided Design)* packages. The word 'Virtual' in VP methodology is attributable to the ability to display simulations and results especially in realistic 3D interactive graphical environment, while 'Prototyping' describes the ability to be a bona fide digital proving ground, with increased processing speed. The VP technologies that are embedded or directly interfaced with CAD that allow early use in the design cycle (also popularly referred to as upfront CAE and CAE centric design), are also today equipped with numerous simulation/analysis features.

Another very important point that is leveraged on as well in doctoral project is that, contemporary VP features that are either CAD embedded or directly interfaced, allow for more *involvement by engineers with strong product knowledge to 'front load' on the product design early in the design process* (Figure 1.6)(3). This is as opposed to a traditional CAE simulation process where simulation/analysis is put in the hands of specialists and experts. So, instead of being 'thrown over the wall' to specialists, and being separate from product design (through CAD) process, CAD integrated simulation/analysis introduced a tool-oriented problem solving, and decouple 'solution seeking' from modeling and VP efforts. Simulation/analysis is performed in parallel to a CAD/CAE design work, resulting in a 'simulation driven design'. VP that is early and integrated in the design process, would also allow for concurrent engineering in addition to a traditional design process, as the product can be studied for instance, for manufacturability and marketability aspects and at the same time simulated and analyzed as it is being designed.

This CAE 'shift in paradigm' however does not completely eliminate the role of specialists as it would support a detail continuous improvement (including failure studies) in Product Lifecycle Management (PLM), and a template based (Figure 1.7) simulation/analysis structure/setup, where simulation experts create subsystem templates and simulation scenarios (which could involve programming) to be utilized by design engineers who would then choose the appropriate parameters and execute the Virtual Prototype model for design evaluation.

The transition period from 2D to 3D CAD which has been underway for over 10 years, has also seen 3D graphical environment evolved (31)(32)(60), and CAD integrated Virtual Prototyping technologies as utilized in the doctoral project benefit greatly from this advance feature. Not only CAD provides an accurate geometry/shape for the virtual model, the graphical environment today is highly realistic, that on 'a priori' observation based on merits of looks, a virtual model created could seem feasible on the first glance, without the 'a posteriori' engineering verification (through simulation/analysis or test engineering) (Figure 1.9).

VP work covered in the dissertation further benefitted from the realistic CAD (through CAD integrated simulation/analysis environment), as the realism attained would also allow for some degree of design ergonomics study for 'human factors'. Since 'seeing is believing', CAE and CAD models provided for MBS and FEA in the VP approach enable engineers to not only qualitatively study designs at an aesthetic level, but also to quantitatively study the performance of a proposed design completely numerically on the computer with high realism, to accurately 'visualize' the problem with the inclusion of real world behavior.

VP for its realistic result and graphics (as the Virtual Prototype is more relatable to the final physical product, (60)) is also believed to facilitate in cross-functional involvement of management, and marketing team early in the design cycle, ensuring a timely and successful product launch and roll-out (1), (2), (8). As mentioned before, it has also allowed for, the concept of concurrent engineering with design manufacturability and marketability considerations factored in early in the design cycle, which further add value to the cross-functional involvement.

VP approach then can hypothetically minimize if not eliminate the expense of multiple intermediary physical prototypes to permit evaluation and optimization of the entire system's kinematics, statics and dynamics response in early phases of the development process - thus the term ‘front or up loaded’ simulation/analysis (Figure 1.4).

Furthermore, for problems traditionally performed via testing (i.e. Control System, Vibration or Durability/Fatigue),VP advanced suites enable various capabilities for dynamic phenomenon studies with the possibility of integration with test engineering and also control design, to be run on numerical models without running the risk of over testing (and possibly damaging the prototype or first article). This, further aid the process of design iterations and trial-and-error, in evaluating numerous more what-if scenarios (including complex ones) to achieve the desired real-world performance (1), (2),(11).

While prototyping through MBS for the motion of an assembly constructed of purely rigid bodies, is a relatively mature technology (especially for Specialized/Standalone CAE), available from a number of software suppliers (3), such simulations does not account for the natural deformability and flexibility of these components. Considering flexibility can be moderately to critically important, such as when simulating a long slender hydraulic cylinder rod (that may buckle and bind), or when modeling parts made of flexible material such as elastomers in MBS (2), (3) (Figure 1.8). Nonetheless, deformability and flexibility of design can also be studied independently using high fidelity FEA environment and ‘batch processed’.

A popular and state-of-the-art way to combine the time-saving characteristics of rigid MBS with flexible responses via FEA is through Craig-Bampton method. In this method, modal FEA analysis is used to capture the linear dynamic response of a flexible assembly in the form of mode shapes and frequencies, or in numerical sense, eigenvalues and eigenvectors. These flexibility numerical system or matrices are used in conjunction with the reduced-order rigid representation to simulate a flexible assembly without running a completely flexible model with its inherently large number of degrees of freedom (DOF) in the model body. The Craig-Bampton method is limited in the following ways, though widely adopted (3), (11), (22):

a) Time-consuming in practice (modal FEA followed by rigid MBS processing)

b) Limited to linear response, so it cannot be used to model nonlinearity associated with:

    i. Material - hyperelasticity, plasticity, and viscoeleasticity behavior.

    ii. Nonlinear geometry and contact, for hybrid rigid-flexible or fully flexible cases.

Nonetheless, there are progressing technologies that would allow approximation for flexible non-linear contact, that in turn assist in realistic simulations of dropped object and impact in general, albeit with more caution and attention needed for modeling the problems (11). Problems involving contact for both rigid and/or flexible bodies are important to capture real world problems - impact studies for example, considered for safety factor in vehicle engineering, are an extension to contact analysis.

As a matter of fact however, contact problem implicit solution of large-strain, and multibody contact systems is one of the most demanding problems in computational mechanics. Complex contact formulations and numerical schemes, including various types of smoothing, frictional laws, and sensitivity analysis, have become progressively and computationally expensive, that even for moderate-size problems can be a bottleneck (13).

As such, MBS users will have to make some trade-offs between model elegance and speed of Virtual Prototyping in the product development work.

The following four quotes paint a big picture on the current and predicted future state of CAD/CAE in general, and specifically MBS and FEA simulation/analysis field, and how these realms evolved over the years:

Firstly, at the beginning of this doctoral project in 2005, according to the Center of Automotive Research (CAR) and Parametric Technologies Corporation (PTC), “In general, all design tools with the notable exception of physical prototypes will gain in influence over the next 5 years. Currently, computer tools for conceptual design and rapid prototyping are the most influential tools used in product design, followed by product simulation technologies. However, within 5 years, the computer-based tools are expected to completely eclipsed the need for physical prototypes......As we move away from physical prototyping toward virtual design and prototyping, we see a decrease in tools that support physical prototyping and an increase in those that support virtual design. Hence, rapid prototyping technologies will be less important, whereas simulation technologies (product, manufacturing, and assembly) will become more important” (46). Figure 1.10 and 1.11 (46, surveyed in 2004) show the predicted trends of the various design tools including virtual prototyping (first three left columns - for simulation versus physical prototype/test) going from 2004 to 2009.

Secondly, in 2007, specifically with regard to VP through MBS, Werner Schiehlen, et al. quoted that, “...impressive success story demonstrates the strong growth of the multibody dynamics community. Research topics are getting wider. The modelling of rigid body systems with kinematically closed loops is still of great interest, the modelling of elastic or flexible multibody systems (MBS and FEA coupled), respectively, is a timely topic. Contact problems and unilateral constraints are fascinating from a mathematical and engineering point of view. The increasing demand on real-time simulations systems encourages research into numerical time integration codes and allows operator-in-the-loop studies. The application to rail and road (ground) vehicle bridges the gap between dynamics and control (mechatronics). Biomechanical models of animals and humans provide an extension of multibody dynamics to completely new problems, and the same is true for crashworthiness (contact-impact cases), where multibody dynamics allows new and much more efficient modelling concepts. Collapsing civil engineering structures can be analyzed with multibody system models and the close connection to design optimization of all kinds of machines and mechanisms by multibody dynamics approaches also must be mentioned here" (38).

Even though it turned out that simulation and analysis did not overcome the role of physical prototyping and testing to the degree as predicted (42), (46), shedding some light to Virtual Prototyping approach, thirdly in 2009 it was quoted in the Design News magazine that, "Thanks to a host of emerging technologies, however, the somewhat elusive concept of virtual product development – the notion of designing, prototyping and developing both the product and the manufacturing process in a fully digital environment – is starting to become a reality. Highly powerful, but cost-effective graphics and computing platforms, easier-to-use visualization, simulation, and 3D collaboration tools, along with integrated systems for developing and testing products that have a mechanical, electrical and embedded software components, are inspiring and enabling engineering organizations to do increasingly more in the digital world" (23).

Finally and fourthly, in 2010 according to a group consisted of Design News, Dassault Systémes, Autodesk, ANSYS, National Instruments, and CFDesign, "Simulation gets a mainstream makeover - MCAD vendors incorporate increasingly sophisticated CAE capabilities into their core product suites. High-end simulation providers deliver a more CAD-like experience, boosting their products' appeal to users that are not analysis specialists. Free from having to master a new tool and/or a new discipline, mainstream engineers will be compelled to embrace simulation far earlier in the design process" (8).

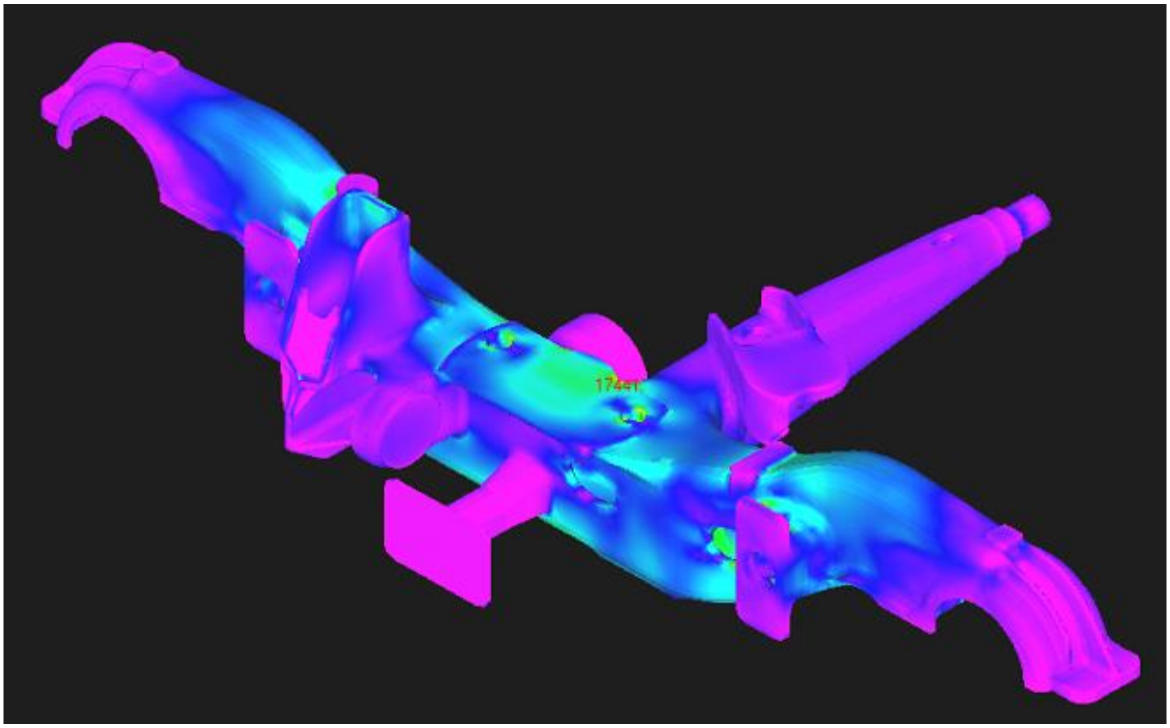

Figure 1.1. FEA of Rail ground vehicle bogie/frame (half) for structural assessment.

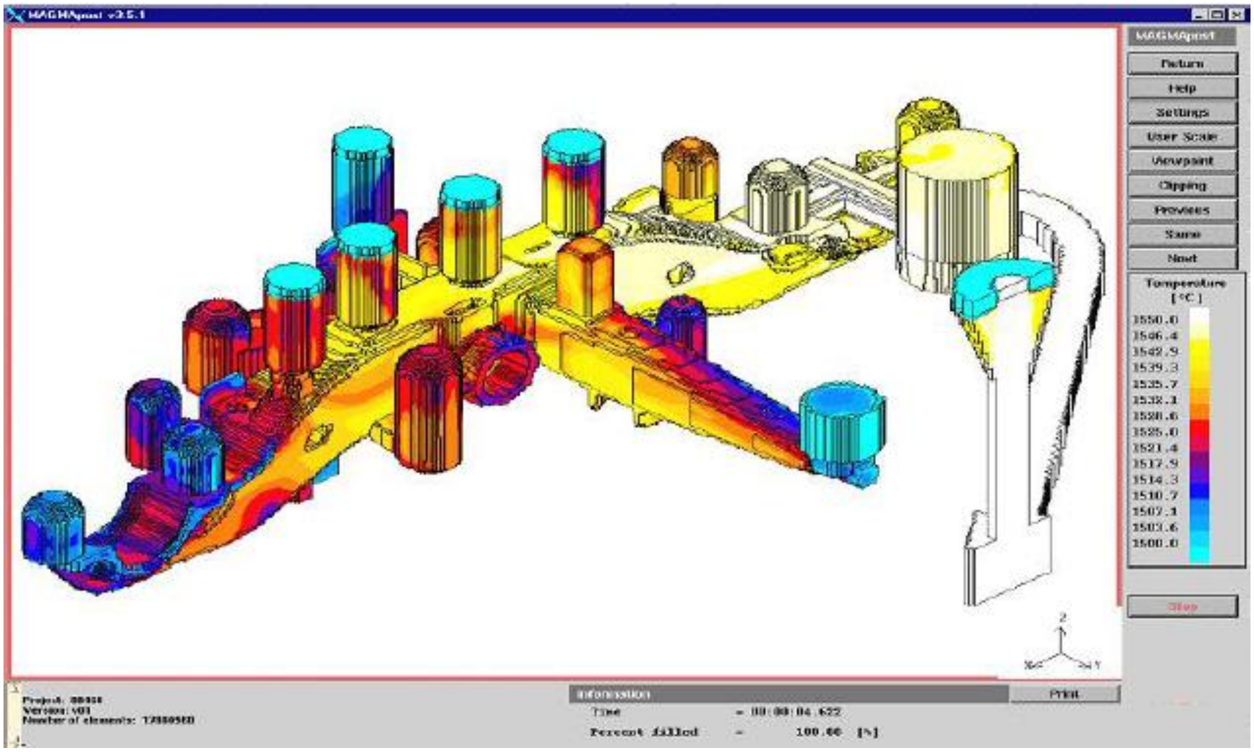

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Figure 1.2. Multiphysics simulation (fluid flow/ thermal) of Rail ground vehicle bogie/frame (half) for casting process studies.

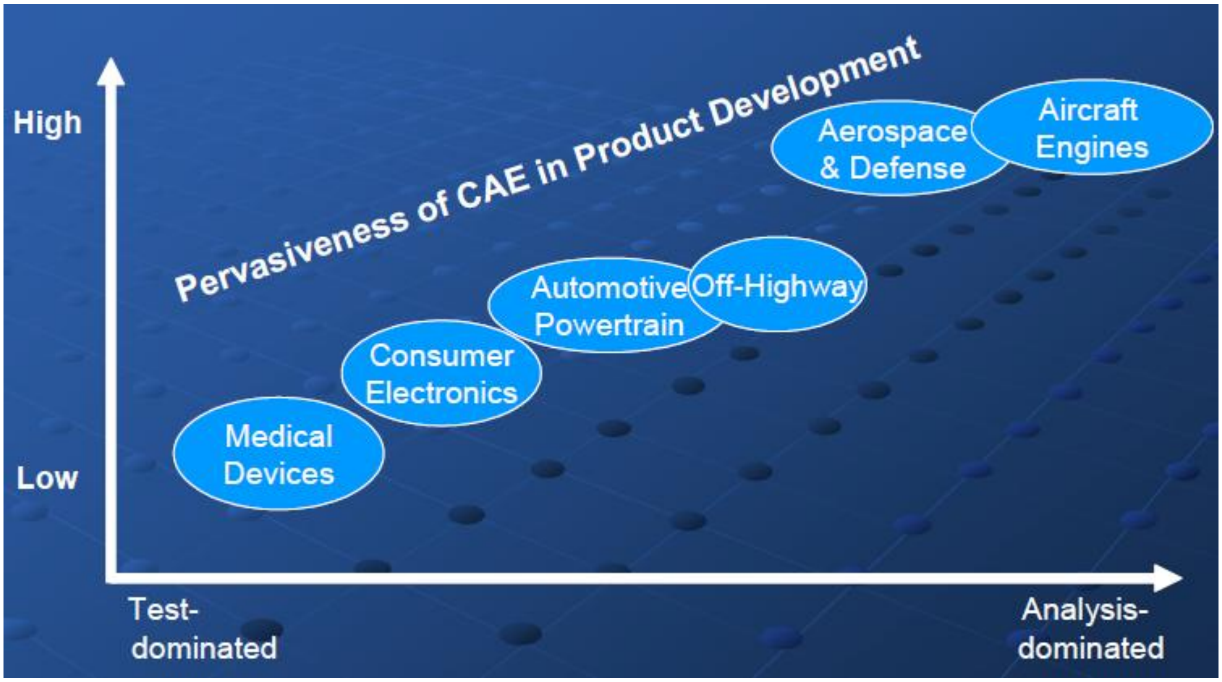


Figure 1.3. Usage of CAE in various industries. CAE for the category of ground vehicle engineering (automotive power train and off-highway) is seen to still have untapped potential to play greater role over physical prototype/test as compared to aerospace engineering (59).

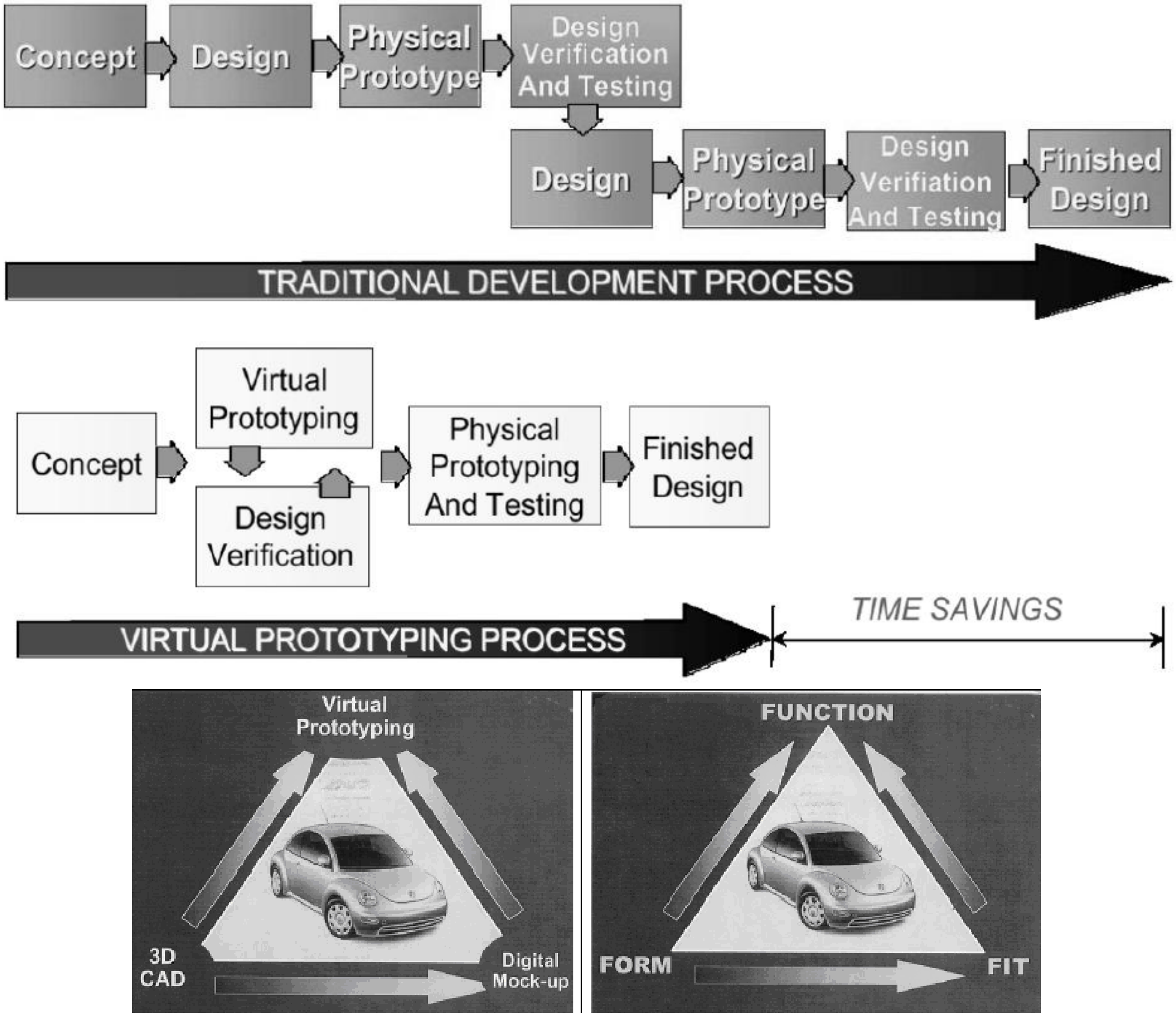
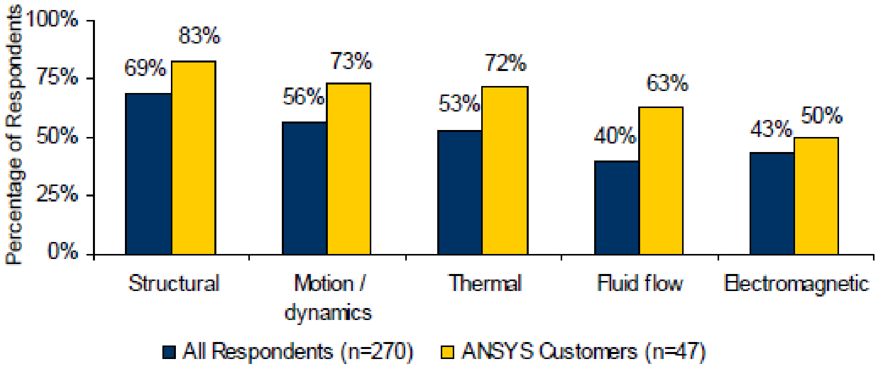
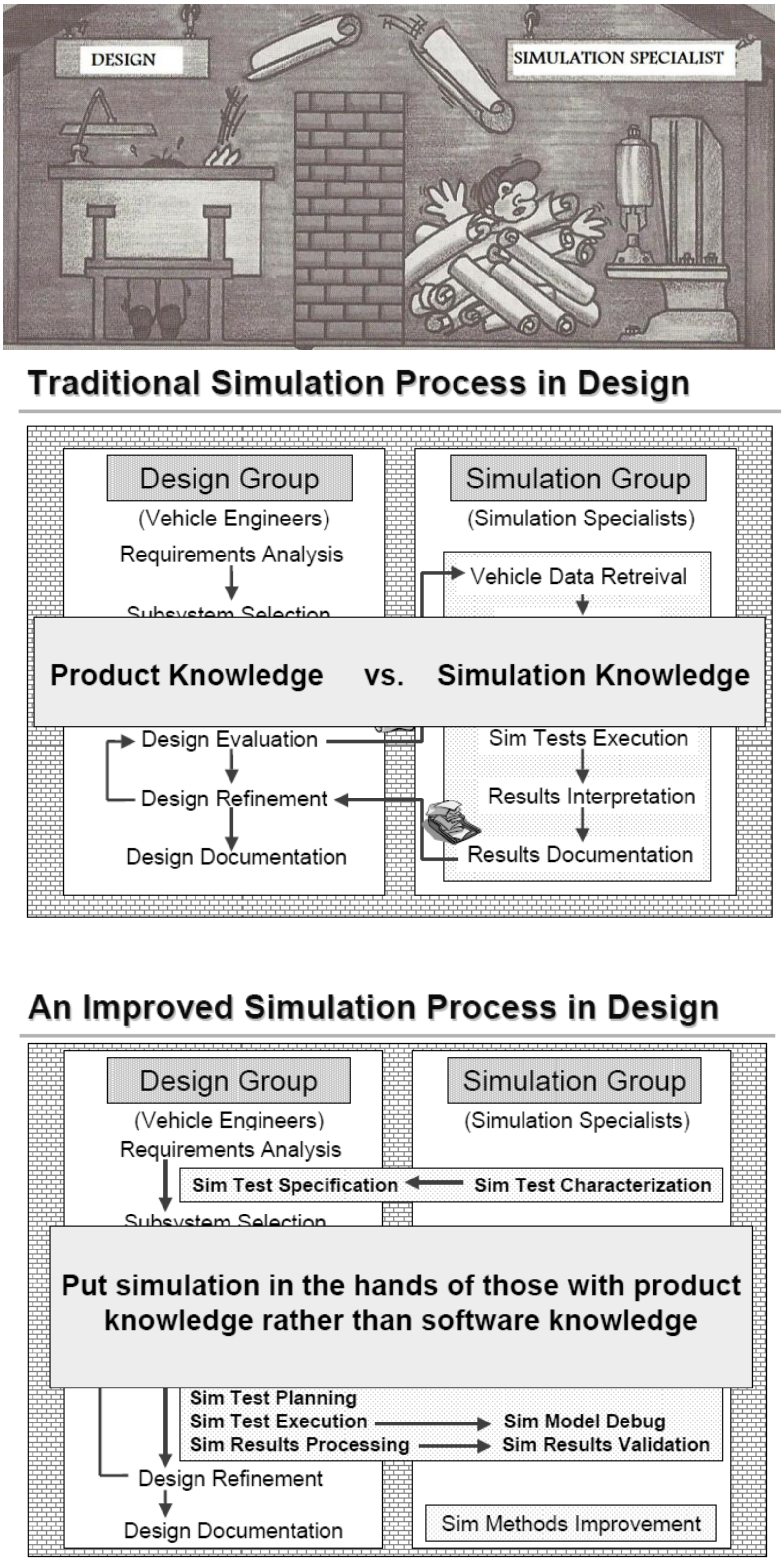


Figure 1.4. Comparison (top) and analogy (bottom) between Virtual Prototyping and Traditional Development process and, Virtual and Physical Prototyping in a design cycle (1).



Source: Aberdeen Group, May 2009

Figure 1.5. Simulations performed for all respondents and ANSYS (popular CAE tool) users (33).



***sim – simulation/analysis**

Figure 1.6. Traditional and more specialized simulation ('throw over the wall to specialist') process. versus Virtual Prototyping (1) .

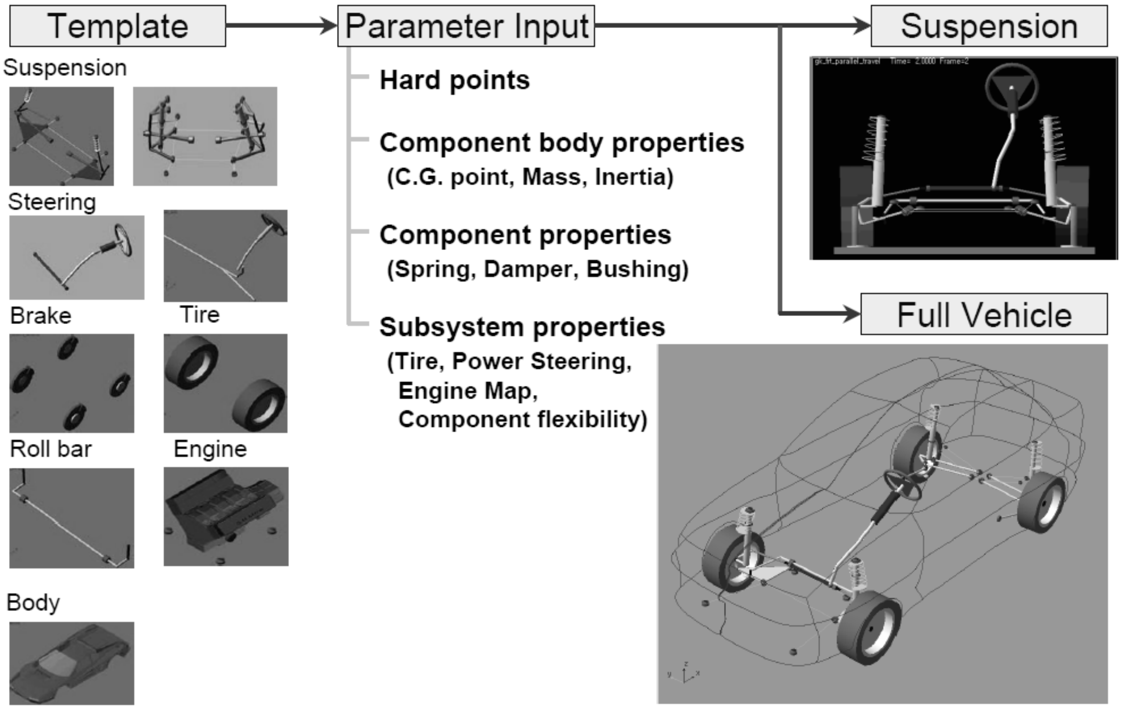


Figure 1.7. An example of template-based vehicle modeling tool (1).

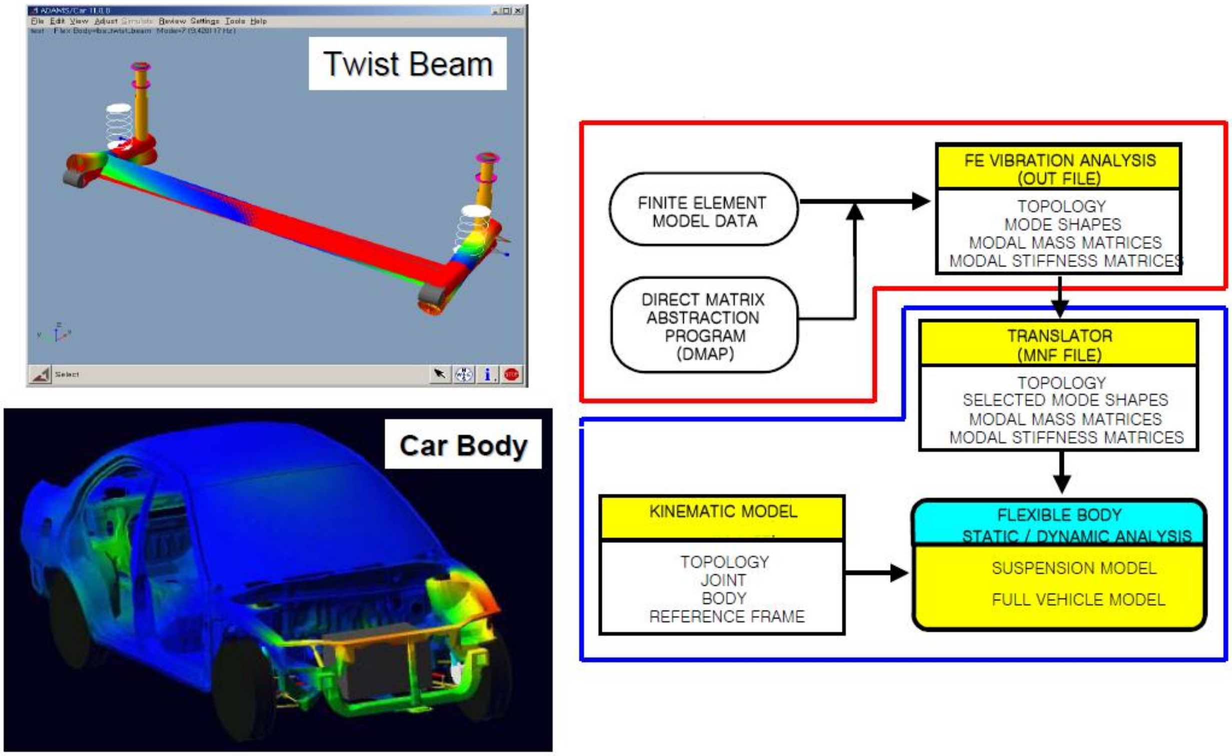


Figure 1.8. Flexible body modeling (1).

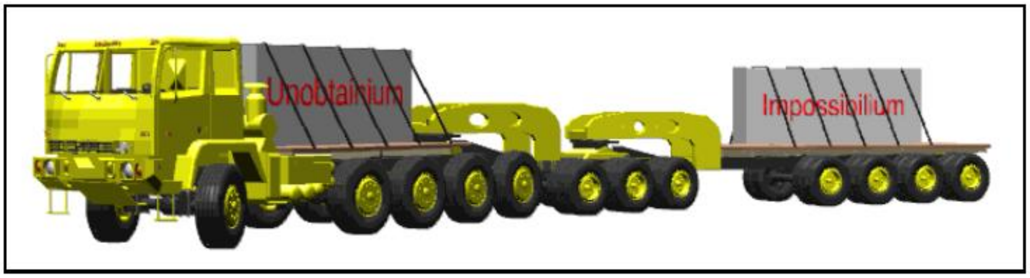


Figure 1.9. Example of a virtual model, which appears realistic and feasible. The design however, cannot be supported with sound engineering projection beyond the third axle, when factoring in real world strength, performance, size, and weight considerations (21).

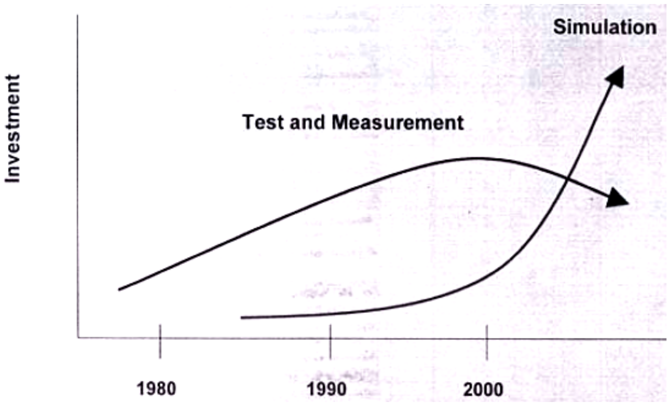


Figure 1.10. Predicted trend for Simulation versus Test (1).

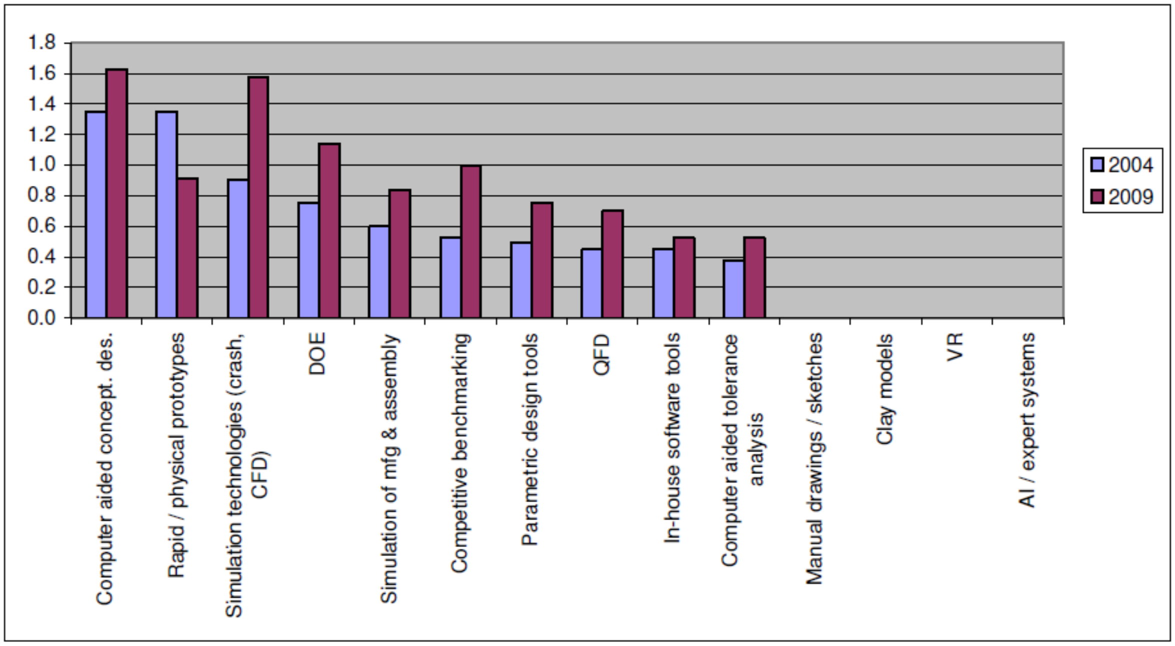


Figure 1.11. Predicted trend for various design tools (including simulation and physical prototype/test) (46).

2. DOCTORAL PROJECT

2.1 Doctoral Project Virtual Prototyping Aims

To fully benefit from the VP state-of-the-art technologies and features mentioned thus far (in competition to Specialized CAE and Physical Prototyping/Test) for Heavy Ground Vehicle engineering, for this doctoral project, VP approach or paradigm based on the following framework is proposed:

Table2.1. Framework for Doctoral Project's Virtual Prototyping Approach

Virtual Prototyping Approach	Attribute
Upfront design-integrated simulation/analysis (through MSB and FEA).	Speedy and early CAE iterations by mainstream product savvy and experienced engineer(s)
	3D CAE that is CAD integrated (embedded or associated)

The overarching aim of the framework is also to address Heavy Ground Vehicle product complexity (associated to its design aspects; refer to Table 2.2) to arrive at *high performing* Heavy Ground Vehicle products through an *accelerated* and *economical* product development process (which appears to be counterintuitive and conflicting demands; refer to section 2.1.1). It should be noted that the proposed framework would effectively eliminate the traditional 'wall' between design and simulation activities in the product development process (Figure 1.6).

Additionally, based on the framework in Table 2.1, further goal for the doctoral project is that with the proposed 'upfront design integrated simulation/analysis' VP process, the hypothetical benefits of the attributes shown in Table 2.1 would inherently become the characteristics of the process.

In the dissertation, as a part of the investigation and 'best practices trade studies', gains from the VP approach would be highlighted - some of which are quantified for objective comparisons to results from status quo Specialized/Standalone CAE and Physical Prototype/Test. Below are additional important aspects of simulation/analysis process, drawn from the doctoral project:

1) 2.1.1 - Winning Approach in Road & Rail Ground Vehicle Innovation Race, and
2) 2.1.2 - Opportunities and 'Paralysis of Analysis',

as they relate to the specific aims of the proposed Virtual Prototyping approach for heavy ground vehicle engineering (as opposed to light ground vehicle or automotive engineering). The aspects are discussed in general in the following sections in this chapter.

2.1.1 Virtual Prototyping - Winning Approach in Road & Rail Vehicle Innovation Race

In industrial product development project, particularly in the ground vehicle industry, time constraint is always a factor. The need to introduce new high quality, customized, and consequently complex product to gain competitive advantage or market share, drive increasingly tight scheduling for product engineering tasks and also called for reduced product development cost (Table 2.2) (18)(20)(27). Additionally today, end-users 'heightened sense of taste' is becoming ever more refined such that the demand for quality of both design and manufacturing are stringent in the product development process.

However, high quality and high performing design usually implicates cost and time increase in the product development process, and unlike ten to twenty years ago, today, there are few genuinely 'bad products' available (49). Also, high performance through simulation/analysis is usually associated with elaborate Standalone CAE performed by specialist in a design process. It seems therefore, that demands for *high performing* products are conflicting with demands for '*shorten product development process*' and '*reduced development budget'*.

Considering it closely, the resolution to this conflict essentially lies in improving the efficiency of the ground vehicle engineering process. It is here, in its role for predicting and simulating real word behavior to validate designs, that CAE timing and winning approaches (or best practices) play a critical and pivotal function to make the product development process more efficient and effective.

Efficient VP through early CAE as an integral part of the design process (as proposed in the framework in Table 2.1), while essentially being *simulation or VP-driven* in addressing complexity in the product development cycle, and 'defining and constraining the design space' effectively, encourages innovation by allowing several specific value-added factors which are (35)(48):

1) Ability to determine design parameters that will optimize performance
    - Optimization of response variables (especially iteratively versus mathematically).

2) Ability to determine trade off decisions that is best for product performance
   - Rapid what-if experimentation with various design configurations (for variables interaction and tradeoffs).
   - Insightful understanding and ranking of design variables.

Accuracy factor on the other hand would be directly related to VP simulation/analysis effectiveness in predicting product behavior in real world environment, all of which are factors required in Virtual Prototyping to result in *high performing* products.

2.1.1.1 VP Attribute - Early CAE by Mainstream Product Savvy Engineers

The value-added factors 1) and 2) , essentially obtained from extensive iterations, provide great insights and ideal design directions. The factors are extremely beneficial when performed <u>early by mainstream engineers</u> in the product development process ensuring 'quality and rich simulations' to arrive at a customized, optimized, and *high performing* ground vehicle design.

With today's increased simulation/analysis processing speed and affordable computational power (Figure 2.1), more engineering and innovation are ensured from the multitude of 'rich' iterations, especially if VP is put in the hands of <u>mainstream engineers with good product knowledge</u>, as the value-added factors assist in the concept of 'getting to the right idea' with clearly defined design intent, faster, while improving product performance. In the past, similar study of design variables is typically performed through elaborate Design of Experiment (DOE) or through heavy mathematical optimization algorithms.

2.1.1.2 VP Attribute - CAD integrated (embedded and associated)

<u>CAE that is CAD integrated</u> provides a familiar environment to mainstream engineers to cultivate its use. As it is integrated and seamless, the simulation can also be performed faster.

The digital mockup from Virtual Prototyping serves as electronic design platform and data (on both simulation/analysis and design, as the simulation/analysis is <u>CAD associated</u>) for future designs needing further iterations and customizations. One of the major wastes in product development is the waste of knowledge - if the knowledge is not stored and captured, or cannot be retrieved easily, time is wasted in finding or recreating it, resulting in unnecessary bottleneck in the product development process.

The CAD realism (because of CAD embedded property) that makes it easier to relate product digital mockup and Virtual Prototype to the final product and real world behavior, while allowing some degree of ergonomics study, also cultivates cross functional collaboration early in the design cycle, further ensuring an overall *accelerated* product development process (60).

2.1.1.3 Product Innovation Race in the Long Haul

So, for ground vehicle engineering, the use of upfront CAE in design-integrated simulation/analysis, performed by knowledgeable mainstream engineers as laid out in the Table 2.1 framework can be imperative to stay ahead in the ‘product innovation race’.

In the long run, the proposed Virtual Prototyping approach can also go hand-in-hand with PLM (Product Lifecycle Management) quality related issues (warranty cost) and continuous improvement/customization work, by ensuring paperless and transferable innovation (as it is digital and CAD associated, coupled with experience gained by mainstream engineers) and valuable CAE/CAD information in the Virtual Prototype, for overall lean product customization process, downstream and in the future.

2.1.2 Virtual Prototyping – Opportunities and ‘Paralysis of Analysis’

At the crux of CAE simulation/analysis is the modeling process. In the context of this doctoral project, CAE modeling for VP involves the approximation of geometry by use of CAD software, and through mathematical or numerical schemes to approximate physical behavior of mechanical systems, dynamically and structurally. Numerical modeling are done through MBS and FEA, which are two very widely used CAE tools for simulation/analysis in the industry and the field of vehicle engineering (33). The proposed combined use of these tools in upfront and design integrated fashion lead to what is referred to as Virtual Prototyping or VP approach in this dissertation, and is used to simulate and analyze the tests and real world conditions that a physical prototype would be subjected to during the development of a new or improved engineering product.

As modeling is a prediction and approximation, it is obvious then that inherently it would involve 'idealization and simplification' in the process. Any method of simulation/analysis must be part of a lean and structured process if it is to produce results in a timely manner. Interesting results that are too late to influence product design are inconsequential and expensive to change, especially in contemporary 'concurrent engineering' practice where functional, cost and manufacturing issues are considered together, simultaneously.

However, although computing power grew around 100 times or more over the last two decades, simulation/analysis tasks seem to be taking as long to complete as they have in the past in product development process. The increased computing power available is an irresistible temptation to add complexity to predictive numerical models (e.g. by making rigid models fully flexible). Unnecessarily complex models require more data to define them and the data would take time to be acquired and more importantly must exist. '**Paralysis of Analysis**' can then occur, causing major bottleneck in the design process, preventing the desired early and upfront design integrated simulation/analysis, as nothing is analyzed until the ground vehicle problem is defined to a level of accuracy matching the complexity of the modeling. More than the model itself, the process within which the problem fits must be suited to the tasks at hand.

Appropriately, to strike a balance in the Virtual Prototyping approach for the doctoral project, comments by RS Sharp (who is a prolific author and researcher in the field of MBS and Vehicle Dynamics) is quoted: "Models do not possess intrinsic value. They are solving problems. They should be thought of in relation to the problem or range of problems which they are intended to solve. The ideal model is that with minimum complexity which is capable of solving the problems of concern with an acceptable risk of the solution being 'wrong'. This acceptable risk is not quantifiable and it must remain a matter of judgment. However, it is clear that diminishing returns are obtained for model elaboration." (48) (Figure 2.2).

Opportunities to 'up and frontload' the design studies through VP in the design cycle is improved with 'idealization and simplification', in avoiding 'big surprises' down-stream, especially when it is close to the time for product roll out. VP early in the design cycle, also typically result in robust products, as fidelity is increased in a hierarchical manner - which can be done effectively and with ease and speed through <u>CAE that is CAD integrated</u>. Further, educated 'idealization and simplification' is ensured by <u>mainstream product-savvy engineers</u> to avoid ‘garbage in – gospel out’ scenario, as the simulation/analysis results are basically as good as its input.

2.2 Procedures and Hypothesis for the Doctoral Project

Using various contemporary VP features, firsthand investigations were performed in the doctoral project, for Virtual Prototyping as the proposed winning approach or ‘best practices’ (tool and process; according to the frame work shown in Table 2.1), to address top pressure factors (which are non-mutually exclusive, Table 2.3) faced in today’s industrial product development project based on surveys (27). In short, the theme of these pressures is in fact, to build *high performing products* at *reduced cost,* and most importantly *faster* with *‘shorter product development schedules’*. Table 2.4 further breaks down additional non-mutually exclusive challenges or pressures faced in arriving at *high performing product* in the product development process, which relate strongly to product complexity and the value-added factors mentioned in Section 2.1.1.

Importantly, as a part of the doctoral project, the improvement brought by VP approach with regard to these pressure factors/demands would be quantified (when possible) and objectively compared against results from status quo Specialized CAE and Physical Prototype/Test of the Heavy Ground Vehicle product development process.

Serving also as ‘trade studies for best practices’, the doctoral project investigation is essentially a culmination of work of over hundreds of pages and drawings, worth of reports and plans (on ground designs, Virtual Prototyping and Tests) in the course of multiple years (2005 to 2009) and projects required for Doctor of Engineering industrial internship. During this time, among around 13 machines designed and built, 7 different ‘Virtual Prototyping-driven Heavy Ground Vehicles’ were successfully developed, from which work ‘winning approaches’, ‘best practices’ and other findings were drawn.

Also in the time period, sometime was spent as a member of an evaluation and steering committee for a heavy ground vehicle engineering team for the purpose of CAD/CAE upgrade and implementation program. Sometime was also contributed on projects outside of ground vehicle realm (electro-mechanical machinery) for additional perspectives. Further, different engineering responsibilities were assumed (Design Engineer, Analyst Engineer, Test Engineer, and Project Engineer) to do first-hand investigations /'trade studies' from which genuine and pragmatic 'best practices' can be drawn, comparing VP to competing status quo Specialized CAE and Physical Prototype/Test in product development process.

Specialized Heavy Ground Vehicle is appropriately chosen (i.e. over aerospace engineering) for the potential VP (through MBS and FEA) still has in the field (in lieu of CFD in aerospace engineering)(46)(59) and is favored over a highly standardized automotive engineering area for the doctoral project. Design of components and systems as they relate to various complex vehicle design aspect (Table 2.2), which are mostly original designs in the Specialized Heavy Ground Vehicle area would be a 'true test' to the proposed VP framework (Table 2.1), as opposed to more customized and continuous improvement designs typically seen in the lighter ground vehicle or automotive engineering area.

Table 2.2 Different aspects to consider in Vehicle Design

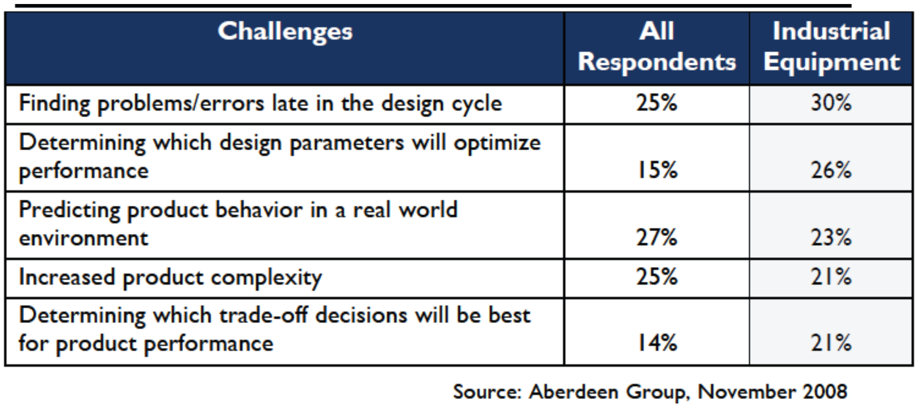
VEHICLE DESIGN ASPECTS	**Safety (Impact/Crash Worthiness)**
	Ride & Handling
	Ergonomics (Comfort/Convenience)
	Aesthetics (Styling)
	NVH (Noise, Vibration, and Harshness)
	Durability

Table 2.3. The Top Five Pressures (Source: Aberdeen Group, February 2008)

Pressures	% of surveyed response
Shorter product development schedules	91%
Reduced development budgets	38%
Increased product complexity (many design variables)	30%
Accelerated product customization	15%
Increased quality-related costs (warranty, etc.)	11%

Therefore, the 'trade studies' and investigations in this dissertation are in the context of heavy ground vehicle engineering, with '*Short Product Development Schedules*' being the key factor to be addressed, results of which will be compared to counter points and previous similar works. With additional considerations of external case studies (for baseline results) and surveys (for statistics and facts) as cross references and in bringing objective comparisons (to a rather subjective topic), the investigations would also be on VP as an *economical*, *effective* and *accurate* approach for demanding problems inherent to various aspects of ground vehicle design (Table 2.2) - simultaneously addressing product customization, complexity, and quality (Table 2.3) and other challenges in improving product (Table 2.4), to ultimately result in overall *high performing* products.

Table 2.4 Top 5 challenges of improving product performance (35).



Challenges	All Respondents	Industrial Equipment
Finding problems/errors late in the design cycle	25%	30%
Determining which design parameters will optimize performance	15%	26%
Predicting product behavior in a real world environment	27%	23%
Increased product complexity	25%	21%
Determining which trade-off decisions will be best for product performance	14%	21%

Source: Aberdeen Group, November 2008

So, more precisely, the main hypothesis of the dissertation for the doctoral project is that VP approach (as in Table 2.1 framework) would tackle the conflicting top industrial pressure factors/demands (*reduced time* and *costs,* and *high performing products*).

Among other things, the investigations in the dissertation would prove how educated 'simplifications and idealization' can be done without greatly sacrificing VP *accuracy* (especially important as it relates to the VP approach ability to predict real world behavior (Table 2.4)). Simultaneously avoiding '*Paralysis of Analysis*', the fidelity can then be hierarchically increased, showing VP versatility and scalability in greatly assisting 'front or uploaded' design integrated simulation/analysis framework.

Interesting and challenging real world problems inherent in ground vehicle engineering (versus other areas) that are considered and investigated on (to study *effectiveness* and *accuracy*) in Virtually Prototyping the vehicles mainly include Safety (structural and impact/ crashworthiness), Durability, NVH (Noise, Vibration, and Harshness) and Ride & Handling (Table 2.2). VP simulation/analysis of these relatively complex problems would also fully explore today's realistic high fidelity graphical environment (that is the attribute of contemporary CAD embedded VP tool), not only simulate problems with 'real world look and behavior', but also further help improve the design aesthetically (i.e. styling and packaging) and ergonomically (i.e. human factors) which are also important in this area (Table 2.2).

2.3 Doctoral Project Heavy Ground Vehicle Engineering Overview

In other words, in this dissertation, VP design integrated approach utilizing MBS and FEA technology by product savvy engineers (refer to Table 2.1 framework), is about numerical modeling process and tool for wide ranging ground vehicle engineering problems, early and upfront in the design cycle, while breaking the traditional barrier between design and simulation/analysis (Figure 1.1). It involves simulation/analysis of today's Heavy Ground Vehicle mechanical systems (vehicle mechanisms, suspension, or hydraulic sub-systems, and etc.) such that as a result, the system's response with regard to kinematics, statics or quasi-static equilibrium, dynamic motion, and forces are predicted in CAE early in the design cycle. The numerical model is iterated and input with load cases or 'front loaded' to reduce 'surprises' late in the design cycle. The approach is a departure from a conventional specialist simulation/analysis mindset (2)(11).

In predicting product's behavior in real world environment and in managing the risk associated with increased product complexity (Table 2.4), input for the ground vehicle VP models (as functions of time in case of MBS) can be displacements (i.e. inverse kinematics and dynamics in MBS), and forces or accelerations (i.e. forward kinematics and dynamics in the context of MBS).

Modeling on computer through CAD/CAE is done by defining the geometrical configuration and topology of bodies, joints or boundary conditions, contacts, and advance elements like bushings and springs. The models are translated into mathematical and differential algebraic equations systems and solved numerically (10), (11), (27).

Output are basically time history results of the system motion (for MBS), the corresponding forces and the resulting effects of the forces on the model (but without time history for FEA).

2.3.1 VP Approach for Heavy Ground Vehicle Engineering

2.3.1.1 Challenges and Idealization/Simplification to avoid 'Paralysis of Analysis'

Being a powerful modeling and virtual prototyping method, paradoxically, MBS and FEA technologies usage comes with a caveat as it is recognized to have a relatively high learning curve due to the inherent complexity of the tools (Figure 2.1), despite the advent of upfront CAE environment with highly intuitive tool-based Graphical User Interface (GUI) (24)(28). Compounding the problem of 'Paralysis of Analysis', complexity of the tool is even higher as for the case for the Standalone/Traditional CAE simulation/analysis because of more specialized/dedicated and involved user interface.

In addition, for MBS, if the simulation is to predict forces, or stresses incase of FEA for problems in heavy ground vehicle engineering, the sensitivities of the results with respect to modeling (friction, non-linear bushings, contact and etc. for real world imperfection), approximation of input data (sampling, interpolation, scaling, simplifications, and etcetera), and solver options is high (9), (10), (11), (27). Therefore, simulating ground vehicle kinematically alone is much easier than also trying to get the correct dynamic forces through MBS, and stresses or deformability through MBS-FEA coupling. Encouragingly however, when used in parallel (separately), MBS would assist in feeding accurate load cases for FEA (uncoupled with MBS).

In addition to 'Paralysis of Analysis', novice user of the tools can then easily fall into 'garbage-in, gospel-out' trap when simulating and analyzing through CAE. Specialist (typical user of Standalone CAE) can also fall into this predicament because of their lack of in-and-out expertise or knowledge of the product itself. As such, lack of expertise and time are cited to be the major obstacles to successful Virtual Prototyping implementation (Figure 2.1).

To avoid 'Paralysis of Analysis' in the doctoral project, modeling for VP simulation/analysis needs to be scaled to single parts and simplified assembly level models, in place of involved multiple complex sub-assemblies, early in the design cycle. Approach for simulation/analysis should be in the order of increasing complexity, performed as the need arise and/or if the schedule allow, to keep the process of simulating and analyzing, lean, economical, and be able to start early.

Introducing fidelity into the VP process as such, hierarchically, would also promote robustness as additional design variables and their responses are better understood and ‘introduced’ into the product in a ‘controlled’ fashion.

Obviously however, it becomes more difficult to simplify and neglect the real world part flexibility, non-linearity and dynamic effects like contact, inertia, or friction, as more parts get added to the simulation and analysis.

2.3.1.2 Rigid bodies MBS Virtual Prototyping versus Flexible Multibody Simulation

Then again, elegant and complex VP through simulation/analysis, which is predictive in nature, only make economic sense if it has significant values on cost and time in the product development work.

From early findings in the doctoral project, flexible MBS (i.e. MBS-FEA coupling) through Craig-Bampton method is an elegant way to capture natural deformability of bodies in motion, but is also found to have slowed computational time by a factor up to 10 (9). Computational time is increased as modal FEA is performed followed by MBS processing, alluding to a ‘dimishing return’ (Figure 2.2) especially in the context of upfront engineering, prompting the priority to rigid bodies modeling given in this doctoral project (2).

This approach is also adopting the standardized practice in automotive engineering, where the loads from MBS are “cascaded” down and used to do detailed stress analysis at both `component and system level FEA (1),(18). The need for flexible MBS is then assessed appropriately based on separate FEA results, especially on deformation or compliance aspects (i.e. to ensure clearance in the mechanical assembly (higher level system) and etc.).

2.3.1.3 Opportunities for Winning approach in the Heavy Ground Vehicle Engineering

On a positive note, computational efficiency of MBS is well recognized, allowing its use in advance Operator/Hardware-in-the-Loop applications (hybrid or coupled simulation-test approach) that demand for real time processing. Also, encouragingly in the case of full road ground vehicles (with limited use of advance elements as generally is the case), MBS models typically run faster than real time (49) (Figure 2.4). FEA has also advanced in recent years with much improved processing speed. So, real opportunities are apparent related to the processing speed, that they could be taken advantage of for more engineering and the needed iterations to be done upfront for the product development process and the associated ‘innovation race’.

As such, a key aspect of the doctoral project in this paper is also to 'streamline' modeling approach in the product development process (through idealization/simplification and introducing fidelity in hierarchical manner and etc.), such that kinematics, motion dynamics, forces and deformability are sufficiently and accurately predicted, in a timely fashion. This is so that, as a result of the VP framework for the design of Road and Rail Heavy Ground Vehicles, more iterations, engineering and innovation are imbued in the product development process beginning at the early stages, in studying and managing trade-offs, and design variables as mentioned in Section 2.1.1, ‘*Virtual Prototyping - Winning Approach in Road & Rail Vehicle Innovation Race*’.

In this broader sense, to arrive at *high performing* Heavy Ground Vehicle products, again, emphasis is given to rigid-bodies modeling, in favor of flexible bodies (MBS-FEA coupling) in motion dynamics simulation. Improved processing speed is also further leveraged with other idealization/simplification. Fidelity which is introduced hierarchically is also beneficial when it results in a robust design since design and response variables are better understood.

Specific modeling of advance elements like bushings/elastomers and contacts, which are critical as it affects optimal and timely VP process, are also investigated for winning approach or ‘best practices’ as part of the doctoral project.

2.3.1.4 High Performing Ground Vehicle - Accuracy, Real World Behavior, and Product Complexity

On top of using basic joints and advance bushing (to emulate elastomer like stiffness element like tire) and force elements in capturing a physical phenomenon, the investigations in this dissertation would make good use of contact constraints especially in MBS to add realism to the simulation, at assembly level – contact technology has advanced quite considerably, which include 3D contacts (Figure 3.6). As real world problems usually occur at higher assembly level, industrial ground vehicle problem investigations are performed showing the constraints being fully utilized in VP studying impact physical phenomena (for safety factors and for Noise, Vibration, and Harshness or NVH considerations) and impact related clearance or gap-contact.

The doctoral project would experiment with numerous kinematic pairing and modeling strategies for MBS and FEA, while keeping in mind their effect on modeling computational time. This is since, computer performance is a limiting factor for models with many bodies (rigid/flexible), loading, boundary conditions, and kinematic pair (joints and etcetera) especially contact elements when simulating and analyzing complicated machines through MBS and FEA (11 to 17). Posing various challenging real world problems for the doctoral project VP investigation, industrial Road and Rail vehicle problems considered in the dissertation would mostly come from Specialized Heavy Ground Vehicle class (particularly in material handling area) for Road (off and on) and Rail applications (Figure 2.3); designs of which range in originality and complexity.

Investigations would show how numerical simulation/analysis for virtual test and experiment through Virtual Prototyping result in high degree of confident (because of its *accuracy*) on design works especially in a *timely* and *economical* manner, including when they are required to work right the first time (no physical prototype/testing).

Tests are used to supplement and compliment VP results. Since CAD embedded MBS and FEA are generally perceived as 'not as accurate', test are also used to show and prove how closely and accurately these VP tools are in predicting real world behavior. Overviews of other opportunities to further optimize the product development process are also given as part of the investigations in the doctoral project.

2.4 Overview of the Structure for the Doctoral Project Dissertation

The following breakdown for the investigations in the doctoral project which also serves as 'best practices trade studies', is given in terms of the type of vehicles (Table 2.5 and Figure 2.8 to 2.14), listed generally in the order they are worked and investigated on, and of varying complexity that are Virtually Prototyped for the doctoral project in this dissertation. The Specialized Heavy Ground Vehicles are of Road and Rail applications in which design work, MBS and FEA are very widely used when simulating and analyzing them.

In this doctoral project, MBS and FEA that are CAD embedded were taken advantage of as upfront design integrated VP tools, as opposed to being used late in the product development cycle through status quo Specialized CAE. The VP approach is based on the VP framework in Table 2.1, with tests included to verify and compliment the VP models, and also physical prototypes of the various vehicles listed in Table 2.5. Highlights are given for each machine on the specific items or areas covered in the studies and VP design work, showing the different VP features taken advantage of for *speedy*, *economical*, and *accurate* simulation/analysis resulting in *high performing* Heavy Ground Vehicle products.

2.4.1 Structure of the Heavy Ground Vehicle Doctoral Project Work

The investigation works a. to d. in the doctoral project are essentially "Kinematic Synthesis" problems (which are inherently time consuming) for extended multiple stages/positions hydraulic implement system consisting of linkages and actuators common in material handling equipments and vehicles (48). The problems are original and kinematically fairly complex and would be next to impossible to solve without the contact technology in MBS (with 2D and 3D contact primarily for kinematic and dynamics problem respectively). The problem is then expanded onto 3D spatial kinematic and dynamic investigations for the demanding heavy duty application with small margin for error. The ground vehicle developed from the problem has to work the first time, as the first article resulting from the VP design work is the deliverable product (an extreme case without a physical prototype).

Table 2.5. List of figures for the various Specialized Ground Vehicles worked on.

Type of Specialized Vehicles	Figure
a. 90 ton Rolled Steel Handler	(Figure 2.8)
b. 50 ton Steel Slag Crucible Handler	(Figure 2.9)
c. 100 ton Steel Slag Crucible Handler	(Figure 2.10)
d. 40 ton Steel Slag Crucible Handler	(Figure 2.11)
e. Specialized Forklift Hydraulic Implement	(Figure 2.12)
f. Specialized Shunter Tractor	(Figure 2.13)
g. Rail Vehicle Bogie for rail cars and locomotives	(Figure 2.14)

VP simulation/analysis investigational works a. to d. are mostly performed on the trailer and implement side which takes up most of the payload of these Specialized Heavy Ground Road Vehicles (as opposed to tractor, 2f). The vehicles which are mainly of Off-Road type, would generally have more stringent requirements, structurally. These vehicles are used to transport and handle both products and by-products typically found at steel foundries and refinery facilities with harsh operating environment. The VP approach through MBS (for extensive kinematic and dynamics, extended with high fidelity 3D graphics) and FEA capabilities (for follow up structural studies), has allowed for rapid digital prototyping and actual product rollout on an aggressive schedule for the vehicles to be deployed at the corresponding facilities.

The problems in 2e and 2f that are investigated and Virtually Prototyped on are mostly spatial or 3D in nature with regard to kinematics and dynamics problems, as opposed to mainly planar or 2D as previously discussed. Vehicles being simulated/analyzed through VP in this section are combination of On/Off Road Vehicles, which involved not only original product development effort but also continuous improvement in PLM (Product Lifecycle Management) phase. The works are focused on the tractor side of specialized vehicles which are motorized, self-propelling, and highly mobile, posing interesting sets of problems with some studied through tests before the consideration of VP. Contacts are extensively used to address challenges in capturing real world contact-impact phenomena in MBS. Possibilities of Hybrid Test/Simulation were also considered.

Investigations in g. are performed on Rail Vehicles. As Rail Vehicles have relatively higher transportation operational load, they pose yet a different and challenging set of problems, structurally. For one, structures are complex surface cast design versus fabricated steel for higher durability (thus less emphasis on steel fabrication and weldment). Also, for the case of the Rail Vehicle design, simulation and analysis are highly standardized by the governing bodies of the industry and is required to be ‘certified’ by test for most cases. The problems are mostly static structural problem which are then expanded into durability dynamic problem, Virtually Prototyped through FEA and then followed up with an extensive physical instrumented test. MBS is mostly used for vehicle dynamics studies in the Rail Vehicle design work.

2.4.2 Structure of the Doctoral Project Dissertation

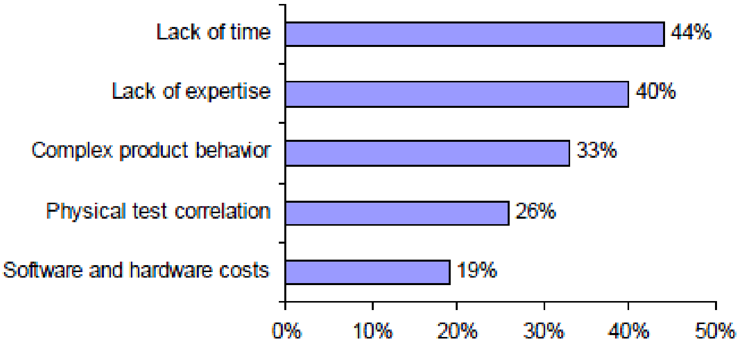
The different areas looked at on these various Heavy Ground Vehicles will be referenced to throughout the paper in the respective pertinent sections. Some of the works performed (as shown in Table 2.5 and Figures 2.3 and 2.8 to 2.14) are only briefly reported in this dissertation, and only the ones that would demonstrate the relevant ideas the best and cohesively is represented in this dissertation, written and elaborated on.

The following chapters would first be on MBS (Chapter 3) and then FEA (Chapter 4) as they relate to the VP approach framework in Table 2.1, with detail discussions on the associated gains, some of which are quantified.

As for the case in Chapter 3, gains from VP are compared to status quo/counterpoint Standalone CAE. In Chapter 4, the comparison would be against status quo Physical Prototype/Test.

This is followed by discussions on VP approach counterpoints which are Specialized CAE and Physical Prototype/Test in Chapter 5, to strike further comparisons.

Finally, Chapter 6 discusses the findings from the doctoral project, from a higher perspective which include further benefits and drawbacks, suggestions and conclusive remarks as they relate to the VP approach as proposed in the framework shown in Table 2.1.



Source: AberdeenGroup, October 2006

Figure 2.1 . Challenges to simulation-driven design (44).

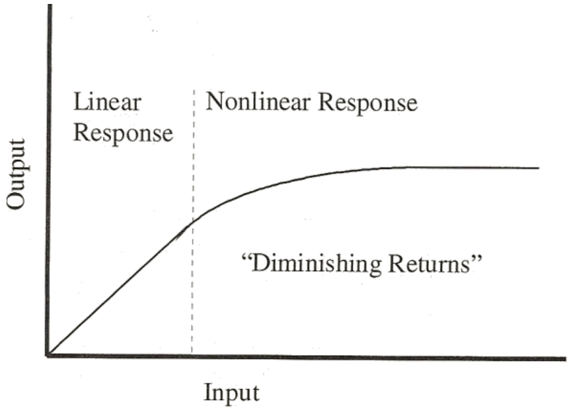


Figure 2.2. The Law of Diminishing returns - with small inputs, the output increases linearly, but with larger inputs, the output levels off. This is "diminishing returns" in the nonlinear region, which means there is not as much output per unit of input.

Figure 2.3. (top) Various road and rail ground vehicles worked and investigated on for the doctoral project on VP applications on their product development process during 2005 to 2009.(bottom) CEO of Ford Motor Company, Alan Mulally is seen in 2009 discussing the finer points of Formula SAE open wheel race car design with the students. The KU FSAE car was worked on at the beginning of the doctoral project .

Figure 2.4. Virtual prototype of University of Kansas Formula SAE car - full vehicle simulation is faster than real time.

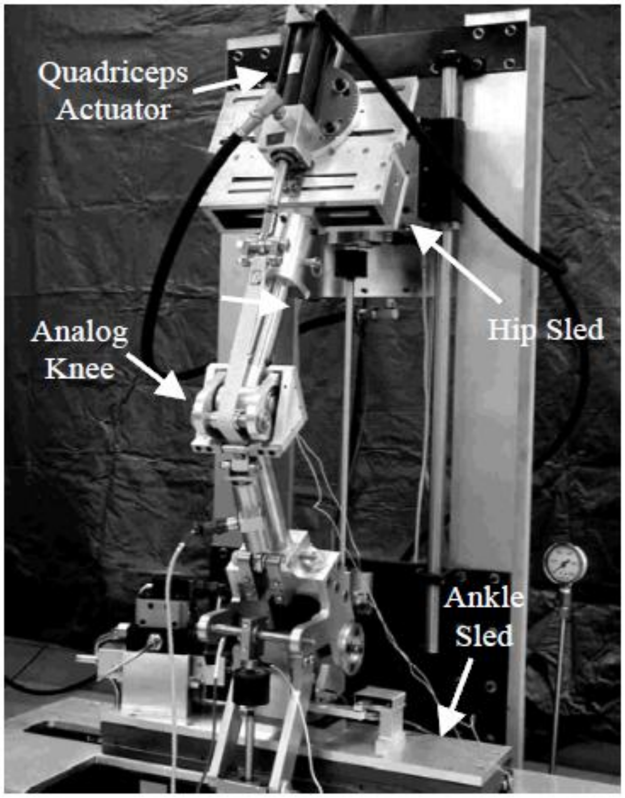
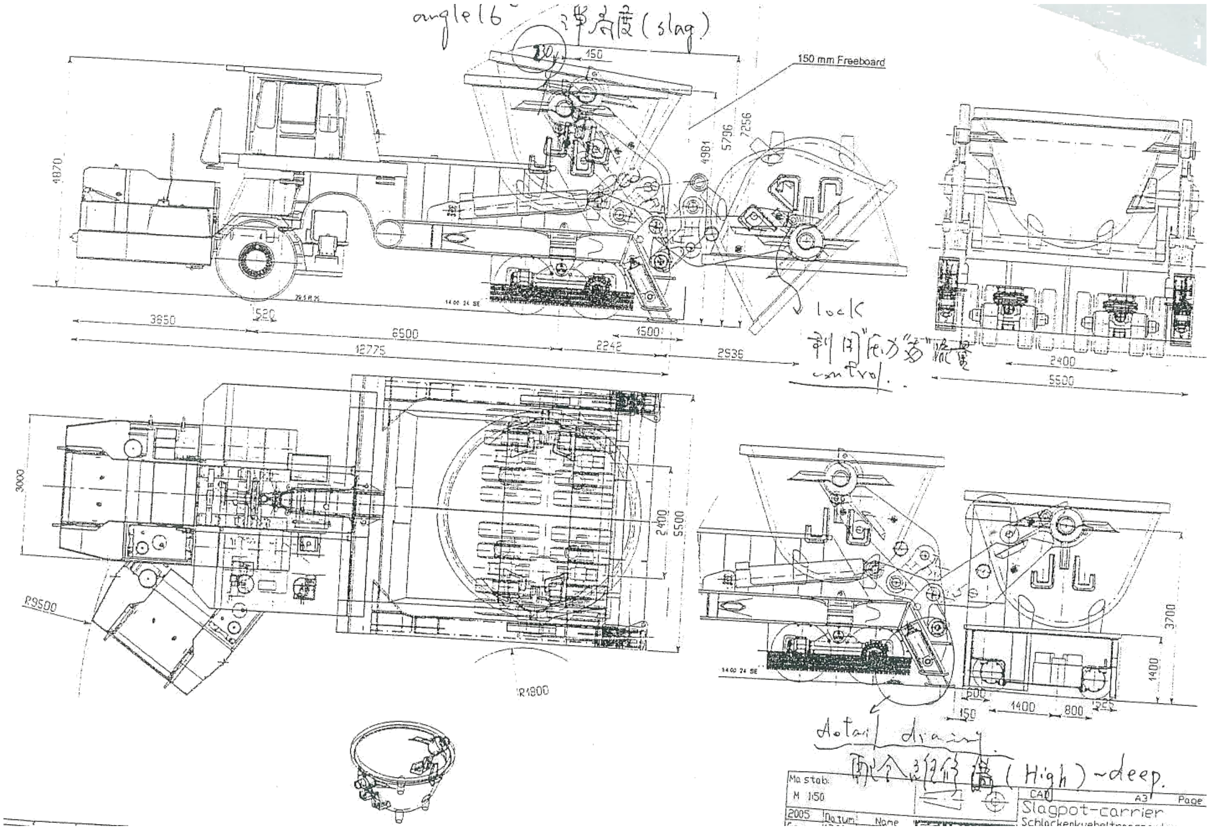
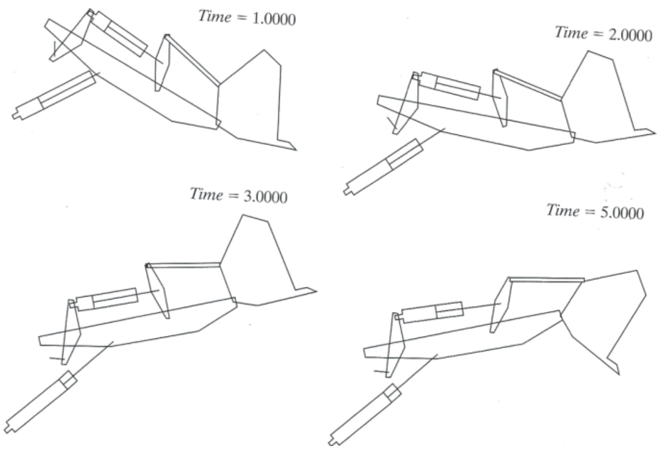


Figure 2.5. Kansas Knee Simulator (KKS) – comparing test-based technology (that is also modeled through Specialized CAE) baseline system and Virtual Prototyping.





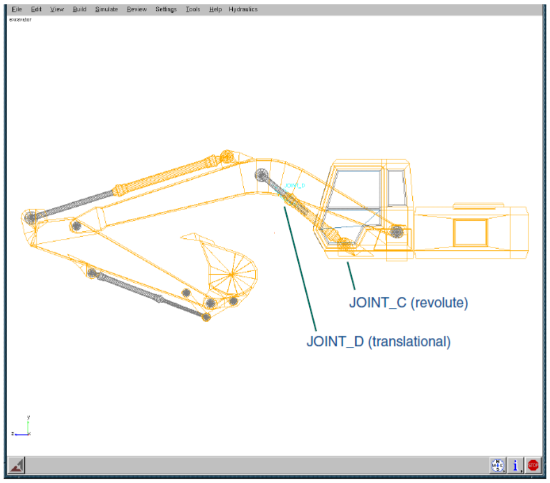


Figure 2.6. Slag Crucible Handler Kinematic Synthesis problem through graphical method (top). An example of graphical method for kinematic synthesis of construction machinery front loader (bottom).

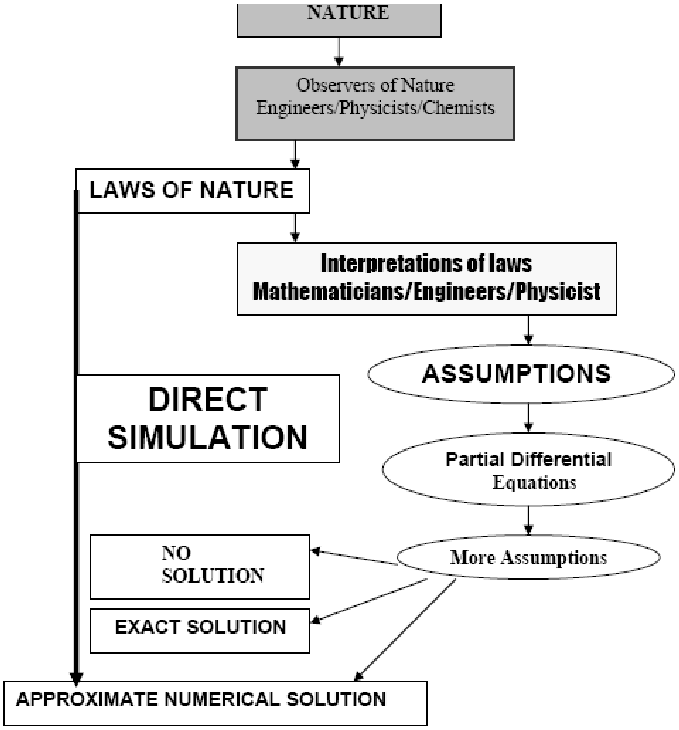


Figure 2.7. Scientific process of numerically modeling real world phenomena for Virtual Prototyping.

<u>MBS used in Virtual Prototyping approach for:</u>

- Kinematics study for clearance and understanding of hydraulic implement linkage (2 Stages) full motion range.
- Hydraulic system load profile for hydraulic implement actuator design and corresponding systems.
- Quasi-static load cases determination throughout linkage motion. Joints in the virtual prototype are used as virtual sensors to measure loads in the simulation in mostly otherwise impossible locations and points physically. Loads generated are also used for retention system (pins, fasteners, and etc.) specification and detail structural studies including for weldment.

<u>FEA:</u>

-Ram of the Steel Coil Handler modeled as plate and solid to confirm maximum deformability

-Steel Coil Handler sub-system/assembly.

Figure 2.8. 90 ton Rolled Steel Handler and the different aspects considered for the studies.

MBS:

- The MBS problem basically entail an open-loop planar kinematic and dynamic control of hydraulic implement.

- Kinematics study for clearance and understanding of implement linkage (3 Stages) full motion range and other sub-system, for the required reach, and detail iteration and manual optimization. Iterative optimization is adopted and preferred over a mathematically based optimization, to fully leverage on MBS quick processing time.

- Linkage hydraulic system load profile:

-- Requirement is 1-minute total cycle, from stow to completely open position. So, inertial effects of the sub-system when simulating is a considerable factor as the speed is relatively high for a large system.

-- Study of noise in the hydraulic system with critical hard points modeled with contact (supplemented with accurate geometry definition through CAD).

- Positioning of open loop sensory system for the implement linkage system.

- Kinematics and ergonomics aspects of machine operator's hydraulic control levers (through CAD embedded environment).

- Quasi-static load cases that accurately capture the load direction/vector and boundary conditions.

FEA:

- Frames of trailer and implement or linkage system mostly modeled as plates.

High-fidelity graphical environment:

- Detail kinematic study, coupled with realistic graphical environment are not only performed on planar (side view) but also on spatial cases for optimal operator's view studies of hydraulic implement system operation.

- Virtual Machine Operation created using VP capabilities for ergonomics and operator's view and videos made in the process help generated additional interest for different vehicle configurations (100 and 40 ton discussed below) by allowing concurrent engineering and early cross functional involvement from sales and marketing.

Test/Validation:

-The resulting cylinder as big as a 200-ton press complimented with instrumented testing and validation.

-Photos/Video on machine implements validation at customer's site overseas.

Figure 2.9. 50 ton Steel Slag Crucible Handler

A lot of the knowledge from VP simulation and analysis of the 50 ton handler are applicable and carried over onto this vehicle implement and linkage system design. Operational load had gone up by 100% for the vehicle.

MBS:

- The increase in load had warranted a need for an additional axle and simulations and studies done on ground borne impact/shock load to dual-axle walking beam using bushings to model rubber tire.
- Simulation results compared to instrumented test performed on container handler trucks.

FEA:

- Simplifications of implement frames in the design as plates are no longer applicable as it is important to understand the effect of fabrication (triangulation (32) and addition of ribs, and other orthogonal strengthener) and weldment on the structure with optimal strength-to-weight ratio due to increased operational load. Topology of the machine frames is now modeled as volume meshes in the Finite Element Analysis.

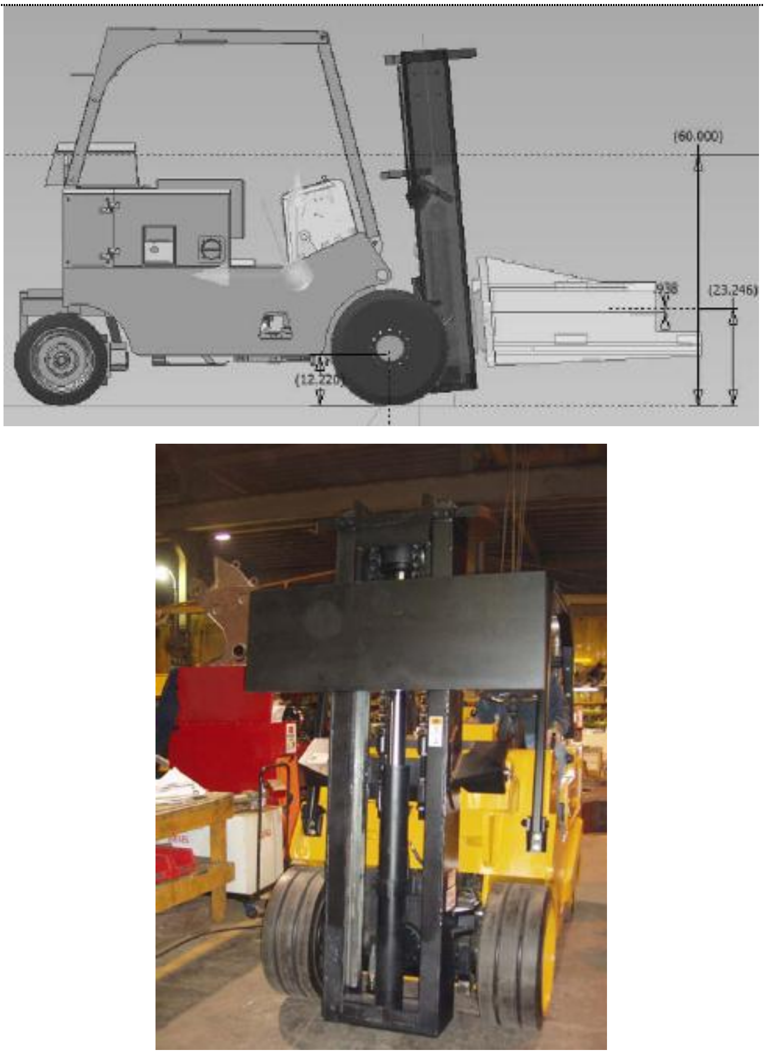
Figure 2.10. 100 ton Steel Slag Crucible Handler

The trailer frame or chassis is similar to 100 ton vehicle that the implement linkage system is mounted to.

MBS and FEA:

- Kinematic and structural study is not as detailed since the implement subsystem is smaller 2 stage links with a lot of knowledge from the previous 2 higher load capacity vehicles trickled down and applied to the design work.

Figure 2.11. 40 ton Steel Slag Crucible Handler.



The vehicle is equipped with a special mast that needs to withstand operational shock loads. Battering hammer outfitted to the forklift mast generated shock load as it pounds on shims used on jigs and fixtures typically seen at steel foundries. Chassis and mast of the tractor is basically typical to that of forklifts.

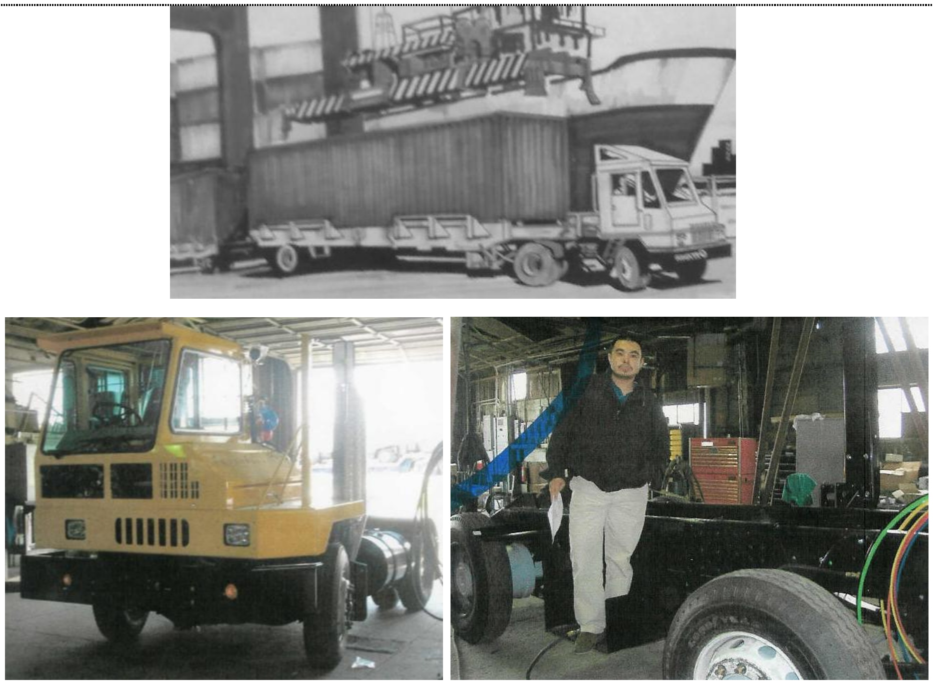
MBS:

- Shock load cases studied using contact elements.

FEA:

- Mast and retention sub-systems specification validation
- Video on impact load simulation to understand the stress flow or propagation (32).

Figure 2.12. Specialized Tractor – with custom forklift hydraulic implement



As the specialized vehicle is a prime mover, they are highly mobile and constantly on the move in material handling operations posing interesting set of problems. Simulation and analysis for the vehicle include failure studies as opposed to prevention.

MBS:

- Impact/Shock load on cab Falling Object Protection System (FOPS).
  --CATIA FEA videos, simulation and physical test.
- Kinematics study of Driveline, Throttle pedal linkage and ergonomics, and cab engine access.
- Quasi-static load case generation for 5th wheel sub-assembly.

FEA:

- Mirror post vibration modal analysis.
- 5th Wheel sub-assembly for failure studies.
- Exhaust Standoff (show dynamic factor from Burma Road test).

Instrumented Test:

- Full-vehicle instrumented test (include Burma Road, J-hook and etc.).
- FOPS dropped object test.
- Engine vibration test
- Mirror vibration test
- Power-transmission subsystem vibration/transient shock test
- Strain gage data on cabs (utilized for durability and fracture mechanics)

Figure 2.13. Specialized Shunter Tractor – Prime mover

MBS:

-Overview of comprehensive rail vehicle dynamics

-Quasi-static load case generation for an equilibrium system simulating a static case.

-Design of rollbar for both MBS and FEA.

FEA:

-Results to further be used for test plan of static and dynamic fatigue tests.

-Overview of elastomeric components and bushings non-linear FEA

-Durability or fatigue studies.

Instrumented Testing:

-Strain gage reading for static and fatigue cases.

-Testing of elastomeric components.

Figure 2.14. Rail Vehicle Bogie/Trucks (assembly of frame and bolster under car body for locomotive and passenger/freight cars)

3. VIRTUAL VEHICLE MULTIBODY KINEMATICS, & DYNAMICS

3.1 Virtual Prototyping Approach for Kinematics and Dynamics.

Table 2.1 Framework of Doctoral Project's Virtual Prototyping Approach

Virtual Prototyping Approach	Attribute
Upfront design-integrated simulation/analysis (through MSB and FEA).	Speedy and early CAE iterations by mainstream product savvy and experienced engineer(s)
	3D CAE that is CAD integrated (embedded or associated)

The focus of the upfront and design-integrated VP in this chapter is mainly through MBS (as it relates to the framework shown in Table 2.1) to simulate/analyze product's kinematics and dynamics behavior that the Heavy Ground Vehicles are subjected to in real world environment. Loads derived from MBS are then used for structural and compliance studies through FEA separately (as opposed to through coupled MBS-FEA or Flexible MBS, to avoid 'Paralysis of Analysis, as it was found to increase processing time up to tenfold). VP approach through FEA is covered in more detail in Chapter 4.

Chiefly, this VP approach frame work is proposed to result in *timely*, and *economical* product development process, producing *high performing* Heavy Ground Vehicle products, which seem to be conflicting goals for the process, especially when VP approach through MBS involves kinematic synthesis, which is inherently a time consuming process. The important gains are then quantified when possible to objectively compare it (in section 3.2) to status quo Standalone CAE simulation/analysis (in this chapter, and to Physical Prototype/Test in Chapter 4, as counter points to the proposed VP approach). The Standalone CAE approach in previous Heavy Ground Vehicle product development process, compared to, was actually contracted out, separating it from the design activity and performed towards the end of the process.

VP approach utilized for multibody kinematics and dynamics of ground vehicle simulated in this chapter cover a broad area of problem in ground vehicle design posing some of the most challenging and complex problem in engineering. Majority of the works in this section are on kinematics problems (specifically kinematics synthesis, which is inherently a long drawn process), that would primarily be on Steel Slag Crucible Handlers and also include a brief mention of Rolled Steel Handler (Figure 2.8). There are 3 VP-driven versions of the Steel Slag Crucible Handlers reported on - 50 ton version which served as a benchmark for 2 other later built vehicles, namely the 100 ton and 40 ton (Figure 2.9 to 2.11) versions mentioned in the previous chapter, which are respectively bigger and smaller physically in comparison. Kinematics problem work is then followed by dynamics studies (which also include its sensitivity aspects), through which 'winning approaches' were drawn.

These investigational works, which also serve as 'best practices trade studies' for VP MBS simulation/analysis are focused on the trailer and implement side for the kinematics studies, which takes up most of the payload of these specialized road vehicles (as opposed to tractor or prime mover end). The VP simulation/analysis work permits myriad of 'upfront' studies and iterations of what if scenarios that would have otherwise been difficult, if not impossible to implement with counterpoint Physical Prototype/Test (or even Specialized CAE).

These vehicles are used to transport and handle both products and by-products typically found at steel foundries and refinery facilities with harsh environment and are mainly of off-road type. Because of the nature of operation, the vehicles would generally have more stringent requirement structurally, performance of which would be iterated through FEA. Loads generated from MBS ensure an accurate load cases setup (with load vector, boundary conditions and etcetera as opposed to manually setting up a load case through free body diagram (FBD)).

The challenging and mostly 'new' (versus improvement) Heavy Ground Vehicle problems would be a 'true test' to the proposed VP Table 2.1 framework in tackling seemingly conflicting *high product*, and *short development schedules* and *reduced cost* pressure factors/demands. The followings are the 2 specific VP problems considered in this section:

1) Pure kinematic design iterations/synthesis (which is inherently time consuming)
2) Dynamic and its sensitivity (with regard to real world imperfections).

Prior to this doctoral project, kinematic studies and validation on most of the specialized ground vehicle design considered in this paper were primarily performed manually through classical, closed form, and 2D graphical methods involving numerous simplifications and assumptions. More recently, the dynamic and static (kinematics, kinetics, and structural) simulation/analysis of the heavy ground vehicle was contracted out and performed through Standalone CAE.

3.2 Objective Comparisons for Virtual Vehicle Multibody Kinematics and Dynamics

Based on the results of the doctoral projects, in this chapter, VP approach as in Table 2.1 framework through MBS, strongly support the hypothesis mentioned earlier that VP would address the various (non-mutually exclusive) pressure factors/demands faced in today's industrial including ground vehicle product development project. The findings in this chapter as they relate to these product development pressure factors are specific to VP approach through MBS for Heavy Ground Vehicle, which are then followed up with FEA for structural studies. Listed in Table 2.3, as they all relate to the VP approach in this chapter, the factors again are:

i) shorter product development (aggressive scheduling and by far the greatest factor)
ii) reduced development budgets
iii) increased product complexity
iv) accelerated product customization
v) increased quality-related costs (warranty, and etc.)

The general theme of these pressure factors to the product development process is to build *high performing* products *faster* and at *lower cost* - which appear to be conflicting demands. Below are further breakdown of the challenges in arriving at *high performing* Heavy Ground Vehicles, through MBS based on Table 2.4, as they relate to this chapter.

a) Predicting product behavior in a real world environment
b) Finding problems/errors late in the design cycle
c) Determining which design parameters will optimize performance
d) Determining which trade-off decisions will be best for product performance

Unlike for the case of VP approach, kinematics and dynamics verification through status quo Standalone CAE and Physical Prototype, do not seem to be able to address any of the *high performing* product pressure factors without posing any penalty on *time* and *cost*.

These conflicting pressure factors, as they are simultaneously addressed by the VP approach as in Table 2.1 framework, will be highlighted in the following sections and are discussed.

In this chapter, important results are quantified for better objective comparisons between VP approach and status quo Specialized/Standalone CAE (VP approach results/gains are compared to Physical Prototype in chapter 4, and results seen in the industry in chapter 6.

3.2.1 Time and Cost Gain for VP through MBS versus status quo Specialized CAE.

All three Steel Slag Crucible Handlers shown in Figure 3.20 were completed from the design work inception to actual product roll-out in a relatively short period time frame of 9 months clearly proving ***accelerated product customization*** and chiefly ***short product development*** – which is the biggest obvious gain or Return on Investment (ROI) out of the VP approach and work. The 3 months average per machine is a 75% gain in time savings versus previous 1 year product development which simulation/analysis was performed through Standalone CAE (that was contracted out).

In general, VP approach has ensured that the design work-simulation/analysis in the product development process is streamlined, with minimum amount of Physical Prototype/Test needed for these Specialized Heavy Road Vehicles. It should be noted that based on the doctoral project, the most savings for both *time* and *cost,* could be realized in the product development process from reduction of Physical Prototype (also, refer to section 6.2).

3.2.1.1 Zero Prototype – Reduced Development Budget

In fact, for the case of the VP-driven Slag Crucible Handlers, the 3 versions successfully built were the first article with no prototype built. This is an extreme case in new product development process, made possible by *strong product knowledge of mainstream engineers,* instilling confidence when Virtually Prototyping, as the true physical tests for the Slag Crucible handlers were at the customer's site. By engineering and management of uncertainty and variability in the design process brought by the increased product complexity, the upfront VP greatly assist in getting to the 'right' product at the 'right' time, which also translates to tremendous ***reduced development budget*** as a direct result of the reduced Physical Prototype.

3.2.2 High Performing Ground Vehicles – MBS Accuracy, Real World Behavior, and Product Complexity

In 'front loading' the Virtual Prototype to avoid *late design problems*, the work benefit greatly from the numerous 'what if's' simulation/analysis, with the aid of speedy VP processing, while at the same time achieved a 9% accuracy or agreement with test in predicting Slag Crucible handler peak load (Figure 3.21 and 3.22). This is comparable to the accuracy attained by simulation/analysis of KKS (Kansas Knee Simulator, Figure 2.5) – a smaller planar system- simulated through VP counter point and status quo Standalone CAE. Accuracy in turn, also proves that contemporary VP tool can further be used in more elaborate studies, like with Specialized/Standalone CAE.

Other tests and VP works proving accuracy of simulation in capturing real world behavior include more advanced problems of contact-impact phenomena and are listed as follows:

- Falling Object Protection Systems (FOPS) (Figure 3.14)
- Forklift Mast for Specialized Tractor (Figure 3.15)
- Walking Beam bump impact (Figure 3.17)

(refer to Appendix A.3.2 for more detail to the advance problems).

As can be seen through the various ‘front loaded’ MBS Virtual Prototyping works in this chapter, contemporary VP technologies if fully utilized, are capable of solving wide ranging real world problems in ground vehicle engineering, addressing ***product complexity*** and ***real world behavior***(Table 2.3 and 2.4). In addition, VP approach through MBS has allowed for kinematics, dynamics and also static problem to be solved up front in the design cycle, while FEA assist in the structural assessment using the loads exported from MBS. In other words, VP approach has enabled modeling of almost full range of real-life customer usage conditions upfront in the design cycle, thus limiting the risk of any big surprises down the road. This is important as *finding a problem late* (Table 2.4) is expensive, as the farther downstream a problem emerges in the design cycle, the costlier it is to fix (Figure 3.21).

Usually there are a lot of conflicting requirements in ground vehicle engineering in attaining ***high performance***- strength requirement for instance, is expected to bring about increased weight (and typically size also) in products. This is as the VP relates to Table 2.4 in determining:

1) Which design parameters will optimize performance
2) Which trade-off decisions will be best for product performance.

Upfront iterations and the corresponding lessons and digital information (that are *CAD/CAE associated*) from it, trickled down stream in the design cycle, has allowed for only minimal weight increase. Mastering the compromise of these conflicting requirements for the Slag Crucible Handler by fully utilizing features of VP technologies for numerous ‘rich’ iterations early in the design synthesis, have helped the design accomplished an ideal strength-to-weight ratio as evident from a small increase of 5% in overall size and 10% on weight going from 50 to 100 ton version (Figure 3.20). The iterations which are richer especially because of *product savvy mainstream engineers*, also result in ***increased quality*** and ***high performing*** product development. Consequently, improvement is also seen in number of recorded failure (quality related cost) of the vehicle especially in the warranty period (typically 1 year).

Additionally and importantly, the upfront VP iterations through MBS for the vehicles resulted in optimal linkages, joint hard points, and payload positioning and packaging, which have great impact on the Heavy Ground Vehicle as it defines its function, and are discussed in the following Kinematic Synthesis section.

3.3 Virtual Prototyping – Planar Linkage Kinematics Synthesis and Simulation

Innately, kinematic synthesis is a long drawn process, but is clearly demonstrated that it could be accomplished in a timely fashion in this dissertation through the VP approach. By definition, kinematic synthesis entails iterations and the finding of the best possible dimensions for a given type of multibody system – it is mainly a geometrical problem at assembly level. Much has been written about this topic since the 1850’s through the present time, during which period many methods were developed, with big majority of them being graphical and 2D with different degrees of ingenuity and complexity (51).

The kinematic synthesis is completely Virtually Prototyped instead in this section for the Slag Crucible Handlers (as opposed to being performed through Standalone CAE and some combination of 2D graphical method, like in previous developments).

Furthermore, the kinematic synthesis and simulation/analysis through the VP approach brought new insights to the virtual Slag Crucible Handler prototype built, and the realistic 3D graphics also resulted in optimal linkage implement packaging and clearance (Figure 3.7).The kinematics synthesis performed through VP MBS kinematic simulation provides a 3D view of the entire range of the vehicle multibody’s motion – a feature that is enhanced because of *CAE – CAD that are integrated*.

The ground vehicle assembly level solution of the kinematic simulation encompasses velocity and acceleration simulation also, with emphasis on the finite displacement problem - it permits one to detect collisions, study the trajectories of points, sequences of the positions of an element of the different multibody systems, and the rotation angles of bodies on the Slag Crucible Handler vehicle. Of particular interest for the Slag Crucible Handler are the rotation angle and trajectory points of the crucible controlled or manipulated by the hydraulic implement linkage system for optimal slag dumping from the crucible (Figure 3.7).

Since all points in a linkage move in parallel planes, the system undergoes planar motion and may be described as a planar linkage, for the Slag Crucible Handler. Other good example for planar linkage kinematic problem is the single chain crank slider mechanism, which is of simple RRRC type. This type of planar linkage represents major components of piston engines, pumps, and compressors, which are systems also typically seen on ground vehicles (refer to Appendix for more information on joints and linkage for Virtual Prototyping).

However, the Slag Crucible Handler planar linkage is kinematically fairly complex with multiple chain, which makes it impossible to be categorized based on joints (as for the case of one chain RRRC crank slider mechanism) – posing challenges to the VP simulation/analysis. It would also be impossible to solve accurately without the 3D contact technology in MBS (Figure 3.6) and 3D high fidelity graphical environment (to emulate real world gap-contact problem). The complexity of Slag Crucible handler is also apparent when compared to another steel industry material handling vehicle, Rolled Steel Carrier (Figure 2.8 and 4.5).

Figure 3.2 shows some of the typical linkages and joints considered for the Slag Crucible Handler. The main feature of Slag Crucible Handlers is the planar linkages that in turn define the hydraulic implement for the ground vehicle. Essentially, the planar kinematic synthesis of the problems considered are hydraulically driven implement system consisting of linkages and hydraulic actuators (basically an extensible link with cylindrical joint) common in material handling equipments and vehicles (48). The planar linkage defines the function of the Slag Crucible Handler as it is used to transport and handle big and heavy steel slag crucibles - picking it up, dumping the slag content, and dropping it off the vehicle (Figure 3.7).

The problem is demanding heavy duty application with small margin for error and has to work the first time (without a physical prototype), as the first article resulting from the VP design work is the deliverable product. This is an extreme case for ***short schedule*** and ***reduced***

development budget for a product development, where no physical prototype (especially for testing) is developed in a new product market introduction, but instead is completely Virtually Prototyped for design verification, starting at the beginning of design cycle.

VP that is embedded with CAD has helped in accurate definition of geometry for the kinematic synthesis - 3D high graphical environment has allowed for a realistic effective detail investigation of these aspects. Simultaneously, advanced CAD graphical feature in which the view is in 3 point perspective (a visual effect where parallel lines converge in a vanishing point, which is the way real objects are perceived by the human eye or camera), has allowed for some ergonomics assessment for optimal operator’s line of sight. This is a rather unique approach to kinematics synthesis, and the high fidelity 3D CAD effect which is the state-of-the art, has also allowed the Virtual Prototype to meet subjective customer expectation.

Importantly, the realistic 3D CAD/CAE graphics in addition allowed collaboration and cross functional involvement of upper management and customer early in the design cycle, which had resulted in the successful marketing of 2 other variants of the Slag Crucible Handlers - namely 100 ton and 40 ton versions. All done without counter point and status quo Physical Prototype, the early cross functional technical communication is made possible and easier with the highly realistic Virtual Prototype (as it is easier to relate to the final physical product), ensuring a timely, successful, and problem-free product roll-out.

Also, the customization of the variants is made easy as the accumulated Virtual Prototype digital information (containing both design and simulation data) is carried over and utilized from the baseline 50 ton Slag Crucible Handler, demonstrating not only capability for **shorter product development** on an aggressive scheduling, but also an **accelerated product customization** benefit of Virtual Prototyping approach.

Further, the iterations during the kinematics synthesis process through VP has facilitated in ‘getting to the right idea’ faster, and reduced the amount of iterations needed as compared to 2D graphical methods. The amount of critical iterations in the kinematic synthesis for the Slag Crucible Handler is around 5 times, which is the amount of major iterations typically encountered in the industry 44% of the time (Figure 3.5).

Other details on VP approach through MBS for the Heavy Ground Vehicle are included in Appendix A (which include more advanced problem in Appendix A.3), and listed as the followings:

A. Detail of Virtual MBS
- A.1 MBS Methodologies
  - A.1.1 Virtual Links
  - A.1.2 Virtual Joints
- A.2 Virtual Dynamic Problems
  - A.2.1 Quasi Static
  - A.2.2 Inverse Dynamic Problem
  - A.2.3 Shake Down and Instrumented Testing
- A.3 Dynamic Motion Sensitivity
  - A.3.1 Idealization and Imperfect Joints
  - A.3.2 Impact and Impulse.
    - A.3.2.1 FOPS for Specialized Shunter Tractor (Figure 2.13 and 3.13).
    - A.3.2.2 Forklift Mast for Specialized Tractor (Figure 2.12 and 3.15).
    - A.3.2.3 Walking Beam Suspension for Slag Crucible Handler (Figure 3.17).

3.4 Attributes of VP Approach through MBS

Attributes of the Table 2.1 framework for the VP approach trough MBS, as it relates to ‘winning approaches’ and ‘best practices’ for this chapter are summarized below:

1) Early CAE by mainstream product savvy and experienced engineers

i) Ensure accurate setup of the problem (knowledgeable about the physics, use of the right element and how different components interact with each other and etcetera).

i) Assist in upfront speedy iterations imbued with product knowledge.

ii) Accuracy combined with product knowledge will allow for reduction of physical test. Strong knowledge and past experience instill confidence and would even eliminate the need for prototype altogether as clearly demonstrated by the 3 VP-driven Slag Crucible Handler products.

iii) Allow for educated simplifications in this chapter for MBS which include:

- Links – rigid body assumptions
- Idealized joint neglecting real world tribology effects.

Educated simplification is important in avoiding ‘garbage-in, gospel-out’ scenario.

Simplifications in more advance contact-impact problems include:

-Tire elastomeric element modeled as bushing to study suspension design bump impact (refer to Appendix A.3.2).

Hierarchical fidelity introduced into the Virtual Prototype would eventually result in robust products as design and response variables relation are more understood.

2) CAD integrated CAE

i) Allow for speedy iterations in familiar design environment for ease of Virtual Prototype setup.

ii) CAD associated data permits rapid product customization indicating its usefulness in future product development as in the case for the 3 versions of Slag Crucible Handler.

iii) Data is reusable going from CAD to CAE and vice versa, saving time in model creation. This is especially useful with design update cycles in the iterations, as kinematic synthesis (an inherently time consuming process) is sped up, demonstrated with the great time savings in the Slag Crucible Handler.

iv) CAD integrated simulation with its familiar design environment, is conducive to early simulation/analysis in the design cycle among engineers.

v) Accurate definition of geometry especially important for the kinematics synthesis.

vi) Realistic graphics assist in cross functional involvement from the beginning of design cycle, as the Virtual Prototype is easily related to the final physical product. In fact for the Slag Crucible handlers, it assisted in successful marketing of other variants.

- In the case for MBS, 3 point view/perspective has extended the kinematics study into an ergonomics study for human factors.

In this doctoral project, because of the advantages brought by these attributes, VP approach through MBS has resulted in *rapid* and *lean* Virtual Prototyping of kinematics and dynamics problems resulting in3 different versions of *high performing* Slag Crucible Handlers.

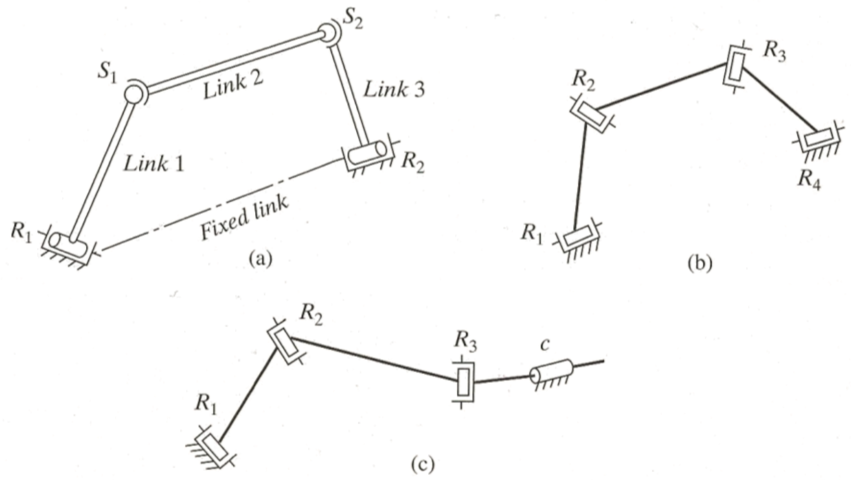


Figure 3.1. Example of linkage system. (a) An RSSR linkage (2 DOF). (b) An RRRR linkage. (c) An RRRC linkage. In the general case, no relative motion is possible in closed loop RRRR and RRRC linkages (48).

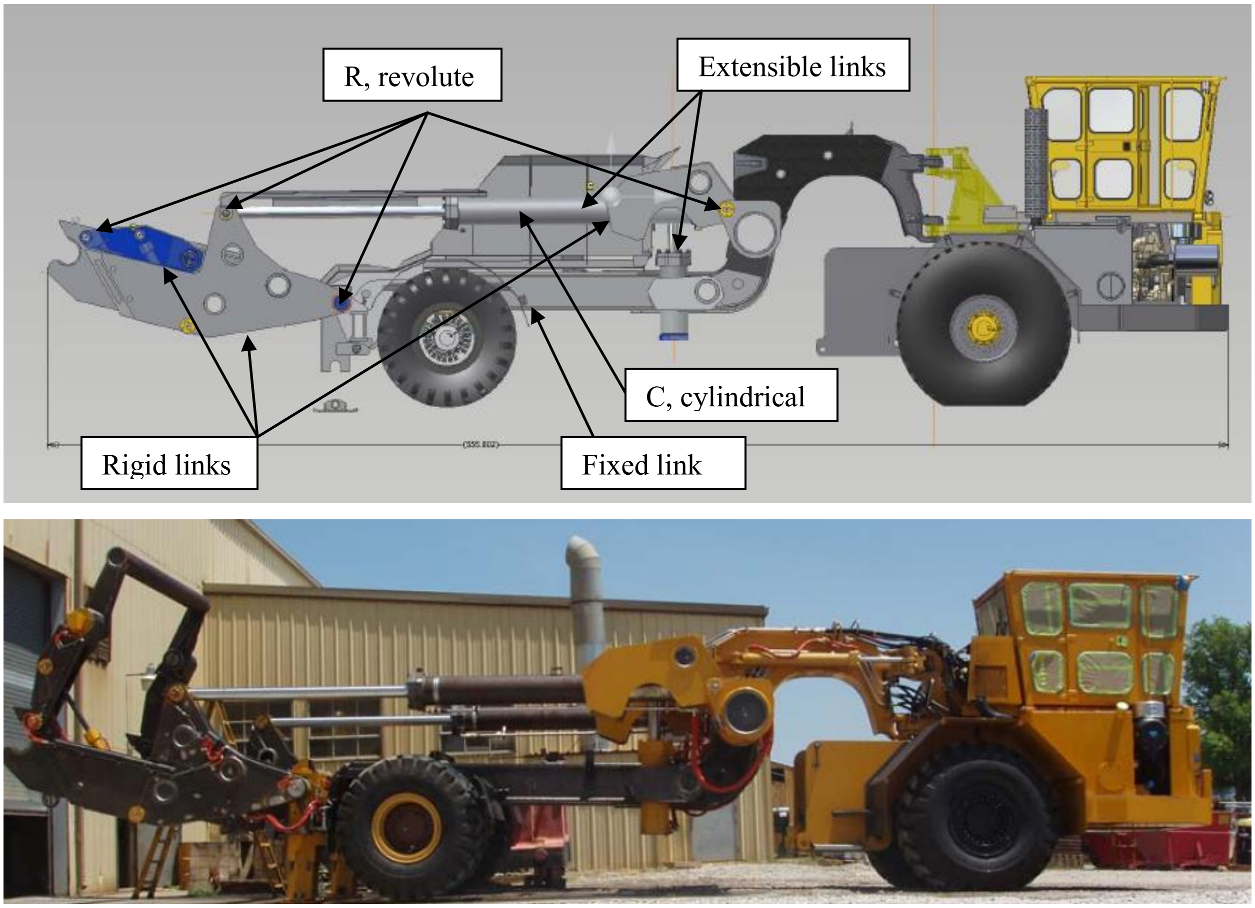
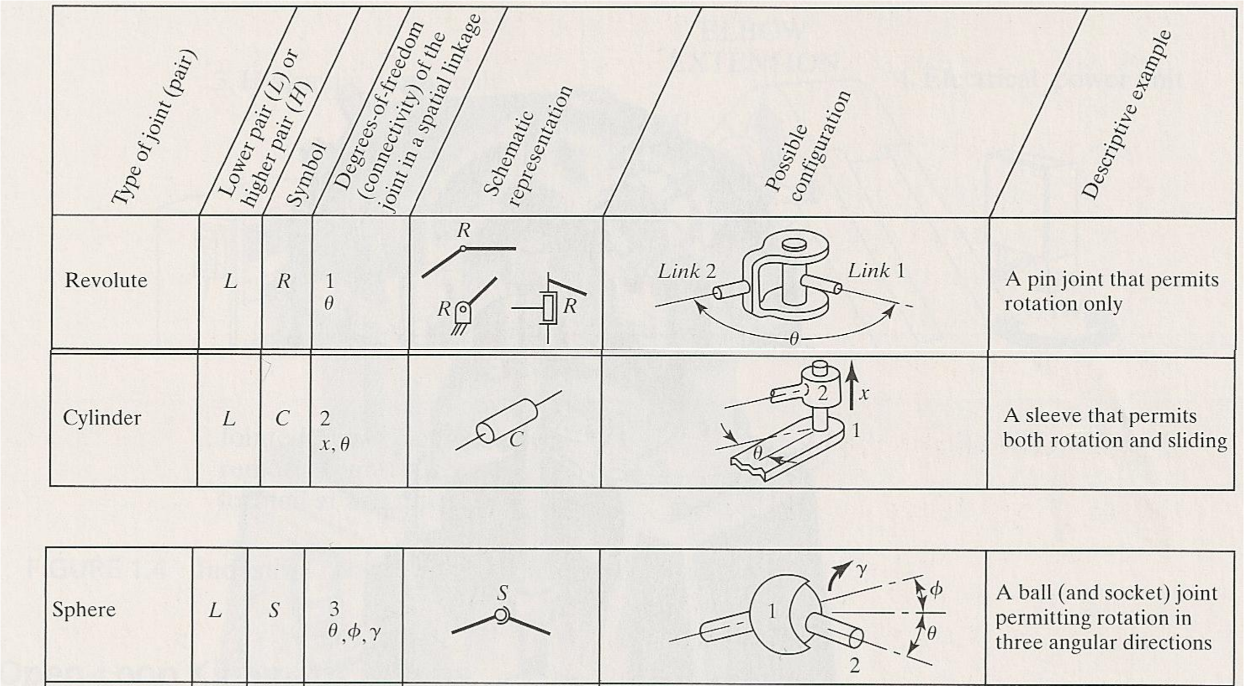


Figure 3.2. Simplified graphical representation of multibody links and joints (top), and the links and joints on Slag Crucible Handler with the linkage deployed and open (bottom).



Type of joint (pair)	Lower pair (L) or higher pair (H)	Symbol	Degrees-of-freedom (connectivity) of the joint in a spatial linkage	Schematic representation	Possible configuration	Descriptive example
Revolute	L	R	1 θ			A pin joint that permits rotation only
Cylinder	L	C	2 x, θ			A sleeve that permits both rotation and sliding
Sphere	L	S	3 θ, ϕ, γ			A ball (and socket) joint permitting rotation in three angular directions

Figure 3.3. Various different types of joints (48) .

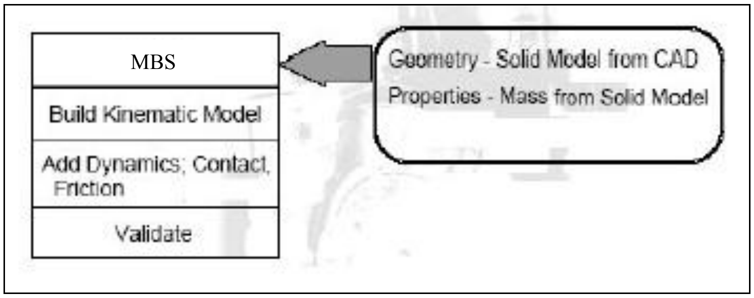


Figure 3.4. Typical workflow in MBS as a part of VP (1).

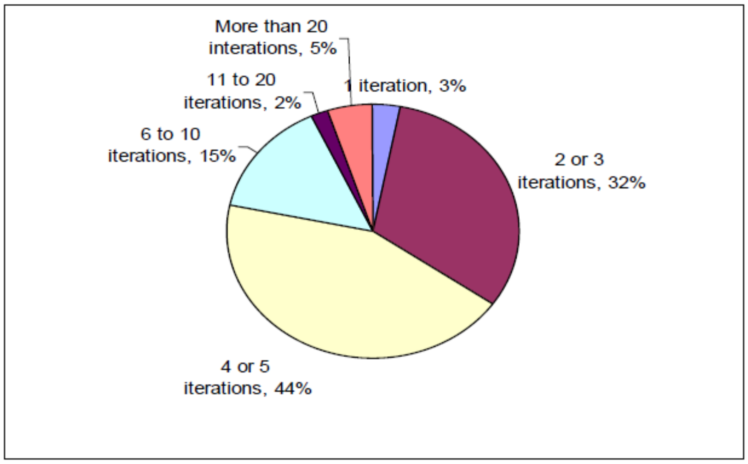


Figure 3.5.Design iterations before release (45).

MSC SOFTWARE

MSC.Dynamic Designer

Motion Professional for Inventor(TM)

What's New

This version of MSC.Dynamic Designer/Motion Professional includes important new features and enhancements to improve your experience with the software and increases the power you need to solve your design problems.

·Improved Online Help

·Improved Interference Check

·Improved 3D contact

·MSC.ADAMS/Solver

·Redundant constraints report

·Orthotropic Bushings

Figure 3.6.New improved 3D contact technology used in MBS and orthotropic bushing/elastomer that benefitted the Virtual Prototyping work (14).

Figure 3.7. Crucible being rotated in kinematic study and synthesis in 3 point perspective through high fidelity CAD environment – a unique approach to kinematic synthesis problem.

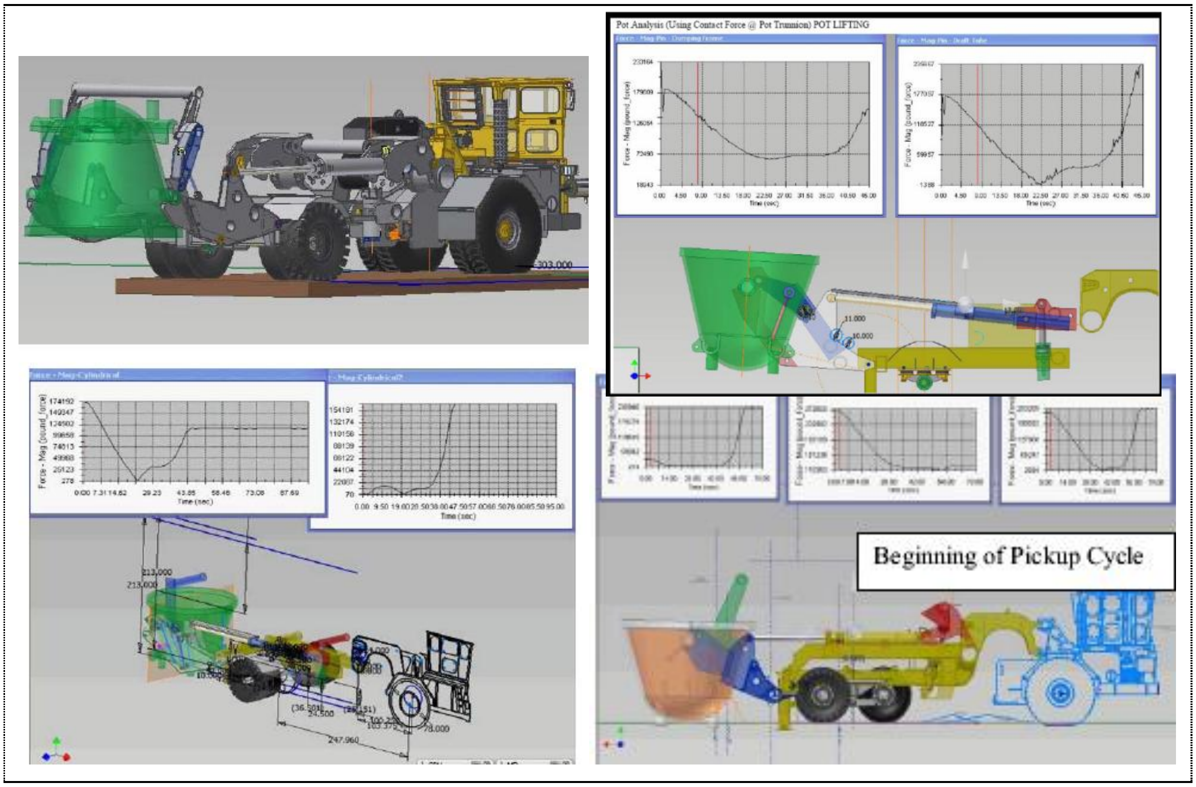


Figure 3.8. Various dynamic simulations performed and 'up and front loaded' at different stages of design cycle on the different versions of the vehicle.

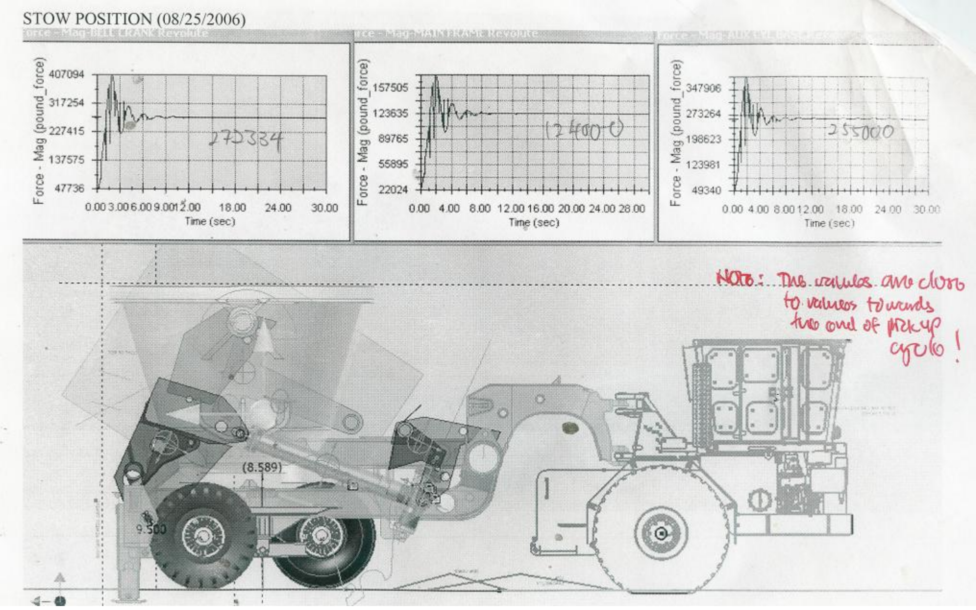


Figure 3.9. Quasi static problem considered for the Slag Crucible Handler.

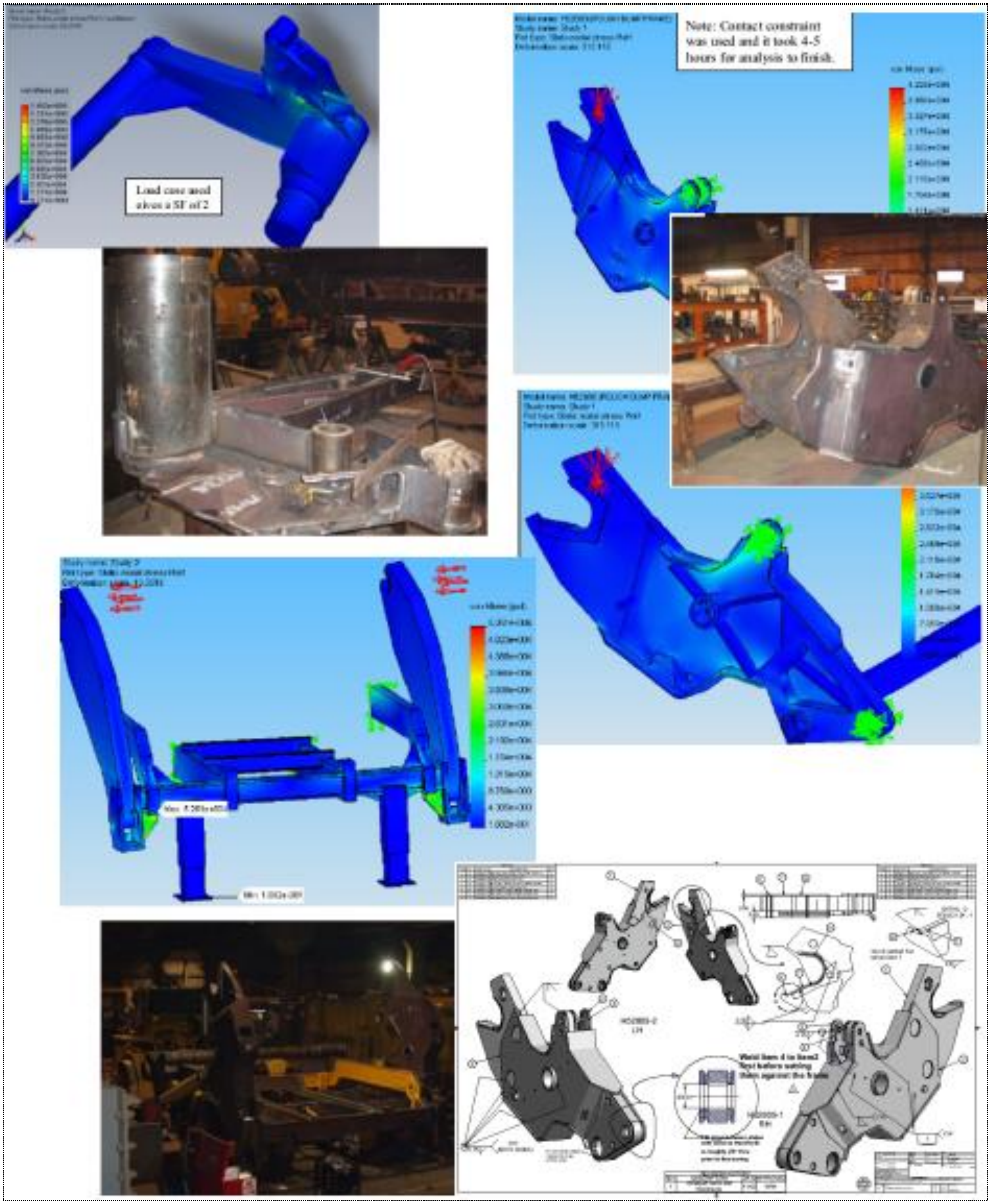
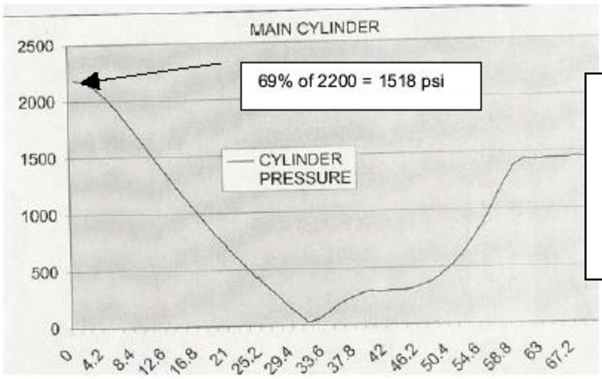


Figure 3.10. Various components of the Specialized Vehicles analyzed for structural studies (through FEA – Cosmos) using load generated from MBS.

Bourbon gage for pressure reading

Highest reading on the Bourdon gage as the test weight is lifted at 1650 psi



Note: Tested at 69% capacity. Can not test at 100% payload because of the mock up weight geometrical constraint.

View from operator's cab during testing

Operator looking at pressure reading

Note: Only tested at 76000 lbs or 69% capacity (full capacity of 110 kips or 50 metric ton) because of the mock up weight geometrical constraint.

Machine in position for test setup with 2 x 38000 lbs mockup weight.

Figure 3.11. Pictures and data taken during the instrumented test and shake down for the special vehicles.

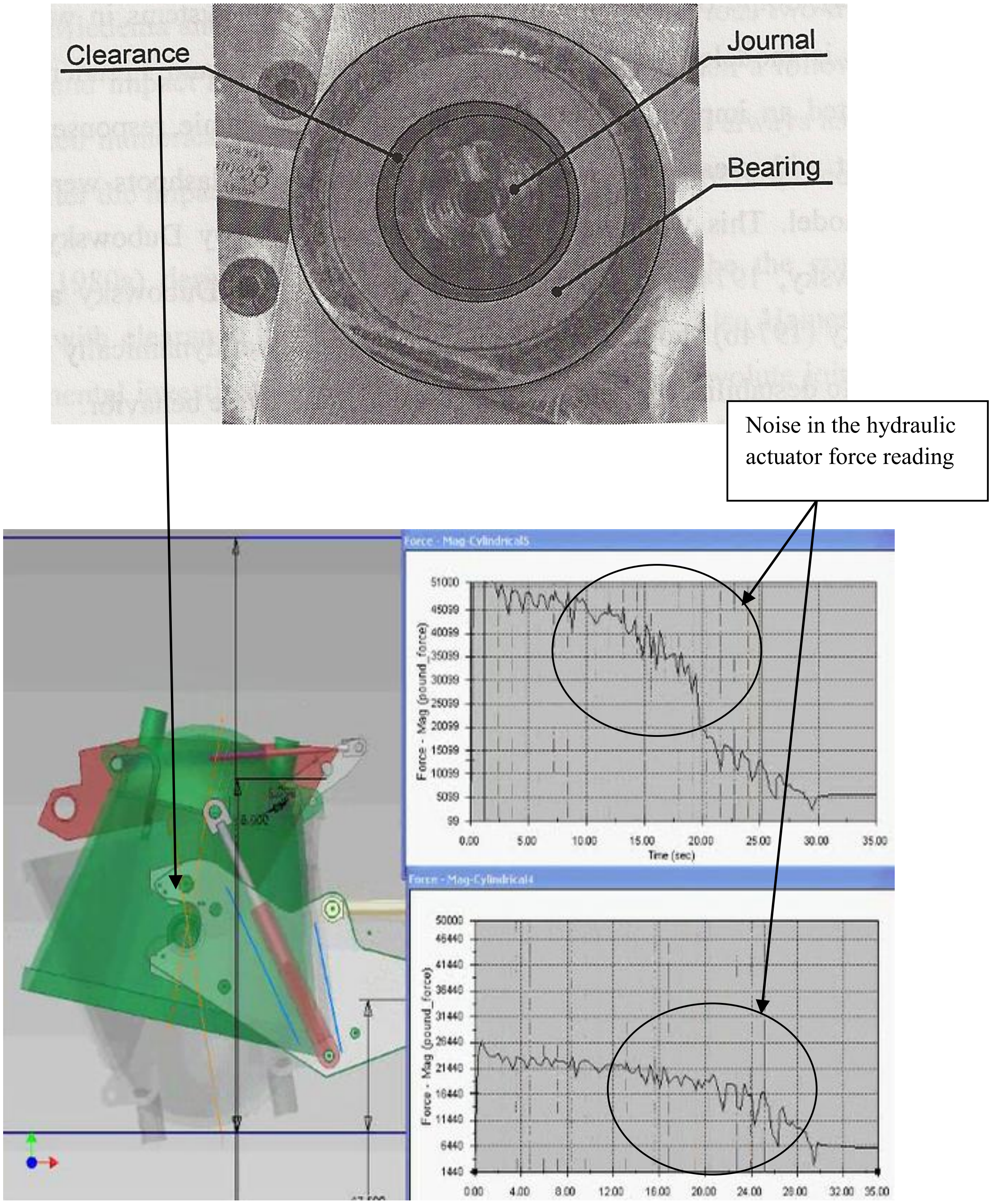
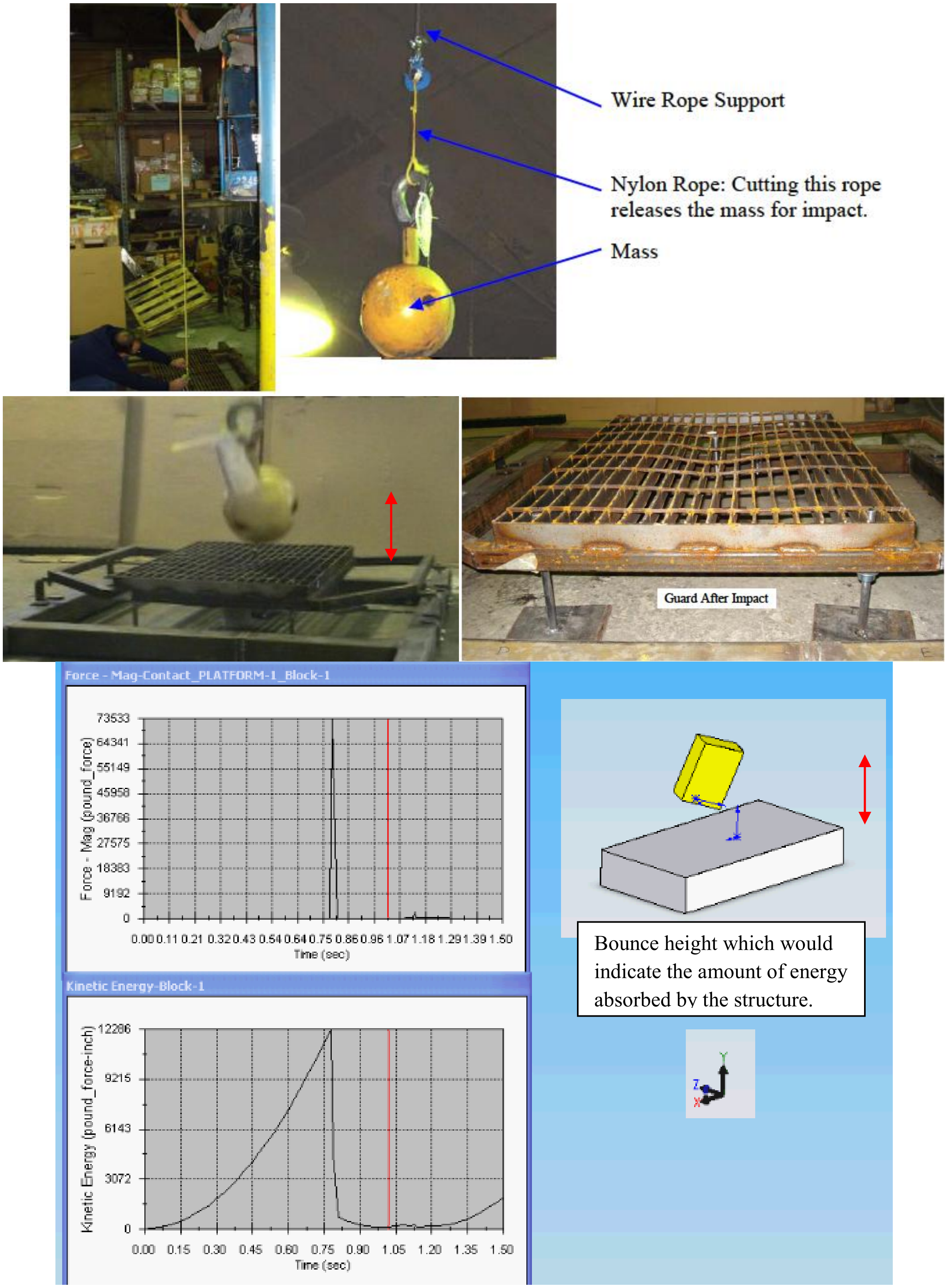


Figure 3.12. (top) Revolute Joint with clearance. (bottom) Gap-contact and Contact-impact phenomena due to the clearance in Slag Crucible Handler.



Wire Rope Support

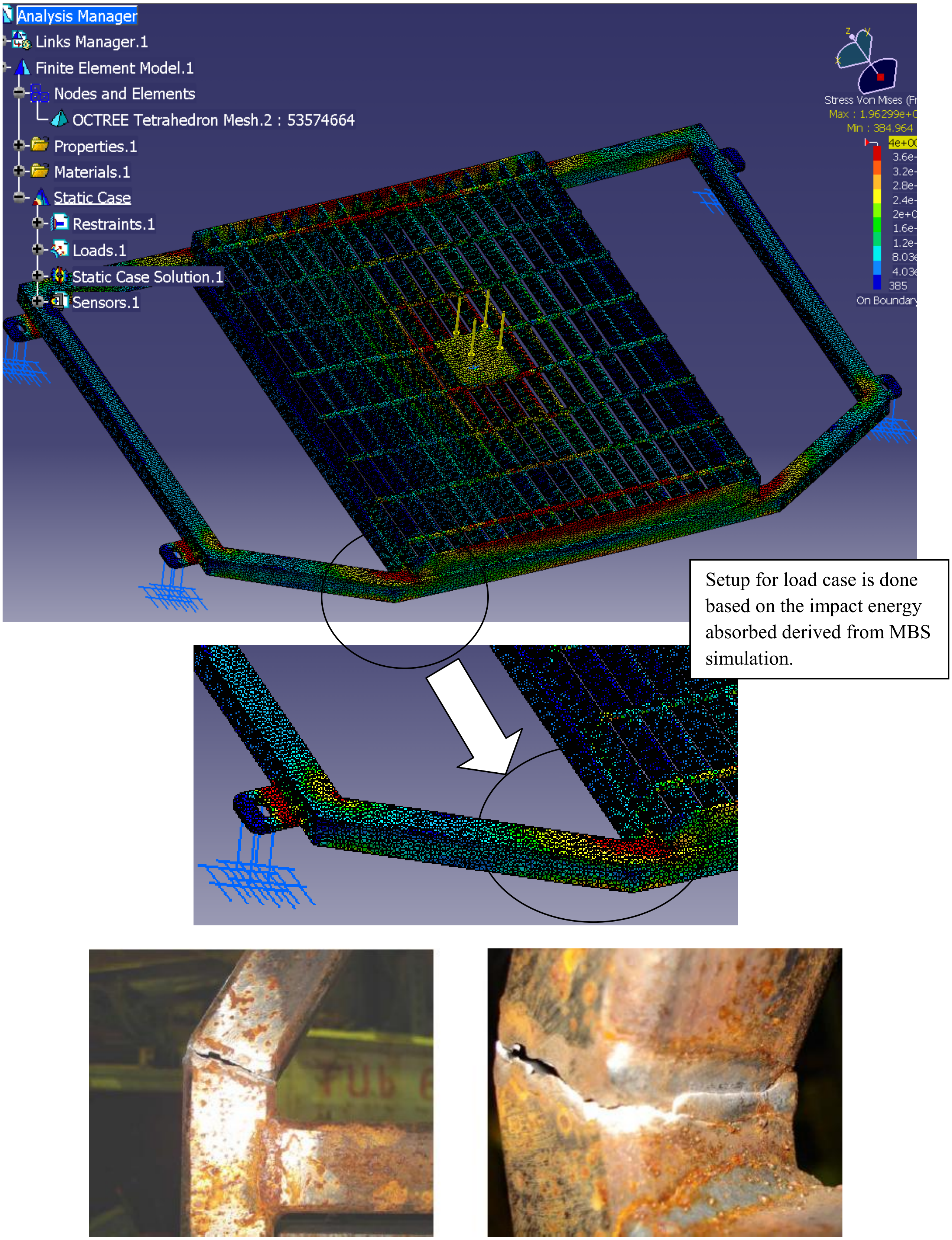
Nylon Rope: Cutting this rope releases the mass for impact.

Mass

Guard After Impact

Bounce height which would indicate the amount of energy absorbed by the structure.

Figure 3.13. Dropped object test and simulation for Falling Object Protection System (FOPS) for the Specialized Shunter Tractor (Figure 2.13.)



Setup for load case is done based on the impact energy absorbed derived from MBS simulation.

Figure 3.14. FEA structural and failure study (through LMS/CATIA Elfini solver).

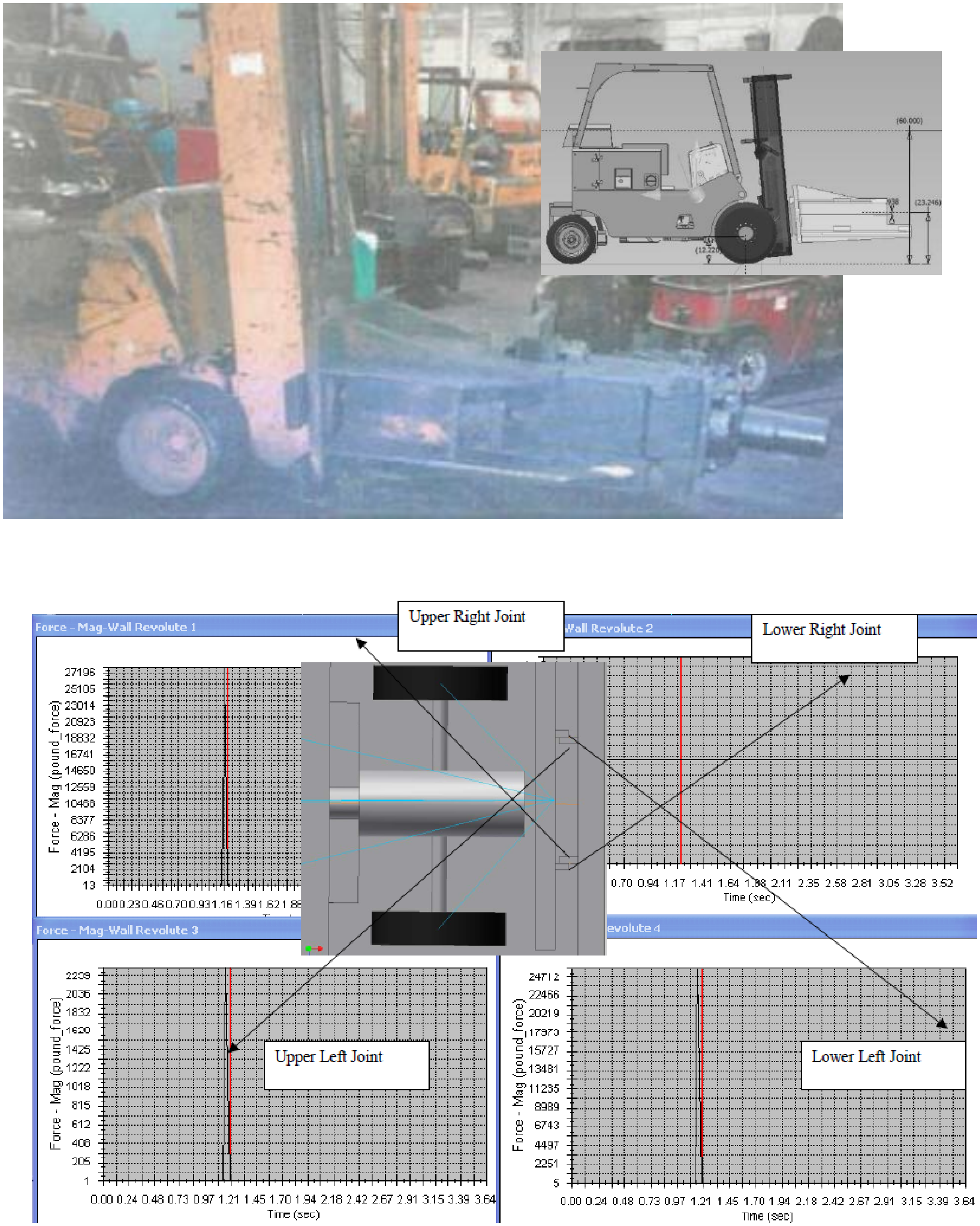
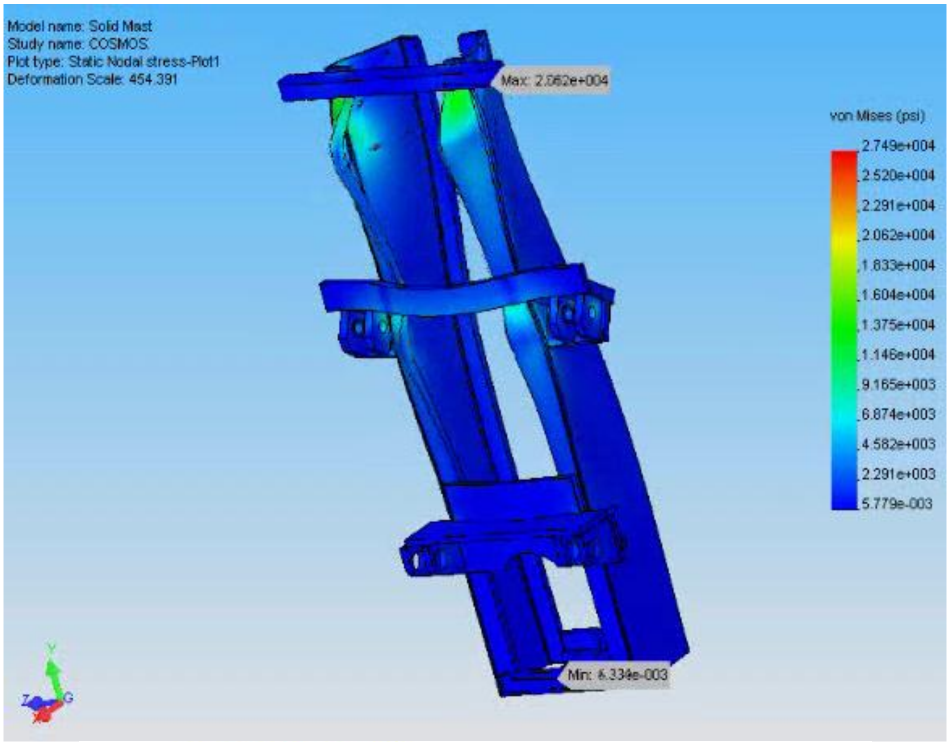
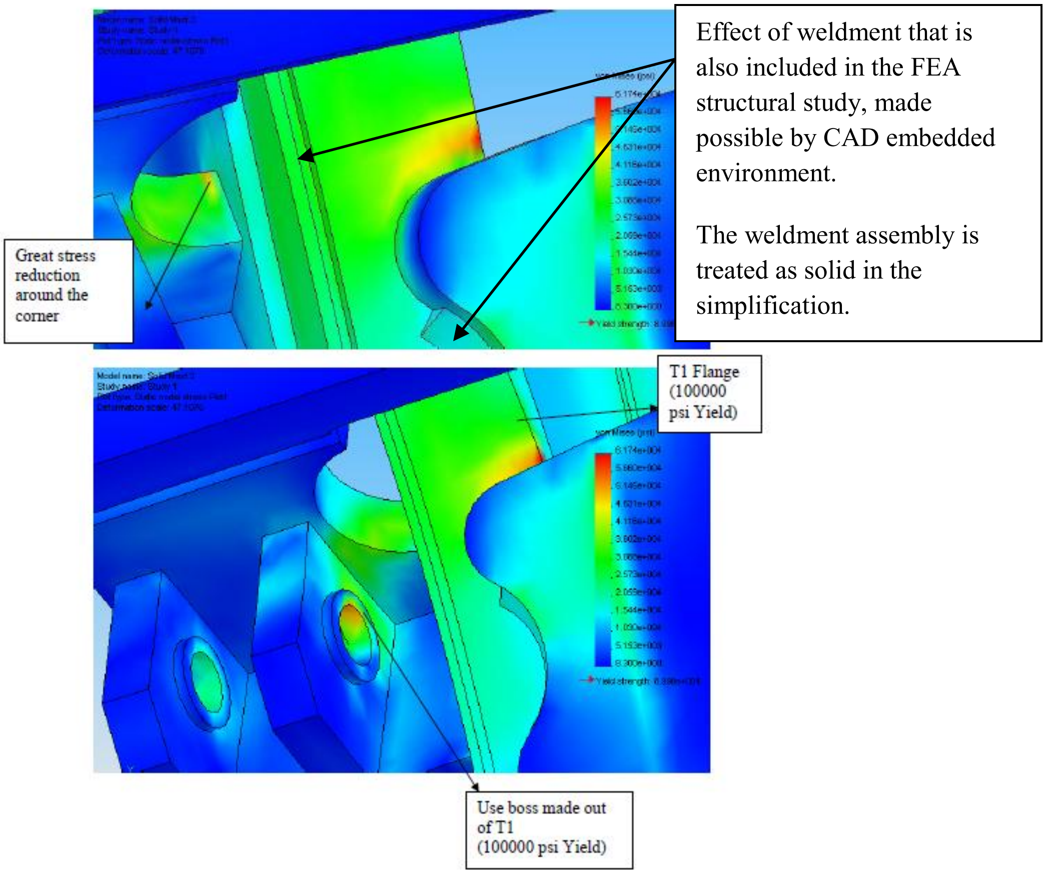


Figure 3.15. Battering hammer subjecting the forklift mast on the tractor to impact and its simulation.



Detail Study on High Stress Area



Effect of weldment that is also included in the FEA structural study, made possible by CAD embedded environment.

The weldment assembly is treated as solid in the simplification.

Great stress reduction around the corner

T1 Flange (100000 psi Yield)

Use boss made out of T1 (100000 psi Yield)

Figure 3.16.Structural assessment of the mast frame subjected to impact load (FEA through COSMOS).

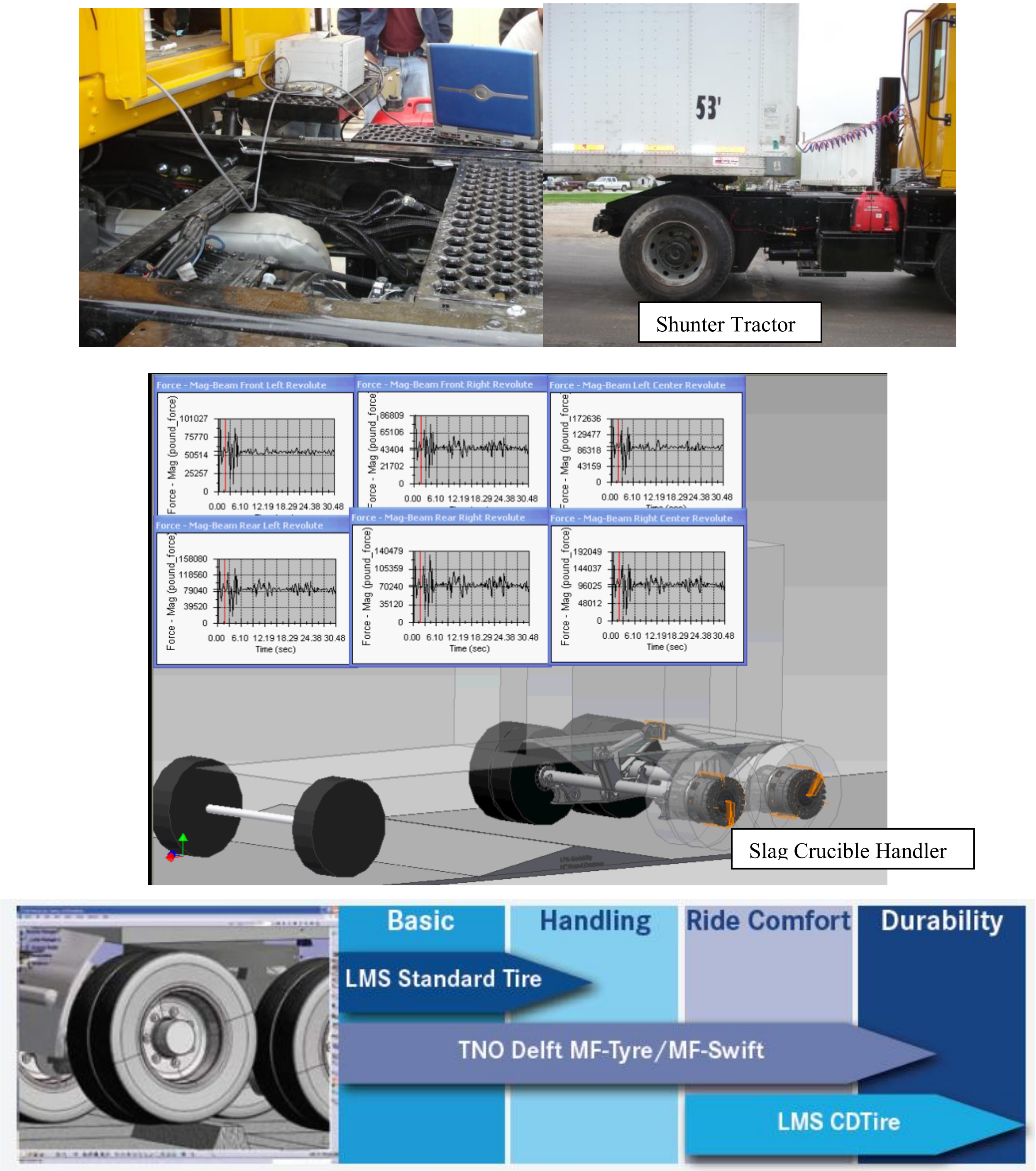
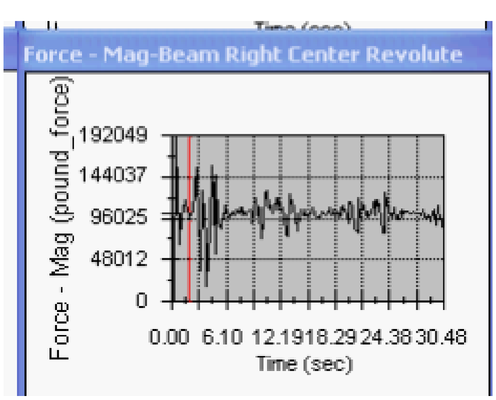
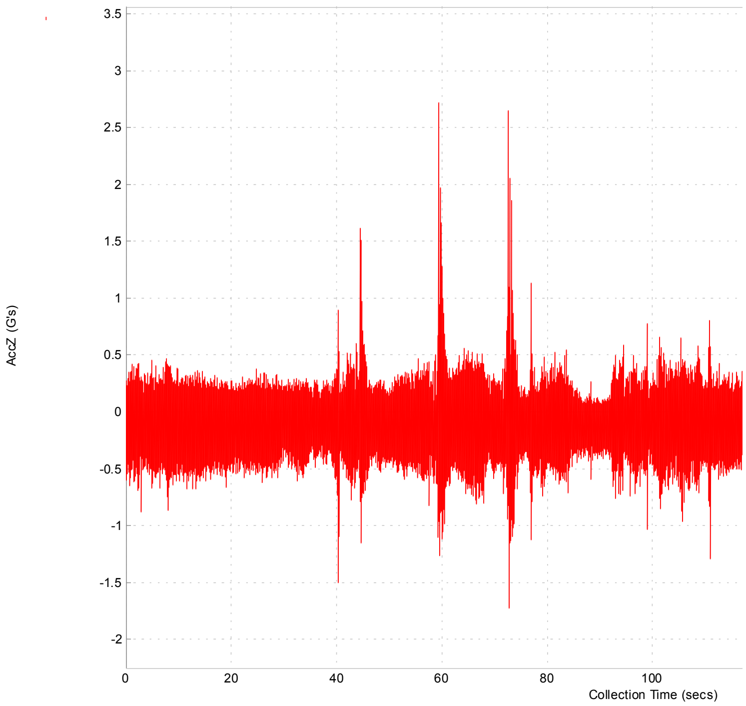


Figure 3.17. Walking Beam axle simulation and Single Beam axle test (top). Different tire models providing versatility and scalability for simplified or hierarchical simulation (2) (bottom).

2g versus 2.5 g peak acceleration between Slag Crucible handler (Walking Beam-simulation) and Shunter Tractor (Single Axle–test) .





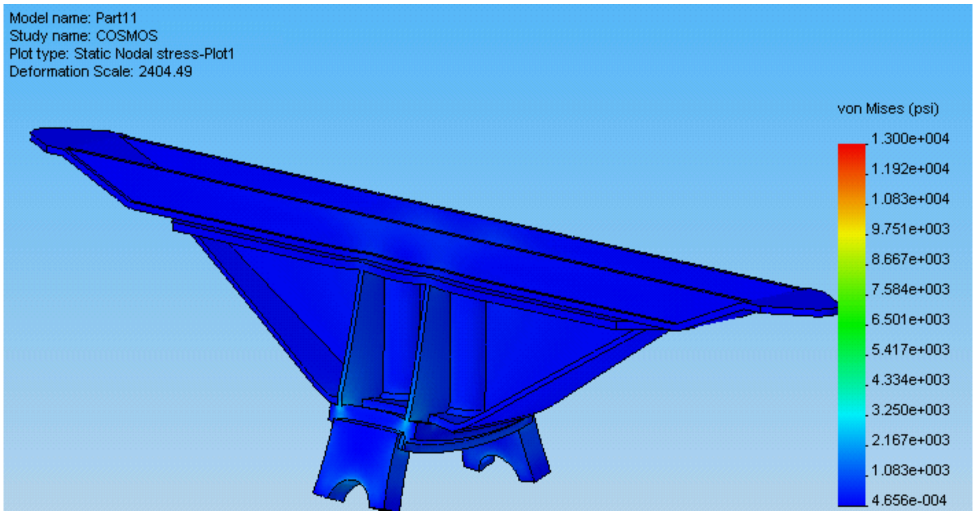
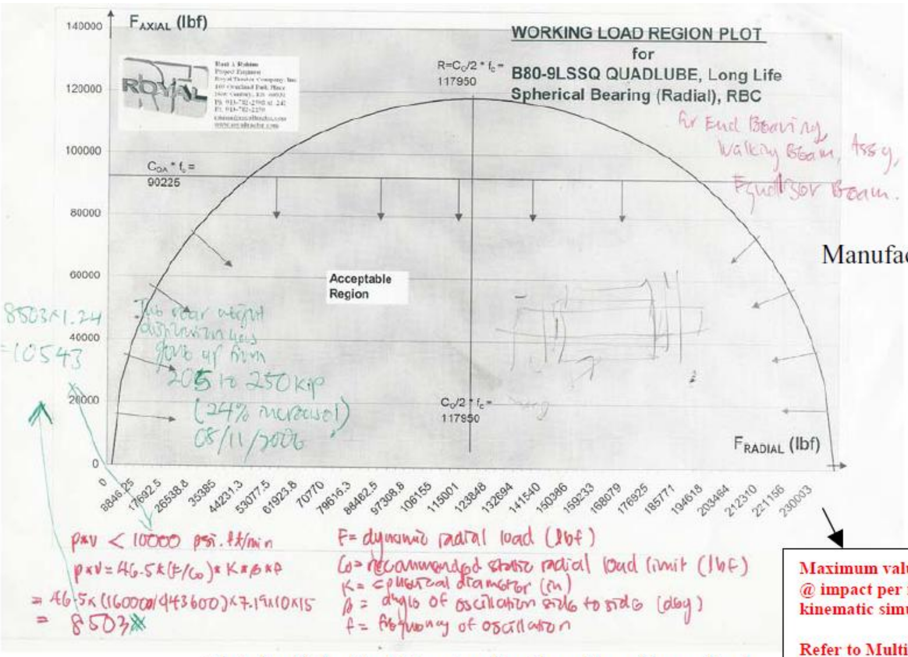

Model name: Part11
Study name: COSMOS
Plot type: Static Nodal stress-Plot1
Deformation Scale: 2404.49

Figure 3.18. Impact load simulation-test comparison (top). FEA on Slag Crucible handler Walking Beam axle mount subjected to impact load (bottom).



Manufacturer SF is 1.5

Maximum value of 240 lbf @ impact per inverse kinematic simulation.

Refer to Multibody Motion Simulation for more detail.

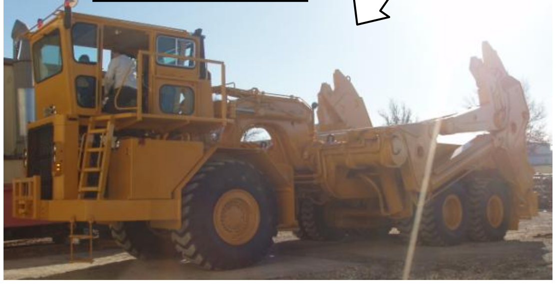
Plot for Spherical Bearing for Equalizer Beam Ends

Figure 3.19. PV(pressure-velocity) characteristics for tribology studies and specification.

50 ton Steel Slag Crucible Handler (base design).

Higher payload

Smaller payload



100 ton Steel Slag Crucible Handler

40 ton Steel Slag Crucible Handler

Figure 3.20. Various configurations of Steel Slag Crucible Handle, which are all fist article deliverable to the customers.

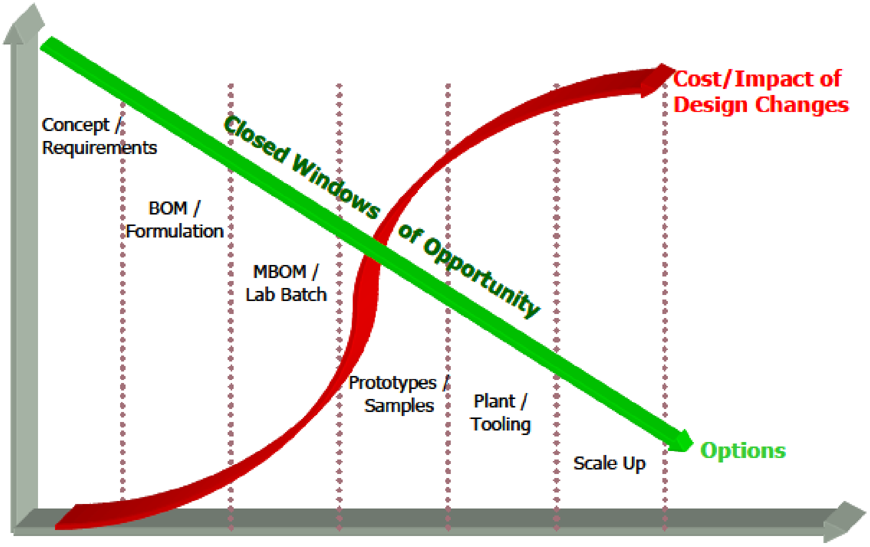


Figure 3.21. Impact of design change over time (1).

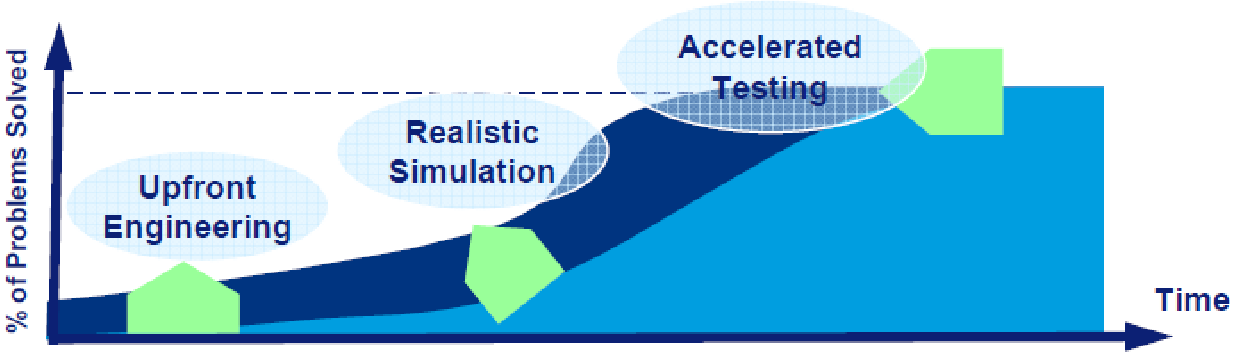


Figure 3.22. Comparison between upfront simulation, realistic or specialized simulation and accelerated testing(2).

4. VIRTUAL VEHICLE STRUCTURAL LOADING

4.1 Virtual Prototyping Approach for Structural Loading and FEA.

Table 2.1 Framework of Doctoral Project's Virtual Prototyping Approach

Virtual Prototyping Approach	Attribute
Upfront design-integrated simulation/analysis (through MSB and FEA).	Speedy and early CAE iterations by mainstream product savvy and experienced engineer(s)
	3D CAE that is CAD integrated (embedded or associated)

Emphasis of the VP approach (shown in Table 2.1 framework) in this chapter is primarily through FEA, to simulate/analyze Heavy Ground Vehicle product's structural response when subjected to real world environment load cases. Principally, the framework is proposed to result in *timely*, and *economical* product development process (which include VP through FEA), producing *high performing* Heavy Ground Vehicle products. The important gains are then quantified (in section 4.2) to objectively compare it directly to status quo Physical Prototyping/Test (versus status quo Standalone CAE in Chapter 3, as the two are main counterpoints to the proposed VP approach).

Based on the doctoral project investigation, the proposed VP Table 2.1 framework through FEA (despite involving a time consuming process like meshing, Figure 4.8), is found to address the seemingly conflicting *high product*, and *short development schedules* and *reduced cost* demands for the following 2 specific problems considered in this chapter – 1) Static, and 2) Durability/fatigue (dynamic).

2 additional important findings during the doctoral project investigation that has bearing on the VP approach through FEA are that:

1) Current processing speed for coupled MBS-FEA would increase simulation/analysis time up to tenfold. Just as effective, MBS load cases can be exported for FEA.
2) VP approach do not necessarily have to compete with Physical Prototyping/Test, as there is synergy in which the two processes can greatly complement each other in design validation.

These investigations and 'best practices trade studies' for VP through FEA simulation are focused on the bogie frame (the main structural component of Rail Ground Vehicles, Figure 4.9 and 4.10). Other works reported on also, involved FEA using MBS generated loads for Slag Crucible Handler vehicles in Chapter 3, which ensured accurate load cases setup. MBS simulation/analysis is also performed on the Rail Vehicle, but late in the design cycle through Standalone CAE, and reported in Chapter 5 (which covers other more extensive VP approach main counter points). The structural VP simulation/analysis works from which 'winning approaches' were drawn from, permits myriad of 'upfront' what-if iterations that would have otherwise been difficult, if not impossible to implement with Physical Prototype/Test.

Before simulation/analysis, in classical method, structural engineering problems lend themselves to simplifying assumptions and approximations which allow the problem to be recast into a formulation for which a direct and closed form solution is available. Hundreds of common geometries, loading, and fixity configurations have been tabulated, allowing a "plug and chug" method where some known values are entered to determine an unknown result be it stress, or flexible deflection/compliance. However, in addition to being manually laborious, classical method is limited to simple problems and serious difficulty arises once the geometry becomes complex and the nature of assumptions or approximations become impractical.

FEA technology that is used in this chapter to completely Virtually Prototype ground vehicle structural problem upfront (Figure 4.8 and based on Table 2.1), in comparison, is also a 'plug and chug' method, but a virtual, batch processed, and 'divide and conquer' version to the increasingly complex structural problems. FEA underlying numerical modeling methods in CAE essentially break down intractable large problems into a collection of inter-related smaller, simpler (meshed elements) and thereby, solvable problems. When taken together, after being meshed (a process that is time consuming but improved with *CAD-CAE integration*), the smaller problem closely approximate the original problem (Figure 4.4), which today, mainly because of computer processing speed allow for 'front loading' and *early iterations by knowledgeable engineers* of 'new' design development through Virtual Prototyping, and investigated on in this section, first hand (refer to Appendix B for more detail on Virtual FEA).

In assessing structural aspects of a design, elaborate Physical Prototype/Test on the other hand, are usually suited to a more established configuration rather than 'new' ground vehicle development which is a much more iterative and repetitive process. Also, depending upon the type of the problem, testing often leads to revelations of ‘what happened’ (making it more suited for top-down, after-the-fact studies), but not necessarily ‘why it happened’, as can be expected with Virtual Prototyping simulation/analysis.

Usually a high degree of planning is needed and proper design of the experiment for Physical Prototyping/Testing is critical to gleaning as much understanding of the nature of the problem as possible (Appendix C; Section C1). In extreme cases, the test development might take as much time as the product development itself as was the case seen in the doctoral project.

4.2 Objective Comparisons for Virtual Vehicle FEA Structural Problems

The main hypothesis for this dissertation is once more established in this chapter, specifically for ground vehicle structural assessment, that VP approach (as in Table 2.1 framework, through FEA) would address the industry’s (non-mutually exclusive) pressure factors/demands faced in today’s industry and ground vehicle product development project. The findings and results with regard to these pressure factors are specific to Heavy Ground Vehicle structural studies, in this chapter. Listed in Table 2.4, some (4 out of 5) of the factors as they relate to this chapter for structural assessment are:

i) shorter product development (aggressive scheduling and by far the greatest factor)
ii) reduced development budgets
iii) increased product complexity
iv) increased quality-related costs (warranty, and etc.)

The general premise of these seemingly conflicting pressure factors to the product development process is to build *high performing* products *faster* and at *lower cost*. Below are further breakdown of some (2 out of 5) of the challenges, strongly applicable to this chapter in arriving at *high performing* Heavy Ground Vehicles, based on Table 2.4:

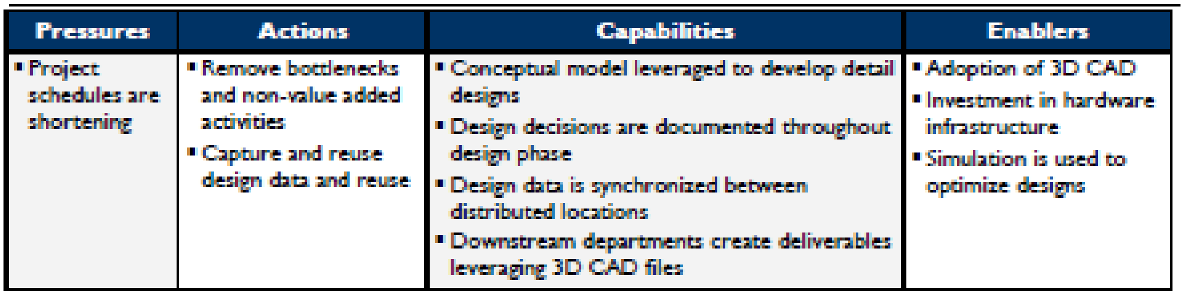
a) Predicting product behavior in a real world environment
b) Finding problems/errors late in the design cycle

In comparison to VP through FEA, as deduced from the doctoral project, Standalone CAE and Physical Prototyping/Test for ground vehicle product structural assessment will not be capable of addressing these conflicting factors without the expense of increased cost and time.

These conflicting pressure factors, as they are simultaneously addressed by the VP approach, will be highlighted in the following sections in this chapter and are discussed.

As it relates to the FEA VP work in this chapter, Table 4.1 is highlighted, as a business matrix that gives a broad overview and elaboration on actions, capabilities (business property), and also enablers adapted by the Best-in-Class in the industry to address *shortening project schedule* (as the main pressure factor).The matrix also reflects the characteristics of the actual ground vehicle engineering process considered for the doctoral project in this chapter - shown as an enabler, investment in hardware has further improved processing speed of VP through FEA (MBS in Chapter 3 however, is not as demanding as FEA when it comes to computing power).

Table 4.1 Best-in-class PACE (Pressure-Actions-Capabilities-Enablers) framework



Pressures	Actions	Capabilities	Enablers
▪ Project schedules are shortening	▪ Remove bottlenecks and non-value added activities ▪ Capture and reuse design data and reuse	▪ Conceptual model leveraged to develop detail designs ▪ Design decisions are documented throughout design phase ▪ Design data is synchronized between distributed locations ▪ Downstream departments create deliverables leveraging 3D CAD files	▪ Adoption of 3D CAD ▪ Investment in hardware infrastructure ▪ Simulation is used to optimize designs

Source: Aberdeen Group, August 2009

On the other hand, the Physical Prototype/Test performed for Rail Bogie frame for structural assessment in terms of stress and durability is highly complicated, involving higher investments on hardware like computers for data acquisitions on hundreds of input channel (refer to Appendix C and D). The hardware for the physical test setup (fixtures, jigs and etcetera) are also involved, which in fact, have to be Virtually Prototyped first to ensure a problem free setup and actually taken more time than the product development time itself. Moreover, it was demonstrated that a physical test can easily be a major bottle neck in product development cycle, in terms of *time* and *cost*, especially without proper planning.

4.2.1 Time and Cost Gain for VP through FEA versus status quo Physical Prototyping / Testing.

In this chapter, FEA VP approach is directly (‘design validation process’ taken as a part, not a collective part of product development process) compared to its counterpoint, Physical Prototyping/Test (as compared to Standalone CAE in Chapter 3. Further comparisons are done in

Chapter 6 to results seen in the industry). The followings are the quantified gains based on the doctoral project:

4.2.1.2 Shorter product development (key pressure factor/demand)

In line for being the key factor/gain, positively, as for the case of Virtual Prototyping of Rail Vehicle Bogie, FEA work for 'virtual test' in assessing product's structural aspect, from planning to the final phase took about 2-3 months as opposed to the planned 6-8 months for physical test (including tooling development time, refer to Appendix C and D). In actuality, the physical test had surpassed the anticipated time of 6-8 months, and took over 1 year to complete – this is longer than the actual product development time itself.

Extension to FEA when doing durability studies also proved to profoundly affect the time savings even when compared to 'accelerated ' physical durability test (6 million load cycle which took 1-3 months to complete, used to simulate 45 years of design life), as time taken is greatly reduced from being in terms of months to merely days, for physical and virtual test respectively. Refer to Appendix B.2 for more detail on Durability VP.

As can be seen from the test plan Gantt Chart, the scheduling is extensive for the Physical Test, for both durability/fatigue and static test (Appendix C). With a greater role by Virtual Prototyping for design validation, among other benefits, considerable **time advantage** can obviously be gained in the product development process.

4.2.1.3 Reduced development budget

Cost savings are evident, which are in the order of $50 000 (billable hours) for FEA Virtual Test versus $500 000 (contract cost) for Physical Prototype/Test for both structure and durability studies, which greatly contribute to overall **reduction of product development budget**.

4.2.2 High Performing Ground Vehicles – FEA Accuracy, Real World Behavior, and Product Complexity

The ability of upfront VP through FEA to solve the system level cast Rail Bogie frame design with complex shape (as it needs to be modeled using advanced CAD surfacing technology) and multitude of boundary conditions and load points, demonstrate the ability to address **increased product complexity** in design. Accuracy of FEA virtual setup (load cases and boundary conditions) is also ensured when it could automatically be generated through MBS (because of *CAD-CAE and between CAE integration*), despite the product complexity, as exemplified by Virtual Prototyping of Slag Crucible Handler and Rolled Steel Handler (in chapter 3). MBS generated loads also saved time as the need for time consuming Free Body Diagram for FEA is avoided.

Product customization for the design, based on customer requirements (Rail Vehicle bogie frame weight reduction with increased payload and etcetera) is also addressed through VP in an accelerated manner, as the 3D virtual prototype data (containing both design and simulation data, made possible by *VP-CAD associativity*) at one design phase to the other is reused (and not wasted), and at the same time optimized. The 3D data (easily relatable to the final product) also assisted in cross functional involvement and communication (with executives and sales/marketing) in the product's early design cycle, further ensuring an efficient and timely product roll out.

As demonstrated by close and highly repeatable correlation with test as in the case for the bogie frame (refer to Appendix D), the accurate and extensive VP through FEA, which is made 'rich' by *product-savvy engineers* ensured an ideal strength-to-weight ratio resulting in **increased quality** and *high performing* product. Test that was done as a follow up investigation, showed a strong correlation within ±13% (fine-tuned, refer to section 4.5) when compared to readings of around 20 instrumented strain gages with up to 27 different load cases, indicating high **accuracy**, despite 'idealization and simplification'. This commendable proven accuracy for VP, also means that the tool and approach can play a greater role in more elaborate and detail simulation/analysis process, like when using Standalone CAE downstream in the design cycle. Speedy extensive iterations for FEA Virtual Prototyping which is made possible by investments made on fast computers (Figure 4.1) further ensure not only an accurate, but also optimal design.

4.3 Virtual Structural Loading

As mentioned before, Multibody Simulation or MBS (used separately or coupled with FEA) would assist in feeding accurate load cases to the FEA virtual prototype. Figure 4.2 to 4.5 show examples where the loads are generated from MBS solver and utilized by FEA for structural assessment. When the loads are exported to FEA, time is also saved as the need for manual creation of Free Body Diagram (FBD) is eliminated.

FEA in allowing for batch processing (which in turn, also enabled speedy upfront processing of the simulation/analysis) however, is not as interactive and speedy as MBS. Nonetheless, the increasingly rapid solving engine allows the design and simulation/analysis to be performed in parallel, in search for an ideal and optimal design direction. The speedy iterations in the design synthesis is continued until all of the structural criteria are fulfilled (Figure C3).

4.4 Virtual Prototyping Idealization in Structural Loading to Avoid 'Paralysis of Analysis'

In Virtual Prototyping for FEA and structural assessment, the complexity of the virtual model itself was simplified in the beginning to ensure efficiency for early iterations in the product development cycle and to avoid 'Paralysis of Analysis'.

In addition to rigid body assumption (refer to section 4.4.1), successful idealization/simplification approaches taken related to structural aspects included:

1) the use of simple 2D plate elements to model a 3D structure,
2) solid geometry representation of weldment assembly (neglecting gap-contact),
3) and non-linear orthotropic bushing material to model rubber material,

which simplified the Virtual Prototype and improved the processing time. The simplifications allowed for speedy repetitive upfront iterations and design synthesis, in arriving at an optimal customized design and are reported in detail in section 4.4.2.

VP tool ability to be versatile/scalable is also proven here, with the problem simulated ranging from being simplified to high in fidelity (e.g. inclusion of contact and hyperelastic rubber material). Numerous scenarios were also Virtually Prototyped and simultaneously solved through FEA batch processing, which is a feature taken advantage of also in this section for speedy processing.

Most importantly as mentioned previously, despite the idealization and simplification, accuracy is retained as demonstrated by strong VP-Test correlation (within ±13%). Moreover, as fidelity is introduced in steps and hierarchical manner, robustness of the Heavy Ground Vehicle products relating to design and response variables can be better understood.

4.4.1 Rigid Body versus Flexible MBS

In this VP doctoral project, flexible MBS (coupled with FEA) is not performed as the simulation/analysis time is found to dramatically increased by at least a factor of 10, which would then hamper the concept of speedy, iterative, and repetitive 'up or front' loading (Figure 4.6) - the various 'what-if' iterations in the design synthesis are important in arriving at an optimized design, which is one of the top reasons for conducting a simulation in the industry (Figure 4.7 and 4.13).

Instead, 'idealization and simplification' through rigid body assumption, structural assessments are performed more efficiently and economically through separate FEA, as is adopted in the extensive Virtual Prototyping work in this chapter. The FEA virtual prototype can then be frontloaded and batch processed with several load cases solved simultaneously, without taking time away from the actual design and detailing work (Figure 4.7 and 4.8). It should be mentioned that the actual design work through CAD program is also a desired integral part of the proposed Virtual Prototyping approach in achieving faster to market goals, as proposed in Table 2.1 framework. *CAD associativity* that allows for upfront VP early in the design process also contributed to a speedy simulation/analysis process, where any CAD geometry update during the design synthesis would automatically and accurately be reflected on the FEA virtual prototype (morphed meshed elements).

Quasi Static loading is performed, for example on the platform of Slag Crucible Handlers through MBS, with the load generated used for FEA. The virtual prototype of the platform is not only assessed for its structural aspect, but in addition used to confirm the rigid body assumption when performing Virtual Prototyping through MBS especially in ensuring no collision between components. As can be seen in Figure 4.2, maximum deflection for critical linkage hard point is as little as less than 3/16” (especially relative to length and overall size of the structure), validating the rigid body assumptions in the extensive MBS performed for the Slag Crucible Handler and also other vehicles considered in the dissertation, in tackling kinematic and dynamics problem.

As for time varying loads, load cases at various time frames in MBS can also be generated for a static FEA simulation/analysis, frame by frame and batch processed accordingly.

The various kinematic pairs setup in MBS also served as virtual sensors, through which loads are generated and then used in FEA. The load information generated at the joints ensure an accurate FEA setup as it would contain the load vector or direction as well. The automatic boundary condition and load cases setup through VP are of significant gain if compared to a more laborious and tedious manual work of setting up load cases through FBD, especially when there are a lot of boundary conditions and loading points (Figure 4.2 and 4.9). The kinematic pair also includes contact, through which the generated contact force is distributed over an area, for more accurate pressure load setup in FEA virtual structural assessment (Figure 4.3).

4.4.2 Other Idealization for FEA

As stated before, simulation/analysis is an approximation, where a real world problem is effectively simplified (which include linearization and etc.) to a degree where it is solvable. ‘Simplification and idealization’ then become a more important aspect in the concept of Virtual Prototyping not only to make a problem solvable, but earlier and quicker to solve as well. The tradeoff that makes the problem simpler also often reduces the model’s fidelity, deviating from the actual non-linear behavior of the item. Therefore, proper choice of the configuration and employed modeling strategy is important for a good understanding of the actual problem, upfront in the design cycle. Non-linearity in FEA virtual prototype as they relate to the proposed VP approach, is typically in the following forms:

1) clearance or gap contact
2) and, material.

As ‘idealization and simplification’ remain a matter of judgment, this is where educated simplification by *mainstream engineers* is important in avoiding ‘garbage-in’ and ‘gospel-out’ scenario. The followings are some detail examples or ‘proof of concept’ of the simplifications made for the doctoral project in this section for structural assessment through FEA. These simplifications/ idealizations again are important as it directly relate to the time savings in virtual prototyping and also allow for the simulation/analysis to start early in supporting VP approach.

In the case of Rolled Steel Handler ram (Figure 2.8), elements are modeled as 2D plate/planar elements and as can be seen from Figure 4.4, despite the simplifications, the virtual prototype still manages to approximate the bending/deflection of the Rolled Steel Handler ram very well. Also, even with the simplification, the virtual prototype captured the effect of changes on structure cross sectional moment of inertia properties, allowing for speedy optimization of strength-to-weight ratio for the Rolled Steel Handler ram. The ram is then modeled in 3D for further product iterations in gaining better understanding of the product nuances at assembly level with non-linear clearance or gap contact included (Figure 4.5).

Also, in case of weldment assembly (Figure 6.10), the geometry is simplified into solids (permitted by *CAD associated* feature). This simplification would neglect gap-contact interaction originally in the assembly level weldment (different components welded and the material were treated as separate components, majority of the time with gaps between them).

Another simplification was done with regard to the material, of the V (or also called chevron) spring to improve on Virtual Prototyping efficiency. Instead of using non-linear hyperelastic rubber elements/material, the V or chevron ‘rubber spring’ is modeled as non-linear 3D orthotropic bushing. The directional stiffness of the elastomer is fine-tuned for accurate results in the process. The accuracy of the simplification is verified through test, enabling further rapid simulation/analysis with credibility or high degree of confidence (Figure 4.11).

A more specialized analysis however is needed in the design of the V spring itself when rubber property carries more bearing in the product development process, simulation of which is also possible through the same contemporary VP tool (that evidently today has been equipped with various enhance features). Rubber property, described on the basis of its stress-strain relationship, is non-linearly elastic, isotropic, incompressible and generally independent of strain rate. The virtual prototype takes a longer time to resolve (and would be compounded in design iterations), but the level of elegance (rubber properties virtually prototyped using hyperelastic Mooney-Rivlin material) is simply needed to capture rubber intricacies for the optimal rubber formulation for the V spring (Figure 4.9, 4.11, and 4.12).

4.5 Synergy - Virtual Prototyping for Validation and in Making Test More Efficient.

Simulation to make physical test more efficient can also be a top goal in performing VP simulation/analysis (Figure 4.13, surveyed in 2008) - instead of competing, simulation and Test would compliment each other in their design validation role, as demonstrated in the doctoral project.

In this chapter, FEA is performed on complex shape cast Rail Vehicle Bogie frame (Figure 4.9 to 4.12), which is the critical payload bearing component interfacing with the Rail Vehicle and in contact with various rail track undulation – VP investigation of which is then followed up with Physical Prototype/Test. The various FEA VP iterations help in determining the worst load case scenario and also help in the mapping of stress gage/sensors, ensuring an efficient and problem free Test - the simulation identified optimal locations and type (linear or rosette) for the strain gages.

Any divergence (which is typically to be expected for initial results) between VP approach and Test can then be checked for and recalibrated – as for the case of the Rail Vehicle Bogie frame, initial divergence was caused by casting manufacturing process first time variability. The initial modeling assumed ideal manufacturing conditions. As the prototype was manufactured, variances arose that were not modeled initially. The final model was modified or 'recalibrated' to accurately represent the true manufactured part. While the initial modeling resulted in rather large, conservative errors (Figure 4.9), the final models were extremely accurate (Figure D1 to D13).

Test performed on the physical Rail Vehicle Bogie prototype demonstrated a strong correlation within ±13% (after calibration process) when compared to readings of up to 20 instrumented strain gages with up to 27 different load cases, indicating not only accuracy but also high repeatability as it translates to permutation of 540 repeated accurate measurements (Figure 4.9 and refer to Appendix C and D for more detail). The gages are outfitted throughout the structure and encircled all critical cross section.

Also, the good correlation matched the stringent requirement in railway industry. The benefit in reaching the agreement is 2 ways between the Virtual and Physical Prototype/Test (refer to section 6.8 for details). Any new data from the test can easily and quickly be seconded with the simulation/analysis. With the agreement, the simulation is now 'calibrated', strongly instilling confidence for further iterations and customizations of future designs through Virtual Prototyping approach as in Table 2.1 framework.

This approach is as opposed to a full reliance on VP in new product development as in Chapter 3 for Slag Crucible Handler, for design validation.

Further discussion of VP-Physical Prototype/Test synergy is in Chapter 5 and 6.

4.6 Attributes of VP Approach through FEA

Attributes of the Table 2.1 framework for structural assessment, as they relate to 'winning approaches' and 'best practices' are summarized as the followings:

1) Early CAE by mainstream product savvy and experienced engineers

i) assist in speedy and early iterations imbued with product knowledge

ii) accuracy combined with product knowledge will allow for reduction of physical test. Strong knowledge and past experience of *mainstream engineers* could even eliminate the need for prototype altogether as demonstrated by the Slag Crucible Handler product development process. In fact, governing bodies in the Rail industry stipulate that physical test can be waived if *past experience* proves strong accuracy or correlation with Test for similar products in structural assessment (static and durability) and design validation.

iii) allow for educated simplifications (cognizant of parts interaction response and etc.) :

- use of simple 2D plate elements to model a 3D structure,
- solid geometry representation of weldment assembly (neglecting gap-contact),
- non-linear orthotropic bushing material to model 'v-spring' made of rubber material,
- rigid body assumptions (and is confirmed with FEA).
-V spring element as 3D orthotropic material.

Educated simplification/idealization would prevent a 'garbage-in' and 'gospel-out' scenario. Hierarchical fidelity introduced through contact or other real world imperfections and then further refined would eventually result in robust product (refer to section 4.4).

2) CAD integrated CAE

i) CAD integrated simulation with its familiar design environment, is conducive to early simulation/analysis in the design cycle among product savvy engineers.

ii) Data is reusable going from CAD to CAE and vice versa, saving time in model creation, and design refinement and customization.

iii) Permits speedy iterations through simulation as design changes can easily be incorporated in the Virtual Prototype for simulation/analysis (especially important in time consuming meshing process, when local changes can quickly 'morph').

iv) Another graphical feature for both VP and CAD/CAE today is that it allows for parts to be 'intersected' for internal information on stress, strain, safety factor and etcetera, giving great insights to product design. Further, video clips if generated from FEA simulation/analysis, gives great understanding of the load path, internally and externally

In this doctoral project, because of the benefits brought by these attributes, these VP approach through MBS FEA has allowed for *rapid* and *lean* Virtual Prototyping of structural problems and the problems' dynamic extension – durability/fatigue (refer to Appendix B2 for more detail on durability) in arriving at *high performing* products.

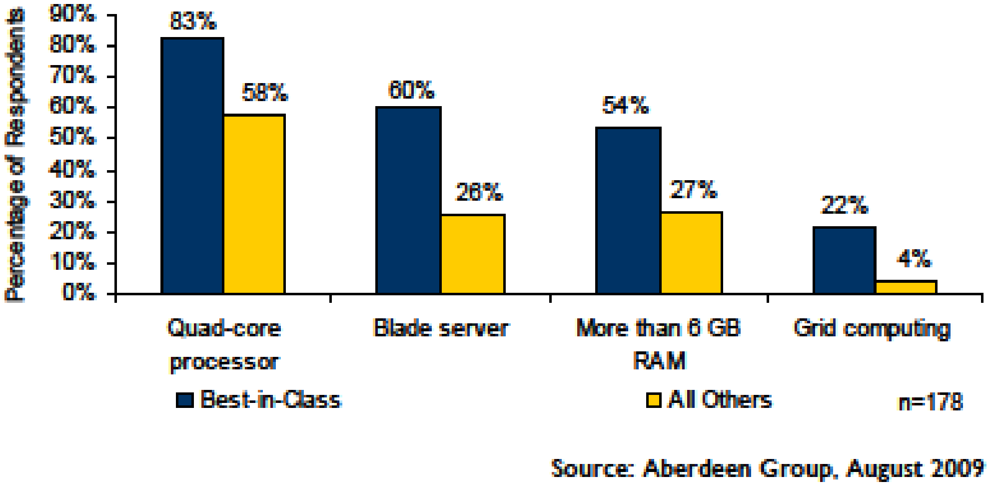
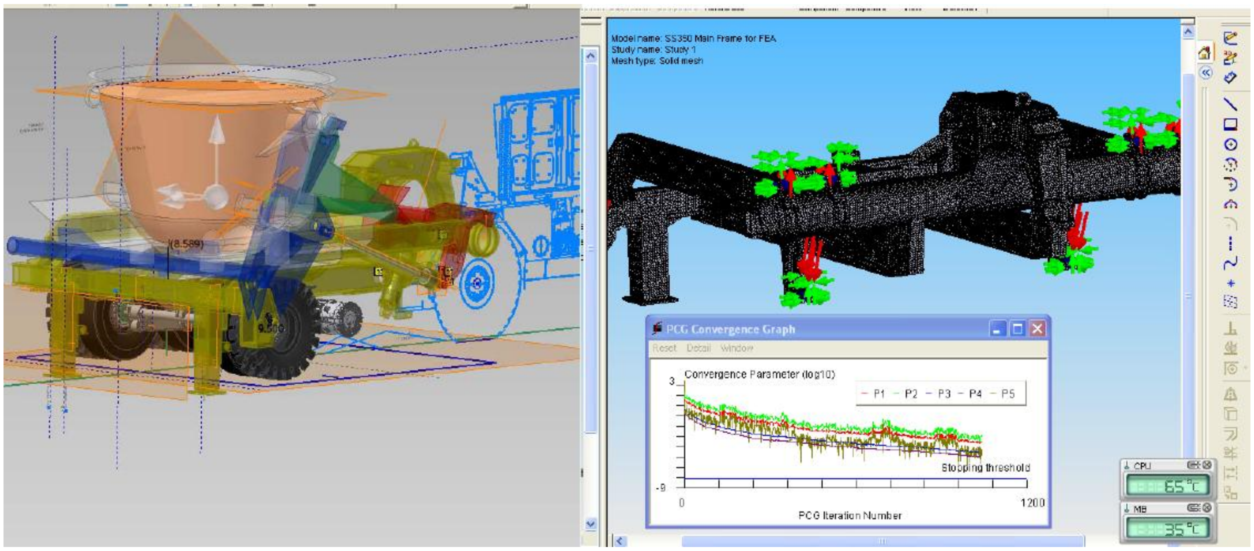
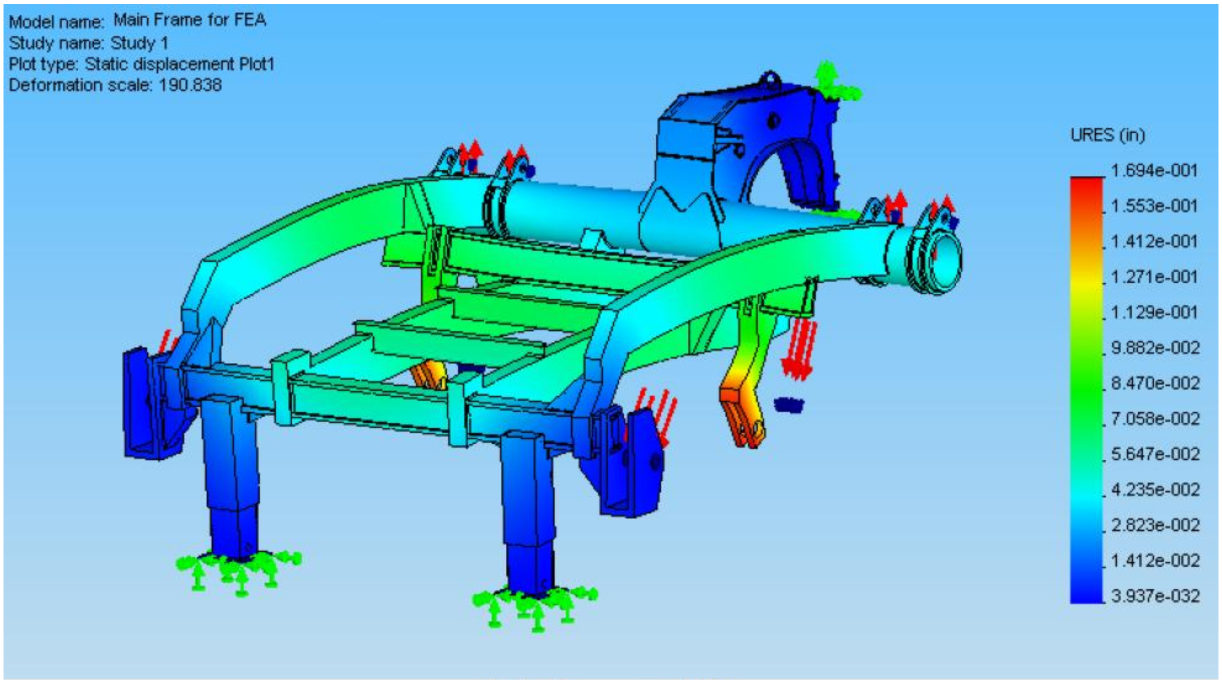


Figure 4.1. Hardware investments made by the Best-in-Class for increased computing performance.



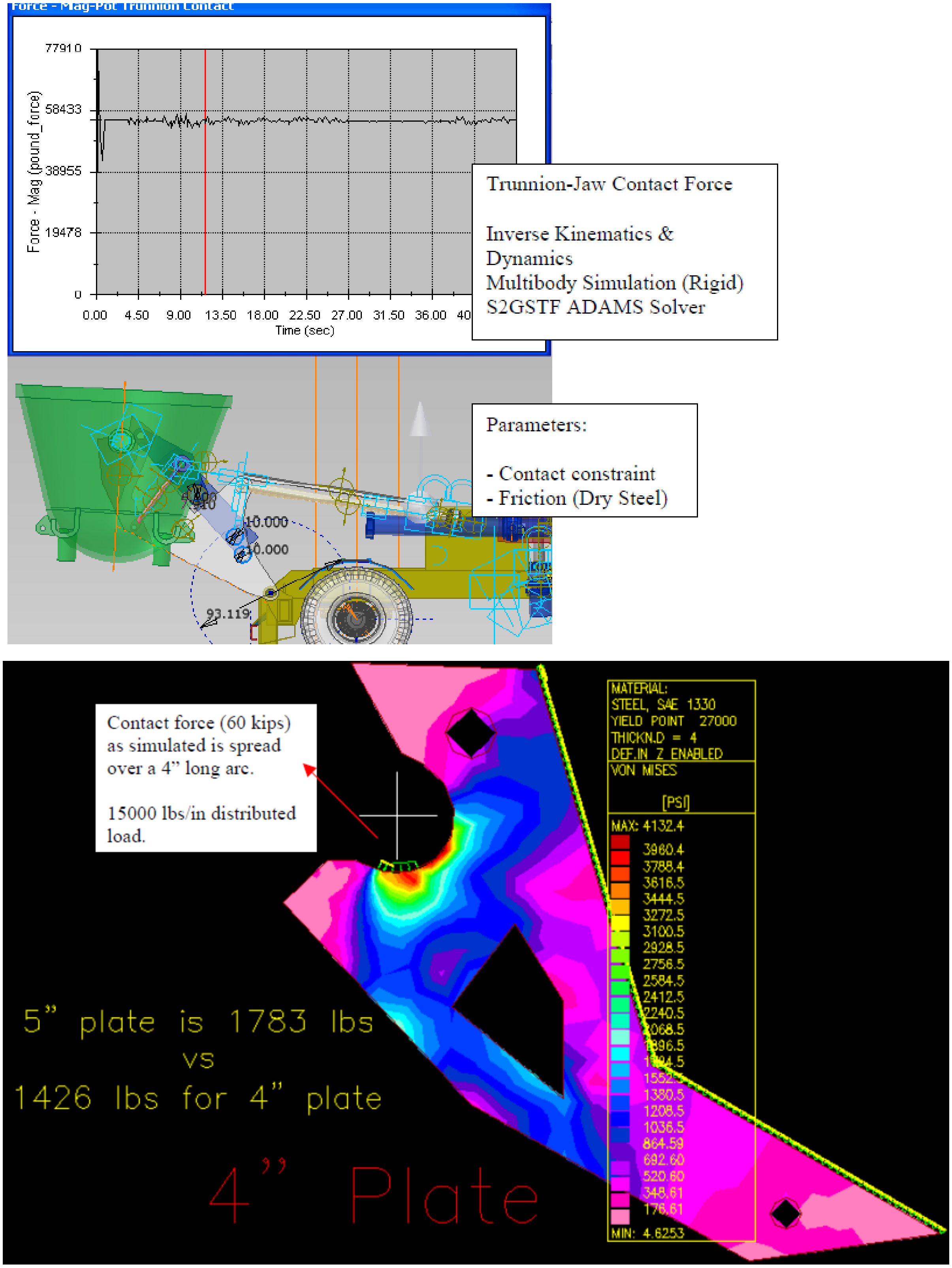
Model name: SS350 Main Frame for FEA
Study name: Study 1
Mesh type: Solid mesh



Model name: Main Frame for FEA
Study name: Study 1
Plot type: Static displacement Plot1
Deformation scale: 190.838

Displacement Plot

Figure 4.2. (top) Optimally meshed Slag Crucible Handler frame with 2 million degree of freedom (DOF) automatically checked for convergence by COSMOS software. (bottom) Structural check on frame which is also to verify rigid body assumption in MBS.



Trunnion-Jaw Contact Force

Inverse Kinematics & Dynamics
Multibody Simulation (Rigid)
S2GSTF ADAMS Solver

Parameters:

- Contact constraint
- Friction (Dry Steel)

Contact force (60 kips) as simulated is spread over a 4" long arc.

15000 lbs/in distributed load.

5" plate is 1783 lbs
vs
1426 lbs for 4" plate

4" Plate

Figure 4.3. Contact load from (gap-contact and contact-impact simulation through MBS) distributed over an area as pressure load in FEA for accurate simulation.

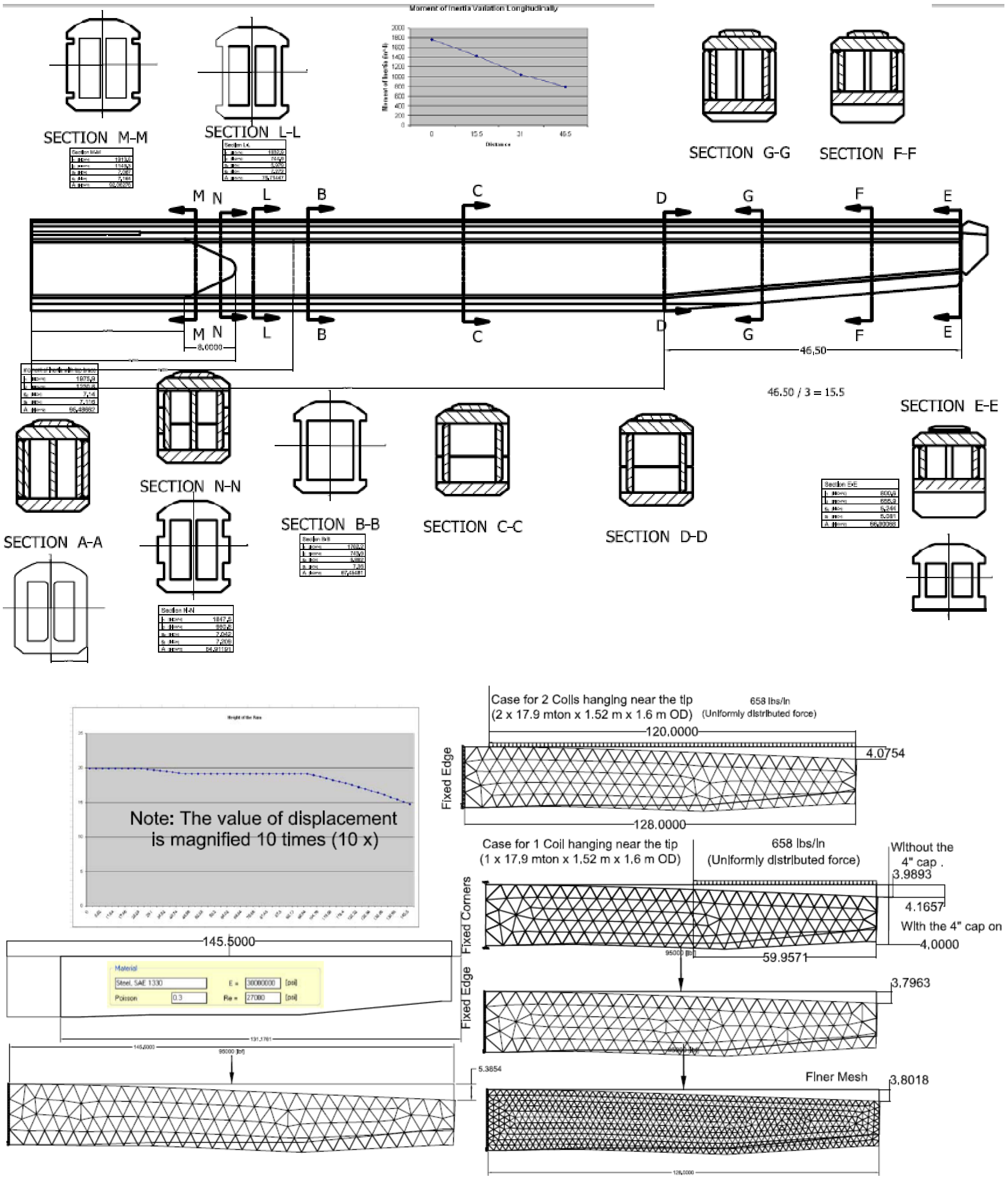
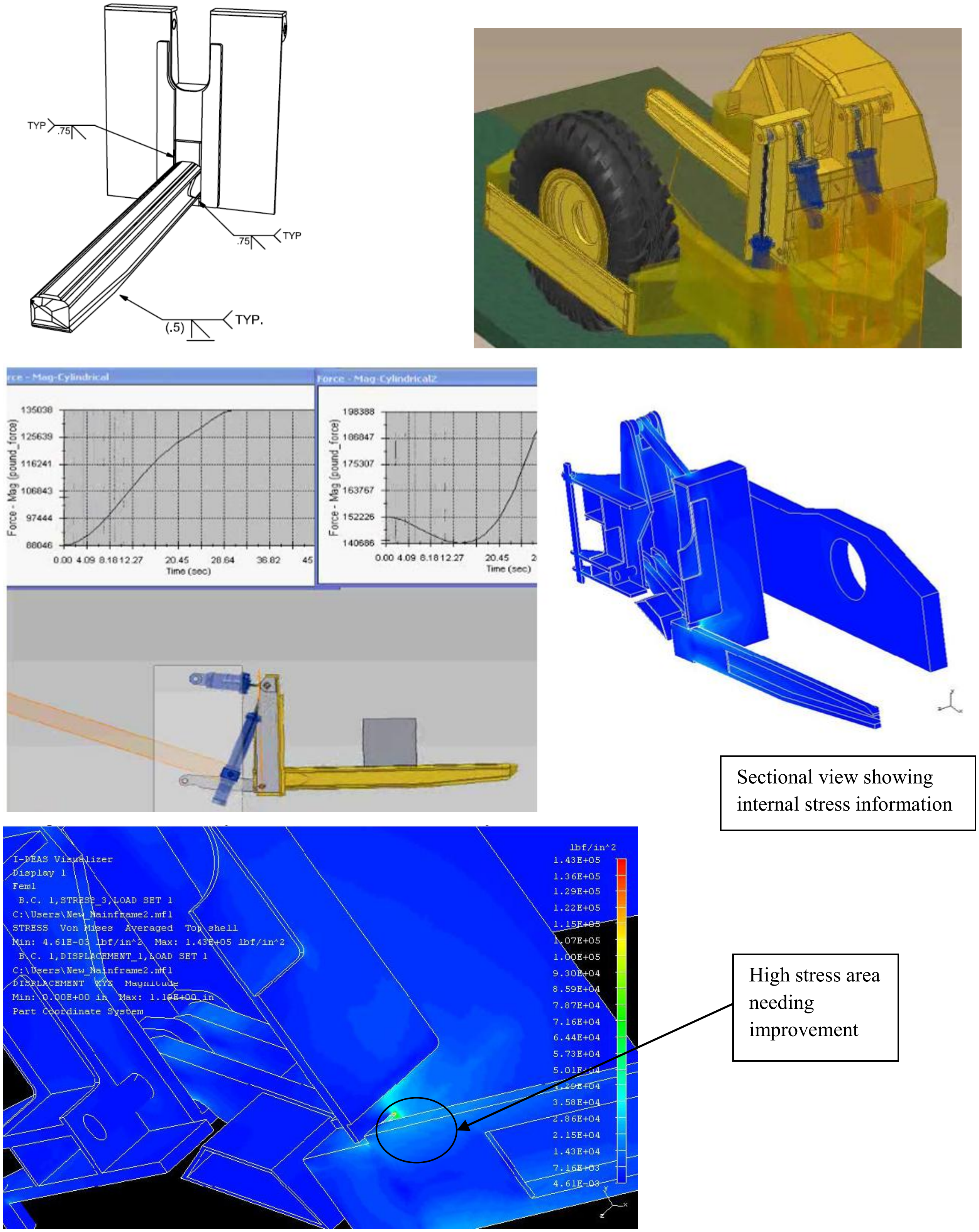


Figure 4.4. Ram on Rolled Steel Handler (Figure 2.8) modeled as 2D plate, effectively and accurately capturing the effect of structure cross sectional changes.

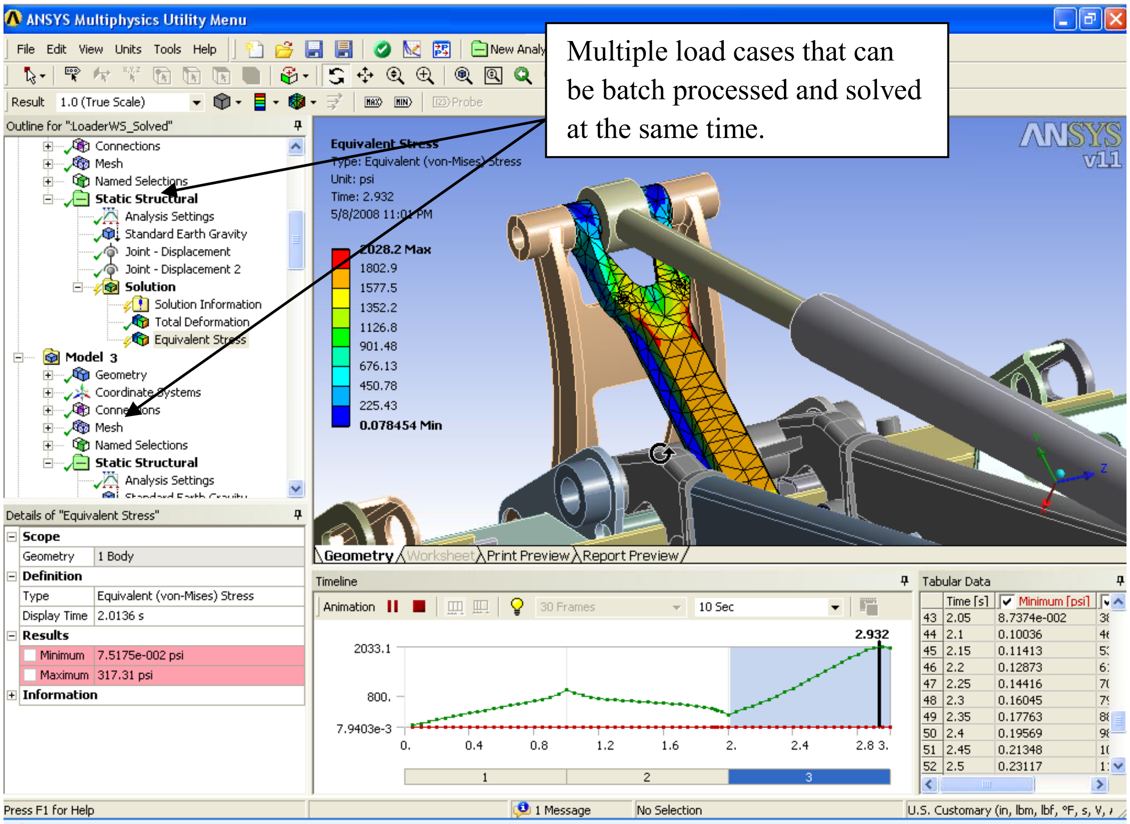


```
I-DEAS Visualizer
Display 1
Feml
 B.C. 1,STRESS_3,LOAD SET 1
C:\Users\New_Mainframe2.mfl
STRESS  Von Mises  Averaged  Top shell
Min: 4.61E-03 lbf/in^2  Max: 1.43E+05 lbf/in^2
 B.C. 1,DISPLACEMENT_1,LOAD SET 1
C:\Users\New_Mainframe2.mfl
DISPLACEMENT  XYZ  Magnitude
Min: 0.00E+00 in  Max: 1.10E+00 in
Part Coordinate System
```

Sectional view showing internal stress information

High stress area needing improvement

Figure 4.5. Assembly level FEA (through IDEAS) which include gap-contact on the ram of Rolled Steel Handler (Figure 2.8), hierarchically introducing real world imperfection into the Virtual Prototype.



Multiple load cases that can be batch processed and solved at the same time.

Details of "Equivalent Stress"

Scope	
Geometry	1 Body
Definition	
Type	Equivalent (von-Mises) Stress
Display Time	2.0136 s
Results	
☐ Minimum	7.5175e-002 psi
☐ Maximum	317.31 psi
Information	

Tabular Data

	Time [s]	☑ Minimum [psi]
43	2.05	8.7374e-002
44	2.1	0.10036
45	2.15	0.11413
46	2.2	0.12873
47	2.25	0.14416
48	2.3	0.16045
49	2.35	0.17763
50	2.4	0.19569
51	2.45	0.21348
52	2.5	0.23117

Figure 4.6. Hybrid Flexible MBS VP of Rolled Steel Handler/Loader variant. Flexible body modeling (of merely one component), increased the simulation time tenfold.

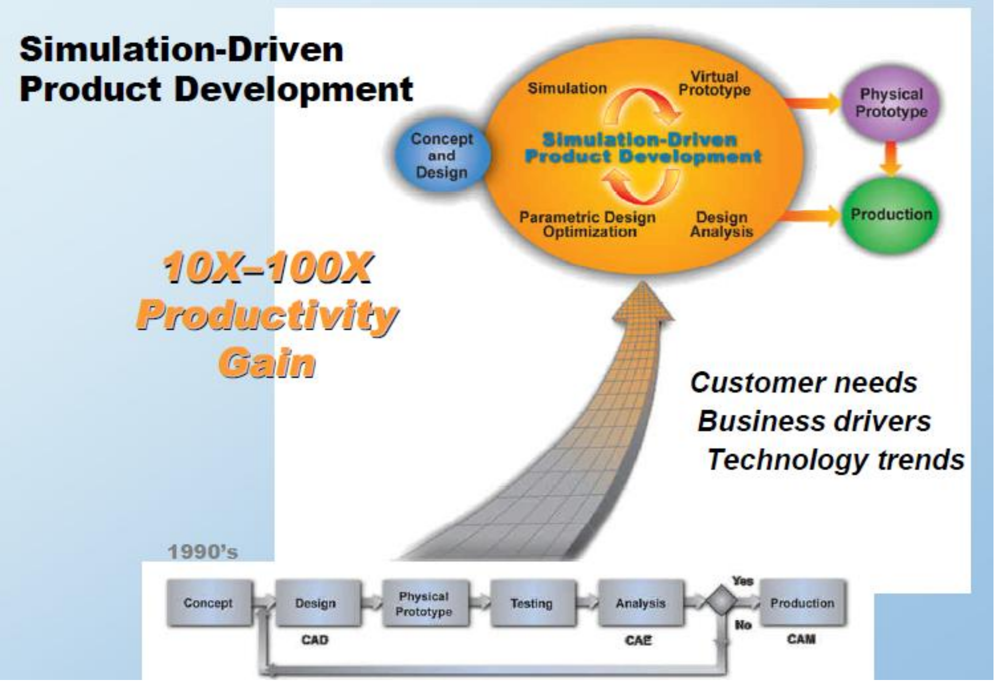


Figure 4.7. Simulation – Driven product development approach by ANSYS.

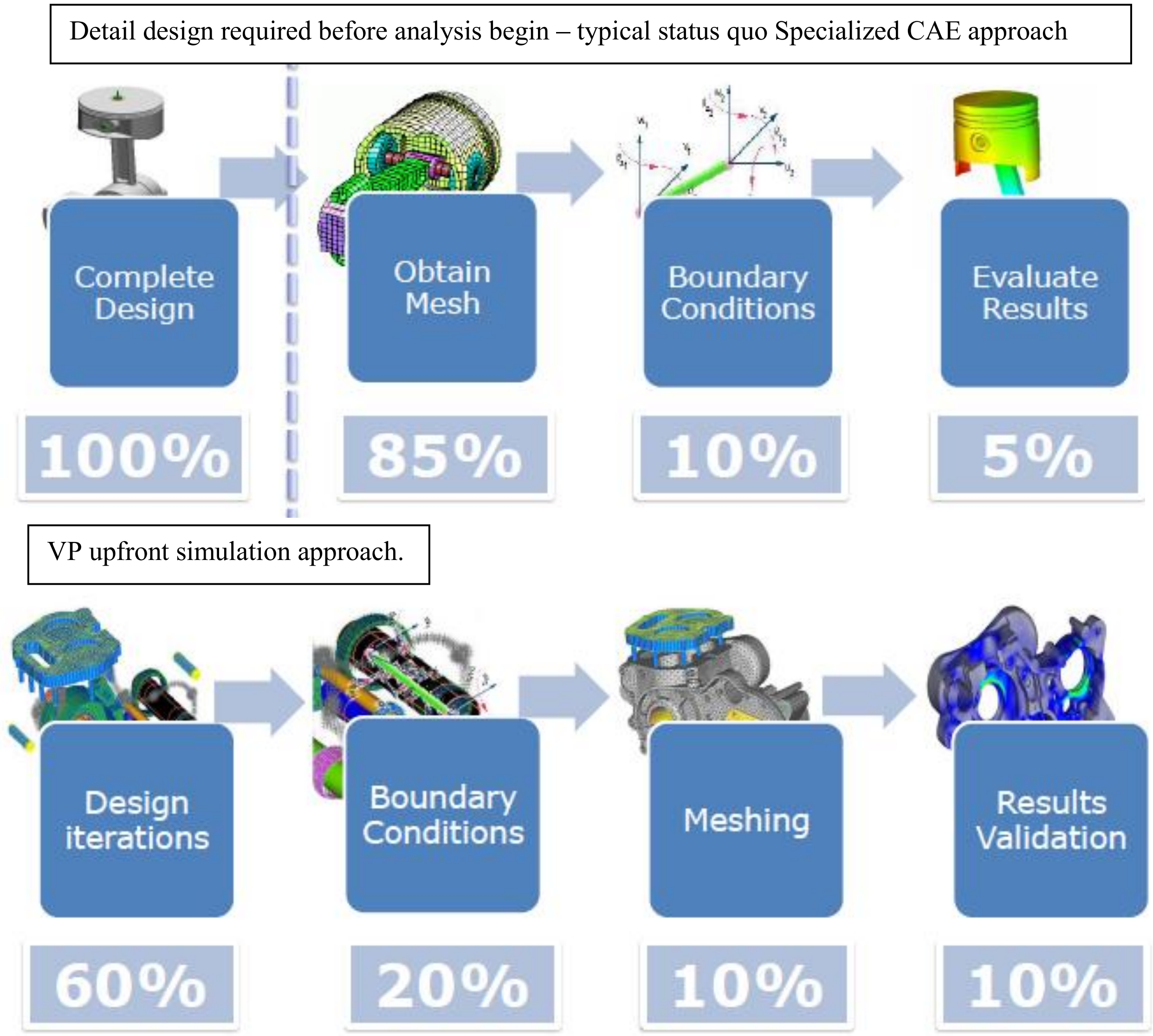
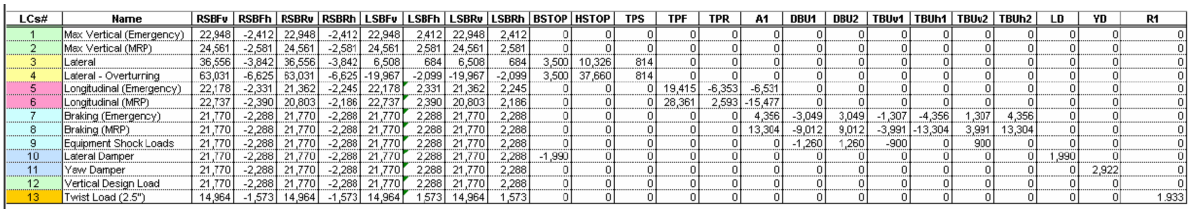
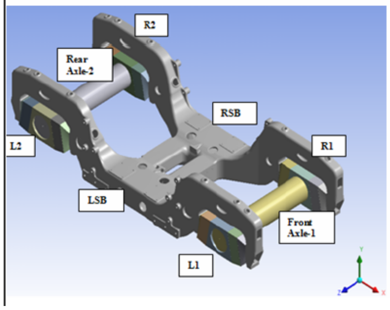
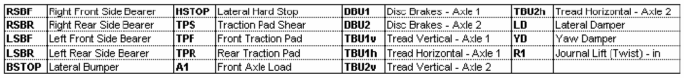


Figure 4.8. Simulation is a part of the design iterations and process in the FEA Virtual Prototyping (8).



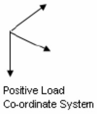
LCs#	Name	RSBFv	RSBFh	RSBRv	RSBRh	LSBFv	LSBFh	LSBRv	LSBRh	BSTOP	HSTOP	TPS	TPF	TPR	A1	DBU1	DBU2	TBUv1	TBUh1	TBUv2	TBUh2	LD	YD	R1
1	Max Vertical (Emergency)	22,948	-2,412	22,948	-2,412	22,948	2,412	22,948	2,412	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Max Vertical (MRP)	24,561	-2,581	24,561	-2,581	24,561	2,581	24,561	2,581	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Lateral	36,556	-3,842	36,556	-3,842	6,508	684	6,508	684	3,500	10,326	814	0	0	0	0	0	0	0	0	0	0	0	0
4	Lateral - Overturning	63,031	-6,625	63,031	-6,625	-19,967	-2,099	-19,967	-2,099	3,500	37,660	814	0	0	0	0	0	0	0	0	0	0	0	0
5	Longitudinal (Emergency)	22,178	-2,331	21,362	-2,245	22,178	2,331	21,362	2,245	0	0	0	19,415	-6,353	-6,531	0	0	0	0	0	0	0	0	0
6	Longitudinal (MRP)	22,737	-2,390	20,803	-2,186	22,737	2,390	20,803	2,186	0	0	0	28,361	2,593	-15,477	0	0	0	0	0	0	0	0	0
7	Braking (Emergency)	21,770	-2,288	21,770	-2,288	21,770	2,288	21,770	2,288	0	0	0	0	0	4,356	-3,049	3,049	-1,307	-4,356	1,307	4,356	0	0	0
8	Braking (MRP)	21,770	-2,288	21,770	-2,288	21,770	2,288	21,770	2,288	0	0	0	0	0	13,304	-9,012	9,012	-3,991	-13,304	3,991	13,304	0	0	0
9	Equipment Shock Loads	21,770	-2,288	21,770	-2,288	21,770	2,288	21,770	2,288	0	0	0	0	0	0	-1,260	1,260	-900	0	900	0	0	0	0
10	Lateral Damper	21,770	-2,288	21,770	-2,288	21,770	2,288	21,770	2,288	-1,990	0	0	0	0	0	0	0	0	0	0	0	1,990	0	0
11	Yaw Damper	21,770	-2,288	21,770	-2,288	21,770	2,288	21,770	2,288	0	0	0	0	0	0	0	0	0	0	0	0	0	2,922	0
12	Vertical Design Load	21,770	-2,288	21,770	-2,288	21,770	2,288	21,770	2,288	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	Twist Load (2.5")	14,964	-1,573	14,964	-1,573	14,964	1,573	14,964	1,573	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.933

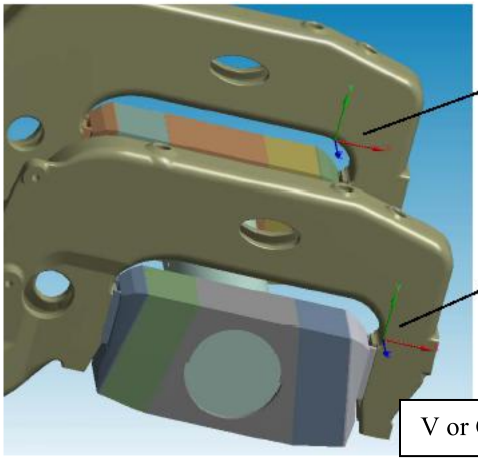


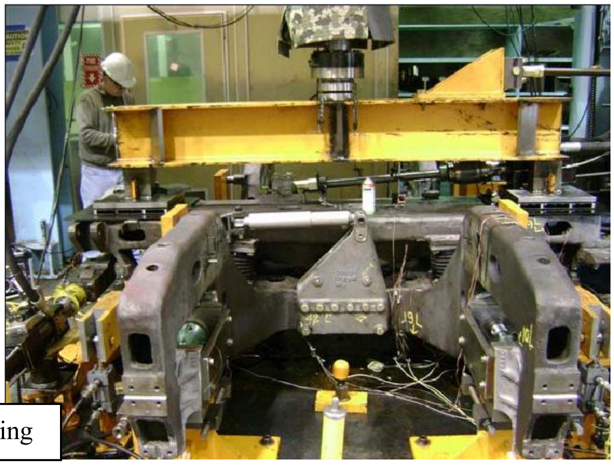


RSBF	Right Front Side Bearer	**HSTOP**	Lateral Hard Stop	**DBU1**	Disc Brakes - Axle 1	**TBU2h**	Tread Horizontal - Axle 2
RSBR	Right Rear Side Bearer	**TPS**	Traction Pad Shear	**DBU2**	Disc Brakes - Axle 2	**LD**	Lateral Damper
LSBF	Left Front Side Bearer	**TPF**	Front Traction Pad	**TBU1v**	Tread Vertical - Axle 1	**YD**	Yaw Damper
LSBR	Left Rear Side Bearer	**TPR**	Rear Traction Pad	**TBU1h**	Tread Horizontal - Axle 1	**R1**	Journal Lift (Twist) - in
BSTOP	Lateral Bumper	**A1**	Front Axle Load	**TBU2v**	Tread Vertical - Axle 2		

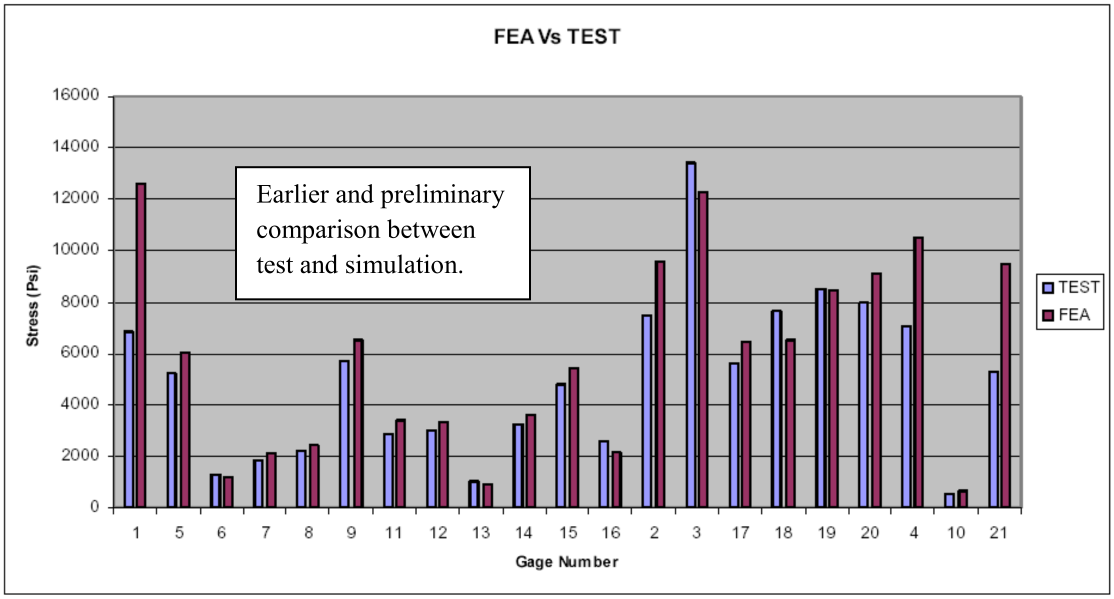
FBD (free body diagram) and the various load cases and boundary conditions.







V or Chevron spring



Earlier and preliminary comparison between test and simulation.

Figure 4.9. FEA Rail Vehicle bogie Virtual Prototyping FBD setup, test, and VP-Test comparison.

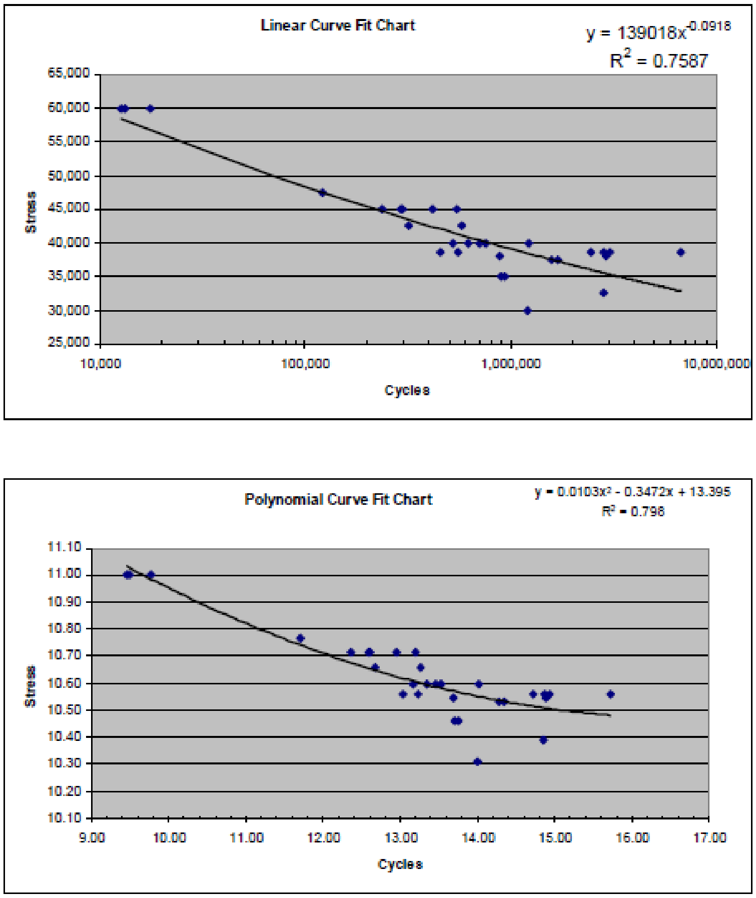


Figure: S-N curve

Material properties obtained from test interpolated into a linear curve fit.

Fatigure Safety Factor.

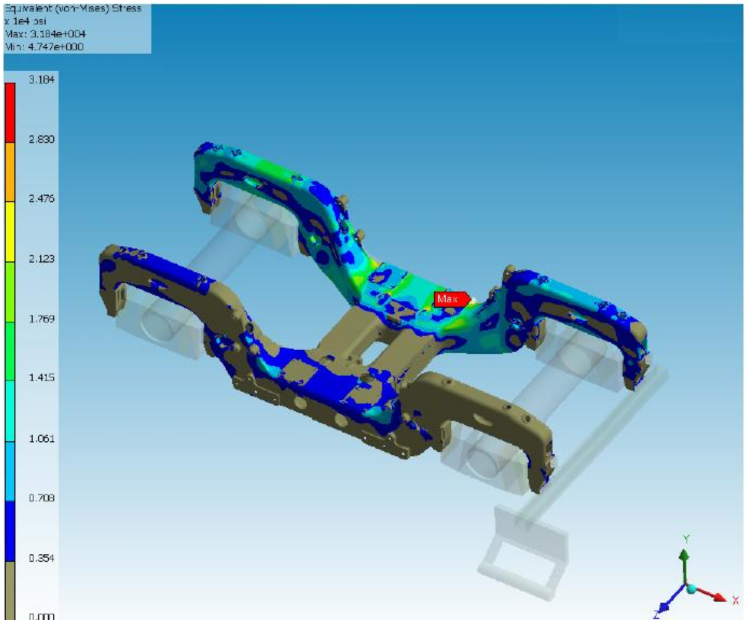


Figure 4.10. Durability, and fatigue simulation for Rail Vehicle bogie (Figure 2.14).

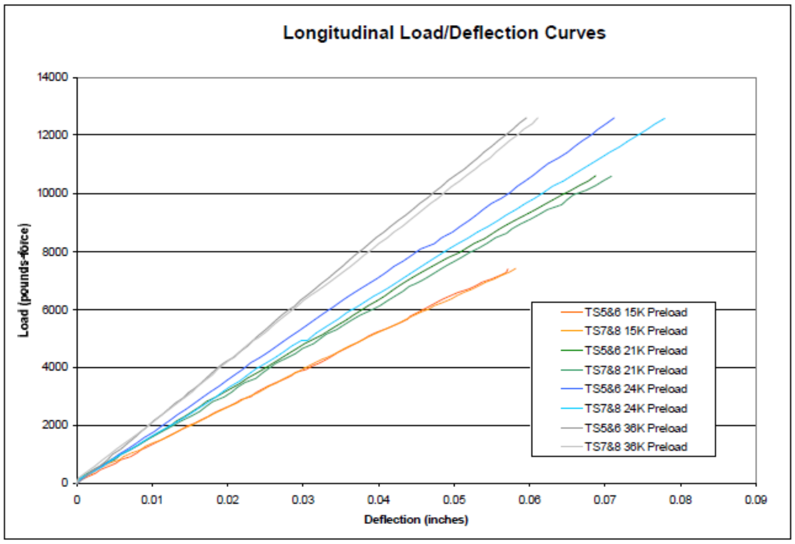
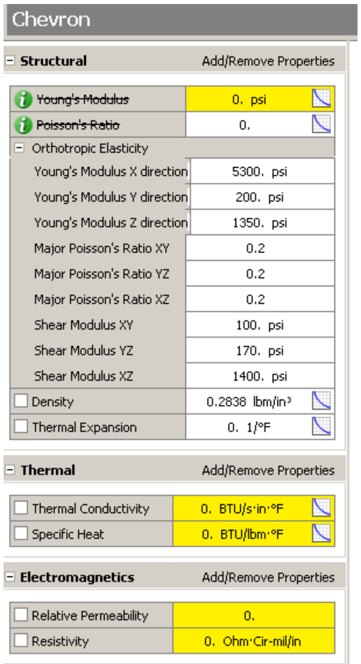
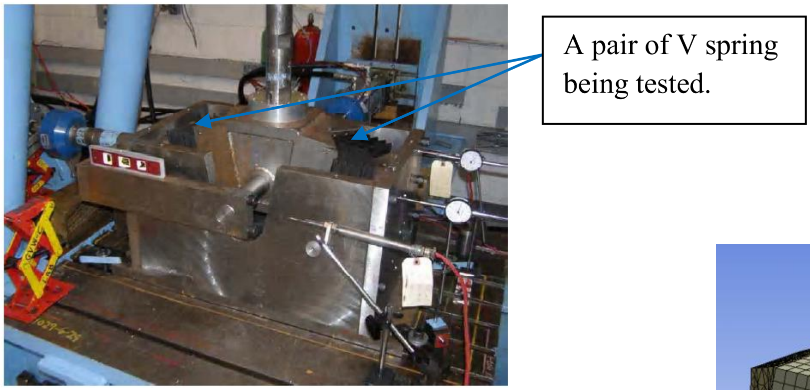


Figure : Longitudinal Load/Deflection Curves for the V 's (Third Cycle Recorded).

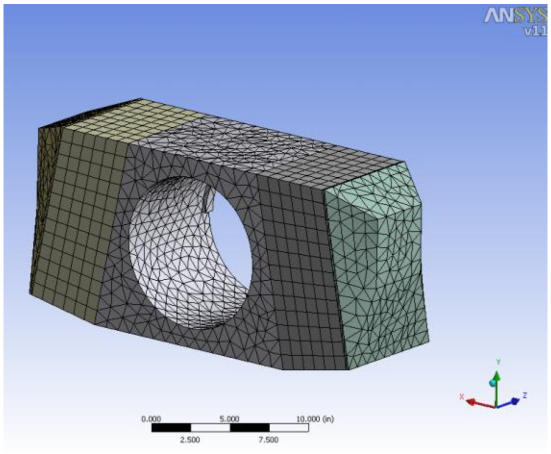


Chevron

Structural	Add/Remove Properties
~~Young's Modulus~~	0. psi
~~Poisson's Ratio~~	0.
Orthotropic Elasticity	
Young's Modulus X direction	5300. psi
Young's Modulus Y direction	200. psi
Young's Modulus Z direction	1350. psi
Major Poisson's Ratio XY	0.2
Major Poisson's Ratio YZ	0.2
Major Poisson's Ratio XZ	0.2
Shear Modulus XY	100. psi
Shear Modulus YZ	170. psi
Shear Modulus XZ	1400. psi
☐ Density	0.2838 lbm/in³
☐ Thermal Expansion	0. 1/°F
Thermal	Add/Remove Properties
☐ Thermal Conductivity	0. BTU/s·in·°F
☐ Specific Heat	0. BTU/lbm·°F
Electromagnetics	Add/Remove Properties
☐ Relative Permeability	0.
☐ Resistivity	0. Ohm·Cir-mil/in



A pair of V spring being tested.



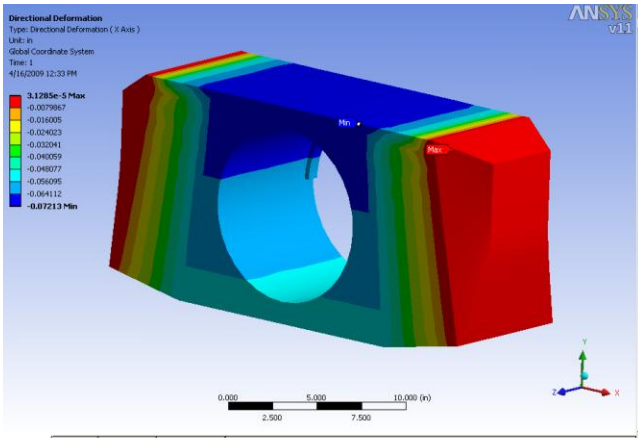
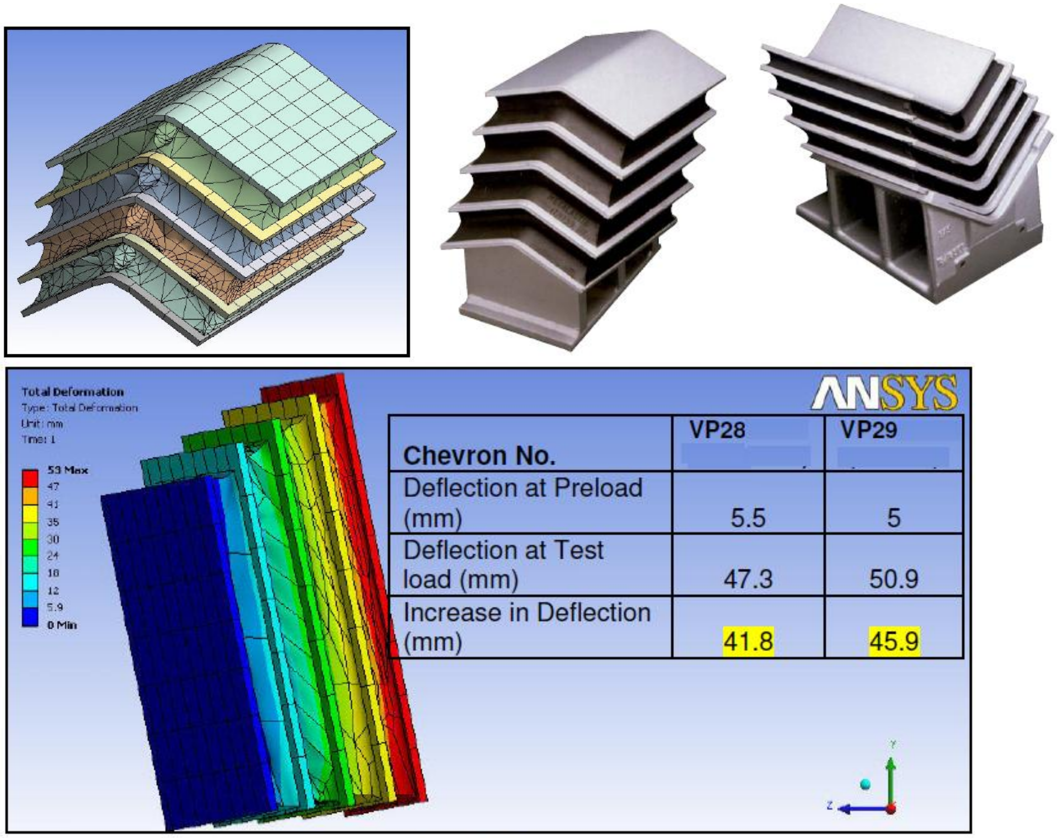


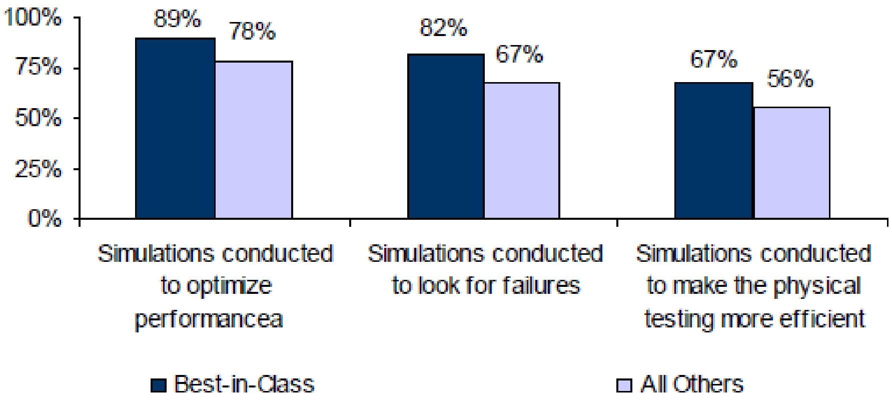
Figure 4.11. V or Chevron spring test and simulation. The Virtual Prototype is modeled as 3D orthotropic bushing/rubber.



Chevron No.	VP28	VP29
Deflection at Preload (mm)	5.5	5
Deflection at Test load (mm)	47.3	50.9
Increase in Deflection (mm)	41.8	45.9

Figure . Typical Deformation under load

Figure 4.12. Detail and more Specialized CAE FEA for the chevron spring with rubber material modeled with hyperelastic Mooney-Rivlin material.



Source: Aberdeen Group, November 2008

Figure 4.13. Top objectives for running mechanical simulations (55).

5. VIRTUAL PROTOTYPING COUNTERPOINTS

On the opposite end of the spectrum to Virtual Prototyping in ground vehicle product development where design and simulation/analysis are essentially separate processes, are the following items:

1) Specialized Traditional CAE (involved, and typically standalone, Figure 2.4 & 5.1), and
2) Test (which necessitate Physical Prototype).

Both were compared to quantitatively in Chapter 3 and 4 respectively, in terms of *time* and *cost* factors/demands in the product development process. Specialized CAE and Test are extensively performed for the doctoral project in this chapter, and further explanations are in place for these counterpoints to VP approach for ground vehicle engineering, to draw firsthand comparisons.

As can be seen from previous chapters, Virtual Prototyping is a more proactive approach to ground vehicle product development, versus being more reactive for the Virtual Prototyping counterpoints listed above (as they are adopted later in the design cycle). In other words, Virtual Prototyping is in the business of early failure prevention, rather than failure studies in product development, and perfectly suited for rigorous ‘original or new’ product development and the ensuing design customizations.

On the other hand, Specialized Traditional CAE and Test are appropriate for well defined design configuration (elaborate model) downstream in the design cycle and in PLM (Product Lifecycle Management) phase. Being elaborate and late in the design cycle, Specialized Traditional CAE and Physical Prototype/Test, instead of being iterative is more appropriate for product pass/fail criteria assessment and therefore is also more suited to continuous improvement (i.e. PLM) and failure studies versus ‘original and new’ product development.

As for failure studies however, simulation/analysis (both VP and Specialized CAE) would give more information, as Physical Prototype explain mostly the ‘what’s’ and not necessarily the ‘how’s’. This also indicates a necessity for Physical Prototype/Test to be coupled with simulation/analysis and not be a stand-alone design validation method, if more insights were to be gained from the design studies.

On the extreme end, there are complex ground vehicle engineering domains that simply would require for Test on Physical Prototype (at a reduced degree if coupled with Virtual Prototyping or Specialized CAE), in the process of understanding a problem or design validation.

5.1 Specialized CAE – Full Vehicle Dynamics Simulation

(Rail Vehicle, Figure 2.14)

Specialized Traditional CAE allow for higher degree of elaboration - more input and higher degree of modeling customization (versus tool and template based) - for the simulation to solve a system or assembly level problem (at the expense of increased time consumption) (Figure 5.1). A lot of detail is required on a design before simulation is performed through Specialized CAE, and therefore it is typically performed late in the design cycle. A major drawback to this approach is that for any discovery from the Specialized CAE simulation/analysis requiring design changes, it would be expensive to implement.

As opposed to the case where VP supplemented test (at the same system level) in chapter 4, section 4.4 for the Rail Vehicle Bogie, here Test (component level) could possibly feed data into the simulation/analysis (higher system level).

Tested elastomeric components, like the V or chevron spring as seen in the previous chapter has a lot of bearings on Ride & Handling and Noise, Vibration, & Harshness (NVH) domain of ground vehicle engineering, along with other passive NVH isolator or more common control elements like spring (displacement sensitive) and dampers (velocity sensitive). In this section, physical test performed previously also provided ‘characterization’ to the V spring, which would then be idealized and linearized for simulation through Specialized and Traditional MBS/CAE.

One outstanding property of a Specialized Traditional CAE for MBS is that geometry/shape of the components are not accounted for – an indication of disconnect from CAD. *Associativity with CAD* is a criterion that is important in the concept of upfront Virtual Prototyping during design synthesis especially for design detail forward planning which also account for geometry/shape optimization, and geometry related interference or collision detection (contact-impact related). In case of Specialized CAE, most of the model geometry are observed at assembly level and highly simplified at component level. Specialized Traditional CAE however, allows for more input for the simulation/analysis, hence more output are available for design performance assessment.

The specialized simulation performed at high system or assembly level for the case investigated in this section, was on full Rail Vehicle bogie simulation/analysis (Figure 5.3).

Preparation prior to simulation was rather elaborate which include time consuming acquisition of track geometry data.

Contact kinematic pairing here again is important in the simulation/analysis for the rail vehicle and track interaction to capture and mitigate real world problem of Rail Vehicle lateral high speed instability phenomenon called hunting (Figure 5.4). The profile of Rail vehicle wheel and track is accounted for with different degree or clearance between them causing intermittent contact-impact.

Stability problems in ground vehicle engineering, if to be tested physically can be dangerous, and simulation/analysis would majority of the time take precedence before an elaborate and very expensive full fledge physical test on-rail or on-road.

Full on-road vehicle dynamics test (Figure 2.4 and 3.7) to assess problems in vehicle dynamics domain cost typically in the hundredth of thousands, and cover several standard Society of Automotive Engineers (SAE) - sanctioned test like J-Hook, Washboard, Burma, and Bump test, and etcetera. The ground vehicle is pushed to the limits in the vehicle dynamics.

A safer way but still expensive test for on-road vehicle is the simulated 4-post test rig useful in 'characterizing' the vehicle dynamics responses. The 4-post test rig conditions can also be simulated virtually, through Specialized Traditional CAE. An example of Specialized CAE being used to build a virtual test apparatus is as in the case of KKS (Kansas Knee Simulator) digital model for virtual testing of prosthesis knee design (Figure 2.5).

5.2 Physical Prototype/Test – 'Chaotic' Mirror Post Vibration

(Specialized Shunter Tractor, Figure 2.10)

In this section, mirror vibration problem caused by power train 'structure-borne-noise', is investigated on through an elaborate Test (Figure 5.5 to 5.8).

Dynamic behavior of non-linear, or chaotic systems is a more complex issue to examine and analyze than linear system and is typically considered in the area of NVH of ground vehicle engineering. It is usually described as a 'black art' and in vibration isolation application where a lot of bushings/elastomers are involved. Hysteresis (non-linear restoring force, Figure 5.2) in the elastomers are typical in the physical multibody system, which makes the dynamic behavior ‘chaotic’, where Test on Physical Prototype is warranted in place of simulation/analysis in design verification (Figure 5.8).

Usually, higher level test is done to understand the problem (Figure 5.5), and then isolated into a smaller problem domain (Figure 5.7) – top-down approach – and therefore can most of the time only be performed after-the-fact, in a product development process. The data is then fed into the simulation for more intimate understanding of the NVH problem, at component level (Figure 5.7 and 5.8).

Intrinsic property to dynamic simulation/analysis is time history. In the simulation, input that are not deterministic (or not repeatable), in essence can be ‘idealized and simplified’ and be represented by frequency content (spectrum) that is statistical in nature. This representation is typically seen in the random vibration analysis, and the ‘spectrum’ is called Power Spectral Density or PSD (13)(15). On the output side, if the appearing pattern seems regular, the system may be periodic, or else it can have a long period or be chaotic. Time histories are a very common way to post process simulation results. However, this representation is difficult to use if the period is long and the behavior varies a lot as a function of time. Therefore, frequency-domain analysis is typically preferred.

Some very interactive contemporary simulation that is FEA based, allows for dynamic response analysis in frequency domain at assembly level and lower, but however, do not include large body movement like in MBS. A less interactive/lively version of dynamic simulation/analysis is FE Vibration and Modal Analysis which would confirm test data on structure’s modal participation and resonance aspects of a product (Figure 5.8), but do not necessarily simulate and illustrate the actual physical phenomenon or real world world behavior or response, as the output are in the form of tabulated numbers.

Central to the ground vehicle powertrain NVH problem in this section (Figure 5.5 to 5.8), is the configuration of the elastomeric isolators as improper choice of vibration isolator can actually worsen the NVH problem instead of damping and mitigating the vibration. Again, test in this domain is obviously elaborate and usually is conducted from the high assembly level down. Non-linearity in the data can be seen and is evident in the mirror vibration problem investigation (Figure 5.6). For the problem, test data is fed into the simulation as random simulation and isolated problems, which are then virtually prototyped.

From the FE vibration and modal simulation/analysis performed, it was found that the mirror was excited at resonance which exacerbated the chaotic mirror vibration problem.

5.3 General Discussion – Virtual Prototyping/Test

In some industry, simulation/analysis and CAE simply have not gained enough credibility to be the overriding qualifier for a new product development (57) (59). For Rail industry product development as an example, extensive Test is still expected and required by the authorities for a simulation as a follow up (especially for critical component like Rail Vehicle Bogie in chapter 4 (Figure 2.14 and 4.9)), but can be requested for a waiver for products based on experience which are very similar to earlier designs with good service history and correlation between simulation and test.

It should be noted, that majority of the time in product development project, especially in ground vehicle engineering, 'new' design or product is actually a modification or improvement to an existing or earlier design – this is especially so in automotive engineering versus Specialized and Heavy Ground Vehicle engineering area investigated for in the doctoral project.

If built on a modular platform, for this instance Virtual Prototyping can play a more meaningful role in the 'new' product development in light of correlated and tighter simulation and test relationship. In addition, a lot of legacy digital data (especially ones that are CAD/CAE associated) from previous design cycle can be carried over and reused not only for 'new', but also for improvement and customization of design, while further pushing a greater role of Virtual Prototyping in optimal product development, down-stream or in the future.

5.4 Hybrid Virtual Prototype/Testing

In arriving at a tighter relationship/correlation between test and simulation, albeit later in the design cycle, there is also an emerging area in product development performance assessment called Hybrid Simulation (2). Both test and simulation were conducted and the Physical Prototype and Virtual Prototype are tuned while being in the same 'loop' at the same time. Testing supplement and compliment Virtual Prototyping and vice versa. Obviously more biased on the Test, the approach is on the basis of ‘Test derived loads’ and ‘Test derived models’ for the hybrid approach.

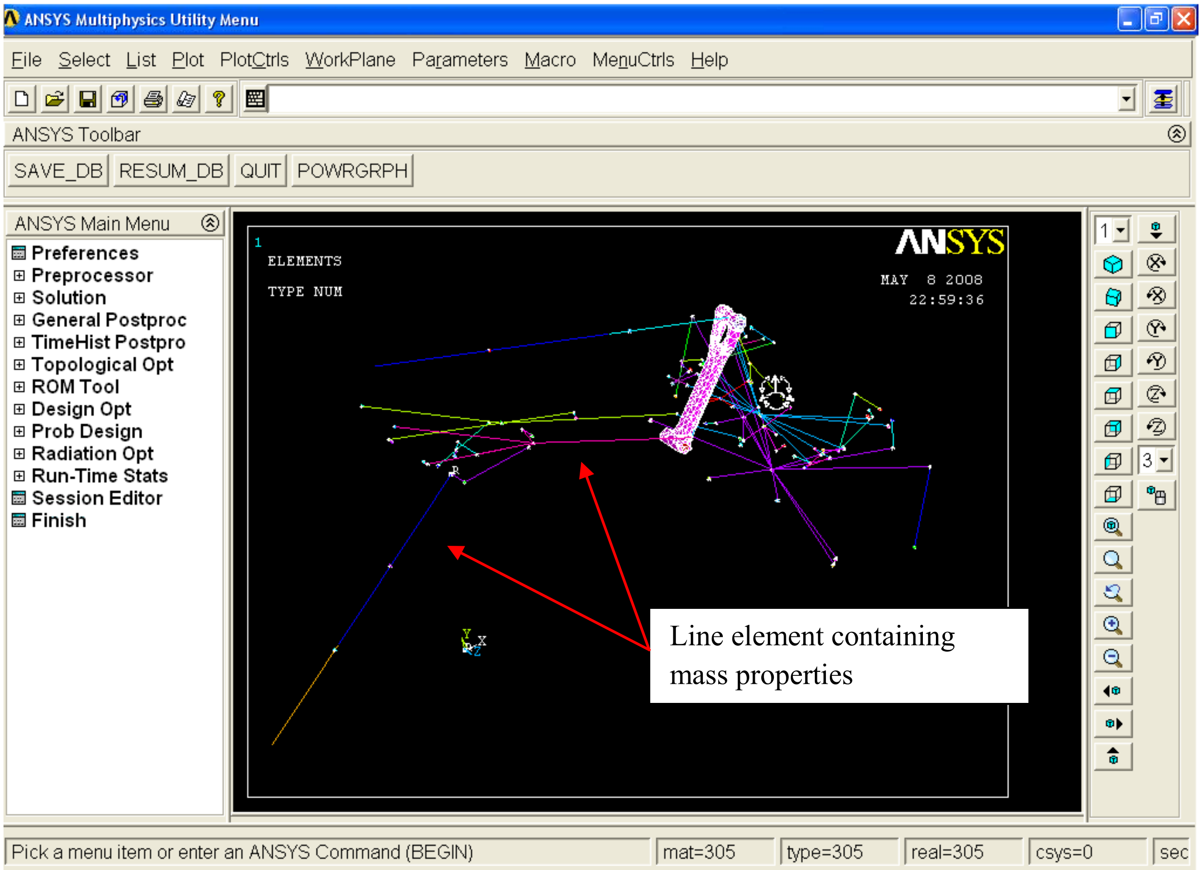
This method is especially attractive when going from component (or lower level system) to assembly or system level design product validation – bottom-up approach. While it is relatively easy to predict performance at the component level, most complex problem like NVH problems are only discovered at full system levels. Experience shows that simplifications (at the expense of reduced fidelity) on factors such as system linearity, model complexity, subassembly interaction or the actual loading environment become more critical as system are assembled. Methodically, fine tuned high fidelity lower level system (component and subsystems) are introduced to the higher level Hybrid Virtual Prototyping / Testing.

By combining the best of the physical test and virtual simulation disciplines, the new engineering process is not only faster, but also more accurate and robust, as test-based validation is built in. The Return on Investment (ROI) can therefore be measured not only in terms of *faster time to market* and *reduced development cost*, but also in terms of improved product quality and a reduction in the number of expensive recall, which are all also a part of main industrial (*high performance*) pressure factors for product development mentioned in earlier chapters.

This Hybrid Virtual Prototype/Testing approach is extended in the ‘embedded control’ ground vehicle engineering domain into a concept referred to as HIL (Hardware-in-the-Loop).

Essentially, these approaches bring the ‘lower level’ (component and subsystem) complexities and intricacies of the real world into the ‘higher (or full system) level’ virtual world of simulation/analysis.

So, after-the-fact failure studies, ‘black art’ NVH area, and other complex problem area (like control), can clearly benefit from this tight correlation between the real world and virtual prototype.



Line element containing mass properties

Figure 5.1. Standalone and Specialized CAE interface for the same rigid/flexible model depicted in Figure 3.6 for Rolled Steel Handler.

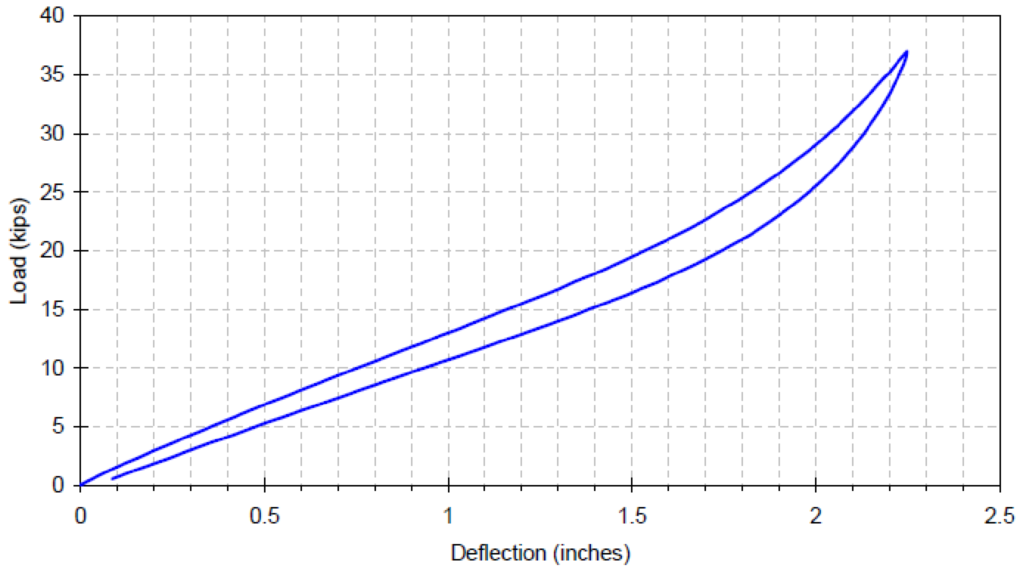
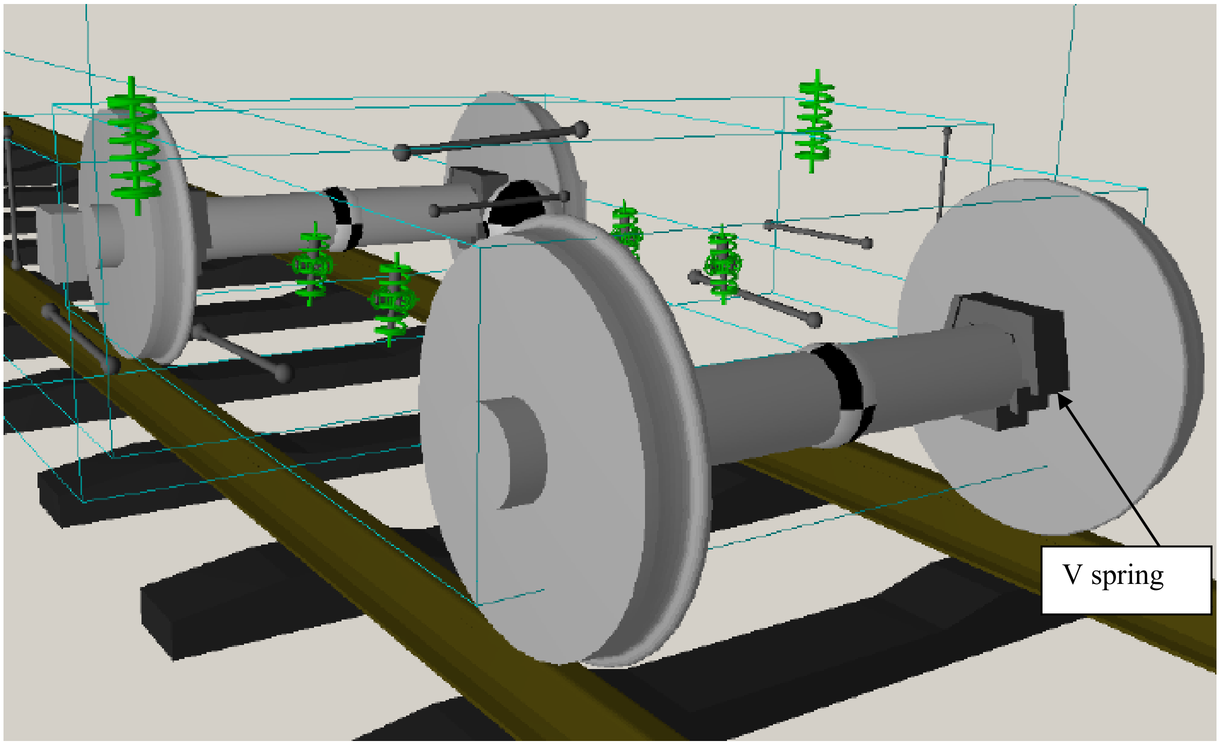


Figure : Primary Suspension Vertical Force versus Deflection Characteristic

Figure 5.2. Hysteresis present in the v spring introduces non-linearity into the system.



	Stiffness	Bumpstop	Damper	Pinlink	Shear Spring	Bush
Primary Suspension Chevrons	0	8	8	0	0	8
Side Bearer Shear Pads	0	24	32	0	0	0
Traction Shear Pads	0	2	0	0	0	2
Lateral Bump Stops	0	2	0	0	0	0
Yaw Dampers	0	0	0	4	0	0
Lateral Dampers	0	0	0	2	0	0
Air Springs and Leveling System	0	8	0	0	4	0
Longitudinal Drag Rods	0	0	0	4	0	0
Lateral Tie Rods	0	0	0	2	0	0
Secondary Vertical Dampers	0	0	0	4	0	0
Miscellaneous	1	0	1	0	0	0
Total	1	44	41	16	4	10

Figure 5.3. (top) MBS using Vampire Rail. (bottom) Other elastomers, along with displacement and velocity sensitive elements that need to be accounted for in the model.

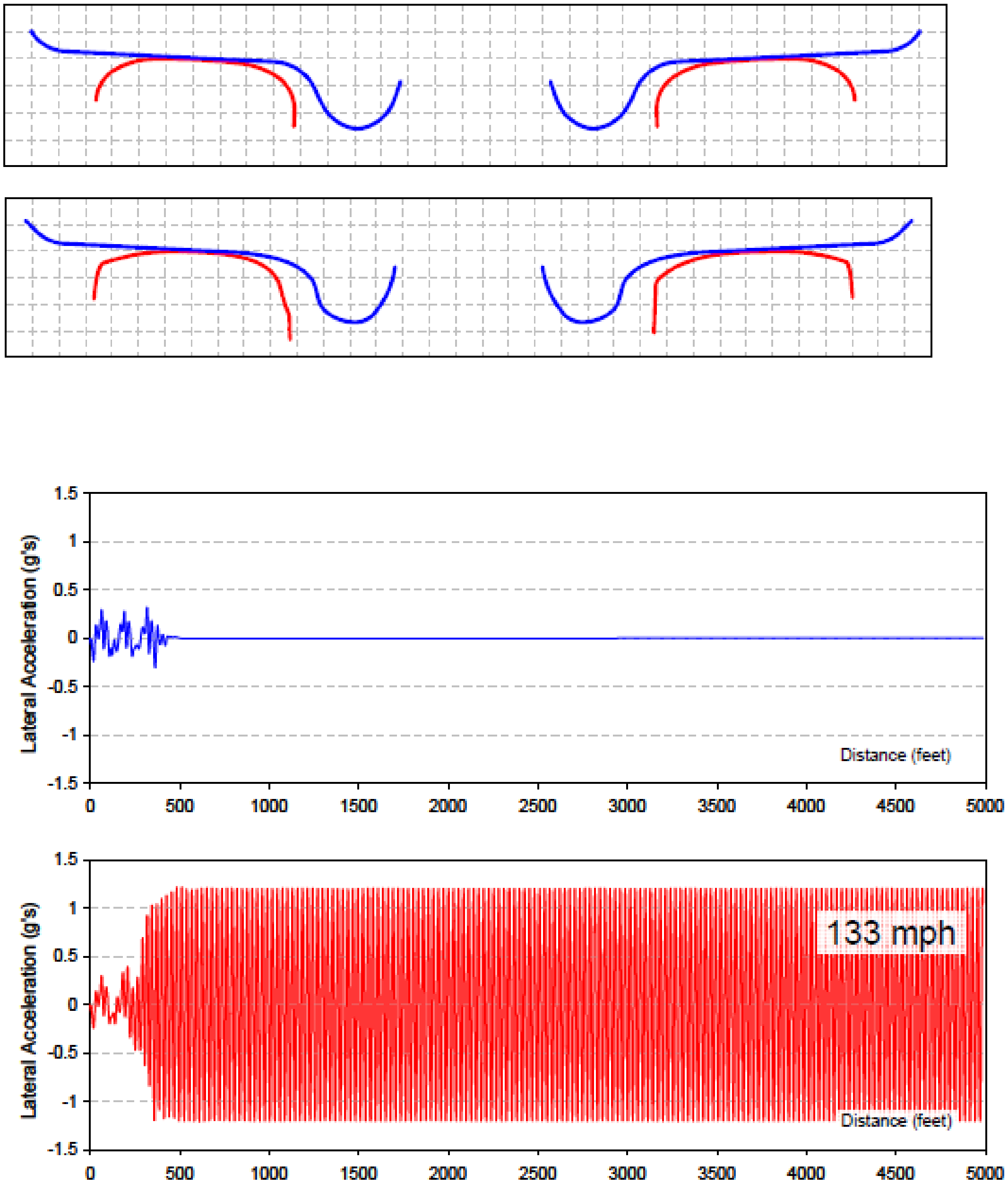


Figure : Example Truck Lateral Accelerations over Ideal Track Geometry

Figure 5.4. (top) Wheel profile. (bottom) Hunting stability which is related to Rail Vehicle lateral stability affect by wheel profile.

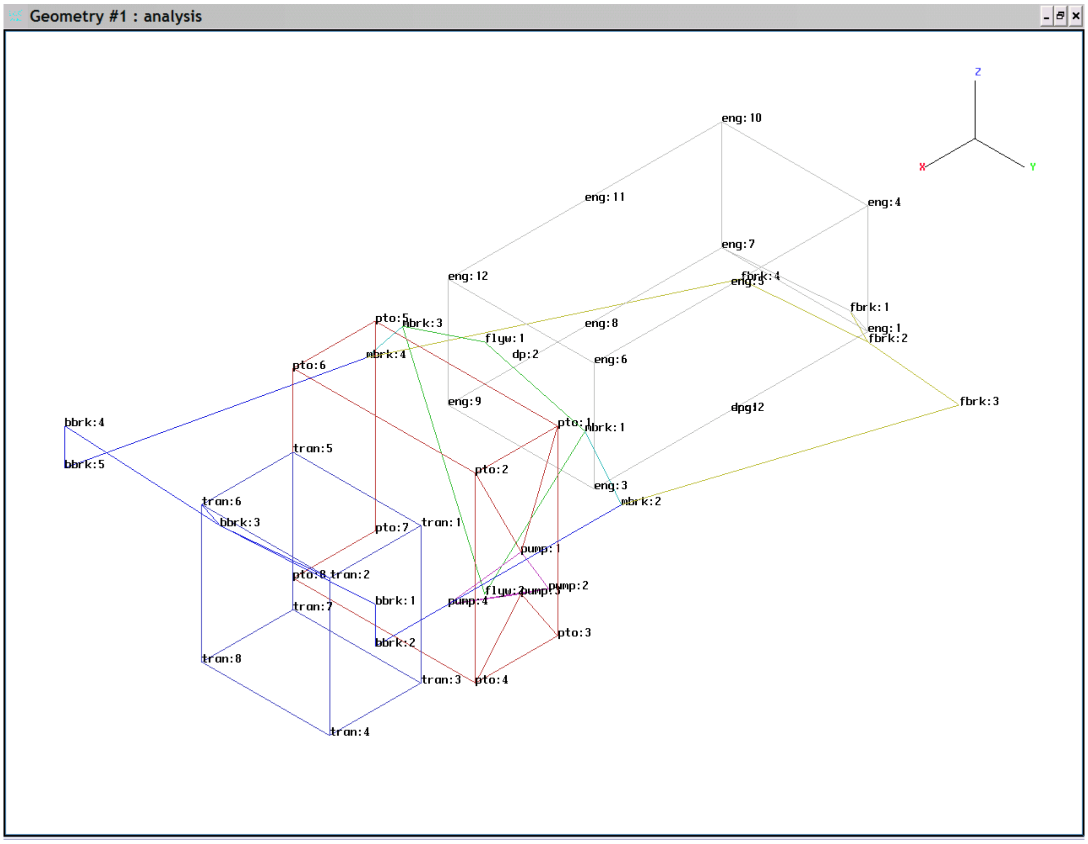


Figure 5.5. (top) Diesel 6 in-line engine and the power train mirror vibration problem high level test. (bottom) Elaborate sensor map/network for the test.

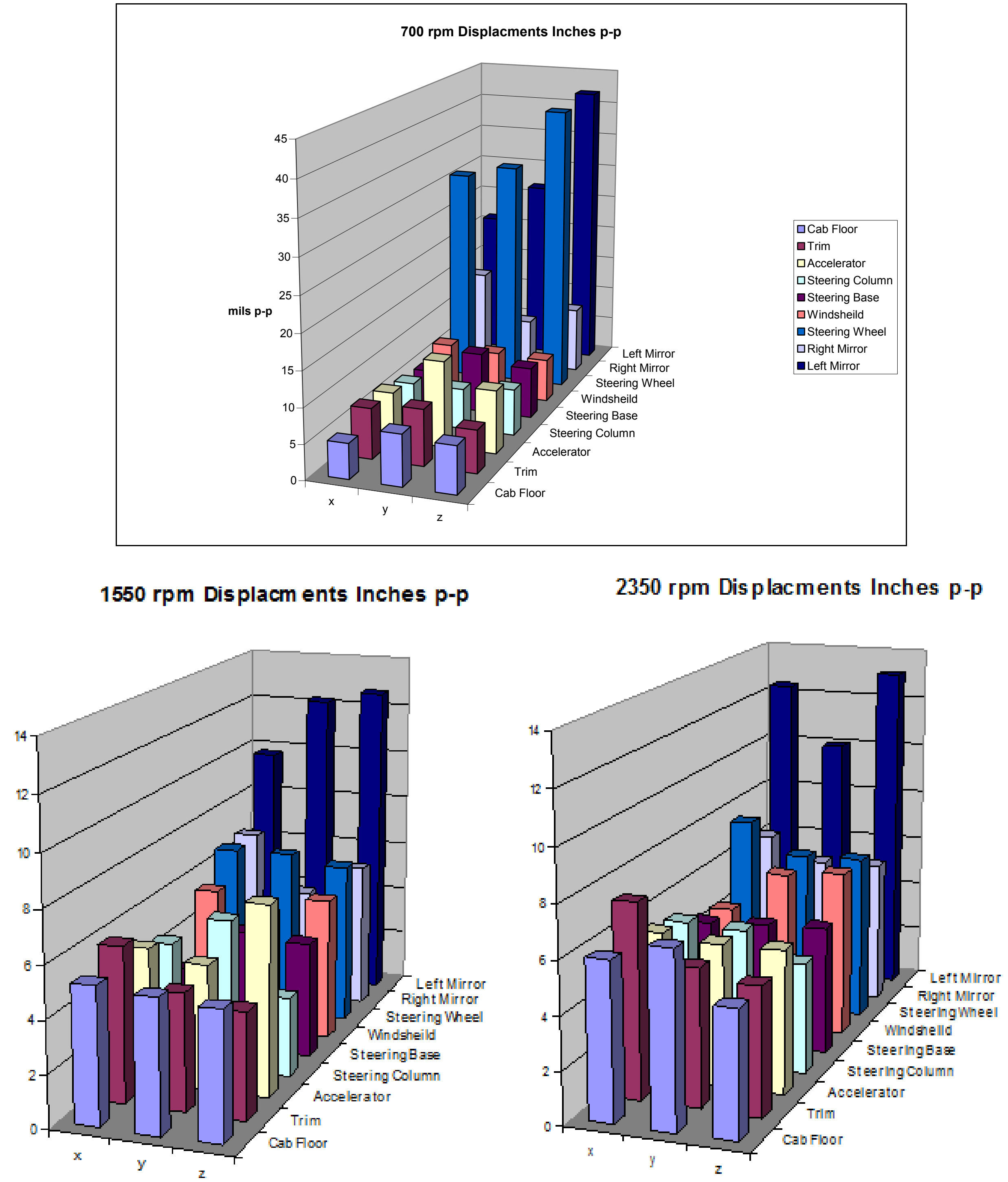
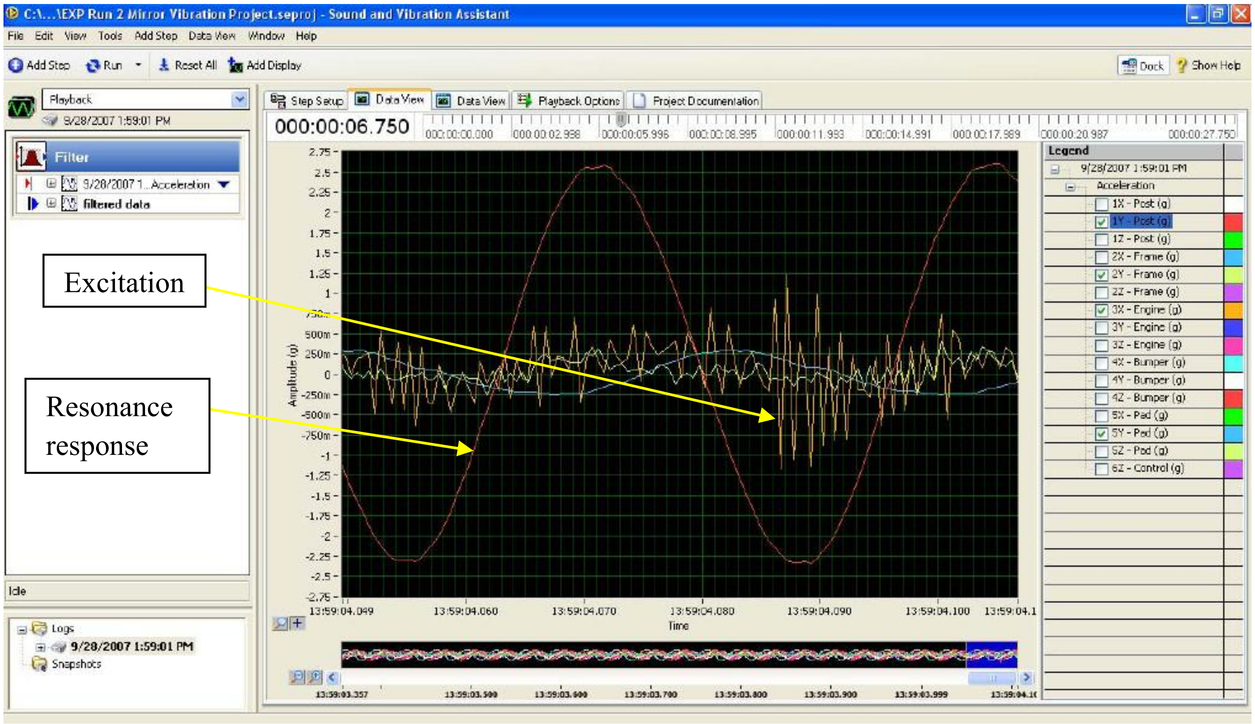


Figure 5.6. Non-linearity is apparent from the vibration data (displacement amplitude in mils p-p (peak to peak)) as the superposition relationship is not applicable with increase in speed of the engine (not proportional). Based on the data, the vibration problem is then isolated to the left mirror post (with the strongest vibration).

Figure 5.7. (top) Test truck instrumented for more isolated and lower level test. (bottom) Blurred image in the mirror is the main symptom for the engine structure-borne vibration. Test data is acquired and processed using National Instruments LabView.



Test data as shown on LabView.

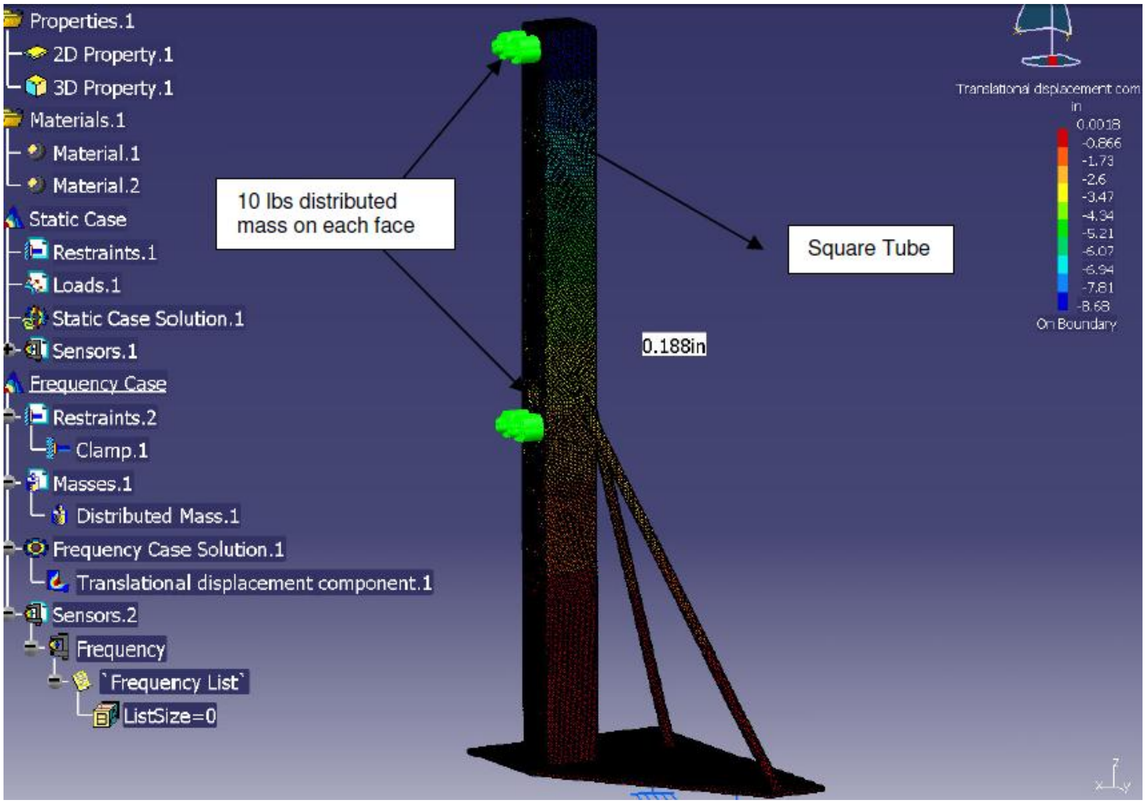


Figure 5.8. Isolated and lower level FE vibration and modal analysis which confirms test data on mirror post's structure modal participation (resonance) that exacerbated the 'mirror vibration problem'.

6. CONCLUDING REMARKS

The results of the doctoral project extensive investigations, strongly demonstrates that Virtual Prototyping (VP) approach (through MBS and FEA as in Table 2.1 framework) fulfilled the overarching goal for an *Accelerated* and *Economical* process and tool, that also produces *High Performing* products. In addition, the VP approach is found to be *effective*, and *accurate,* and therefore should be emphasized in Ground Vehicle product development processes.

Not only would it greatly mitigate risks and validate designs related to real world problems, the associated ‘product innovation race’ (refer to section 2.1.1) in the area is supported while VP approach cultivate simulation/analysis to be performed early by *mainstream engineers (with strong product knowledge)* for higher quality and quantity simulations, simultaneously breaking the ‘traditional wall’ between design and simulation process.

The proposed VP approach (that is also simulation-driven and *3D CAD associated*) additionally encourages concurrent engineering and cross functional involvement by executives and other downstream functions (sales/marketing and additional product development decision makers). This further ensures a successful product development and the corresponding product rollout.

The gains in time and cost savings due to the VP approach can be expected to improve (compared to results from the doctoral project) in the future as simulation processing speed increases. Higher fidelity models can then be added to the virtual prototype without posing as much penalty to the product development process.

In this chapter, gains and positive outcome from the VP approach implementation in the doctoral project is further compared to what are typically seen in the industry, for more objectivity and also conclusive remarks.

6.1 Virtual Prototyping Addressing Main Industrial Pressure Factors in Ground Vehicle Product Development.

As evident from the doctoral project, using various state-of-the-art VP tools, running today’s *high performing* ground vehicle product development process *timely* and *economically* is akin to solving a complex problem with competing and conflicting constraints (Table 2.3).

Ground vehicle products must be developed to exacting *high performance* specifications (Table 2.4) and yet must be able to meet increasingly *tighter development schedules* at *lower cost*. Therefore, there needs to be an *effective* and *accurate* design validation process, and balance on the trade-offs between the status quo methods (Specialized CAE and Physical Prototype/Test) and VP approach.

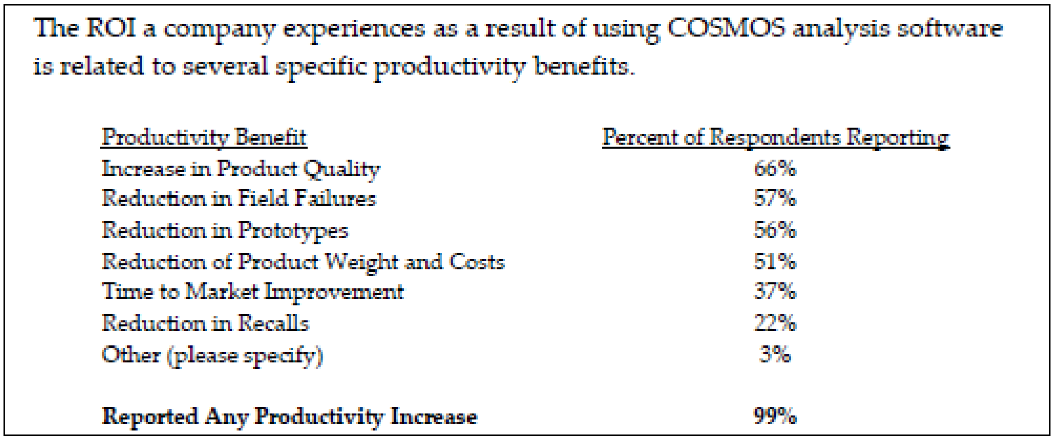
Figure 6.1 shows how Virtual Prototyping simulation/analysis strategy is leveraged in the industry in general (surveyed in 2008, towards the end of the doctoral project), and coincidentally also for the doctoral project, further signifying the VP approach in Table 2.1 as the ‘best practices’ for Heavy Ground Vehicle engineering. As seen in the figure, high in the strategy list is to ‘assess product performance early in the design process’, which is in line with the upfront VP strategy adopted in this dissertation. VP in its design synthesis also allow ‘assessment of the performance for more design iterations/alternatives’, while ‘empowering more involvement of design engineers’, for both higher quantity and quality simulations.

Because of *VP (MBS and FEA) tight integration with CAD*, all these strategies are highly feasible resulting in *high performing* products and supporting the VP approach for *accelerated* and *economical* product development process that is simulation-driven. This process provides unambiguous design direction upstream in the ground vehicle engineering process as demonstrated in the doctoral project. These VP strategies are in contrast to Specialized CAE and Physical Prototype/Test approach.

Even though, generally perceived to be ‘first-pass’ lower fidelity as compared to Specialized CAE (and Physical Prototype/Test), the VP approach is proven to not only be *effective* (with its versatility/scalability especially with regards to modeling) but also *accurate* (with good VP and test correlation). Yet it still addresses all of the seemingly conflicting demands (*high performing* product, and *reduced time* and *cost*) for the Heavy Ground Vehicle product development process. VP versatility/scalability enables Virtual Prototyping fidelity to be increased hierarchically in assisting early simulation/analysis for the design process without greatly sacrificing accuracy. At the same time, this approach build-in robustness in the product as design and response variables are better understood with greater insights.

It should be noted that the findings from the doctoral project is in contrast to a study done in 2006 (Table 6.1), where instead of being the key gain, *time savings (time to market improvement)* is reported to be a low fifth gain (after *cost*) in the list of 7 gains brought by simulation/analysis (FEA specifically, which may include Specialized CAE approach), and in which it was reported also that quality related gains are the main benefits of simulation/analysis.

Table 6.1: ROI from using COSMOS/ FEA software (52).



The ROI a company experiences as a result of using COSMOS analysis software is related to several specific productivity benefits.

Productivity Benefit	Percent of Respondents Reporting
Increase in Product Quality	66%
Reduction in Field Failures	57%
Reduction in Prototypes	56%
Reduction of Product Weight and Costs	51%
Time to Market Improvement	37%
Reduction in Recalls	22%
Other (please specify)	3%
Reported Any Productivity Increase	**99%**

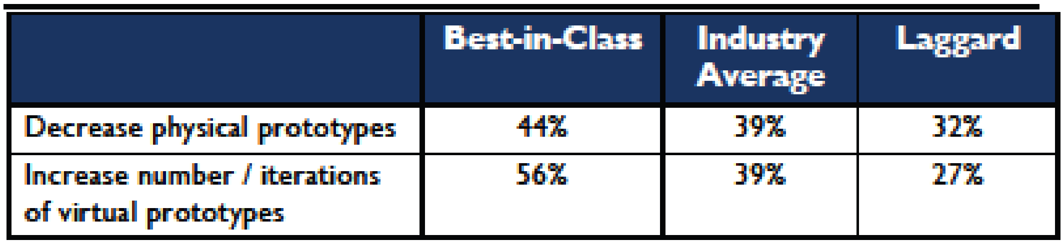
Figure 6.2 is shown to bring perspective to the different *time savings* from CAE generally (which again may include Specialized CAE approach) in product development process, seen by various companies and products as compared to the cases of the doctoral projects in this dissertation, for Heavy Ground Vehicle. For the Slag Crucible Handler (in chapter 3), the VP *time savings* is around 75% (3-4 months versus about 1 year for previous product development through Specialized CAE). As for the case of Rail Vehicle bogie (in chapter 4), comparing directly ‘digital test’ to ‘physical test’, time taken for the design validation is reduced to months from in terms of year(s), for VP and Test respectively (2-3 months versus 1 year translating to 75 to 83% *time savings*; percentage would have been diluted if other activities in product development were also included). Generally, industrial average *time savings* varies between 20-30% (compared to previous product development) according to (8).

As mentioned previously, this dissertation is about ‘Virtual Prototyping Driven Design’ (simulation-driven with rich iterations), rather than ‘Virtual Prototyping Verified Design’ (which is more an attribute of simulation through Specialized Traditional CAE sometimes coupled with test, and the area most researched on when it comes to simulation/analysis). In the product development of ground vehicle, an efficient process is needed in which CAE tools are found to best be used upfront and in design-integrated manner as in Table 2.1 framework. Again, one clear pattern is that the simulations need to be performed early for the highest value-added (Table 6.2).

‘Virtual Prototyping Driven Design’, in making the ground vehicle product development process efficient and streamlined, also focuses on doing dozens of upfront comparative analysis rather than a single perfect analysis, giving profound insights and unambiguous direction to the design like as clearly exemplified by kinematic synthesis for Slag Crucible Handler linkage system, in chapter 3. Approach opposite to this paradigm (like when adopting the Specialized Traditional CAE and Physical Test) forces the tool/method to be used later in the design process - to start the simulation, enough production definition must first be in place to actually build a digital/physical prototype which caused ‘Paralysis of Analysis’, adversely introducing bottleneck to the product development process.

Figure 6.3 additionally illustrate how the concept of Virtual Prototyping resulted in time savings. By frontloading dozens of real world loading, more information is learnt about the design, early in the product development cycle, trickling the benefit of the lesson downstream in the design cycle (as seen for example in the optimal strength-to-weight ratio accomplished for variant of Slag Crucible Handlers), and well into Product Lifecycle Management (PLM) phase.

Table 6.2. Objective behind early simulation and analysis (54)



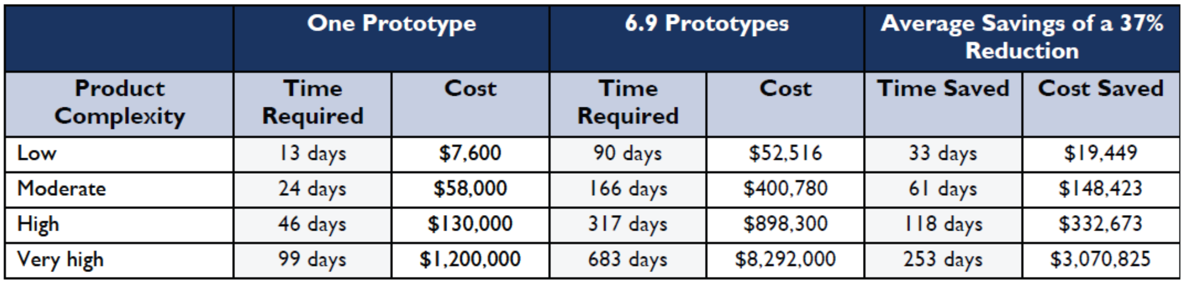
	Best-in-Class	Industry Average	Laggard
Decrease physical prototypes	44%	39%	32%
Increase number / iterations of virtual prototypes	56%	39%	27%

Source: Aberdeen Group June 2008

As mentioned, early use of simulation in the design synthesis provides direction to the design process, allowing exploration of more options to optimize the design (Table 6.2). Simultaneously, VP-driven approach also identifies weaknesses in the design, avoiding going down paths that lead to product failure. In either case, this means compressing the design cycles, making better design decisions, and avoiding trouble areas that can lead to **expensive rework and scrap too late in the design cycle**. Also importantly, VP simulation/analysis early could reduce the amount of physical prototype downstream in the product development cycle (Table 6.2). In point of fact, physical prototype can be reduced to zero as for the case of 3 Slag Crucible Handlers covered in Chapter 3.

6.2 Virtual Prototyping in Addressing 1) Short Product Development Schedule (Time Savings), and 2) Reduced Development Budgets (Cost Savings)

Table 6.3. Average Prototype Costs and Savings (34)



	One Prototype		6.9 Prototypes		Average Savings of a 37% Reduction	
Product Complexity	**Time Required**	**Cost**	**Time Required**	**Cost**	**Time Saved**	**Cost Saved**
Low	13 days	$7,600	90 days	$52,516	33 days	$19,449
Moderate	24 days	$58,000	166 days	$400,780	61 days	$148,423
High	46 days	$130,000	317 days	$898,300	118 days	$332,673
Very high	99 days	$1,200,000	683 days	$8,292,000	253 days	$3,070,825

Source: Aberdeen Group, September 2007 and November 2008

where,

Product Complexity	Number of Parts
Low	Less than 50
Moderate	Between 50 and 1000
High	Between 50 and 10000
Very High	Between 1000 and 100000

Table 6.3, shows the different figures on *time and cost savings* (on the basis of prototype reduction savings) in the industry in general allowed by simulation/analysis (which include Specialized CAE) as compared to the VP approach results in the doctoral project for ground vehicle, and to the industry average improvement of 20-30% according to (8) (compared to previous development). These figures or numbers in Table 6.3 obtained by Aberdeen Group are usually conservative (58). Also, based on the matrix/table, ground vehicles investigated on in this doctoral project fall in ‘very high complexity’ and ‘high complexity’ product category, for Slag Crucible Handler and Rail Vehicle Bogie respectively.

In the doctoral project, for the case of VP through MBS, 3 Slag Crucible Handler variants shown in Figure 3.20 were built and completed from the design work ideation to actual product roll-out in a relatively short period time frame of 9 months (average of 3 months per product) clearly proving *time savings* and an *accelerated product development,* versus over one year for previous product development through Specialized CAE (75% improvement). In average, the ‘very high complexity’ Slag Crucible Handler were built in a matter of 3 months (90 days time-to-market) as compared to 99 days (for first prototype, not for market release, Table 6.3) as typically seen in the industry. The time accounted for could have been lower as it includes simulation/analysis time (instead of time actually used to build prototype) and as the Slag Crucible Handlers were built as a final product complete with the ‘bells and whistles’, compared to a more simplified representative of the product by Physical Prototype. So, for the case of Slag Crucible Handlers, the 3 versions are the first article with no prototype built (for performance assessment and testing), which is an extreme case as compared to the industrial average of 6.9 prototype. The true ‘Physical Prototype Test’ for the Slag Crucible Handlers was in fact when the products were first used at the customer’s site (Figure 3.20).

Further, in the VP through FEA investigation for the doctoral project, comparison is done directly on cost of VP (digital test) versus its Physical Test counterpoint of an elaborate product development project on Rail Vehicle Bogie (high complexity category, Table 6.3). *Cost savings* for VP is evident, which is in the order of \$50 000 (billable hours) for FEA Virtual Test versus \$500 000 (contract cost) for physical test for both structure and durability studies (4), clearly contributing to overall reduction to product development budget. This is a \$450 000 cost savings versus industry’s \$332 000 (on prototype savings basis, Table 6.3) for high complexity product.

More importantly, for the *time savings*, FEA work for 'virtual test' in assessing product’s structural aspect, from planning to the final phase took about 2-3 months as opposed to the planned 6-8 months for physical test (including tooling development time, refer to Appendix C and D). In actuality, the physical test had surpassed the anticipated time of 6-8 months, and took over a year to complete, longer than the actual product development time itself. This is almost 1 year of time savings versus industry’s 118 day (again on prototype savings basis, Table 6.3).

Extension to FEA when doing durability studies also proved to have a tremendous effect on the *time savings*, as even when compared to 'accelerated ' physical durability test (6 million load cycle in 2-3 months used to simulate 45 years of design life), time taken is greatly reduced from being in terms of months to merely days, for physical and virtual test respectively.

It should be noted that *time savings* for VP through FEA can be expected to increase in the future as computing power improves which would result in faster processing time. Also, with speedier processing time, elegant and more realistic flexible MBS (coupled FEA and MBS) can then be more practical for upfront VP for accelerated and economical product development.

6.3 Virtual Prototyping in resulting High Performing Product

Factors/Demands related to *high performing* products are as the following, derived from Table 2.3 and 2.4 and are covered in section 6.3 and 6.4:

1) Product Complexity
2) Accelerated Customization
3) Quality related issues
4) Predicting product behavior in a real world environment
5) Finding problems/errors late in the design cycle
6) Determining which design parameters will optimize product performance
7) Determining which trade-off decisions will be best for product performance

Table 6.4 Different aspects considered in the various Ground Vehicle designs

		Ground Vehicle
VEHICLE DESIGN	**Safety (Impact/Crash Worthiness)**	**Specialized Tractor, Specialized Shunter Tractor**
	Ride & Handling	**Slag Crucible Handler, Specialized Shunter Tractor**
	Ergonomics (Comfort/Convenience)	**Slag Crucible Handler**
	Aesthetics (Styling)	**Slag Crucible Handler**
	NVH (Noise, Vibration, and Harshness)	**Specialized Shunter Tractor, Rail Vehicle Bogie**
	Durability	**Rail Vehicle Bogie**

In this dissertation, VP is also found to be an effective contemporary tool for challenging problems inherent to various aspects of ground vehicle designs (Table 6.4), covering dynamic, kinematic, static, and durability problems as oppose to Specialized CAE and Physical Prototype/Test.. This demonstrate the versatility of VP in solving wide-ranging complex ground vehicle problems (including complex shape geometry) addressing **product complexity** while at the same time addressing **product customization** as it relates to the various ground vehicle design aspects (Table 6.5), which all need to be done in *timely* and *economical* manner.

The speedy **customization** of the product variants is evident for Slag Crucible Handlers as the accumulated MBS Virtual Prototype digital information is carried over seamlessly and with ease from the baseline 50 ton Slag Crucible Handler, to the other 2 variants for the 40 ton and 100 ton versions (which took an average of 3 months of built time for each machine, as mentioned before)(Figure 3.20). The reusability of digital information in customization is greatly assisted by *CAD embedded VP*, which allow the required 'design update-simulation/analysis cycle' in speedier fashion, in customizing product. This demonstrates not only **accelerated product customization** benefit of Virtual Prototyping, but also *shorter product development* as a whole, on an aggressive scheduling. As there is typically a disconnect between CAD and Specialized CAE, reusability of digital information is less for further customization and usage.

The **accelerated product customization** in case of Slag Crucible Handlers is also attributed to the extreme case where no time was spent on physical prototype for the customized product variant. With past history in digital form (of correlated simulation and test), as credibility is established, physical prototype and elaborate test can be bypassed with high degree of confidence. Therefore, clearly a good documentation is needed in the process, and VP assists this concept with all the digital model and data (associated between simulation and test because of *CAD/CAE integration*) created in the product development process.

6.4 Accuracy, Real World Behavior, and Quality Related Cost

At the epicenter of the VP doctoral project is accuracy, which allow for a 'Virtual Prototyping Driven Design' to be performed with confident, especially when comparing its relevance in relation to Physical Prototype/Test counterpoint. Accuracy of VP strongly relates to the quality of product developed and the corresponding **quality related cost**. As VP-driven simulation and its early and rigorous iterations provides optimal design direction, accuracy further ensures a *high performing*, **problem free design downstream**.

In the doctoral project, despite 'simplifications and idealization', accuracy is proven to be effectively obtained and retained in addressing challenges for predicting product behavior in a real world environment. Tests are used to supplement and compliment VP results, and also to show and prove how closely and accurately VP tools are in **predicting real world behavior**. This demonstrates the versatility and scalability of contemporary VP tools in allowing for different degree of fidelity promoting *accelerated product development*, which is difficult to do with Standalone/Specialized CAE, let alone Physical Prototype/Test.

Accuracy is mainly proven in the doctoral project by the followings:

1) Peak load estimation for Slag Crucible Handler with strong test correlation of 9%.
2) Contact-impact phenomena validated with test with the same amount of rebound for dropped object test capturing accurately recorded energy pre and post impact.
3) Close correlation in peak acceleration in vehicle bump test.
4) Highly repeatable correlation between strain gage reading (540 reading permutations of 20 strain gages of up to 27 different load cases) for complex surface shape of cast Rail Vehicle Bogie (all within 13% after recalibration).

Despite the proven accuracy, however, it is the finding and recommendation of the doctoral project that VP and simulation/analysis should not be a wholesale substitute for Physical Prototype/Test, and experience (57). However, clearly when coupled with experience, the degree of Physical Prototyping and Test can greatly be reduced. This is as demonstrated by the investigation on 3 variants of Slag Crucible Handler where experience, knowledge, and information from one variant is carried over to the other, in which case new product to market was launched without any physical prototype built and subjected to 'shake down' instead of full fledge test.

In addition, as for the case of VP approach through FEA, generally according to (57), "…customers now insist on some type of model validation for an existing design prior to predicting the performance of designs in a competing material or process….If overall strength and deflections are predicted well in the test case, then credibility is established." With accurate and credible VP, and reduced Physical Prototype, Virtual Prototyping early iterations can then be expected to increase, which also means more engineering and greater rate of innovation introduced into the product development process.

This concept is also further facilitated as VP put the simulation/analysis together and seamlessly with design process, *early in the hands of mainstream engineers* with the required good product knowledge and experience. Versatility of VP tools can then be fully taken advantage of by *knowledgeable engineers* (as it is only appropriate to idealize/simplify as model itself is an approximation), where educated simplification can improve speed and early timing of simulation/analysis in the product development process, without sacrificing accuracy much. As demonstrated by the doctoral project, these early iterations result in **optimization** and **better decisions on trade-offs** for *high performing* products and consequently **avoiding problem/errors late in the design cycle**.

6.5 Further Remarks: Main stream Engineers and CAE-CAD Integration

Also, from the investigations in the doctoral project, outstanding factors allowing for VP to be performed upfront effectively include *tight integration between CAD and CAE (MBS and FEA)*. Such integration brings about a comprehensive GUI (user-friendly for both CAD/CAE) and tool based environment, which encourages simulation/analysis by *product savvy mainstream engineer* (versus specialist) while product is designed and refined in early and the rest of design cycle phases. Desirable characteristics of attribute 1 (*Early CAE by mainstream product savvy and experienced engineers*, based on VP approach Table 2.1 framework), is shown in section 3.4 and 4.6 in more detail.

As for attribute 2 (*CAE that is CAD integrated (embedded or associated)*), tight integration was either in the form of *embedded VP simulation/analysis in CAD* application or *directly interfaced VP and CAD* - to be fully efficient, *directly interfaced VP and CAD* also has to allow a bi-directional or 2-way associativity (Figure 6.4)).

In comparison, as for the case of Specialized CAE because there is disconnect between simulation and design digital information, reusability of such data is much less and disorganized. On the other hand, as mentioned before, *VP seamless integration with CAD* and their corresponding associated digital information can be carried over with ease and proven to result in not only *shorten product development*, but also **accelerated customization**.

The *integration/associativity of VP and CAD* would translate to great time savings especially at assembly level as constraints between parts assigned in CAD would also be carried over into VP models for MBS and FEA. Also, a lot of the detail manufacturing feature can also be included for the purpose of VP simulation/analysis. Traditionally these manufacturing features like weldment would have to be 'defeatured' to simplify the virtual prototype to allow for more efficient simulation/analysis (Figure 6.5). Today's contemporary simulation/analysis however could allow inclusion of weldment in pre processor environment, but at the expense of being more time consuming – positively however, *CAD-CAE associativity* permit quick and practical geometry simplification of weldment into a solid (one component instead of being treated as assembly, neglecting gap-contact interaction) making the FEA VP faster. The *tight integration between VP and CAD* also allow for the inclusion of complex surface geometry (an advance CAD feature) in the virtual prototype as can be seen in the VP simulation/analysis of Rail Vehicle cast bogie in chapter 4. This proved great model geometry creation/manipulation advantage of *tight integration between CAD and CAE*.

To further improve the close integration, associativity is needed not only with CAD but also between the CAE packages (FEA and MBS). As for the case of MBS and FEA, the tight associativity facilitate in feeding accurate load case and definition of constraints (between joints in MBS and boundary conditions in FEA). However, from the doctoral project it was found that coupling between MBS and FEA could be at great expense of time savings, which is allowed by elegant but time consuming flexible MBS simulation/analysis. However, with improved computing power, flexible MBS processing time can be expected to improve. On a positive note, separate (uncoupled) FEA can be performed accurately and quickly when using MBS exported load cases – further, time is saved as the need for manual FBD is eliminated in setting up boundary conditions and load cases.

CAD integrated simulation with its familiar design environment, is conducive to *early simulation/analysis in the design cycle among engineers*, braking the traditional barrier between design and simulation/analysis process. As more simulation/analysis can be expected from *engineers (with strong product knowledge)*, VP ensures more engineering and innovation in the product development cycle.

VP further benefit from today's high fidelity graphical environment of CAD, as it enables not only executive visibility and involvement in efforts for product *high performance*, but also cross functional involvement of sales and customer early into the product development process since the virtual prototype is more easily relatable to the final physical product. As for the case of Slag Crucible Handler (chapter 3), the real-world realistic 3D simulation/analysis (recreated mainly in video format) used in marketing had spurred customer interest in further customized variants for lower and higher operational load version of the Slag Crucible Handler at 40 ton and 100 ton respectively. The 3D model or virtual prototype proved to be highly portable and can be shown and marketed easily at early stages of product development by sales to customers as compared to Physical Prototype (digital figure of Slag Crucible Handler – Figure 6.6).

Advanced CAD graphical feature provides for MBS and FEA a VP ‘realistic life environment’ enabling engineers to not only qualitatively study designs at an aesthetic level, but also to quantitatively study performance of designs completely on the computer with high realism, to better ‘visualize’ problems with the inclusion of real world responses and behavior.

Another graphical feature for both VP and CAD/CAE today is that it allows for parts to be ‘intersected’ for internal information on stress, strain, safety factor and etcetera, giving great insights to product design. This type of graphical manipulation capability is further enhanced with *CAE and CAD that is integrated*. Further, video clips if generated from FEA simulation/analysis, gives great understanding of the load path, internally and externally. In addition, internal information at assembly level can also be obtained on forces through MBS at joints that act as virtual sensors, which in real world would be next to impossible to accomplish. (In comparison, CFD (which is also a great simulation/analysis tool pervasively used in aerospace engineering, but not investigated in this doctoral project), gives external information and would be easier to test).

Also, a rather novel approach of using 3 point graphic visualization (enhanced *Integrated CAD/CAE* graphical feature) to spatial kinematic synthesis brought new insights which basically extended the problem for effective ergonomic studies for ‘human factors’ (Figure 6.7).

These beneficial features undoubtedly could allow for detail failure studies in PLM phase (post product development cycle), a role traditionally assumed by Specialized CAE.

6.6 More Advanced Problem - Tackling Real World Problem Efficiently and Timely

6.6.1 Contact

As stated in the 2007 editorial of 10th Anniversary of Multibody System Dynamics journal by Werner Schiehlen, et al. - multibody dynamics allows new and much more efficient modeling concepts for simple crashworthiness problems that is contact-impact related (38).

This fact is leveraged on and demonstrated in the doctoral project to greatly boost the VP approach ability to **capture real world problem** with higher fidelity (for gap-contact, contact-impact and etcetera (refer to Appendix A.3)). Impact study although idealized are captured sufficiently, versus ‘explicit, non-linear and large deformation’ CAE simulation like of LS DYNA (3).

In the future however, with better processing time of flexible MBS (coupled MBS-FEA), real world imperfections (non-linearity and etcetera) can further be included in upfront VP for more realistic contact-impact simulation.

6.6.2 Durability

VP simulation/analysis advancement has also allowed for important durability studies in product development, as in ground vehicle it accounts for 50-90% of structural failure (refer to Appendix B3 for more detail). Durability is also one of the top simulation/analysis performed across the board in the industry for general product development (Figure 6.8, surveyed in 2008).

However, as the simulation/analysis is performed through stress-life approach, the simulation result in terms of safety factor is highly predictive and experimental (interpolated). There is no real way to correlate the simulation/analysis result to Physical Prototype/Test, unless if the simulation is performed using elegant fracture mechanics (with time history) as fatigue failure reveal itself in term of fracture or ‘cracks’ in real world. Elegant simulation/analysis would clearly be at the expense of being time consuming (refer to Appendix C and D and Figure D.2.12 to D.2.28 for physical inspection for fatigue fracture).

Nonetheless in the dissertation, VP investigation for durability was performed with great time savings when compared to physical test (accelerated).

As mentioned before, even when compared to an 'accelerated ' physical durability test (6 million load cycle used to simulate 45 years of design life), time taken is greatly reduced from being in terms of months to merely hours, for physical and virtual test respectively (Appendix C and D).

However, validation through physical test is highly appropriate as a follow up to the highly predictive durability/fatigue simulation/analysis considering the predictive and experimental nature of the fatigue simulation/analysis.

6.7 VP versus Specialized Traditional CAE

Every day, the distinction between Specialized CAE and VP approach (*CAD/CAE integrated*) tools are becoming more and more blur, as state-of-the-art VP simulation/analysis tools are equipped with more features (non-linear, dynamic response, and etcetera). Specialized CAE today also features CAD like environment which allow it to be used, more and more as upfront CAE tool (versus separate and stand-alone feature for example for FEA meshing and etcetera) (59). Based on the doctoral project, the difference in being a more effective VP tool then basically lies in the process implementation, e.g. early in the design cycle (which also put simulation/analysis in the hands of mainstream engineers, as proposed in Table 2.1 VP approach framework) or otherwise. Specialized and customized CAE setup (separate from design cycle), however is still beneficial to support template based simulation/analysis for VP by specialist (with software knowledge, Figure 1.6).

Generally, Specialized Traditional CAE through complex pre processor allow for more input and customization (typically down to machine language level) in terms of modeling as can be seen in the elaborate investigation of Computational Modeling of Dynamic Knee Simulator (Kansas Knee Simulator (29)). Elaborate and extensive investigation through simulation is also usually needed in failure studies (in PLM), in ground vehicle engineering, that today, VP tools (*CAD embedded simulation/analysis*) can also be utilized for with its added advanced features (8). VP's proven accuracy as seen in this dissertation would further support its use in elaborate and detail design verification, like when using Specialized CAE.

Table 2.1. Framework for Doctoral Project's Virtual Prototyping Approach

Virtual Prototyping Approach	Attribute
Upfront design-integrated simulation/analysis (through MSB and FEA).	Speedy and early CAE iterations by mainstream product savvy and experienced engineer(s)
	CAE that is CAD integrated (embedded or associated)

But there are complex domain areas or realm in ground vehicle and in the industry in general, that themselves requires specialist (as oppose to design engineer) because of in-depth knowledge required, like vehicle dynamics domain, that further require elaborate model definition, not only at component but at system level as well before a meaningful simulation/analysis can be performed. Another similar example of Specialized CAE needing specialist knowledge includes LS DYNA for detail impact and crash worthiness simulation (explicit, non-linear, large body deformation), even though today the software comes with the option to be integrated with CAD and FEA-CAE (3), as desired by the VP approach framework in this doctoral project.

It is worth noting here that for more advanced FEA problems, according to (57), "…. most new FEA users are design engineers. Though highly trained and well educated, many do not have a specialist's familiarity with finer points of nonlinear mechanics, fracture, fatigue, creep, yield, and phase transformations. These physical phenomena are central to FEA." This comment only strengthen the reasoning behind VP approach that upfront and speedy simulation/analysis iterations be performed by experienced and *product savvy mainstream engineers (*as in Table 2.1 VP approach framework).

6.8 Supplemented/Complimented Test-Simulation and Hybrid Simulation

While Virtual Prototyping can provide a great deal of benefit to the product development process, they are recast into simplified problems based on theory. While they can very accurately represent a product's behavior as demonstrated in the doctoral project, even the most experienced analyst let alone engineers can have major difficulty in setting up a digital/virtual prototype to accurately represents the operational environment of the final product, especially trough Specialized Traditional CAE.

So the best VP simulation/analysis approach will mitigate this effect by closing the loop on the product development process between simulation/analysis and Test like exemplified in the case of elaborate VP work on Rail Vehicle Bogie in chapter 4. Testing will be compared with simulation, and the simulation setup recalibrated until a close correlation in the results is found (which was ±13% in the case of Rail Vehicle Bogie) (35)(36)(37), for further highly accurate design iterations for the same product development process or future work.

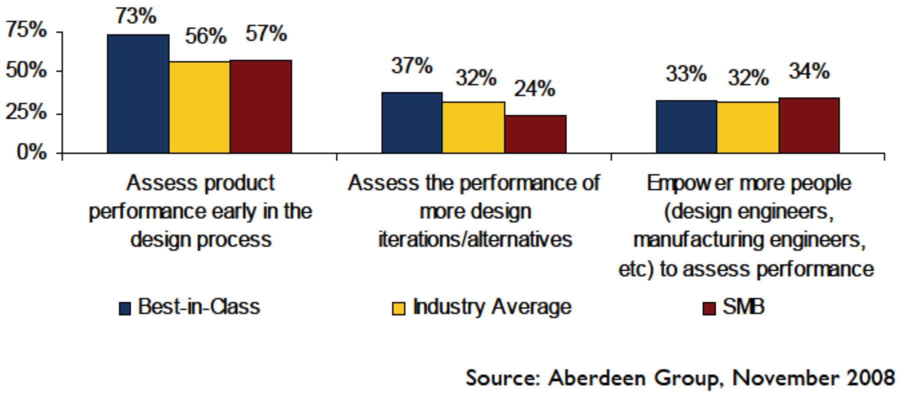
This approach is also greatly adopted in Control Engineering (electro-mechanical system and embedded system), where the 'hardware' and 'software' parts of the design are both Virtually Prototyped early in the design cycle, for 'proof of concept', and then validated with

'Physical Prototype/Test' . VP simulation/analysis while being theory based and being essentially an approximation, allow not only the 'what's' but also the 'how's' as well to be explained as Test mostly reveal 'what happen' and not necessarily 'how it happened'. By closing the loop, the process benefit from the best of both worlds. It is a 2-way street that is mutually beneficial, as demonstrated by the VP approach through FEA for Rail vehicle bogie in chapter 4, involving the following steps:

1) Calibrate simulation based on testing results -
   This is done in order to understand what caused the two to diverge (e.g. because of first time non-ideal manufacturing variation as for the case of Rail Vehilce bogie, refer to section 4.5) and subsequently recablirating simulations accordingly.
2) Base test instrumentation on simulation -
   This help identify the locations of different physical phenomena of interest that needs to be measured during the test. Reviewing simulations in this way allows for instrumentation setup to capture data on these phenomena accordingly.

Investment on VP approach and Physical Prototype/Test (for close correlation) would pay dividend and greatly pay off in the future, especially for similar products or future products customization, as when coupled with knowledge and experience, test can be bypassed with confidence (as demonstrated by 3 variants of Slag Crucible Handler ground vehicle, in Chapter 3 and as supported and stipulated in the Rail industry by its governing bodies).

In arriving at tighter relationship between test and simulation, there is also an emerging area in product development performance assessment called Hybrid Simulation. Both test and simulation were conducted on the basis of 'Test derived loads' and 'Test derived models' for the hybrid approach. The physical prototype and virtual prototype is tuned while being in the same 'loop' in real time. This approach is especially beneficial when going from component to assembly or system level design product validation, as most complex problem like in vibration problems are only discovered at full system levels. Methodically, fine tuned high fidelity lower level system (component and subsystems) are introduced to the higher level Hybrid Virtual Prototyping / Testing. This hybrid method is highly effective in the 'black art' area of NVH involving non-linear vibration. Here, Specialized Traditional CAE could lose its role for introducing high fidelity which instead is introduced via 'Test derived models'.

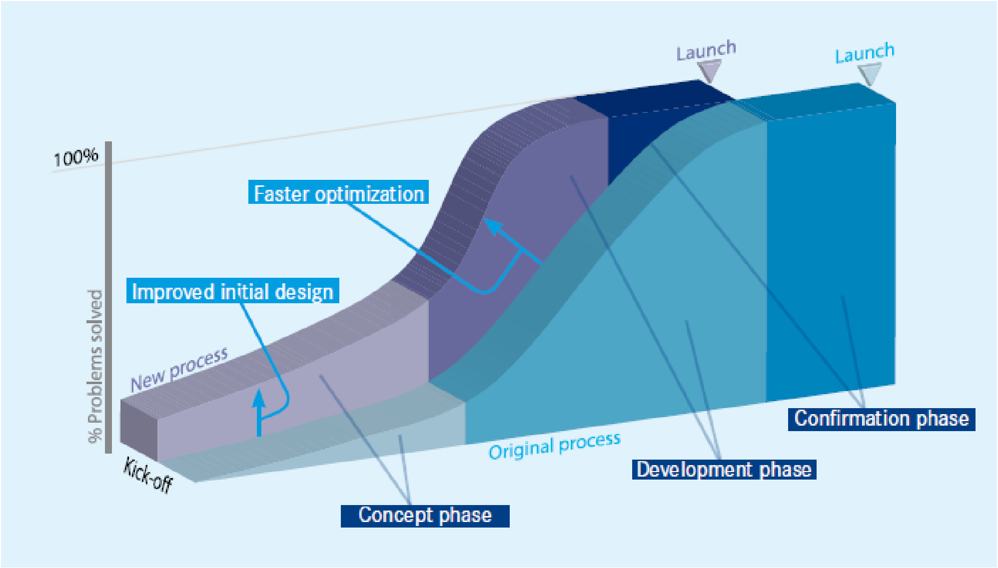


Source: Aberdeen Group, November 2008

Figure 6.1. Strategies of the best-in-Class in leveraging simulation/analysis (34).

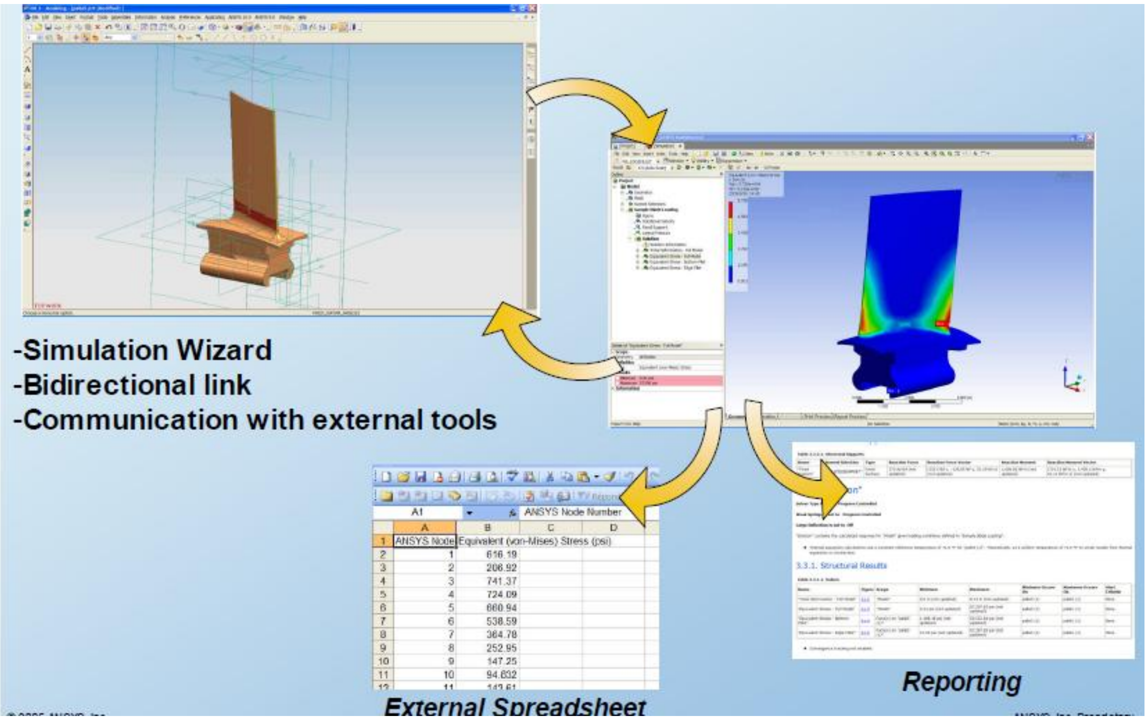

Manufacturers report significant improvements in product development performance with Pro/ENGINEER.

Figure 6.2. Breakthrough performance for PTC users (53).



Mitsubishi Motors compresses vehicle development by refining the design in the concept phase before detailed CAD and by performing fewer and faster analysis/test/redesign iterations during development

Figure 6.3. New process (Virtual Prototyping) versus original process (Specialized CAE and Physical Prototype/Test)(2).



-Simulation Wizard

-Bidirectional link

-Communication with external tools

	A	B	C	D
1	ANSYS Node	Equivalent (von-Mises) Stress (psi)		
2	1	616.19		
3	2	206.92		
4	3	741.37		
5	4	724.09		
6	5	660.94		
7	6	538.59		
8	7	384.78		
9	8	252.95		
10	9	147.25		
11	10	94.632		

Figure 6.4. Communication and bidirectional link, an important feature of successful VP tool (3).

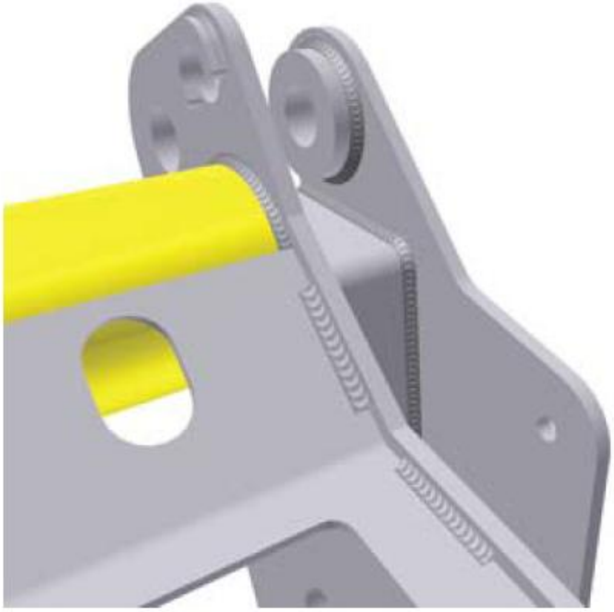
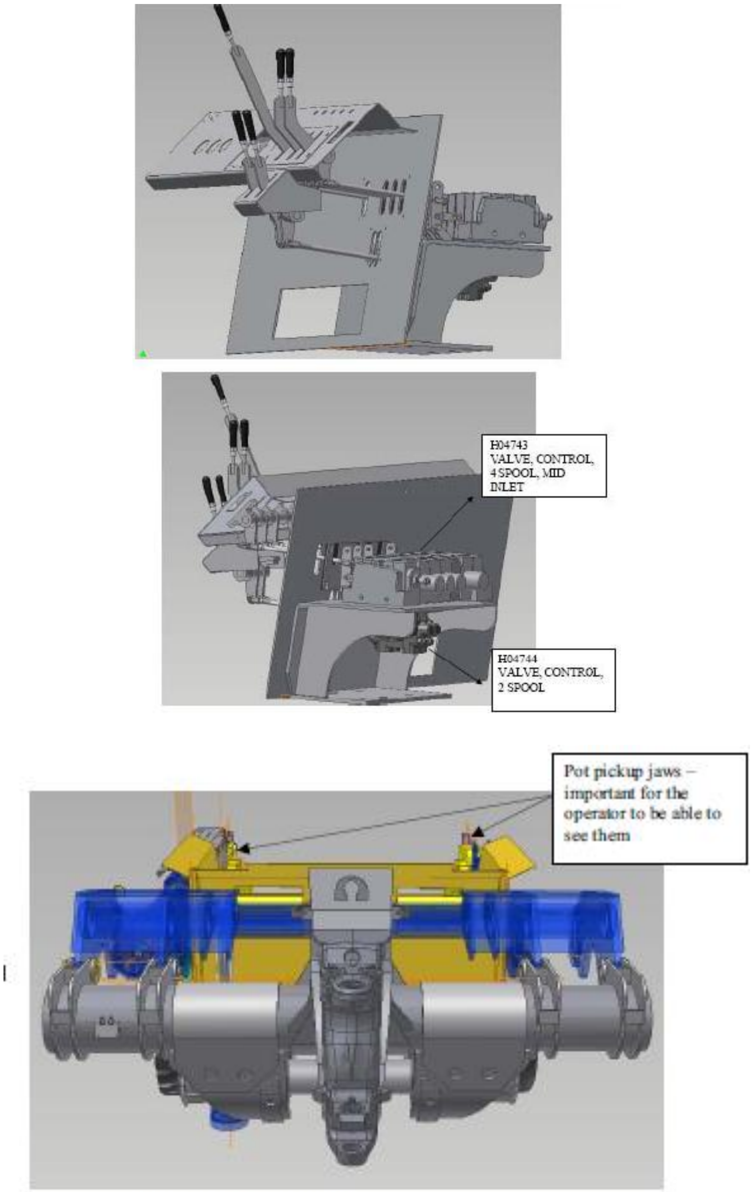


Figure 6.5. Automatic/Intelligent weld creation in CAD/CAE carried over to VP for simulation/analysis of the ground vehicle.

Figure 6.6. 3D virtual model of 50 ton (top) and 100 ton (bottom) useful in marketing effort, when compared to Physical Prototype. Videos of the machines in operation is also created to better assist in the marketing effort.



H04743
VALVE, CONTROL,
4 SPOOL, MID
INLET

H04744
VALVE, CONTROL,
2 SPOOL

Pot pickup jaws – important for the operator to be able to see them

FRAMES AT LOADING / PICKUP POSITION

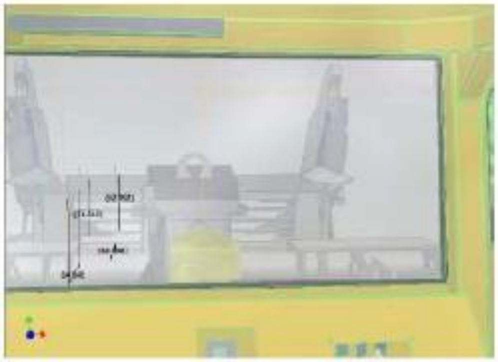
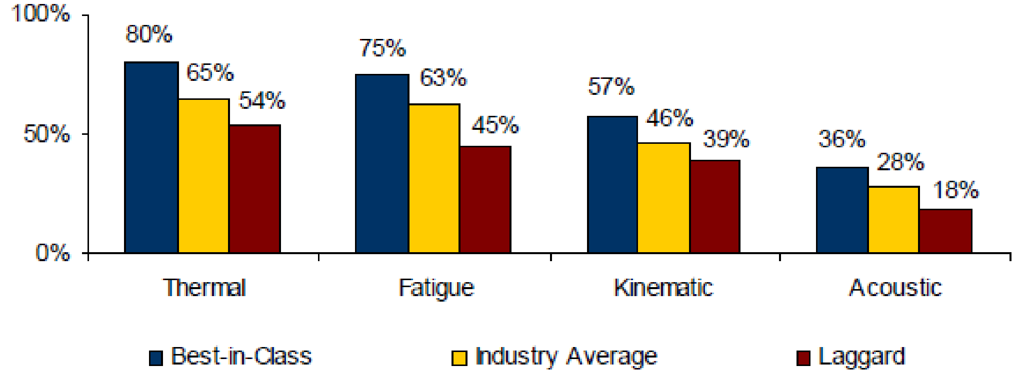


Figure 6.7. Regular view kinematic study (top, of hydraulic controls) versus realistic 3 point view kinematic study (bottom, of main linkage system) of Slag Crucible Handler.



Engineering Evolved

Source: Aberdeen Group, November 2008

Figure 6.8. Other mechanical simulations in addition to structural (FEA) and dynamic (MBS) for Virtual Prototyping.

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APPENDIX:

A. Detail of Virtual MBS

A.1 MBS Methodologies

Critical elements in MBS methodologies are links and joints. Definition of links (bodies) and joints in modeling is performed in a preprocessing stage of the MBS Virtual Prototyping, and usually is an inherent part of CAD assembly. Pre processing is then followed by processing through interactive MBS involving kinematic and/or dynamic analysis. Post processing of the results are then generated in the forms of plots and charts which can then be verified through Physical Prototype/Test.

A.1.1 Virtual Links

A link is defined as one of the rigid bodies or members joined together to form a kinematic chain. The term link, is an idealization used in the study of mechanisms of the various ground vehicle components that does not take into account small deflections due to strains. As is the case for the vehicles virtually prototyped in this section, rigid body assumption is usually reasonable because for typical vehicle parts, the maximum changes in dimensions are on the order of only 1/100 to 1/1000 of part length.

Virtual Prototyping complexity is kept down to the minimum when solving the kinematic and dynamic problem, be increased in fidelity as needed, and consequently verified via test as a show of accuracy. The fidelity of the virtual prototype is progressively increased in a hierarchical manner, as needed so that simulation/analysis can begin early, while keeping in mind the limited amount of gain in percentage of problem solved with the more elegant and realistic simulation.

A system of linkages is often named according to their joint configurations, using the symbols given. For example, RSRC describes a linkage system with R for revolute joint, S for Sphere, another R for revolute joint and C for cylindrical in its kinematic chain. This signifies the importance of joints in a multibody system (Figure 3.1 and 3.3).

A.1.2 Virtual Joints

As mentioned earlier in the paper, joint elements provide kinematic pair or simply connectivity and interface between parts dynamically in motion. Various joint elements are available for vehicle multibodies, to connect flexible and/or rigid bodies to each other. Other advance ways of 'pairing' bodies include contact, and force elements like bushings (velocity sensitive), and spring elements (displacement sensitive). Contact elements allow for parts separation while force elements do not provide direct connection between parts and serve as force transmission element. In addition, contact elements enable a more detail way for detecting collision (contact-impact) between the various ground vehicle components.

As for a general joint element, it is defined by 2 nodes with 6 degree of freedoms (DOFs) at each node. Relative motion between the 2 nodes is characterized by the 6 relative DOF. The process of defining joints in MBS modeling can also be translated into boundary conditions for FEA especially at assembly level (i.e. multi components or bodies) by today's contemporary VP technologies. Depending on the application, different kinds of joint elements can be configured by imposing appropriate kinematic constraints on any, or some, of these 6 relative DOF, allowing for various degree of accuracy of real world problem analysis (Figure 3.3). Physically, the more a joint is constrained, the more expensive it is to produce in real world, as it involves tighter tolerance. In VP, these joints are easily defined as components are put together leading to assembly level design especially in CAD embedded environment (3), (7), (48), (49).

In the Virtual Prototype, the kinematic constraints in the joint elements are imposed using the Lagrange multiplier method (19), (26), (27). Common joint types available for defining connections in MBS include spherical, revolute, universal, translational, cylindrical, and planar to name a few and could be referred to differently from one commercial software or code to another (1), (2), (3), (14), (15), (16), (17).

On the Slag Crucible Handler, and as can be seen from Figure 3.2, cylindrical joint is used to model the hydraulic cylinder actuator, revolute for journal bearings, and sphere for spherical socket bearing. Contacts are also used in more advance application to capture shocks and impact. These joints or kinematic pairs also served as virtual sensors in the vehicle simulation/analysis. Contacts also allow the study of real world imperfections in lieu of idealized joints.

Joints are initially modeled as perfect elements, with imperfection like friction, tribology aspects and clearance excluded from the simulation/analysis and the virtual prototype. Overtime, mass on the frames and linkages in the implement system tend to increase as they are optimized, built-up, and detailed, which necessitate some refinement on the 'front loading' simulation/analysis through VP.

In the process, scenarios of contact kinematically, and contact-impact dynamically need to be accounted for to account for clearance, permitted by 2D and 3D contacts feature of VP tools, demonstrating a versatility/scalability and effectiveness to capture/simulate simplified and progressively high fidelity real world problems. This is contact impact at micro or smaller scale.

Contact elements are also important to capture real world phenomena of contact-impact at larger scale or collision.

A.2 Virtual Dynamic Problems

In general, dynamic problems are more complicated to solve than kinematics ones. The kinematic problems need be resolved before the dynamic problems. The outstanding characteristic about dynamic problems is that they involve the forces that act on the vehicle multibody system and its inertial parameters as follows - mass, inertia tensor, and the position of its center of gravity. These inertial parameters are readily available in the CAD embedded environment as the assembly and components are detailed early in the design cycle.

A.2.1 Quasi Static

MBS solving engine can not only solve dynamic problems, it could also solve for forces in the joint that is in stationary or equilibrium condition. The study of forces and torques in stationary vehicle systems (and systems with negligible inertial effects) is called statics and in the simulation/analysis, the Slag Crucible Handler multibodies system is allowed to come to an equilibrium for static force value to be solved accurately – the force values can then be exported and used in structural assessment through FEA without having to devise Free Body Diagram (FBD) which can be laborious, and leaving no room for guessing (Figure 3.8 to 3.10).

A.2.2 Inverse Dynamic Problem

For the ground vehicle simulation/analysis, the solution to the inverse dynamics has two different purposes. Firstly, it determines the forces to which the multibody system is subjected to, for both dynamics and kinematic simulation problems. Secondly and importantly is the fact that the inverse dynamics yields the driving forces necessary to control the hydraulic Slag Crucible handler implement system so that it follows a desired trajectory, in a timely fashion.

In particular, results of the driving forces used for the hydraulic system from the virtual prototype simulation/analysis are plots or profile of force/pressure time history of the different cycles of implement operations.

For the Slag Crucible Handler, the plot also gave insights on:

1) Induced and generated pressure in the hydraulic circuit.

- Facilitate on the design and sizing of the hydraulic actuator and corresponding hydraulic control systems and components.

2) Optimal value to set hydraulic implement pressure relief to make the system fail-safe.

3) The effect of running the various linkages in different sequences.

4) Induced noise in the hydraulic circuit and system to study the need for accumulators for noise suppression (refer to impact/impulse section).

Plots are also produced at various joints in the linkage systems, which also served as virtual sensors (or force transducers) where, in reality testing and obtaining measurement with sensors at these difficult locations, is near impossible. The values obtain through the virtual prototype are then used for structural studies of the various components in the implement linkage system ensuring an accurate setup for FEA loading and boundary conditions.

A.2.3 Shake Down and Instrumented Testing

The dynamic simulation results are validated through instrumented testing. Pressure reading is acquired by bourdon hydraulic gage. Mock-up weights are used to simulate operational load in the validation process (Figure 3.11) and generally serves three purposes:

i) Peak pressure reading to compare against simulation.

ii) Check of physical structural integrity and also to confirm FEA (Figure 3.10).

iii) Vehicle implement system shake down.

It should be noted that validation of the simulation for the pressure reading (of the hydraulic actuator) is limited to only peak value because of the geometry of the mock-up weight (limiting the actual linkage range). In addition simulation pressure reading/profile (which is on-demand) would differ from actual pressure (generated by hydraulic pump) based on the operator input (Figure 3.10).

Nonetheless, in this VP investigation, MBS models for the Slag Crucible Handlers which are used to predict peak operational load of the large mechanical linkage system have strong agreement within 9% matching the accuracy of modeling in a specialized work of 'Computational Modeling of Dynamic Knee Simulator' of a smaller system through Specialized/ Traditional CAE (29) (Figure 2.5).

A.3 Dynamic Motion Sensitivity

The versatility, scalability, and ability to greatly simplify and then increase the virtual prototype fidelity in stages is important for VP methodologies. The upfront VP was performed in a hierarchical manner, encouraging the simulation to begin early in the design process. Level of complexity is increased over time for more reliable results to account for various dynamic sensitivities (Figure 3.4).

A.3.1 Idealization and Imperfect Joints

Joints are initially modeled as perfect elements, with imperfection like friction, tribology aspects and clearance excluded from the simulation/analysis and the virtual prototype. Overtime, mass on the frames and linkages in the implement system tend to increase as they are optimized, built-up, and detailed, which necessitate some refinement on the ‘front loading’ simulation/analysis through VP.

In the process, scenarios of contact kinematically, and contact-impact dynamically need to be accounted for to account for clearance, permitted by 2D and 3D contacts feature of VP tools, demonstrating a versatility/scalability and effectiveness to capture/simulate simplified and progressively high fidelity real world problems.

A.3.2 Impact and Impulse.

As stated by Werner Schiehlen, et al., in the 2007 editorial of 10th Anniversary of Multibody System Dynamics journal - multibody dynamics allows new and much more efficient modelling concepts for crashworthiness (contact-impact cases) (38).

In this section, this technology is taken advantage of in the upfront VP approach through CAD integrated environment. This is as opposed to a more Specialized CAE which is disconnected from design tool and process, and late in the design cycle.

Impact simulation capability is an extension to contact element in MBS, which greatly benefitted the upfront VP work in this section in capturing real world behavior. Contact element is used to mimic contact-impact or shock phenomena for the Specialized Ground Vehicle and is done in 3D to capture any possible out-of-plane forces – it is a rather ingenious way to study impact as compared to using more specialized non-linear, explicit CAE to study impact in vehicle engineering (38). The contact-impact is to account for movement in a joint due to clearance (Figure 3.12), modeled implicitly with the application of Hertzian theory.

Mechanically, impact and shock relates to a transient phenomena, impulse (or percussion) which is force that spike and occur in a very short period of time. It is beneficial to distinguish between impulse and impact problems. In the case of impulse, it is assumed that a very large force of known value acts during an infinitesimal amount of time. Impulse is also the value of change in momentum (the integral of the force in relation to time).

A typical characteristics of an impulse is that it produces discontinuities (finite jumps) in the distribution of velocities, which are determined from the value of the applied impulse. This problem is of limited practical importance because in practice the impulse value is seldom ever known. The impact problem is more important.

The impact involves the collision of bodies in which at least one of them experiences an abrupt change in velocities. The point of contact undergoes an impulse, which is generally unknown. In order to be able to calculate the effect of the impact on the system’s velocity distribution, it is necessary to introduce into the Virtual Prototype an additional parameter of experimental and predictive nature – coefficient of restitution - which measures the nature of the surfaces and the corresponding friction in contact and the type of impact.

The study of the effects of impulse and impacts in the distribution of velocities and accelerations of a multibody system can be carried out separately or within a VP dynamic or MBS simulation/analysis program. Since it is a transient phenomenon, choice of integrator and correct minimal time step for the strategy of VP modeling is important (Figure 3.19 to 3.20).

Consideration of contact-impact phenomena for the Slag Crucible Handler is critical as the clearance because of the contact-impact introduced noise into the system (Figure 3.12). With regard to the noise, configurations of the design can be suited to mitigate the effect, and what-if's study facilitate this through the upfront Virtual Prototyping.

The followings are other problems investigated on with respect to impact:

A.3.2.1 FOPS for Specialized Shunter Tractor.

(Figure 2.13 and 3.13)

FOPS is the acronym for Falling Object Protection System, and for the case of the Shunter Tractor (Figure 3.14), it is outfitted at the top of the roof of the driver/operator's cab as a safeguard. Both virtual prototype and test are performed for the problem to assess the structural integrity of the system (Figure 3.13 and 3.14). The problem is actually a dropped object-impact scenario. In case of the physical test, the dropped object is mimicked with a ball dropped from a predetermined height.

In Virtual Prototyping, through MBS, upfront impact/shock simulation is performed to get an estimate of the impact force, while the FOPS design is being developed. Important in impact scenario is the estimated amount of energy absorbed - the simulation/analysis is in good agreement with the physical test where it predicted the same amount of kinetic energy and also bounce-height of the dropped object, indicating an acceptable accuracy of the contact-impact simulation.

Through FEA, the impact force was used as an input for structure analysis. FEA predicted well the high stress area where failure actually occurred on the physical FOPS frame (Figure 3.14).

Close agreement between the test and Virtual Prototyping simulation/analysis gave a high degree of confident for further VP work, not only for the FOPS system, but other designs subjected to impact as well. This also demonstrates upfront CAE technologies to sufficiently and accurately assess design performance quickly and early in the design cycle as opposed to a elaborate 'thrown over the wall' to specialist approach typical for Specialized CAE.

A.3.2.2 Forklift Mast for Specialized Tractor

(Figure 2.12 and 3.15)

For the specialized tractor/forklift, contact-impact simulation was performed for the vehicle's mast (frame that carries, lift/lowers, and tilts the frontal fork like carriage). The mast is subjected to impact by a battering hammer outfitted to it, used to pound shims for jigs and fixtures typically seen at steel industry facilities (Figure 3.15).

From the simulation, impact forces were derived and used in FEA to assess the mast structurally (Figure 3.16). An important criteria is for the mast to be away from plastic deformation, structure wise when subjected to the impact forces. Not only important structurally, if any of the stresses indicates a plastic deformation, the simulation would be rendered invalid as it would require an explicit capability, beyond the scope of the upfront MBS technology used.

With acceptable accuracy of the impact simulation, the results gave a good guidance to assess the mast (in the linear non plastic region) and also the corresponding retaining system (pins, bolts, and etc.) against its structural requirement (Figure 3.16). Not only would a test be time consuming, it would have been especially difficult to setup a test for these conditions physically on the forklift mast, let alone to measure the impact.

A.3.2.3 Walking Beam Suspension for Slag Crucible Handler

(Figure 2.10 and 3.17)

The 100 ton Slag Crucible Handler increased requirement on the operational load has warranted for another axle to be added for the trailer of the specialized vehicle. The resulting 2-axle for the trailer is outfitted in a walking beam parallelogram suspension configuration, to negotiate and 'walk' on any road undulation encountered by the vehicle considering that the vehicle is of off-road type.

Outstanding characteristic for the upfront simulation is that the vehicle tires are simplified as 3D orthotropic elastomer/bushing elements. Tire model would have been a more elegant one (for example, Pacejka and TNO MF tire model) if the simulation was to be specialized and elaborated (Figure 3.17) (47)(49). Bushing element is a reasonable estimation to the tire, especially considering that it is only to account for the forces in the vertical direction, without much regard to lateral cornering force or tire roll/slip (47).

The simulation gave a good estimation on the impact forces for the walking beam simulation, which are then used for FEA for structural studies (Figure 3.18). The impact forces measured also assist the proper spherical bearing sizing (Figure 3.19).

More importantly in the VP simulation, is the estimation of g multiplication factor. The g factor derived from the simulation proved to be comparable to physical test performed on similar vehicle (Specialized Shunter Tractor).

B. Detail of Virtual FEA

B.1 Virtual FEA Terminologies and Its Advancement.

FEA in general numerically models a physical system comprising a part or assembly, material properties, and applicable loading and boundary conditions (steps collectively referred to as pre-processing), provide the solution of that numerical or mathematical representation (solving), and the means to study the results of that solution (post-processing) (Figure 1.1, Figure 4.2 to 4.5 and 4.8)(15)). It should be noted that a big part of FEA pre-processing is meshing, where a geometry is broken down into solvable FEA elements.

Simple geometry and simple static problem can be, and often are studied manually through classical analytical method. However, most real world parts and assemblies for ground vehicle today are too complex to be simulated and analyzed accurately, let alone quickly, especially to be front and uploaded in Virtual Prototyping without the assistance of CAE and appropriate software like FEA (3).

However, numerical methods are composed of numerous simplifications and approximations. The tradeoff that makes the problem solvable also often reduces the model's fidelity from the actual behavior of the item being modeled. Problems when simplified are linearized, whereas in reality they are non-linear in terms of geometry, material, and contact (because of gap and clearance in boundary condition).

Therefore, proper choice of, and configuration of the employed numerical method modeling or virtual prototyping strategy is critical to gaining as complete an understanding of the nature of the problem as is possible.

For FEA, to give a perspective to the advancement of the technology especially in terms of processing speed (which allow for rapid upfront VP), the original software code had a limit of 68000 degrees of freedom (DOF or variables that are directly solved by FEA solver engine), which was believed to be larger than anyone would ever need using mainframe computers in the 60's. Today, models with 1 million DOF are being run on deskstop computers with ease and capable of running in excess of 1 trillion operations per second as compared to 100000 operations per second in 1970s in solving both linear and non-linear problems (refer to Figure 4.2 of Slag Crucible Handler meshed platform with 2 million DOF). Additional investment on hardware can further improve FEA and CAE software performance (Figure 4.1, surveyed in

2009). It should be noted, however, that FEA is considerably more demanding on computing performance as compared to MBS in Virtual Prototyping.

The development in computer graphics technologies also had a profound effect on FEA as graphic ‘pre’ and ‘post’ processors (Figure 4.2 and 4.3) became available and engineers could examine colored stress contours instead of poring over tabular output on green-bar fanfold papers. The link to CAD was the catalyst to this quantum leap to FEA development and the concept of Virtual Prototyping to structural problems, allowing design engineers to seriously and more frequently consider incorporating FEA into the general product design process, especially early on, by ‘front or uploading’ the problem leading to simulation driven product development (Figure 4.7).

For almost 3 decades, structural CAE simulation/analysis and VP FEA followed a monotonous direction of complicated software tools built for highly trained, highly specialized users. Then there was a divergence when the technology branches split into two – Upfront and Specialized/Traditional. Traditional tools are still required to handle a minority of highly complex research projects (or failure studies in PLM) or to support template based structure FEA. Upfront CAE and Virtual Prototyping however, has emerged as the simulation workhorse enabling engineering teams to tackle the majority of live industrial projects in today’s shrinking ground vehicle art-to-part design cycles (1)(3), and is taken advantage of in this dissertation.

These VP tools allow a quick down-selection through numerous design options in a structured qualitative way that is simply not possible with Specialized CAE, let alone Physical Prototypes. As the best directions emerge in the design synthesis iterations, more details can be included, moving toward rigorous quantitative simulation phase (akin to traditional CAE), depending on project schedule. The real business benefit of upfront CAE, however, lies in the early phase through Virtual Prototyping.

Unfortunately, this fact is often lost on new upfront CAE adopters, as ‘paralysis of analysis’, lack of expertise, and time are cited to be major obstacles to successful Virtual Prototyping implementation (Figure 2.1).

B.2 Virtual Durability and Dynamic Loading

It is estimated that 50-90% of structural failure is durability related. Durability of a design is closely associated to fatigue physical phenomena and reveal itself in real life in the form of cracks, which necessitate a need for effective fatigue design tools. At the time when the doctoral project for the dissertation begun, fatigue tools which provides both flexibility and usefulness comparable to other types of VP tools considered are becoming available and improving, to be deployed upfront in the design cycle. With high operational load on Rail Vehicles, a good fatigue study is critical for its Specialized Rail Vehicle Bogie frame (Figure 4.10).

In this section, fatigue study is basically Virtually Prototyped as an extension to FEA simulation/analysis. By definition, fatigue is caused by changing the load on a component overtime, and therefore is considered as a dynamic phenomena. Thus, unlike the static stress assessment tools, which perform calculations for a single stress, fatigue damage occurs when the stress at a point changes over time. Therefore, stress data is first required before fatigue simulation/analysis can be conducted.

Contemporary VP simulation/analysis tools can perform fatigue calculations based on stress life approach and depending on proportionality of loading (non varying principal stress) or on whether amplitude of loading is constant. Perfect example of non constant amplitude fatigue load case is strain gage time history data of suspension subjected to ‘g’ or transient impact loading as seen in Figure 3.17 and 3.18. A scale factor can be applied to base loading if desired and is useful to see the effects of different finite element load magnitudes without having to re-run the stress analysis, further facilitating in ‘what-ifs’ iterations.

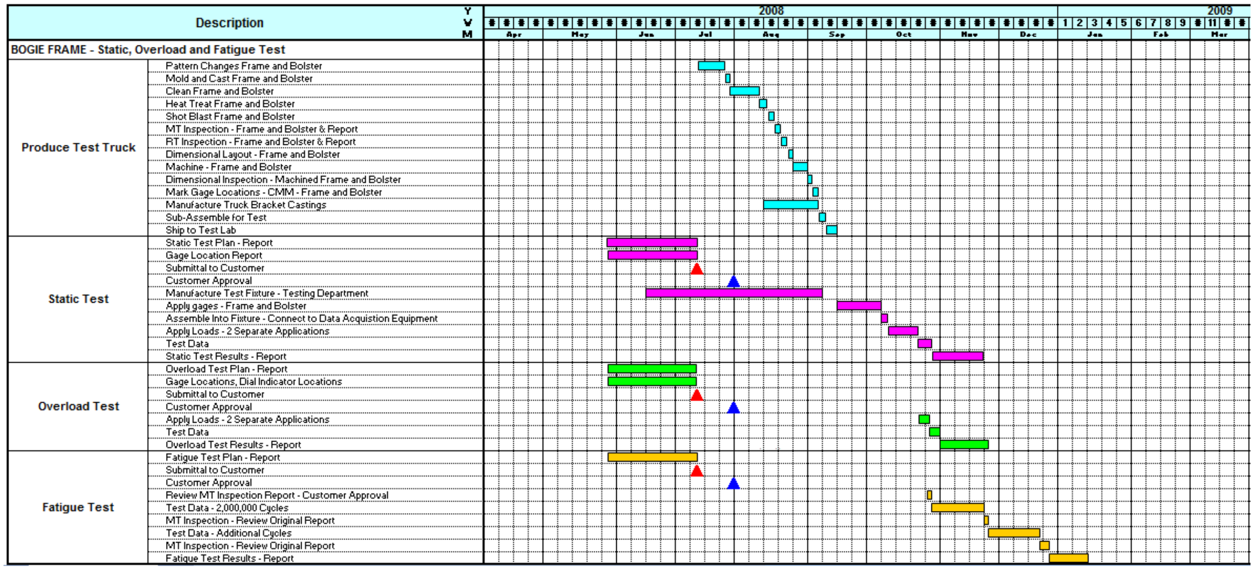
A large part of a fatigue analysis is getting an accurate description of the fatigue material properties. As stress-strain property is required for static stress analysis, the analogue S/N (Strength-Number of Cycles to failure) property is needed for fatigue analysis. Fortunately, for the doctoral project considered in the dissertation, materials considered are mostly of steel and its standard alloy, with data widely available. Since fatigue study is so empirical, sample fatigue curves accuracy acquired through test are very important, especially for custom alloy material which are used on some components on the Rail Vehicle Bogie (Figure 2.14). With the fatigue curve (S/N curve), output from fatigue simulation/analysis include safety factor (Figure 4.10).

As a follow up, an accelerated physical test was performed at 6 million cycles to mimic the ground vehicle 45 years of design life. An outstanding advantage of virtually simulating a fatigue problem in addition to time and cost savings, is that it would limit the case of over testing - as in physical test, the prototype is subjected to millions of load cycle, for the fatigue study (failure would be in the form of fatigue fracture/cracks; refer to Appendix C and D and Figure D.2.12 to D.2.28 for physical inspection for fatigue fracture).

C. SUMMARIZED STRUCTURAL TEST PLAN

C1. Test Schedule

Table C.1. Detail Test Schedule and Timetable



Description	
BOGIE FRAME - Static, Overload and Fatigue Test	
Produce Test Truck	Pattern Changes Frame and Bolster
	Mold and Cast Frame and Bolster
	Clean Frame and Bolster
	Heat Treat Frame and Bolster
	Shot Blast Frame and Bolster
	MT Inspection - Frame and Bolster & Report
	RT Inspection - Frame and Bolster & Report
	Dimensional Layout - Frame and Bolster
	Machine - Frame and Bolster
	Dimensional Inspection - Machined Frame and Bolster
	Mark Gage Locations - CMM - Frame and Bolster
	Manufacture Truck Bracket Castings
	Sub-Assemble for Test
	Ship to Test Lab
Static Test	Static Test Plan - Report
	Gage Location Report
	Submittal to Customer
	Customer Approval
	Manufacture Test Fixture - Testing Department
	Apply gages - Frame and Bolster
	Assemble Into Fixture - Connect to Data Acquistion Equipment
	Apply Loads - 2 Separate Applications
	Test Data
	Static Test Results - Report
Overload Test	Overload Test Plan - Report
	Gage Locations, Dial Indicator Locations
	Submittal to Customer
	Customer Approval
	Apply Loads - 2 Separate Applications
	Test Data
	Overload Test Results - Report
Fatigue Test	Fatigue Test Plan - Report
	Submittal to Customer
	Customer Approval
	Review MT Inspection Report - Customer Approval
	Test Data - 2,000,000 Cycles
	MT Inspection - Review Original Report
	Test Data - Additional Cycles
	MT Inspection - Review Original Report
	Fatigue Test Results - Report

Comment: Test actually took almost a year than the anticipated 6-7 months.

C2. Loading Schematic

Vertical – Test Load Schematic

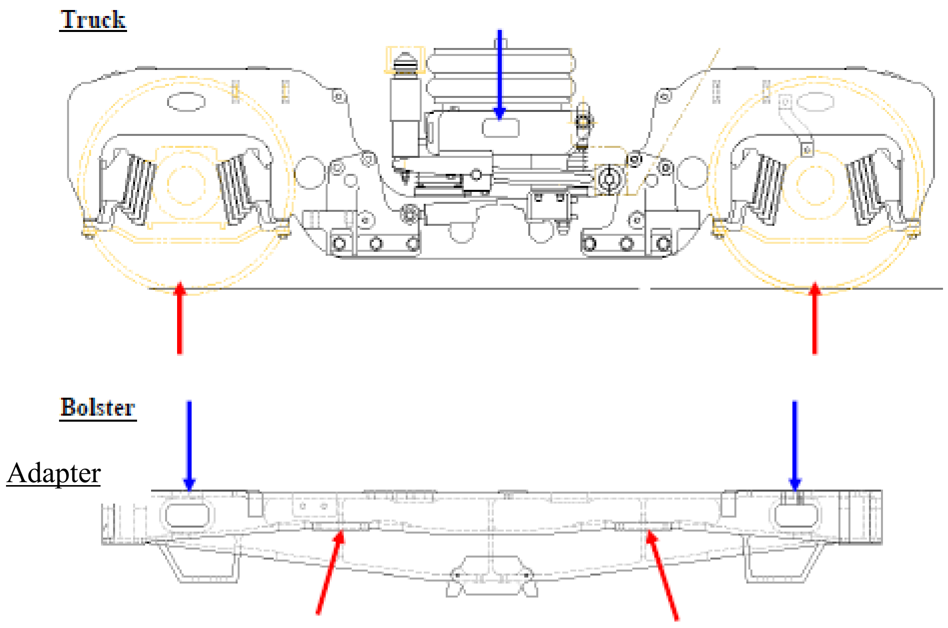
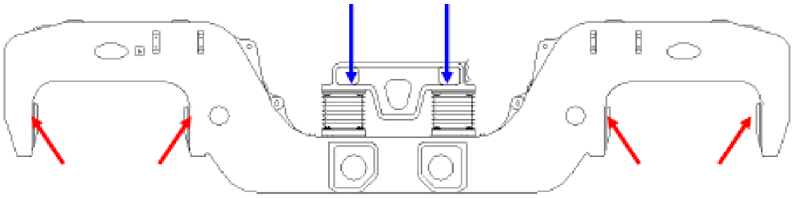


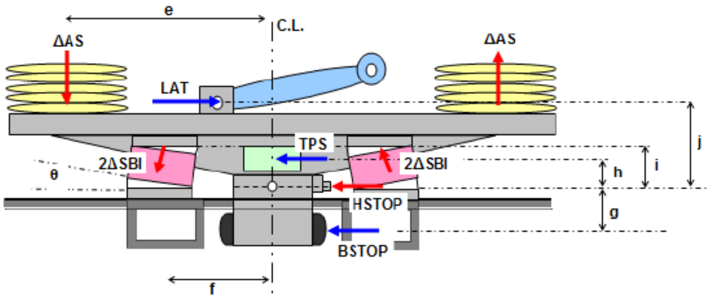
Figure C.1. Sample Test Load schematic and Free Body Diagram

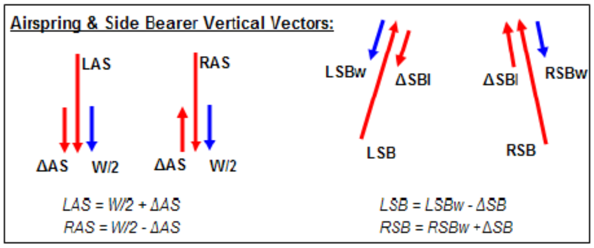
Frame



Load Transmission:
Carbody vertical loads [carbody weight, weight transfer] are transmitted to the truck through the air spring location on the bolster with test fixtures fabricated to simulate the air spring loading. Vertical loads are transfer from the bolster to the frame at the four side bearer mounting locations with steel test fixtures to replace the side bearers.

Load Reaction:
Vertical loads are resolved where the eight chevron adaptors interface with the frame pedestals.





$LAS = W/2 + \Delta AS$
$RAS = W/2 - \Delta AS$
$LSB = LSBw - \Delta SB$
$RSB = RSBw + \Delta SB$

Starting Simplification: *Side Bearers and Airsprings are Compression Only Supports*
RAS = 2LSB = 0 lbs [Allows initial solution of load change due to lateral load offset 'h']
Then assuming equal loading/unloading for side bearers and airsprings we solve for actual SB and airspring loads

LATERAL LOADING *(Positive Lateral Case)*

Definition	Symbol	Value	Units
Hardstop - Bumpstop	g	4.125	in
Hardstop - Traction Pad	h	2.375	in
Hardstop - Side Bearers	i	8.625	in
Hardstop - Lateral Tie Rod	j	16.875	in
Lateral Bumper Load	BSTOP	6,406	lbs/stop
Traction Pad Shear Load	TPs	814	lbs/pad

Side Bearer Load Delta	ΔSBl	3,806	lbs/sb	$\Delta SBl = [LAT(j) + BSTOP(g) - 2TPs(h)]/[4(\cos\theta(e+f)+4\sin\theta(i)]$
Airspring Load Delta	ΔASl	7,571	lbs/airspring	$\Delta ASl = 2\Delta SBl(\cos\theta)$
RHS SB @ Design Load	RSBw	21,651	lbs/sb	$RSBw = W/4\cos\theta$
Right Side Bearer Load	RSB	60,542	lbs/sb	$RSB = RSBw + \Delta SBl + \Delta SBr$
RHS S.B. - Vertical Load	RSBv	60,210	lbs/sb	$RSBv = RSB(\cos\theta)$
RHS S.B. - Horizontal Load	RSBh	6,328	lbs/sb	$RSBh = RSB(\sin\theta)$
LHS SB @ Design Load	LSBw	21,651	lbs/sb	$LSBw = RSBw$
Left Side Bearer Load	LSB	-17,240	lbs/sb	$LSB = LSBw - \Delta SBl - \Delta SBr$
LHS S.B. - Vertical Load	LSBv	-17,146	lbs/sb	$LSBv = LSB(\cos\theta)$
LHS S.B. - Horizontal Load	LSBh	-1,802	lbs/sb	$LSBh = LSB(\sin\theta)$
Right Side Bearer Front-Vert.	RSBFv	60,210	lbs/sb	

Figure C.1. Continued…

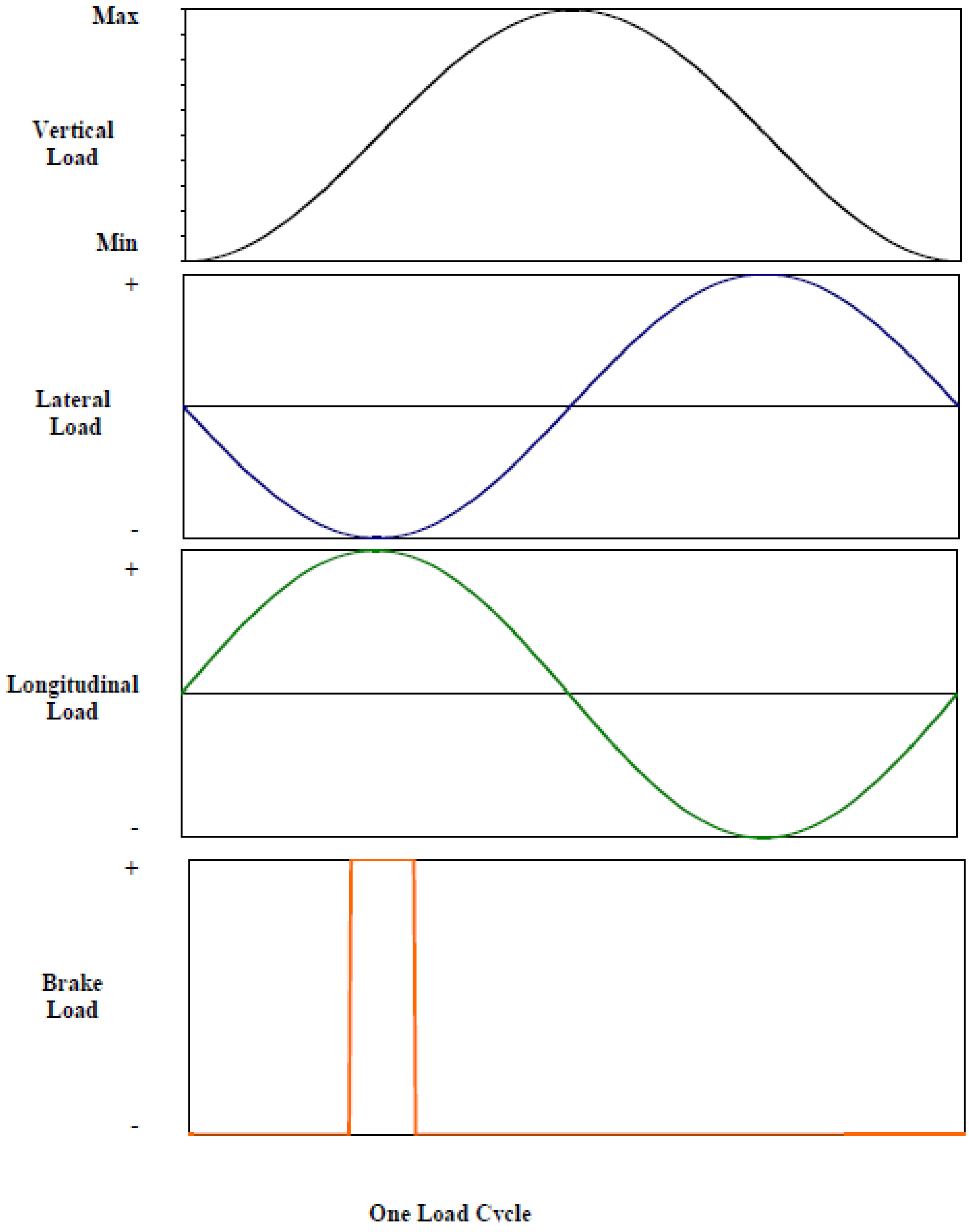


Figure C.2. Fatigue Test Load Phasing

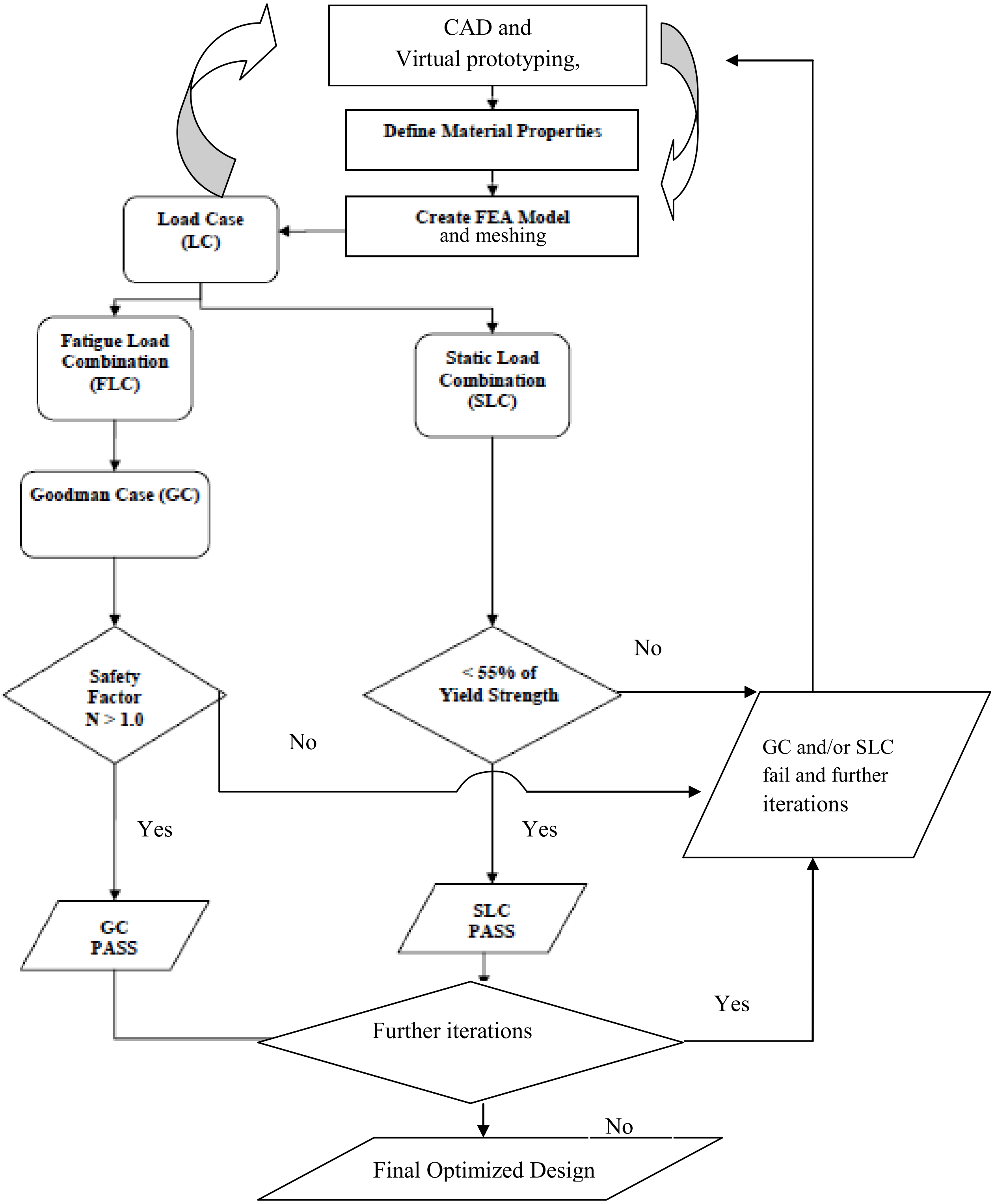


Figure C.3. Workflow for FEA Virtual Prototyping

C3. Gage/Sensor Placement or Mapping

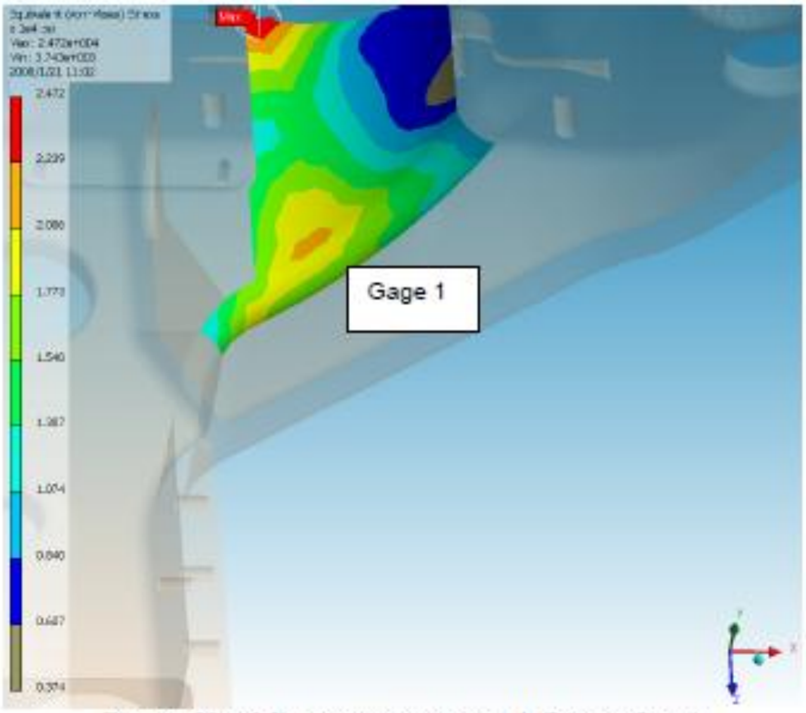


Figure: Von Mises stresses at gage 1 (Linear Gage)

Gage	Node Number	X	Y	Z	Von Mises Stress	Gage Type
1	34463	15.491	-1.8505	-15.343	21000	Linear

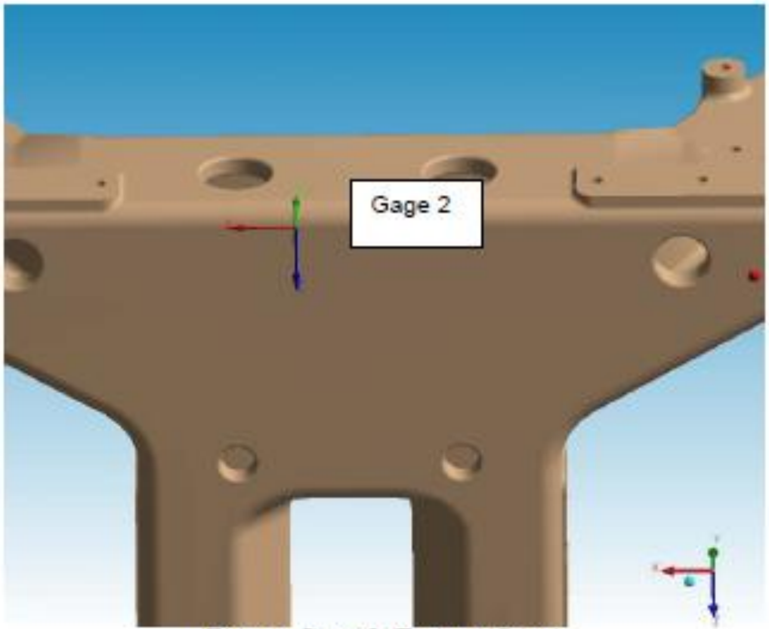


Figure: Gage 2 (Rosette Gage)

Figure C.4. Placement of a linear gage (top) and rosette gage (bottom).

C4. Test Setup Virtual Prototype

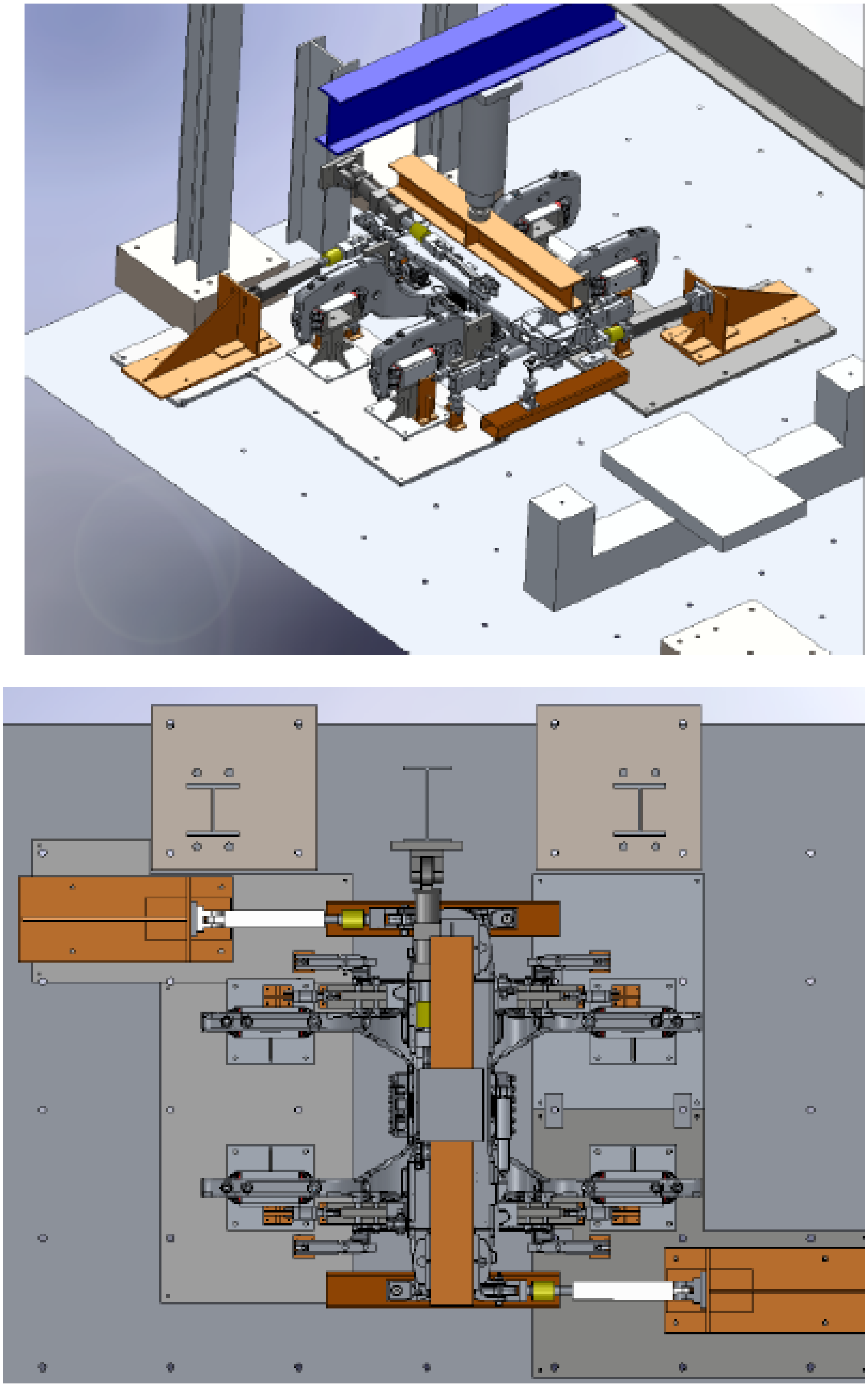


Figure C.5. Test Jigs and Fixtures Virtual Prototype

D. STRUCTURAL TEST REPORT

D1. Comparison Virtual Prototype-Test

Vertical Load Case: Load Case 4

Gage	Test (Psi)	FEA (Psi)	% Difference
1	6864	7500	8%
5	5244	6007	13%
6	1287	1176	-9%
7	1839	2102	13%
8	2196	2400	9%
9	5700	6500	12%
11	2842	3214	12%
12	2992	3326	10%
13	1032	922	-12%
14	3218	3600	11%
15	4811	5450	12%
16	2565	2300	-12%
2	7506	8264	9%
3	13398	12221	-10%
17	5607	6145	13%
18	7650	8312	8%
19	8511	8476	0%
20	7947	7126	-12%

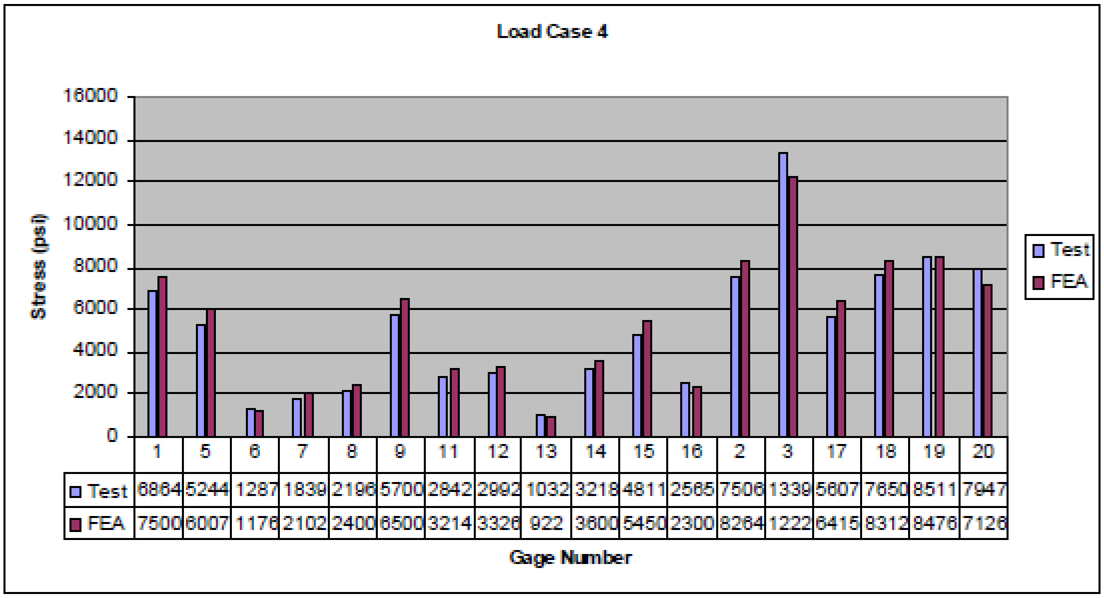


Figure: Comparison of FEA and Test results for vertical load case 4

Figure D.1. Load Case (LC4) Test-Simulation result comparison

Vertical and Lateral Load Case: **Load Case 9**

Gage	Test Stress (psi)	FEA Stress (psi)	% Difference
1	7653	6891	9.96%
4	6723	6333	5.80%
5	3300	3240	1.82%
7	1596	1450	9.15%
8	1791	1666	6.98%
9	3150	3331	-5.75%
11	1727	1688	2.27%
12	1292	1362	-5.39%
14	3860	3854	0.16%
15	2640	2737	-3.67%
16	1638	1551	5.31%
2	7049	6318	10.37%
3	11955	12570	-5.14%
17	3787	3591	5.17%
18	5649	4900	13.26%
19	5862	5057	13.73%
20	6549	5766	11.96%
21	5448	5806	-6.57%

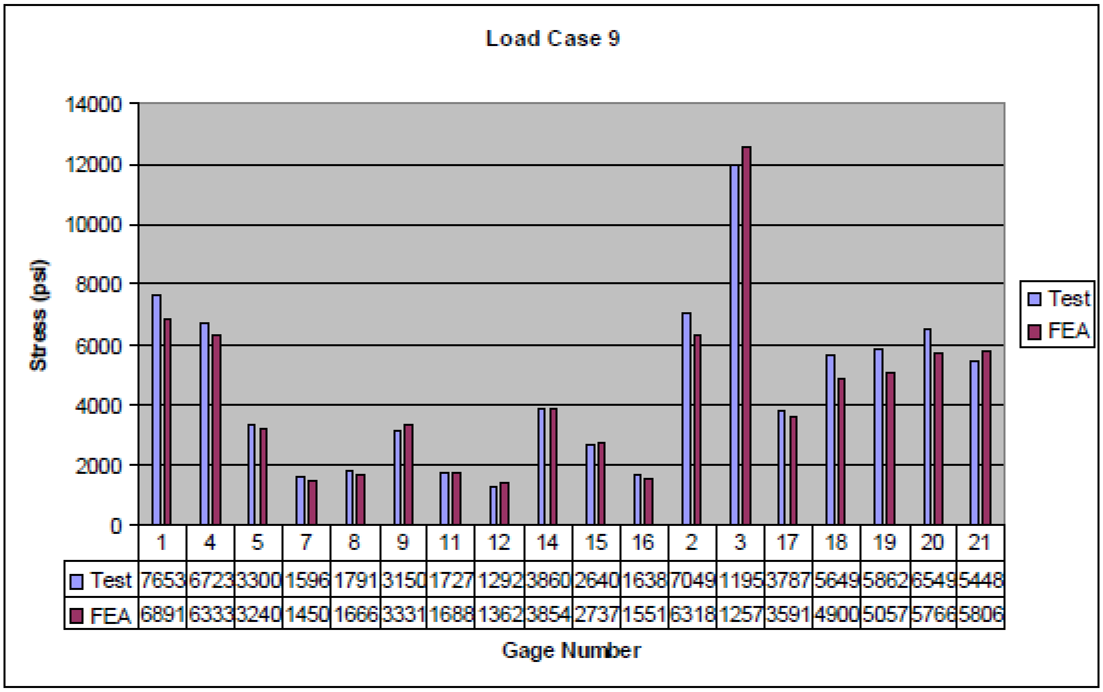
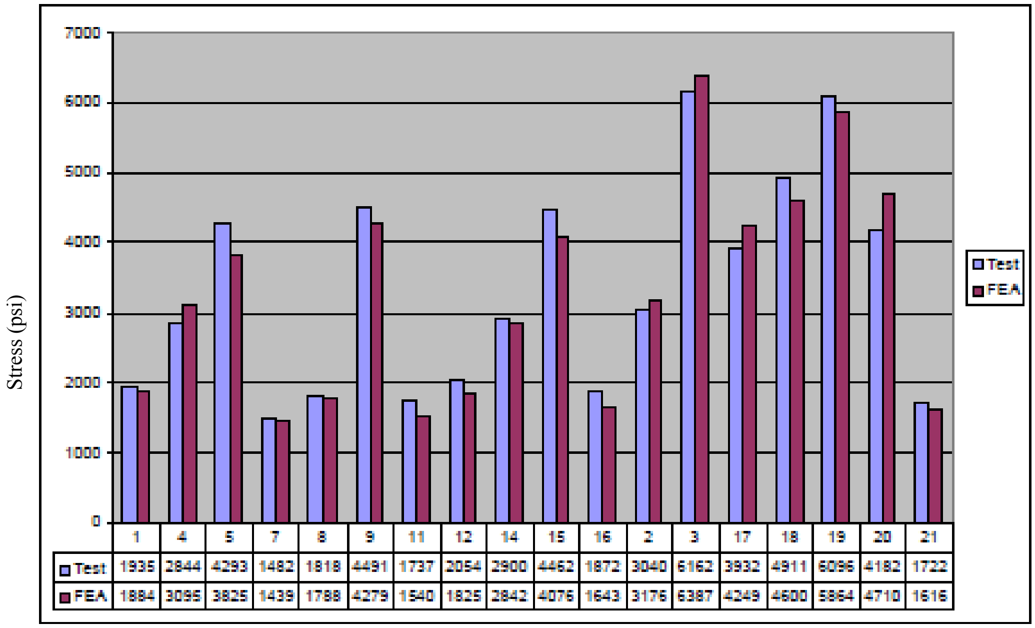


Figure: Comparison of FEA and Test results for load case 9

Figure D.2. LC9 Test-Simulation result comparison

Load Case 10: Vertical and Lateral

Gage	Test Stress (psi)	FEA Stress (psi)	% Difference
1	7653	6891	9.96%
4	6723	6333	5.80%
5	3300	3240	1.82%
7	1596	1450	9.15%
8	1791	1666	6.98%
9	3150	3331	-5.75%
11	1727	1688	2.27%
12	1292	1362	-5.39%
14	3860	3854	0.16%
15	2640	2737	-3.67%
16	1638	1551	5.31%
2	7049	6318	10.37%
3	11955	12570	-5.14%
17	3787	3591	5.17%
18	5649	4900	13.26%
19	5862	5057	13.73%
20	6549	5766	11.96%
21	5448	5806	-6.57%



	1	4	5	7	8	9	11	12	14	15	16	2	3	17	18	19	20	21
▢ Test	1935	2844	4293	1482	1818	4491	1737	2054	2900	4462	1872	3040	6162	3932	4911	6096	4182	1722
■ FEA	1884	3095	3825	1439	1788	4279	1540	1825	2842	4076	1643	3176	6387	4249	4600	5864	4710	1616

Figure: Comparison of FEA and Test results for load case 10

Figure D.3. LC10 Test-Simulation result comparison

Load Case 15: Vertical and Longitudinal

Gage	Test Stress (psi)	FEA Stress (psi)	% Difference
1	4626	5057	-9.32%
4	4944	4762	3.68%
5	3474	3106	10.59%
7	969	921	4.95%
8	1218	1312	-7.72%
9	4143	3734	9.87%
11	1490	1651	-10.84%
12	1882	1820	3.29%
14	1648	1856	-12.59%
15	3360	3010	10.42%
16	2028	1760	13.21%
2	5401	6074	-12.46%
3	9774	10490	-7.33%
17	4007	4235	-5.70%
18	4923	4350	11.64%
19	6024	5742	4.68%
20	5826	6112	-4.91%
21	3687	3381	8.30%

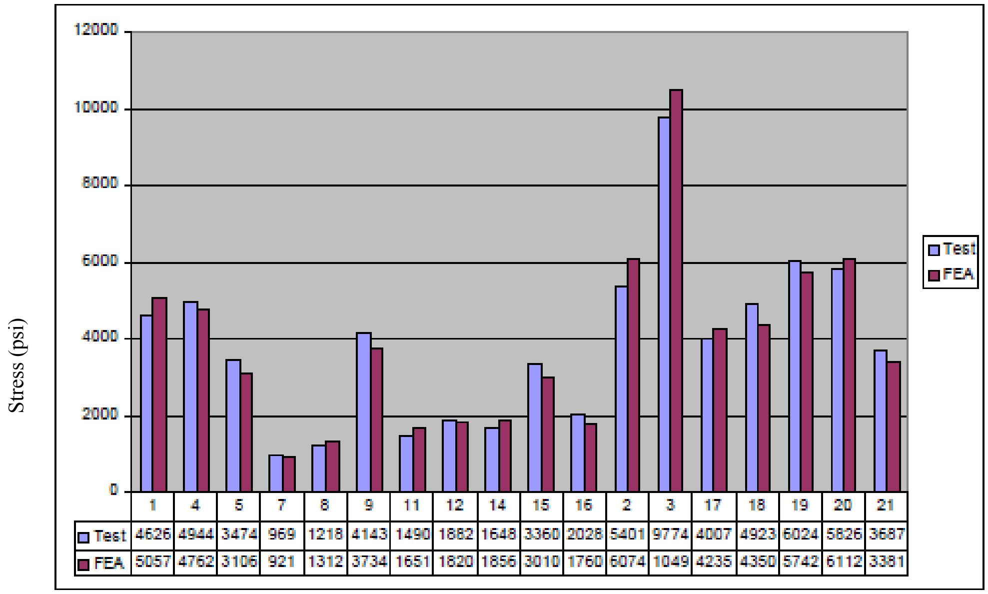


Figure: Comparison of FEA and Test results for load case 15

Figure D.4. LC15 Test-Simulation result comparison

Load Case 16: Vertical and Longitudinal

Gage	Test Stress (psi)	FEA Stress (psi)	% Difference
1	4992	4711	5.63%
4	4683	4390	6.26%
5	4104	3995	2.66%
7	1380	1510	-9.42%
8	1758	1986	-12.97%
9	2937	3102	-5.62%
11	877	957	-9.17%
12	1315	1226	6.78%
14	2866	3286	-14.66%
15	2255	2360	-4.68%
16	1536	1642	-6.90%
2	5068	4662	8.02%
3	8719	9155	-5.00%
17	3778	4297	-13.73%
18	5655	4950	12.47%
19	5961	6495	-8.96%
20	5211	4562	12.45%
21	3504	3674	-4.85%

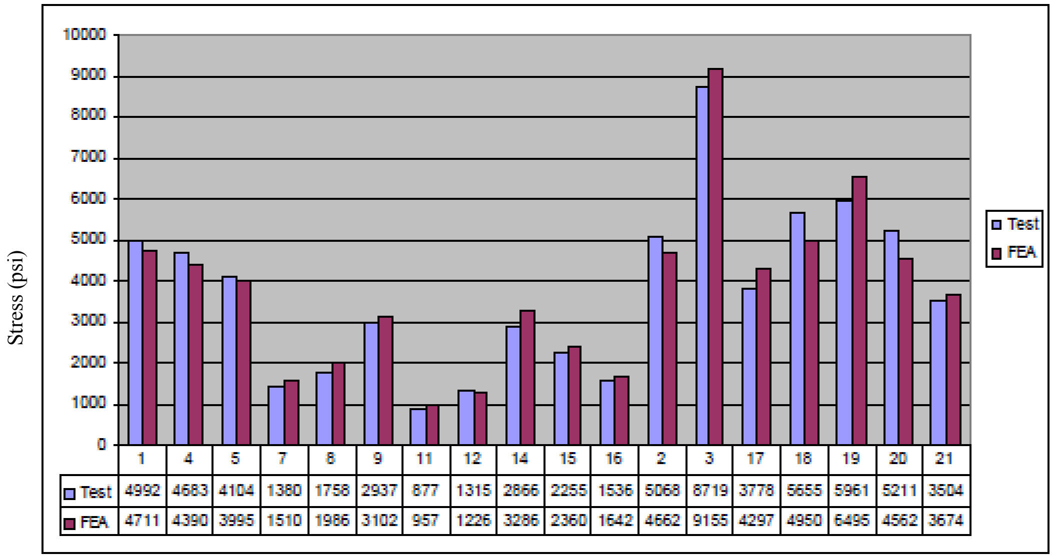
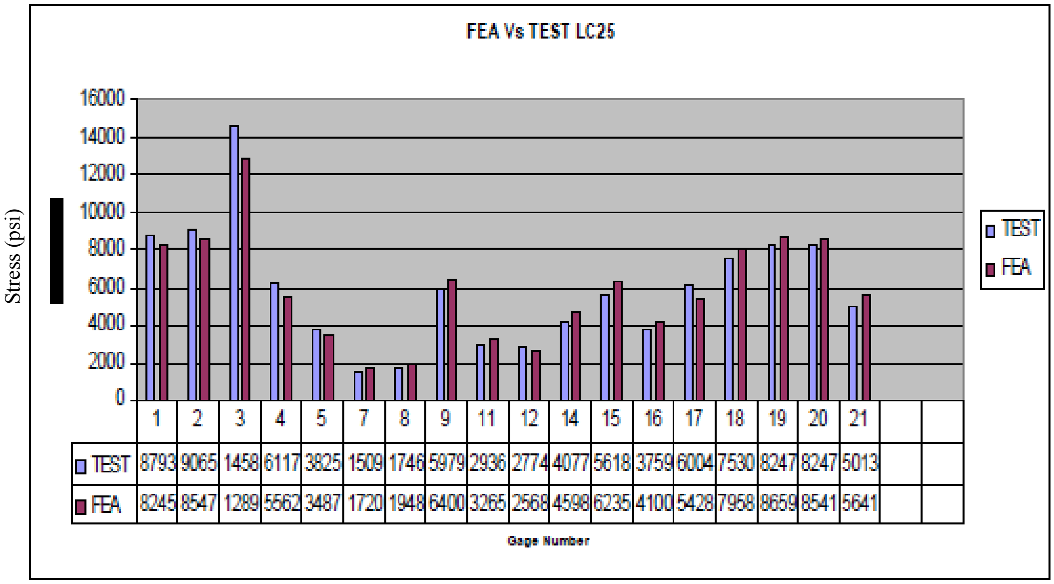


Figure: Comparison of FEA and Test results for load case 16

Figure D.5. LC16 Test-Simulation result comparison

Load Case 25

GAGE	TEST	FEA	% Difference
1	8793	8245	6%
2	9065	8547	6%
3	14583	12895	12%
4	6117	5562	9%
5	3825	3487	9%
7	1509	1720	-14%
8	1746	1948	-12%
9	5979	6400	-7%
11	2936	3265	-11%
12	2774	2568	7%
14	4077	4598	-13%
15	5618	6235	-11%
16	3759	4100	-9%
17	6004	5428	10%
18	7530	7958	-6%
19	8247	8659	-5%
20	8247	8541	-4%
21	5013	5641	-13%



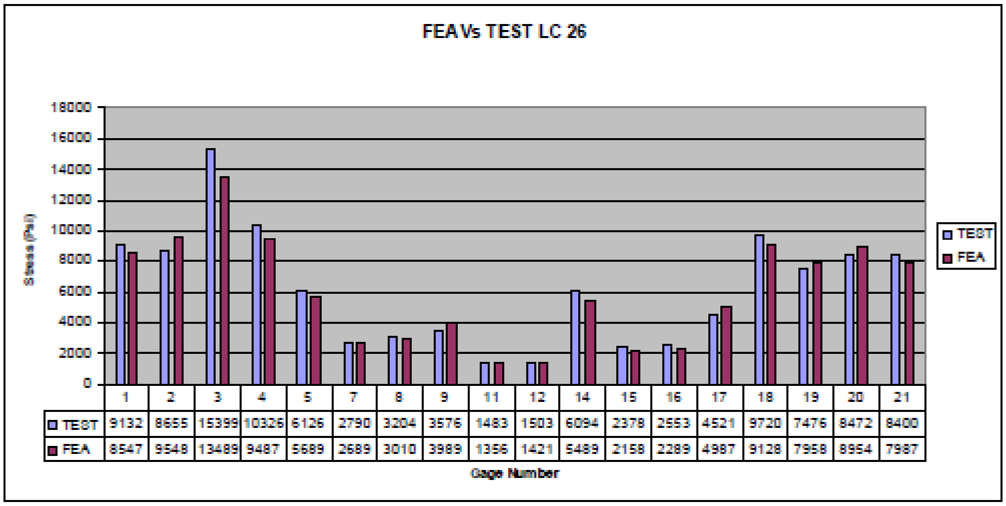
	1	2	3	4	5	7	8	9	11	12	14	15	16	17	18	19	20	21		
▨ TEST	8793	9065	1458	6117	3825	1509	1746	5979	2936	2774	4077	5618	3759	6004	7530	8247	8247	5013		
■ FEA	8245	8547	1289	5562	3487	1720	1948	6400	3265	2568	4598	6235	4100	5428	7958	8659	8541	5641		

Figure: Comparison of FEA and Test results for load case 25

Figure D.6. LC25 Test-Simulation result comparison

Load Case 26

GAGE	TEST	FEA	% Difference
1	9132	8547	6%
2	8655	9548	-10%
3	15399	13489	12%
4	10326	9487	8%
5	6126	5689	7%
7	2790	2689	4%
8	3204	3010	6%
9	3576	3989	-12%
11	1483	1356	9%
12	1503	1421	5%
14	6094	5489	10%
15	2378	2158	9%
16	2553	2289	10%
17	4521	4987	-10%
18	9720	9128	6%
19	7476	7958	-6%
20	8472	8954	-6%
21	8400	7987	5%



	1	2	3	4	5	7	8	9	11	12	14	15	16	17	18	19	20	21
▫ TEST	9132	8655	15399	10326	6126	2790	3204	3576	1483	1503	6094	2378	2553	4521	9720	7476	8472	8400
▪ FEA	8547	9548	13489	9487	5689	2689	3010	3989	1356	1421	5489	2158	2289	4987	9128	7958	8954	7987

Figure: Comparison of FEA and Test results for load case 26

Figure D.7. LC26 Test-Simulation result comparison

Load Case 27

GAGE	TEST	FEA	% Difference
1	3165	3452	-9%
2	4745	5105	-8%
3	7901	8654	-10%
5	3873	4125	-7%
7	963	2689	-179%
8	1446	1601	-11%
9	6156	5689	8%
11	2179	2345	-8%
12	3392	3684	-9%
14	3192	2951	8%
15	7219	7658	-6%
16	4005	4355	-9%
17	5968	5202	13%
18	5949	6542	-10%
19	8271	7958	4%
20	5628	6127	-9%

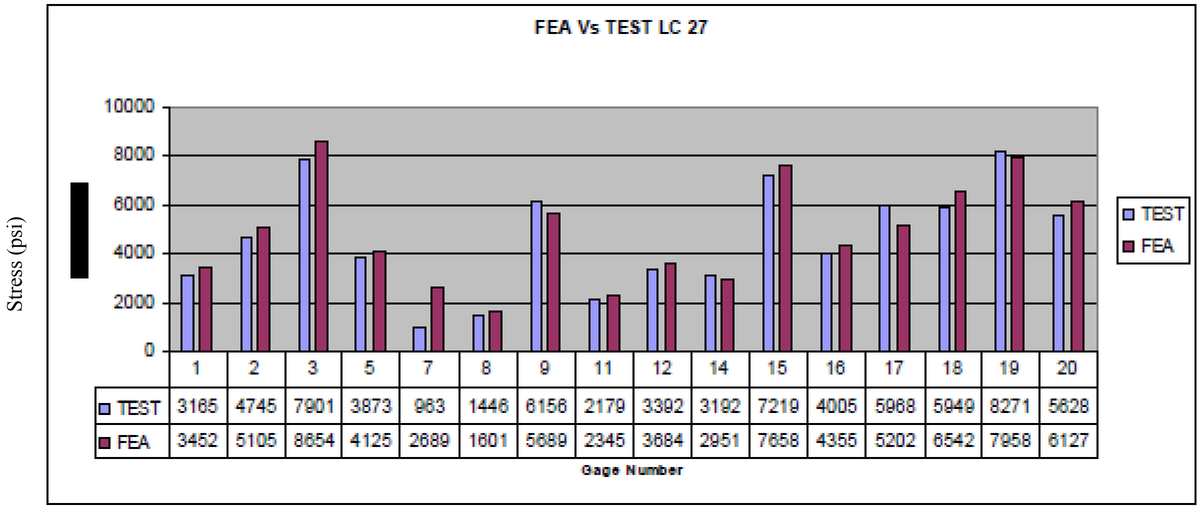


Figure: Comparison of FEA and Test results for load case 27

Figure D.8. LC27 Test-Simulation result comparison

Load Case 28

GAGE	MAX	MIN	TEST	FEA	% Difference
1	4,035		4035	3452	14%
2	-236	-5147	5033	5105	-1%
3	12039	2520	10998	9875	10%
5	-6,948		6948	6521	6%
7	-2,511		2511	2689	-7%
8	3,234		3234	3624	-12%
9	-4,425		4425	4985	-13%
11	-3	-1467	1466	1325	10%
12	2416	-154	2497	2754	-10%
14	-1224	-6876	6353	5981	6%
15	-257	-4256	4134	3798	8%
16	2,412		2412	2566	-6%
17	3524	-2487	5232	5202	1%
18	-9,255		9255	9655	-4%
19	-8,385		8385	7958	5%
20	6,975		6975	6127	12%
21	-5061		5061	5425	-7%

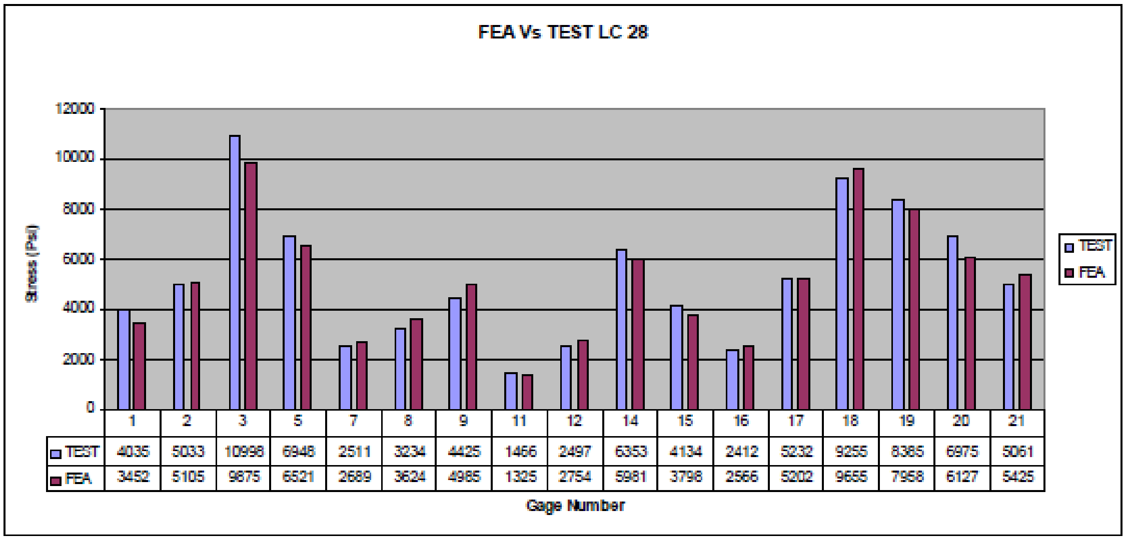
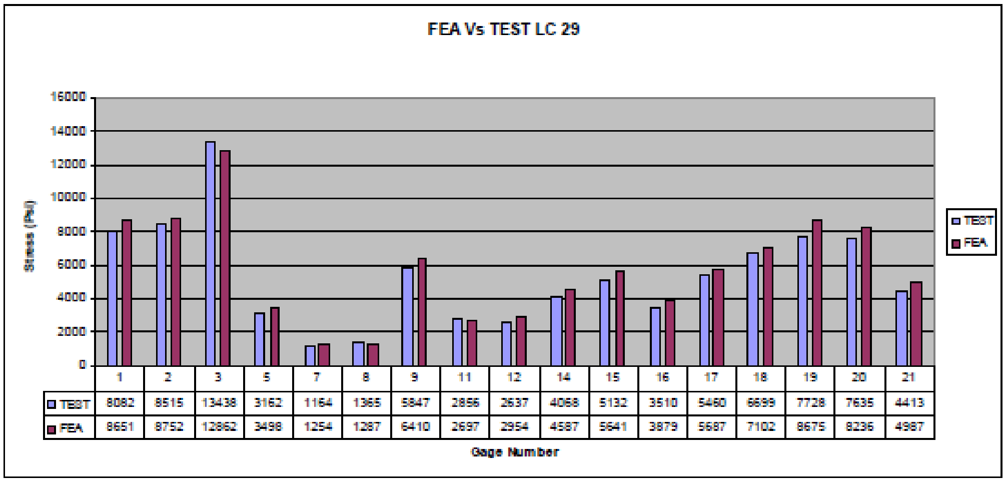


Figure: Comparison of FEA and Test results for load case 28

Figure D.9. LC28 Test-Simulation result comparison

Load Case 29

GAGE	MAX	MIN	TEST	FEA	% Difference
1	8,082		8082	8651	-7%
2	-234	-8629	8515	8752	-3%
3	15430	6294	13438	12862	4%
5	-3,162		3162	3498	-11%
7	-1,164		1164	1254	-8%
8	1,365		1365	1287	6%
9	-5,847		5847	6410	-10%
11	-322	-3003	2856	2697	6%
12	2700	132	2637	2954	-12%
14	1079	-3419	4068	4587	-13%
15	-697	-5445	5132	5641	-10%
16	3,510		3510	3879	-11%
17	3253	-3051	5460	5687	-4%
18	-6,699		6699	7102	-6%
19	-7,728		7728	8675	-12%
20	7,635		7635	8236	-8%
21	-4413		4413	4987	-13%



	1	2	3	5	7	8	9	11	12	14	15	16	17	18	19	20	21
TEST	8082	8515	13438	3162	1164	1365	5847	2856	2637	4068	5132	3510	5460	6699	7728	7635	4413
FEA	8651	8752	12862	3498	1254	1287	6410	2697	2954	4587	5641	3879	5687	7102	8675	8236	4987

Figure: Comparison of FEA and Test results for load case 29

Figure D.10. LC29 Test-Simulation result comparison

Load Case 30

GAGE	TEST	FEA	% Difference
1	9351	9863	-5%
2	8942	9658	-8%
3	16322	14562	11%
5	6342	6987	-10%
7	2835	2612	8%
8	3264	3568	-9%
9	3870	4100	-6%
11	1525	1458	4%
12	1643	1785	-9%
14	5758	6423	-12%
15	1738	1685	3%
16	1833	2000	-9%
17	4713	5349	-13%
18	9870	10258	-4%
19	7896	8398	-6%
20	8904	9658	-8%
21	8838	9722	-10%

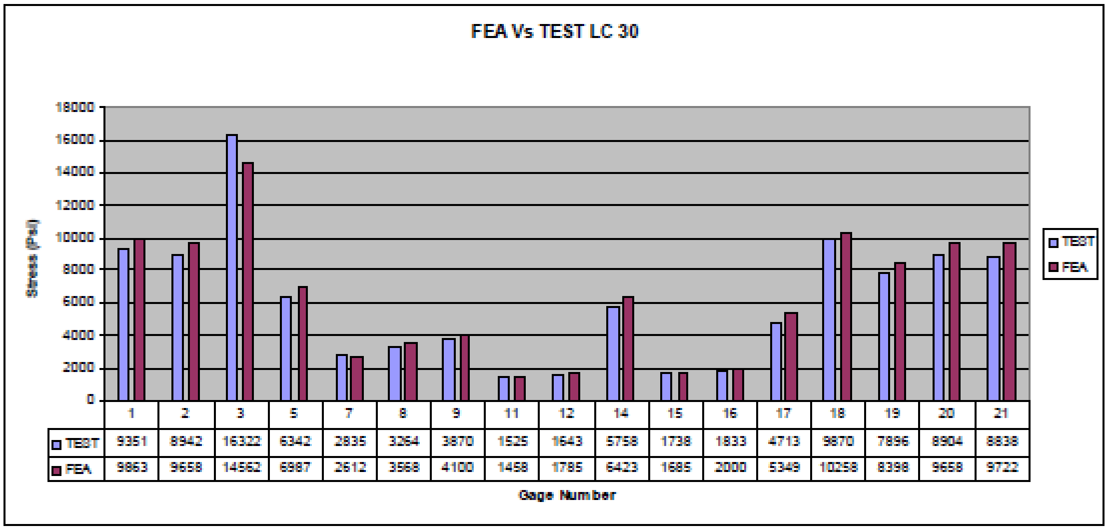


Figure: Comparison of FEA and Test results for load case 30

Figure D.11. LC30 Test-Simulation result comparison

Load Case 31

GAGE	TEST	FEA	% Difference
1	2688	2869	-7%
2	4851	5425	-12%
3	8336	8958	-7%
5	4035	4558	-13%
7	990	1120	-13%
8	1464	1658	-13%
9	7314	8000	-9%
11	2693	2913	-8%
12	3906	4218	-8%
14	3032	3385	-12%
15	7120	7655	-8%
16	3978	4451	-12%
17	6192	6847	-11%
18	6150	6752	-10%
19	8493	9125	-7%
20	5892	6589	-12%

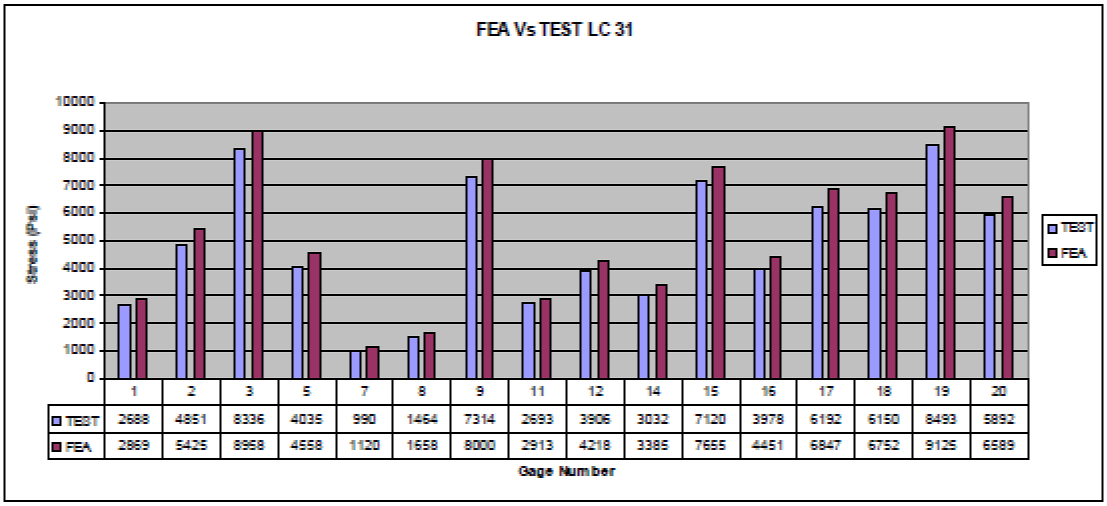


Figure: Comparison of FEA and Test results for load case 31

Figure D.12. LC31 Test-Simulation result comparison

Load Case 32

GAGE	TEST	FEA	% Difference
1	3987	4352	-9%
2	4995	5645	-13%
3	11206	10258	8%
5	7191	7854	-9%
7	2700	2658	2%
8	3342	3658	-9%
9	4482	4955	-11%
11	1457	1650	-13%
12	2381	2658	-12%
14	6247	6855	-10%
15	4587	4688	-2%
16	2178	2455	-13%
17	4914	5522	-12%
18	9231	9855	-7%
19	8229	8955	-9%
20	6915	7655	-11%
21	5556	6100	-10%

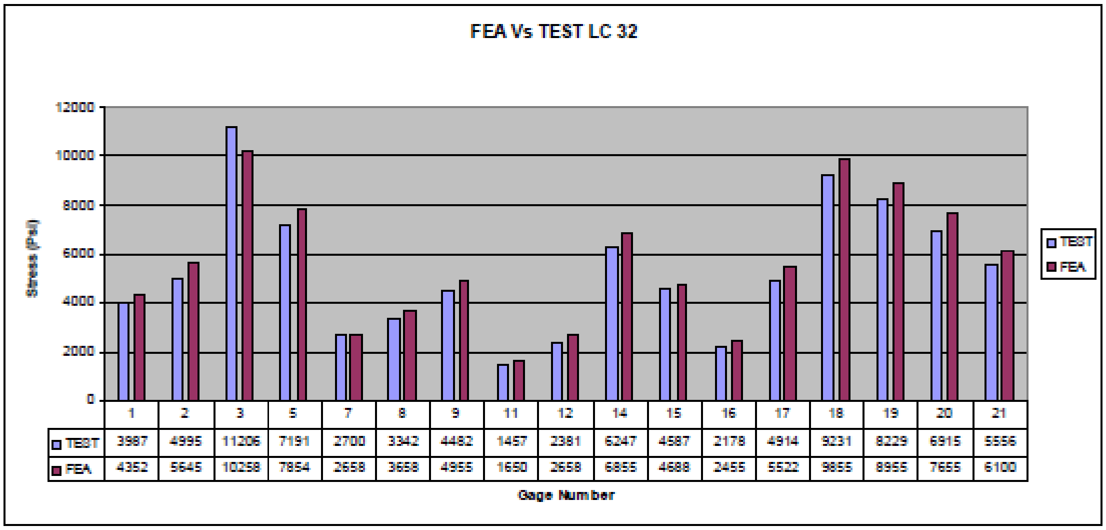


Figure: Comparison of FEA and Test results for load case 32

Figure D.13. LC32 Test-Simulation result comparison

D.2 Full Scale Static and Fatigue Tests On Specialized Rail Bogie

Tests Setup Highlights

A static load test was performed to verify the maximum allowable stresses on the truck frame and bolster under AW3 load conditions were not exceeded. An overload static test was conducted to ensure the truck frame and bolster had adequate strength to sustain a maximum load in the presence of a combination of minor manufacturing defects. A six million cycle fatigue test was conducted to demonstrate that the truck and adapter/bolster has adequate fatigue strength under dynamic loading. The same truck frame and bolster were used for both static tests and fatigue testing.

Static and overload testing for the respective load cases, met the requirements of the specification. The truck frame and bolster withstood 6 million cycles of fatigue testing with no visible indication of cracking.

D.2.1 Introduction

D.2.1.1 Static Test Set-up

Photographs of the truck frame and bolster test setup used for static and fatigue tests are shown in Figures B.2.1 and B2.2. The rail bogie frame was supported at the pedestal areas by machined chevron adaptors, as shown in Figure B2.3. The adapter was attached to the bogie frame as it would be in service through the use of rubber side bearers and traction pads. The vertical load was applied to the air spring locations on the bolster as shown in Figure B2. 4.
Longitudinal and lateral loads were applied to the bolster through the drag rods as shown in Figure B2.5. The four main loads were applied with MTS closed-loop servo-hydraulic loading systems that maintained the specified load regardless of test sample movement. The brake and damper loads were applied through the use of Miller hydraulic actuators which were monitored and controlled by pressure transducers. The brake loads were applied at the point where the brakes would make contact with the wheels. This was accomplished through the use of fixturing designed and approved by engineering as shown in Figure B2.6. The damper loads were applied to the brackets to which the dampers were mounted to as shown in Figure B2.7.

D.2.1.2 Dynamic Test Set-up

The dynamic test set-up was the same as the static test with the exception that the hydraulic actuators used to apply the damper loads were removed. The longitudinal and lateral dampers, used in service, were then installed as shown in Figures B2.8 and B2.9, respectively.

D.2.1.3 Instrumentation

Strain gages were applied on both the bogie frame and its adapter as indicated from the FEA virtual prototype. The strain gages were monitored and recorded with a high-speed computer-based data acquisition system during the static tests and periodically during the fatigue test as shown in Figure B2.10.

D.2.1.4 Test Procedures

The static and fatigue tests were conducted on the bogie frame and its adapter with the bogie frame and adapter assembled together. The test loads were applied as indicated by the virtual protoype. Specific loads applied to the bogie frame and adapter for each load case are listed in Tables B2.1, B2.2, and B2.3. These values are derived per the specification from the customer. Prior to testing, the bogie frame and adapter was visually inspected for defects and indications.

Table D.1. Static Test Loads

Static Load Test

Load Case	Vertical
1	-60,956
2	-69,664
3	-78,372
4	-87,080

	Vertical	Lateral
5	-60,956	10,885
6	-60,956	-10,885
7	-60,956	16,328
8	-60,956	-16,328
9	-60,956	21,770
10	-60,956	-21,770

	Vertical	Longitudinal S	Longitudinal N
11	-60,956	3,266	-3,266
12	-60,956	-3,266	3,266
13	-60,956	4,898	-4,898
14	-60,956	-4,898	4,898
15	-60,956	6,531	-6,531
16	-60,956	-6,531	6,531

	Vertical	Damper Vert	Damper Lat	Damper Yaw
19	-60,956	1,415	1,990	2,922
20	-60,956	-1,415	-1,990	-2,922

	Vertical	TBU Hor	TBU Vert S	TBU Vert N	DBU Vert S	DBU Vert N
21	-60,956	-2,178	1,104	-1,104	1,949	-1,949
22	-60,956	-4,356	-2,207	2,207	-3,898	3,898

	Vertical	Longitudinal S	Longitudinal N	Lateral	TBU Hor	TBU Vert S	TBU Vert N	DBU Vert S	DBU Vert N
23	-60,956	4,898	-4,898	16,328	-2,178	1,104	-1,104	1,949	-1,949
24	-60,956	-4,898	4,898	-16,328	-2,178	1,104	-1,104	1,949	-1,949

	Vertical	Longitudinal S	Longitudinal N	Lateral	TBU Hor	TBU Vert S	TBU Vert N	DBU Vert S	DBU Vert N	Damper Vert	Damper Lat	Damper Yaw
25	-87,080	6,531	-6,531	21,770	-4,356	-2,207	2,207	-3,898	3,898	1,415	1,990	2,922
26	-87,080	-6,531	6,531	21,770	-4,356	2,207	-2,207	3,898	-3,898	1,415	1990	2922
27	-87,080	6,531	-6,531	-21,770	-4,356	-2,207	2,207	-3,898	3,898	1,415	1,990	2,922
28	-87,080	-6,531	6,531	-21,770	-4,356	2,207	-2,207	3,898	-3,898	1415	1990	2922
29	-87,080	6,531	-6,531	21,770	-4,356	-2,207	2,207	-3,898	3,898	-1415	-1990	-2922
30	-87,080	-6,531	6,531	21,770	-4,356	2,207	-2,207	3,898	-3,898	-1,415	-1,990	-2,922
31	-87,080	6,531	-6,531	-21,770	-4,356	-2,207	2,207	-3,898	3,898	-1415	-1990	-2922
32	-87,080	-6,531	6,531	-21,770	-4,356	2,207	-2,207	3,898	-3,898	-1,415	-1,990	-2,922

Table D.2. Overload Static Test Loads

Static Overload Load Test

Load Case	Vertical
1	-60,956
2	-69,664
3	-78,372
4	-87,080

	Vertical	Lateral
5	-60,956	29,041
6	-60,956	-29,041
7	-60,956	43,561
8	-60,956	-43,561
9	-60,956	58,081
10	-60,956	-58,081

	Vertical	Longitudinal S	Longitudinal N
11	-60,956	6,396	-6,396
12	-60,956	-6,396	6,396
13	-60,956	9,593	-9,593
14	-60,956	-9,593	9,593
15	-60,956	12,791	-12,791
16	-60,956	-12,791	12,791

	Vertical	Damper Vert	Damper Lat	Damper Yaw
19	-60,956	1,415	1,990	2,922
20	-60,956	-1,415	-1,990	-2,922

	Vertical	TBU Hor	TBU Vert S	TBU Vert N	DBU Vert S	DBU Vert N
21	-60,956	-5,650	1,695	-1,695	3,150	-3,150
22	-60,956	-11,300	-3,390	3,390	-6,300	6,300

	Vertical	Longitudinal S	Longitudinal N	Lateral	TBU Hor	TBU Vert S	TBU Vert N	DBU Vert S	DBU Vert N
23	-60,956	9,593	-9,593	43,561	-5,650	1,695	-1,695	3,150	-3,150
24	-60,956	-9,593	9,593	-43,561	-5,650	1,695	-1,695	3,150	-3,150

	Vertical	Longitudinal S	Longitudinal N	Lateral	TBU Hor	TBU Vert S	TBU Vert N	DBU Vert S	DBU Vert N	Damper Vert	Damper Lat	Damper Yaw
25	-87,080	12,791	-12,791	58,081	-11,300	-3,390	3,390	-6,300	6,300	1,415	1,990	2,922
26	-87,080	-12,791	12,791	58,081	-11,300	3,390	-3,390	6,300	-6,300	1,415	1,990	2,922
27	-87,080	12,791	-12,791	-58,081	-11,300	-3,390	3,390	-6,300	6,300	1,415	1,990	2,922
28	-87,080	-12,791	12,791	-58,081	-11,300	3,390	-3,390	6,300	-6,300	1,415	1,990	2,922
29	-87,080	12,791	-12,791	58,081	-11,300	-3,390	3,390	-6,300	6,300	-1,415	-1,990	-2,922
30	-87,080	-12,791	12,791	58,081	-11,300	3,390	-3,390	6,300	-6,300	-1,415	-1,990	-2,922
31	-87,080	12,791	-12,791	-58,081	-11,300	-3,390	3,390	-6,300	6,300	-1,415	-1,990	-2,922
32	-87,080	-12,791	12,791	-58,081	-11,300	3,390	-3,390	6,300	-6,300	-1,415	-1,990	-2,922

Table D.3. Fatigue Test Loads

Load Case	Actuator	Vertical	Lateral	Longituinal	TBU Horizontal	TBU Vertical	DBU Vertical
1st 2 million cycles							
Fatigue Loads	**Max (kip)**	**-61.6**	**11.5**	**5.8**	**0.3**	**0.3**	**0.3**
	Min (kip)	**-92.4**	**-11.5**	**-5.8**	**3.6**	**1.8**	**3.1**
2nd 2 million cycles							
Fatigue Loads +10%	**Max (kip)**	**-67.8**	**12.7**	**6.3**	**0.3**	**0.3**	**0.3**
	Min (kip)	**-101.7**	**-12.7**	**-6.3**	**4.0**	**2.0**	**3.4**
Final 2 million cycles							
Fatigue Loads +20%	**Max (kip)**	**-73.9**	**13.8**	**6.9**	**0.4**	**0.4**	**0.4**
	Min (kip)	**-110.9**	**-13.8**	**-6.9**	**4.3**	**2.2**	**3.7**

D.2.2 Test Loads

D.2.2.1 Static Load Tests

Prior to conducting the fatigue test, static load tests were conducted to measure the strain in each test sample at the strain gage locations. Each test sample was statically preloaded twice with the load completely released between each loading. Strain gage readings were recorded at each load increment.

D.2.2.2 Fatigue Tests

The dynamic loads for the fatigue tests are presented in Table B2.3, after every two million cycles the fatigue loads were increased by 10%.

Fatigue test loads were applied simultaneously and in accordance with the dynamic loads shown in Table B2.3. All dynamic loads were applied sinusoidally at a rate of two cycles per second (cps). Vertical loads were applied with one 220-kip actuator, the longitudinal loads were applied with two 10-kip actuators, the lateral load was applied with one 55-kip actuator and the brake loads were applied with twelve 14-kip actuators.

D.2.2.3 Inspections

The bogie frame and adapter were magnetic particle inspected after every two million cycles. The inspection performed at the completion of two and four million cycles were done while the bogie frame and adapter were in the test fixture. Once the truck frame and bolster completed six million cycles they were brought back to assembly bay for a final inspection. A visual inspection was also performed on the bogie frame and adapter twice a day.

D.2.3 Test Results

D.2.3.1 Static Tests

Static load tests were conducted on the bogie frame and adapter prior to starting the fatigue tests. A summary of the stresses for each load condition for the static and static overload test are presented in the virtual prototype and test comparison, Section B1.

D.2.3.2 Fatigue Tests

Fatigue testing was conducted for six million cycles with no visual indications. The bogie frame and adapter both were able to maintain the applied test loads for the entire six million cycles. There were several indications identified after 2 million cycles during magnetic particle inspection. The indications did not grow in size during the remaining 4 million cycles and were removed by grinding confirming that they are not cracks. Figure B2.11 shows the locations of indications 1-5 on bogie frame. Figures B2.12-28 show the indications after 2, 4 and 6 million cycles.

D.2.3.3 Test Conclusions

One bogie frame and adapter were sent for testing and static tested, overload static tested and fatigue tested as an assembled unit. During the static and static overload test, the recorded stress for both load applications remained less than the allowable stress for each load case. The bogie frame and adapter withstood 6 million cycles of fatigue testing with no visible indication of cracking. After completion of the fatigue test the bogie frame and adapter were sent back to assembly bay for a more detailed inspection. After 6 million cycles, wet magnetic particle inspection was performed on the adapter and bogie frame. No visible indications were identified. The indications identified after 2 million cycles did not grow in size and were removed by grinding confirming that they are not fatigue fracture/cracks.

Figure D.14. Test Set-up

Figure D.15. Test Set-up

Figure D.16. Machined Pedestal Supports

Figure D.17. Application of the Vertical Load

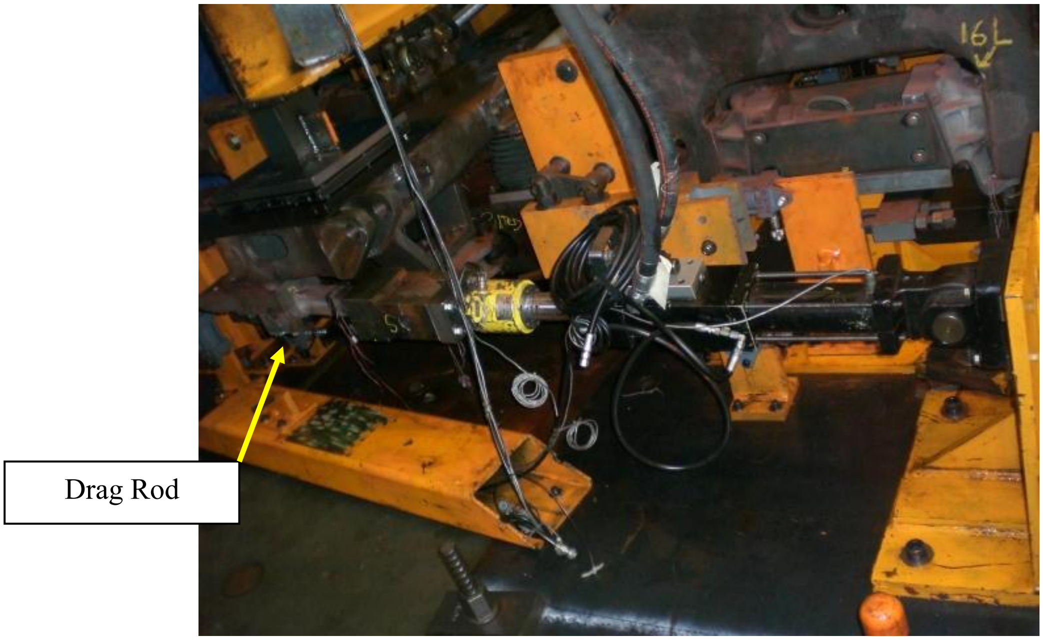


Figure D.18. Application of Load Through the Drag Rods

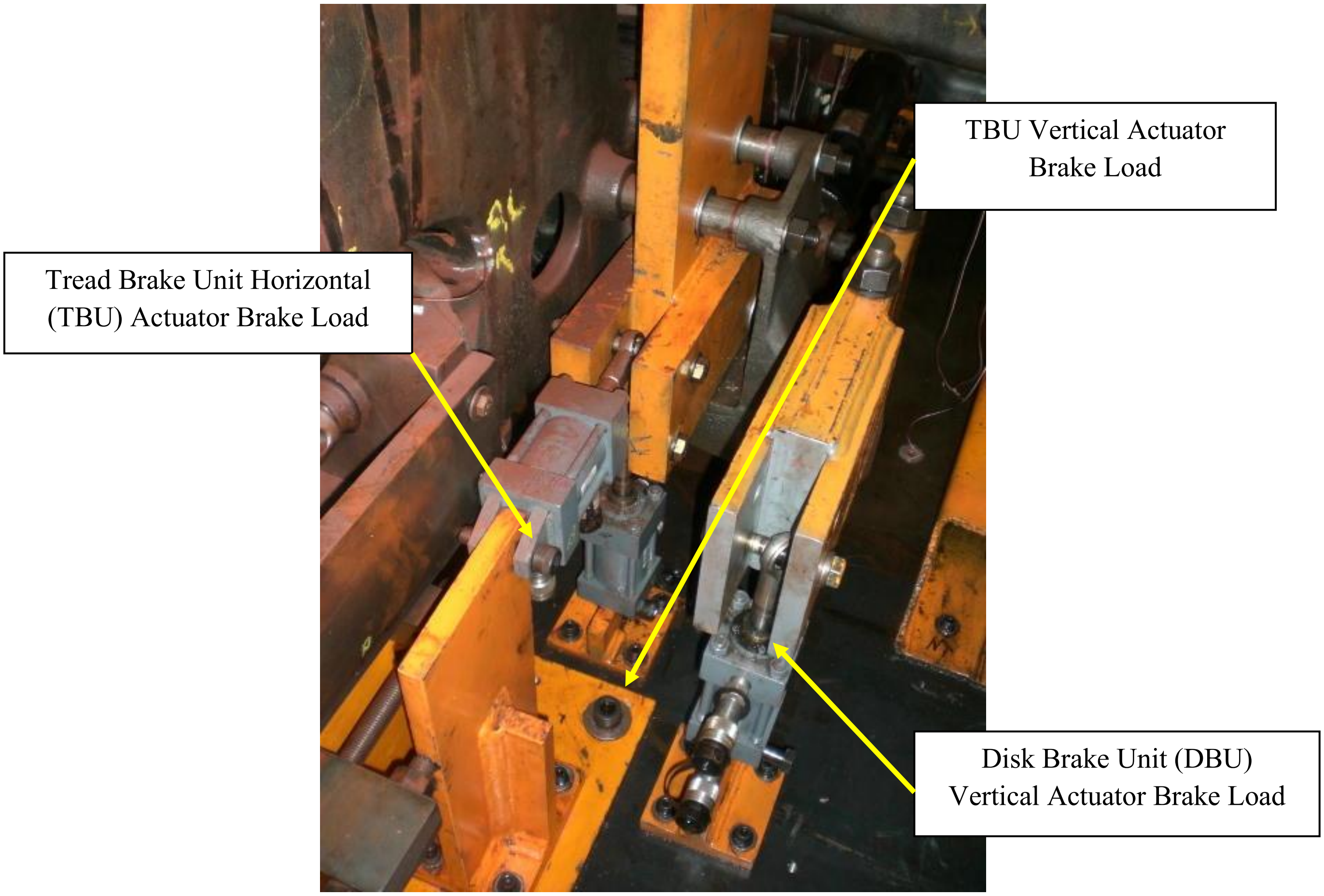


Figure D.19. Application of Brake Loads

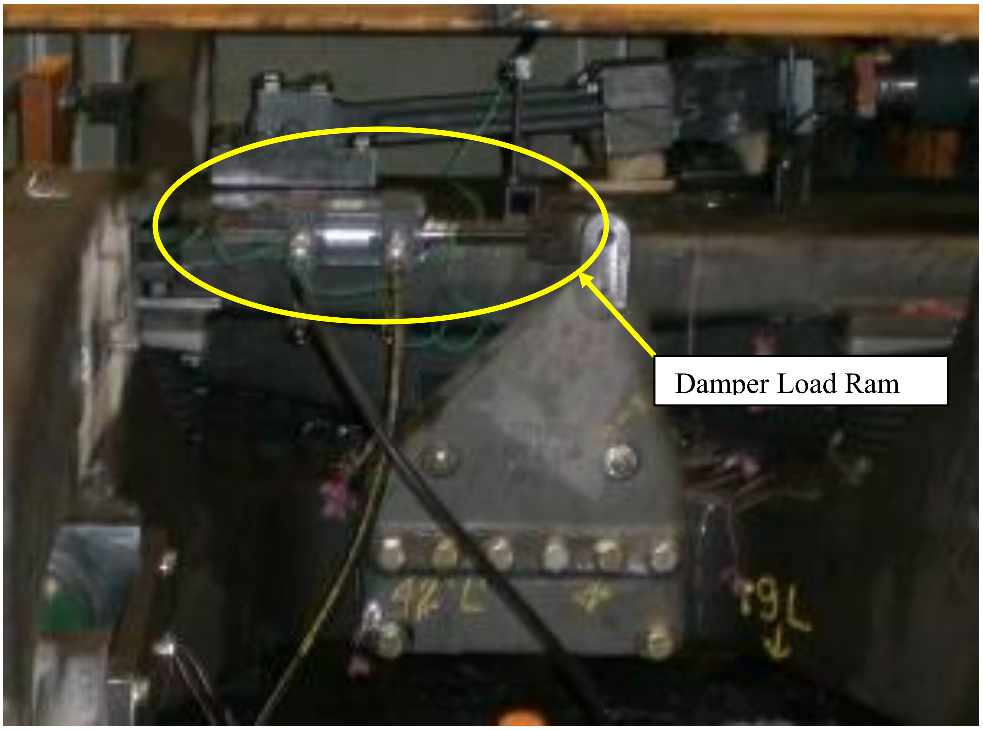


Figure D.20. Application of Damper Loads

Figure D.21. Lateral Damper

Figure D.22. Longitudinal Damper and wired strain gages.

Figure D.23. Data Acquisition

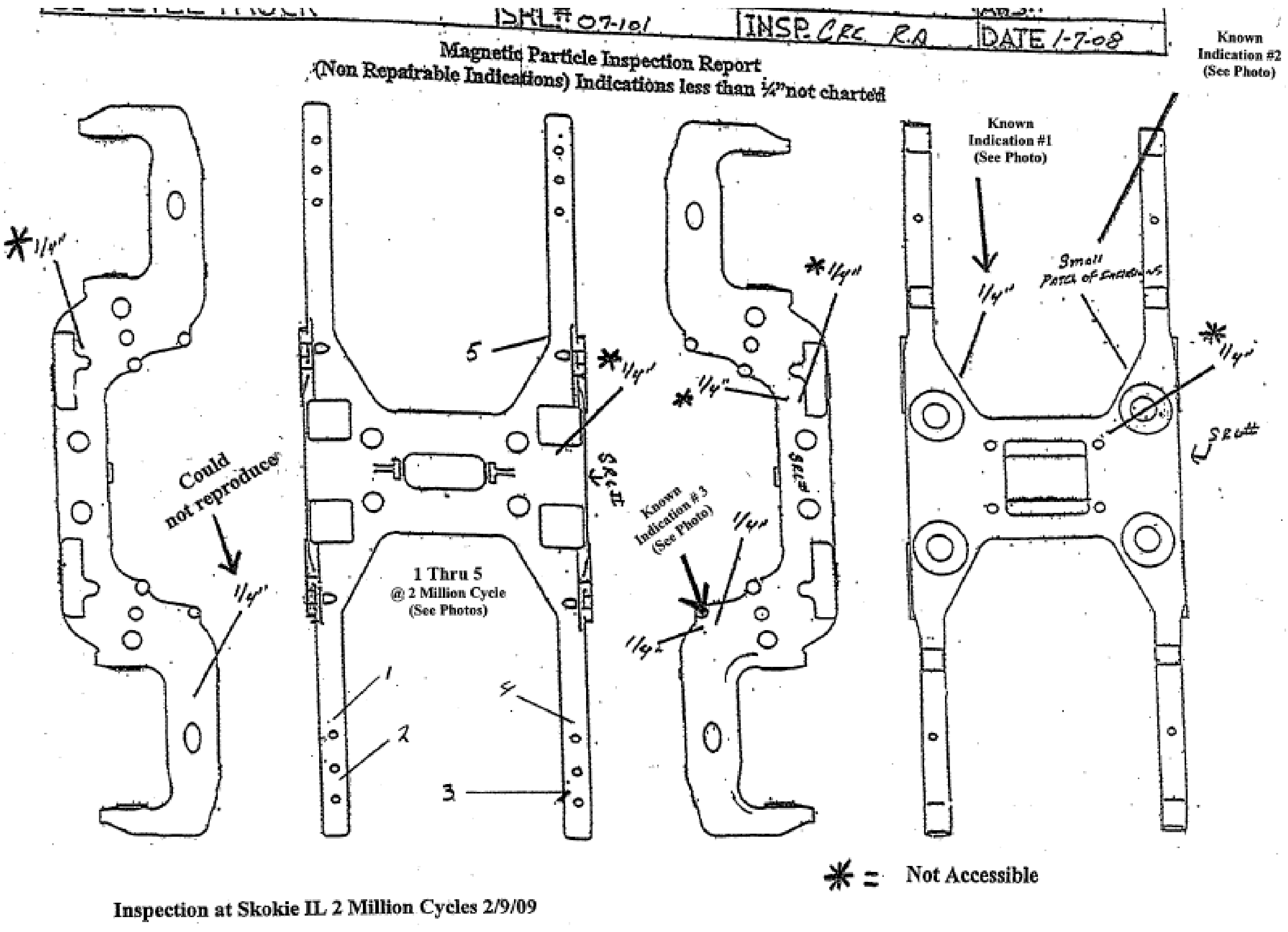


Figure D.24. Locations of indications 1-5 on truck frame

Figure D.25. Indication 1 at gage 8 (top of pedestal after 2 million cycles)

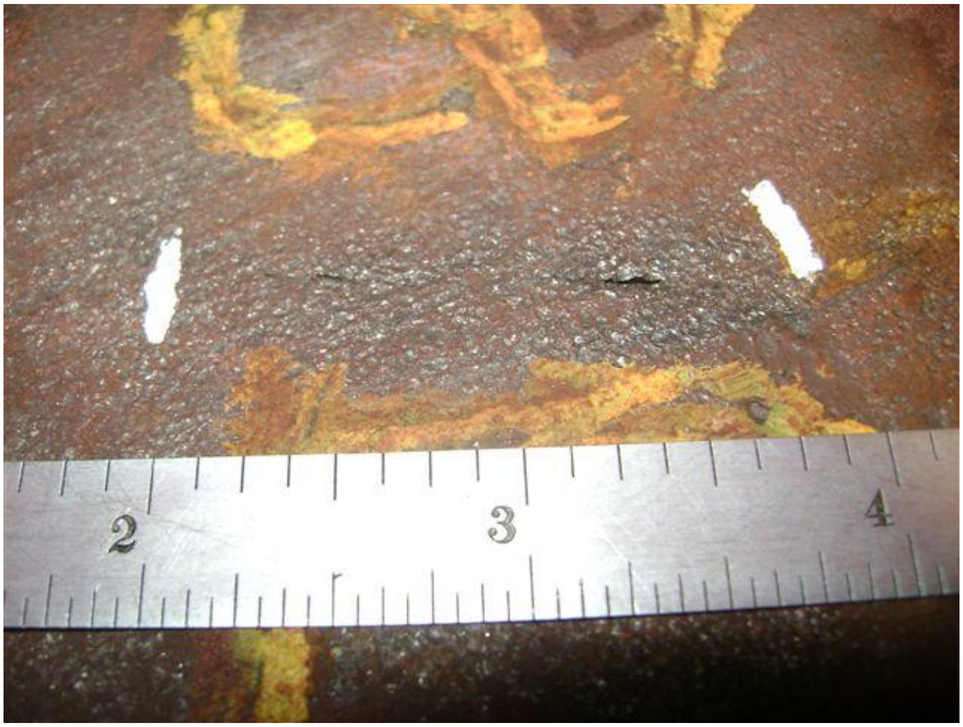


Figure D.26. Indication 1 at gage 8 (after 2 million cycles)

Figure D.27. Indication 2 (top of pedestal after 2 million cycles)

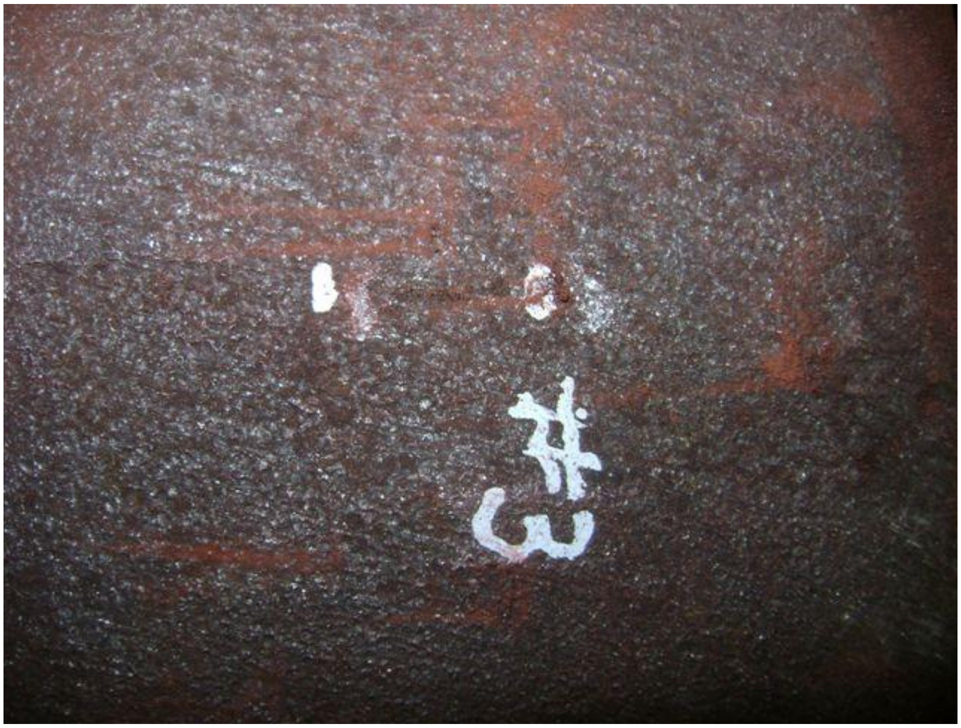


Figure D.28. Indication 3 (top of pedestal after 2 million cycles)

Figure D.29. Indication 4 (top of pedestal after 2 million cycles)

Figure D.30. Indication 5 (after 2 million cycles)

Figure D.31. Indication 1 at gage 8 (top of pedestal after 4 million cycles)

Figure D.32. Indication 2 (after 4 million cycles)

Figure D.33. Indication 3 (after 4 million cycles)

Figure D.34. Indication 4 (after 4 million cycles)

Figure D.35 Indication 5 (after 4 million cycles)

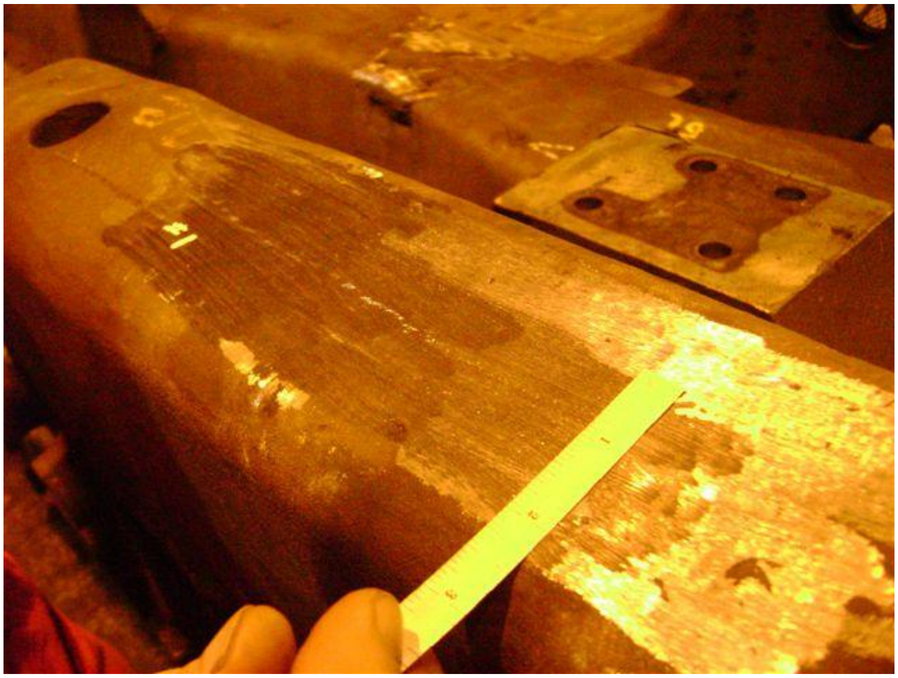


Figure D.36. Indication 1 at gage 8 (top of pedestal after 6 million cycles and grinding)

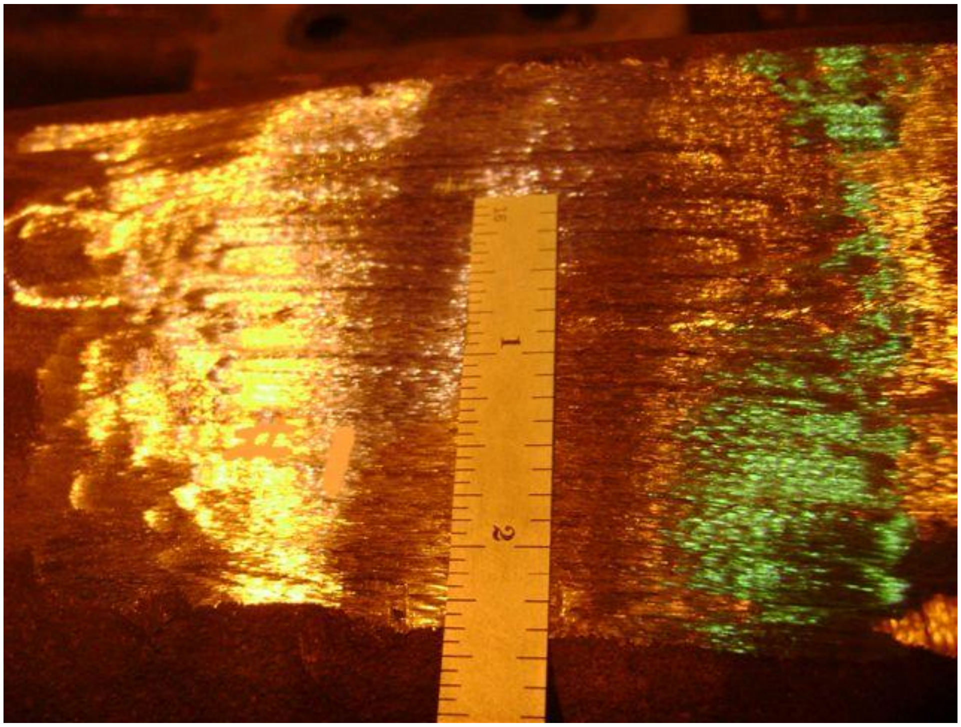


Figure D.37. Indication 1 (after 6 million cycles)

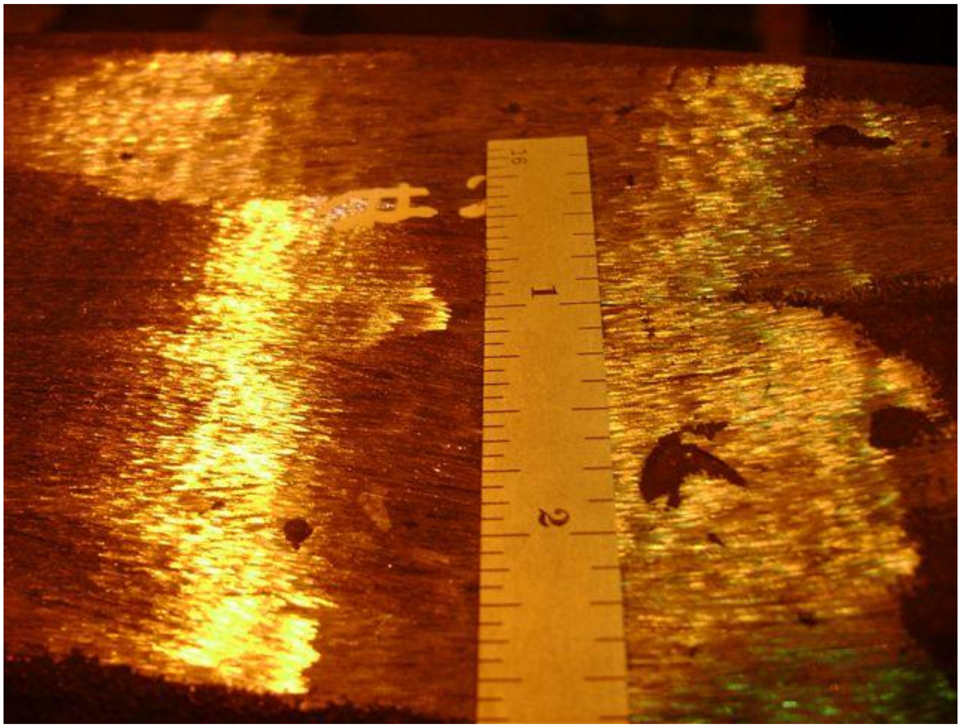


Figure D.38. Indication 2 (after 6 million cycles and grinding)

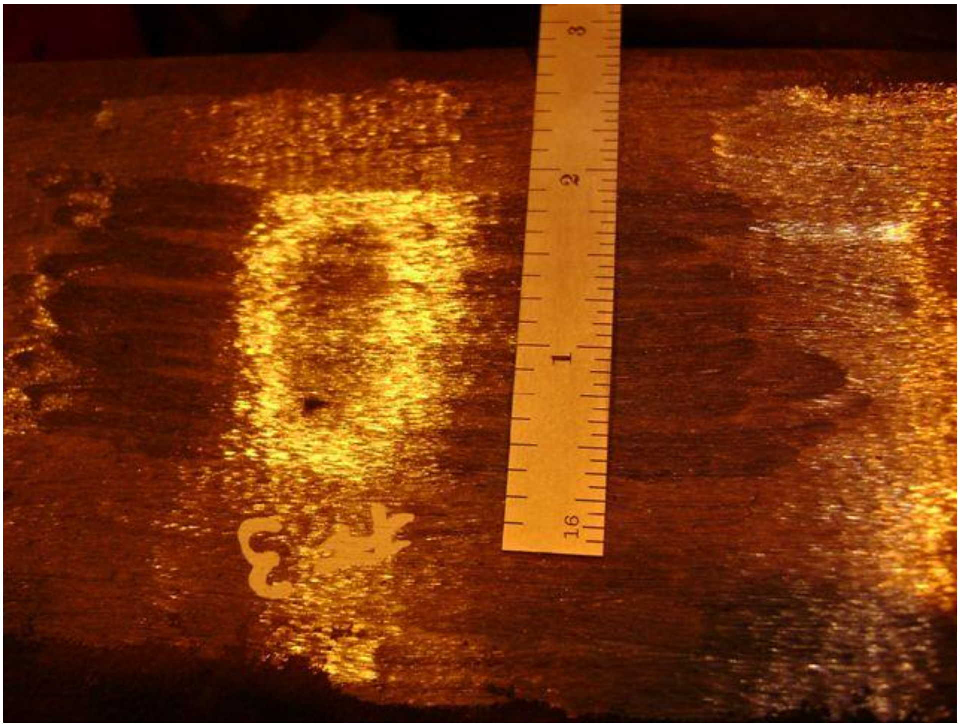


Figure D.39. Indication 3 (after 6 million cycles and grinding)

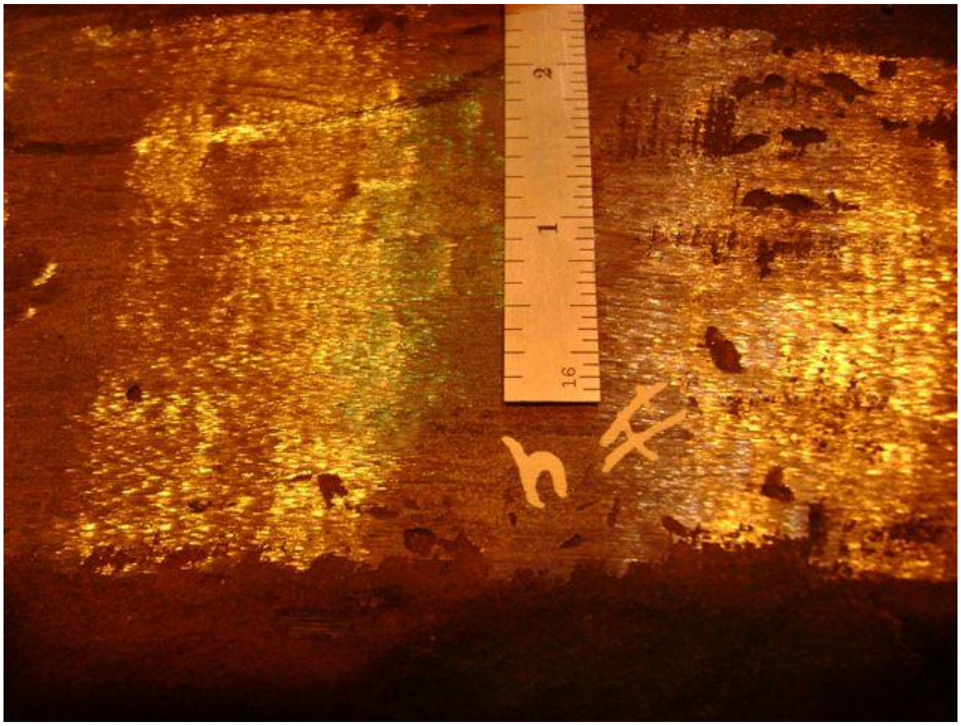


Figure D.40. Indication 4 (after 6 million cycles and grinding)

Figure D.41. Indication 5 (after 6 million cycles and grinding)