MATERIALS, ENERGY AND CNGDI VEHICLE ENGINEERING

PROFESSOR IR. DR. BARKAWI BIN SAHARI

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Contents

ABSTRACT

Materials, energy and car are essential for our daily life, especially, in our modern society. The common materials in mechanical engineering works are metal and composites. They are used in components for power generation, automotive vehicles and machineries. Some examples are vehicle body platforms, pressure vessels, engine cylinders, plates, heat exchangers, steam and gas turbines rotors, shafts and casing and gears. The common energy sources available are petroleum and natural gas. Other sources and forms are also available. Energy is needed for our daily activities. Cars are required to move us around. Materials, energy and cars are interrelated. Cars use materials in their construction and require energy to make them move. In the design of cars, materials and energy need to be considered. The lecture described the research tool (finite element) and its application to continuum mechanics of materials, followed by description on the behaviour, ratchetting of mechanical components and studies on crash behaviours. This is followed by description and discussion on the energy scenario for the years 2005 to 2050. The material research and energy studies have lead towards the development of Compressed Natural Gas Direct Injection (CNGDI) vehicle. A detail description on the development of CNGDI vehicle body platforms is given together with the crashworthiness characteristics results. The last section of the lecture describes how to manage a multi-institutional research project with specific reference to CNGDI Engine and Transmission under the IRPA PR mechanism from 2002 – 2007, led by UPM. The projects are multi-institutional research projects where, the author is the Program Head as well as Project Head for Vehicle Architecture and Integration. The lecture ends with a conclusion.

INTRODUCTION

Materials, energy and cars are essential in our everyday lifes, especially so in modern society. The common materials in mechanical engineering works are metals and composites. They are used in components for power generation, automotive vehicles and machineries. Some examples are vehicle body platforms, pressure vessels, engine cylinders, plates, heat exchangers, steam and gas turbine rotors, shafts and casing and gears. For these applications, the loadings are "severe". Very often, the components are subjected to high mechanical loads, combined with thermal fluctuations and operate at high temperature. At the same time, the weight of the components needs to be reduced and less materials need to be used.

All materials, such as metals and composites, no matter how "strong" they are, can and do fail and when they do, the consequences are devastating. Some of the failure modes are fatigue fracture, crash, excessive plastic strain due to yielding, ratchetting and localised fracture due to stress concentration. Hence, it is almost always necessary that in the design of these types of components, component integrity is ensured. Failure mechanisms need to be determined and predicted, failure loads need to be assessed so that component failure can be prevented and structural integrity maintained.

There are several methods of prediction; namely, the closed form analytical method, experimental method and numerical method. All these methods have their own advantages and disadvantages. The Closed form analytical method provides fast results but this is usually limited to simple component geometry and loading. The Experimental method is inhibited by the cost of equipment, materials and skilled manpower.

Energy is another important commodity in our everyday life. The most common form of energy that we normally take for granted is energy from the sun. The form of energy that powers most equipment is electrical energy. However, the energy source that we use today is mostly from petroleum, gas and coal. The form of energy source used has high impact on technology. We will look briefly at the energy scenario in a later section. The need for people to move around led to the invention of vehicles. On land, perhaps the earliest form of land vehicle is the bicycle, followed by carts powered by horses, cows and mules, after which came the steam powered vehicles and later, with the discovery of petroleum, we had petrol fuelled vehicles. With petrol reserves reducing and prices increasing, natural gas is a necessary choice. Research works on natural gas vehicles carried out by the author will be described in a later section. Materials, energy and cars are interrelated and the author is very highly involved in the usage of these important commodities in life.

FINITE ELEMENT AND THE CONCEPT OF VERIFIED PREDICTIVE METHOD

The finite element method was developed as early as the 19th century [1]. However, due to its massive computing power requirement, its application only become widespread using mainframe computers in the early 1900s and in personal computers as recent as 1990 [2]. In mechanical engineering, finite element is a method used to solve partial differential equations associated with continuum mechanics; namely equilibrium equations, material constitutive laws and compatibility conditions. The equilibrium equation with X and Y as body forces, is written as,

Equation 1
$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + X = 0$$
$$\frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + Y = 0$$

The material constitutive law is represented by,

Equation 2
$$E\varepsilon_{xx} = \sigma_{xx} - \nu\sigma_{yy} - \nu\sigma_{zz} + E\alpha T$$
$$E\varepsilon_{yy} = -\nu\sigma_{xx} + \sigma_{yy} - \nu\sigma_{zz} + E\alpha T$$
$$E\varepsilon_{zz} = -\nu\sigma_{xx} - \nu\sigma_{yy} + \sigma_{zz} + E\alpha T$$
$$G\gamma_{xy} = \tau_{xy}, G\gamma_{yz} = \tau_{yz}, G\gamma_{zx} = \tau_{zx}$$

The strain displacement relation is given by,

Equation 3
$$\varepsilon_{xx} = \frac{\partial u}{\partial x}, \varepsilon_{yy} = \frac{\partial v}{\partial y}, \varepsilon_{zz} = \frac{\partial w}{\partial z},$$
$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial y}, \gamma_{yz} = \frac{\partial w}{\partial y} + \frac{\partial u}{\partial z},$$
$$\gamma_{zx} = \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}$$

These are the fundamentals relations related to stress analysis and mechanics of materials. The equilibrium equations relate forces acting on a body with the internal stresses. The material constitutive laws give the relationship between stress and strain of a material elastic as well as plastic. The compatibility conditions relate the strain with the displacement.

The finite element is a numerical method and gives approximate solutions to problems. In the finite element method, the displacement, u, is determined through the following equation,

Equation 4 $$u_s = K_s F_s$$

where K is the stiffness matrix and F is the generalised consistent load vector. The subscript s refers to the structure. Once u is determined, the stress and strain can then be evaluated by applying the strain displacement and material constitutive equations.

The accuracy of the prediction obtained depends on many factors such as:

a. The size of the element,
b. The accuracy of the material constitutive models,
c. The appropriate material parameters and their values,
d. Accuracy of loading and boundary conditions, and
e. Precision in the computer programming.

As many factors affect the accuracy of the finite element prediction a concept of verified predictive approach is introduced, at least in the earlier part of the research work [3]. This is to minimise, if not eliminate, errors arising from the numerical prediction of the finite element. The concept, as shown in Figure 1, relates the need for experimental work to be conducted in the development of material behaviour models and the associated material parameter values. By doing this, errors resulting from inaccurate material behaviour can be minimized. This will increase the confidence in the finite element prediction. This concept has been used throughout the research work carried out by the author. It also lays the fundamental philosophy in the author's work.

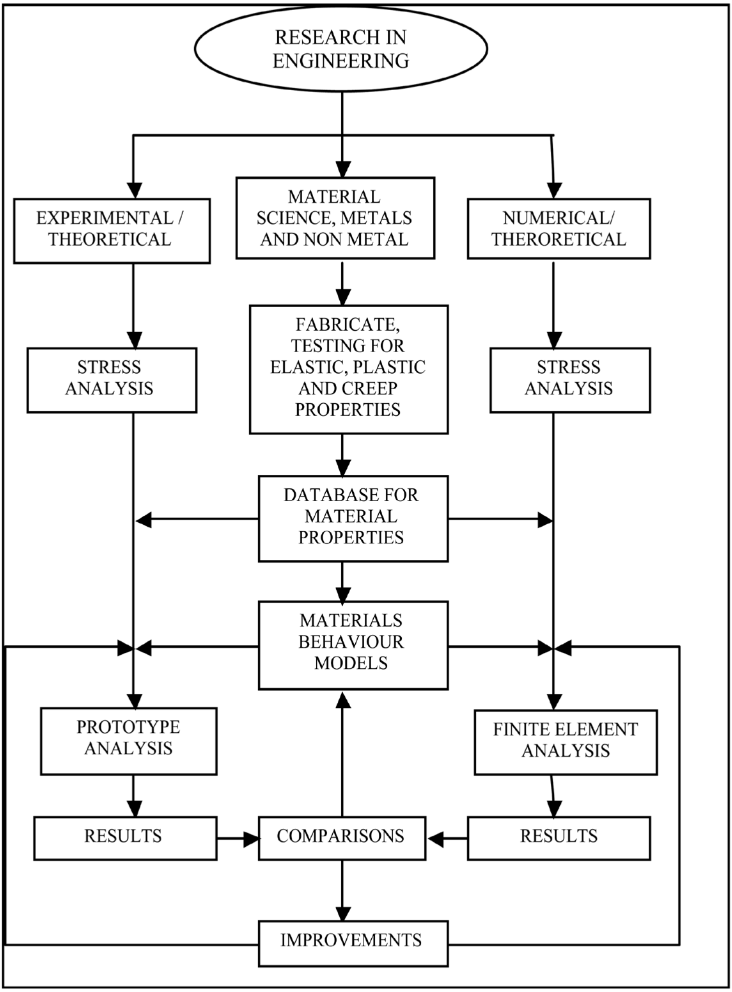


Figure 1 The concept of verified predictive method [3].

MATERIALS – RATCHETTING PHENOMENA, COMPONENT BEHAVIOUR, CRASHWORTHINESS AND FUNCTIONALLY GRADED

This section presents the research works carried out on the subject related to materials engineering. The main interests are in ratchetting, component behaviour, crashworthiness and functionally graded materials.

Ratchetting Phenomena

Most engineering components are subjected to a combination of steady and cyclic loads. Vehicle body structure for example, carries a constant load due to its weight and payloads and, at the same time, when the vehicle moves, uneven roads cause cyclic loads. The cylinder of a four stroke engine, on the other hand, exerts high pressure during compression stroke and zero pressure during intake and exhaust strokes and reducing pressure during power stroke. The temperature is uniform during steady state operations but high heat loads occur when starting and during cooling after stopping. Under these conditions, the components may exhibit either elastic, shakedown or ratchetting behaviour [4,5,6,7,8,9,10].

Elastic behaviour occurs when the stress in the material does not exceed yield stress. Shakedown occurs when the deformation does not increase with cycle after an initial plastic deformation. Ratchetting is related to the incremental plastic deformation in components subjected to combined steady and cyclic loads. Very often, the steady load is mechanical (examples are pressure, tension, bending) and the cyclic load is often thermal and could also be mechanical (examples are through thickness temperature variation, bending, torsion). Ratchetting is usually associated with long term effects and involve many cycles.

The main problems in designing components subjected to combined steady and cyclic loads, where these loads cause plastic strains, is first, to determine the load regimes that may cause ratchetting. Subsequently, the value of incremental deformation (or ratchet rates) needs to be determined. This may include deformation per cycle ($\Delta u/\Delta N$) or strain per cycle ($\Delta \varepsilon/\Delta N$). By limiting the total values of u or ε, the maximum number of cycles, N, could be determined.

The different types of behaviour could be represented by an interaction diagram, also known as the Bree diagram [10]. For a tube subjected to constant pressure and cyclic through thickness temperature, the Bree diagram is as shown in Figure 2 [10]. For a tube enclosure subjected to constant pressure and cyclic through thickness temperature, the interaction diagram is shown in Figure 3. For a clamped circular plate subjected to steady transverse pressure and cyclic radial temperature distribution, the interaction diagram is shown in Figure 4. It can be noted from Figure 2, Figure 3 and Figure 4 that the interaction diagrams are not the same. This is due to the differences in the ratchetting mechanism between the tube, tube enclosure and circular plate. Hence, in design, the interaction diagram derived from one component may not be directly applicable to another. For these reasons, for safe design, the interaction diagram for each type of component needs to be developed and the mechanisms of ratchetting need to be studied independently. Some materials exhibit "material ratchetting" phenomena. For these materials, the stress strain behaviour under constant strain cycling is shown in Figure 5. This type of material will enhance ratchetting even if the load is in the shakedown regime of the interaction diagram for similar components made of non-ratchetting materials. Hence, the prediction of ratchetting phenomena not only requires loading history but also material behaviour. Therefore, fundamental studies in material behaviour are important to be carried out in parallel with component behaviour.

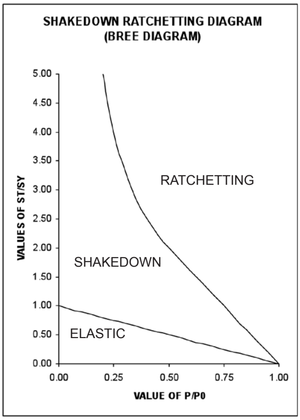
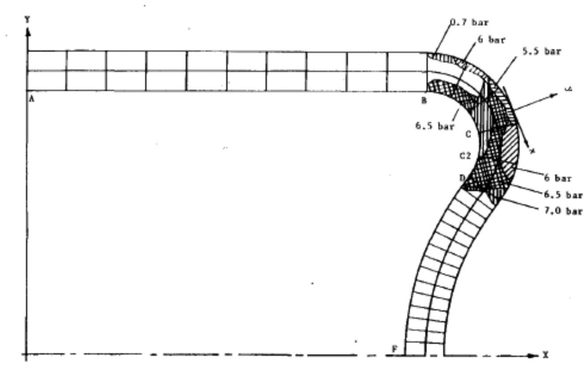
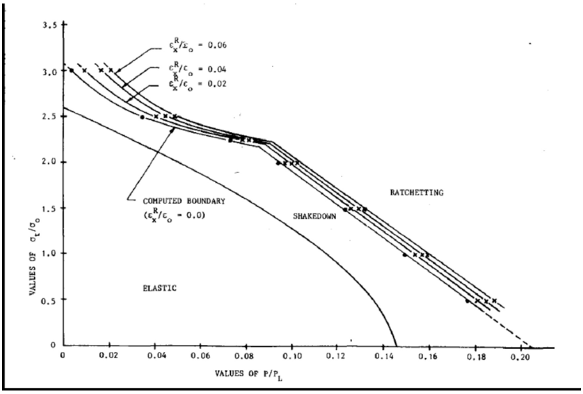


Figure 2 Shakedown ratchetting diagram (Bree diagram) for tube subjected to steady internal pressure and cyclic through thickness temperature variation [10].



(a) Tube enclosure geometry and growth of plastic zone



(b) Shakedown ratchetting diagram

Figure 3 Tube enclosure subjected to steady internal pressure and cyclic through thickness temperature variation [8].

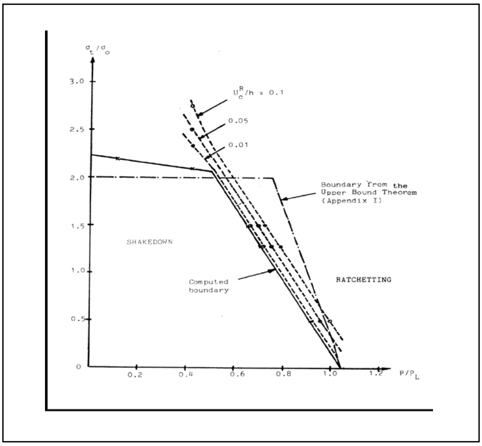


Figure 4 Shakedown ratchetting for clamped circular plate subjected to steady transverse pressure and cyclic radial temperature variation [4,9].

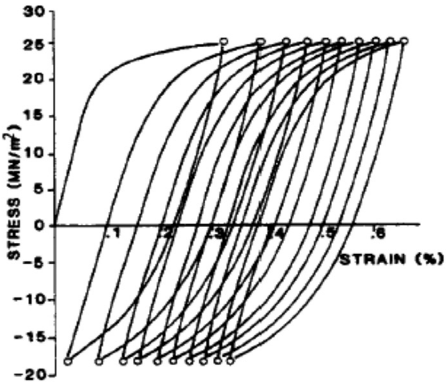


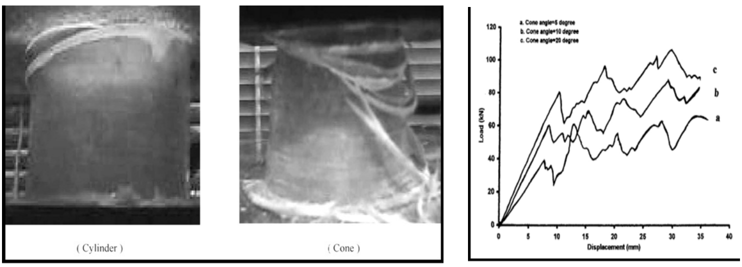
Figure 5 Stress strain behaviour of material ratchetting [7].

Component Behaviour

Apart from ratchetting, failure of components is also associated with bending, tension and torsion [11, 12, 13, 14, 15, 16, 17, 18, 19, 20]. This is typical especially for metallic components subjected to steady loads and as results of stress concentration at joints, intersections and changes of geometry. Ways and means to reduce the stress has to be introduced [16,17]. Again the finite element analysis combined with experimental verification is a suitable method for the investigation. Research works on composite materials and components have been conducted extensively [21,22,23,24,25]. The components are in the form of tubes, beams and shafts subjected to steady bending and torsion. It was found that the properties depend on the types of fibre, type of matrix, fibre volume fraction and methods of fabrication. Depending on the loading, failure is usually associated with delamination, matrix cracking, fibre pull-out and fatigue failure. These properties are very much needed in later works on crash properties and suitability of use in vehicle design, especially crashworthiness requirement.

Crashworthiness

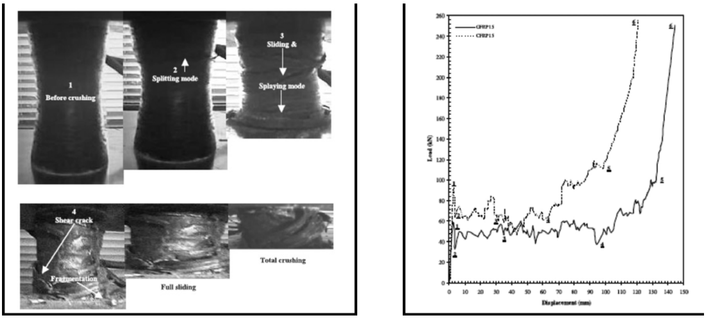
Another type of load associated mostly with the vehicle body structure is crash. Crash is an event where the load is applied over a short duration of time. Most crash analysis is carried out up to 100 milliseconds (ms). Under these conditions, the component normally behaves elastically over a few milliseconds and thereafter plastic deformation occurs which causes the structure to crumple. Crash behaviour of many cylindrical and conical components with different materials such as laminated composites has been studied [26, 27, 28, 29, 30, 31,32,33,34,35,36,37,38,39] and panels [40,41,42,43]. The main aim of these works is to determine the crash energy absorbing capability for automotive applications. The results for selected crash behaviour of cylindrical components are shown in Figure 6 [39,75] and Figure 7 [29,76]. From these figures it can be seen that crash behaviour depends on the material and geometry of the components and the loading arrangement. In all cases, there is a limit to the ability of the component to absorb the kinetic energy of the impacting rigid wall. For this reason, in the design of vehicle components ability to withstand crash loads, material and geometry need to be considered.



(a) Crash sequence

(b) Load displacement curve

Figure 6 Crash behaviour of cylindrical and cone composite tubes [39, 75].



(a) Sequence of crash (b) load displacement curve

Figure 7 Crash behaviour of cone-cone intersection tubes [29,76].

The information and understanding of crash properties as described above are very important in crash analysis of the automotive vehicle body.

Functionally Graded Material

Functionally Graded Material (FGM) is defined as material whose properties vary continuously with location according to specified distribution functions. This is achieved by combining two or more materials in different volume fractions at different locations. A lot of research works have been carried out utilising FGM [44,45,46,47,48]. The commonly used materials are metal and ceramic FGM. Examples of FGM components are turbine rotors where the central portion is metal and the outer part is ceramic. Hence, the materials' properties vary in radial direction with metallic values at the central part and ceramic values at the periphery. The properties in between these locations differ according to a specified degradation relation.

The property variation P(r) of the material in the FG circular disk, along the radial direction, is assumed to be of the following two forms [46]:

Equation 5 $$P(r) = (P_0 - P_i)\left(\frac{r - r_i}{r_0 - r_i}\right)^n + P_i \; ; \; r_I, < r < r_o$$

Equation 6 $$P(r) = P_0\left(\frac{r}{r_0}\right)^\gamma$$

where P_0 and P_i are the corresponding properties of the outer and inner faces of the disk; r_0 and r_i are the outer and inner radii of the disk respectively; $n \geq 0$ is called the grading index; γ is a parameter whose value depends on the material and geometric properties of the disk and assumed to be not a function of r. The power-law Equation 5 is widely accepted and reflects a simple rule of mixtures in terms of the volume fraction of the materials. The power-law Equation 6 has also been widely used in literature. In applying these equations, the Poisson's ratio, υ, is assumed to be constant and the elastic modulus E and the mass density ϱ are assumed to vary according to the gradation relations Equation 5 and Equation 6. For example, the form for the modulus of elasticity E is:

Equation 7 $$E(r) = (E_0 - E_i)\left(\frac{r - r_i}{r_0 - r_i}\right)^n + E_i \; ; \; r_i < r < r_0, \text{ or } E(r) = E_0\left(\frac{r}{r_0}\right)^\gamma$$

Using the infinitesimal theory of elasticity and the rotational symmetry, the strain-displacement and stress-strain relations are given by:

Equation 8 $$\varepsilon_r = \frac{\partial u}{\partial r} = \frac{du}{dr}, \varepsilon_\theta = \frac{u}{r}$$

And

Equation 9 $\sigma_r = \frac{E(r)}{(1-\nu^2)}(\varepsilon_r + \upsilon\varepsilon_\theta), \quad \sigma_\theta = \frac{E(r)}{(1-\nu^2)}(\varepsilon_\theta + \upsilon\varepsilon_r)$

where u is the radial displacement, E is the modulus of elasticity and υ is the Poisson's ratio. The equation of motion is given by

Equation 10 $\frac{d}{dr}(h(r)r\sigma_r) - h(r)\sigma_\theta + h(r)\rho(r)\omega^2 r^2 = 0$

Substitution of these relations in the equation of motion yields the Navier equation for the radial displacement as follows:

Equation 11
$$rh_r E_r \frac{d^2u}{dr^2} + \left(rE_r \frac{dh_r}{dr} + rh_r \frac{dE_r}{dr} + E_r h_r\right)\frac{du}{dr} +$$
$$\left(\nu E_r \frac{dh_r}{dr} + \upsilon h_r \frac{dE_r}{dr} - \frac{1}{r} E_r h_r\right)u + \left(1-\nu^2\right)h_r \rho_r r^2 \omega^2 = 0$$

For brevity, the symbols h_r, E_r and ρ_r are used for the functions h(r), E(r) and ρ(r) respectively. In Equation 11, the displacement u is a function of r only due to axial symmetry and plane stress condition. The displacement, u, can be obtained by solving Equation 11 and putting the appropriate boundary conditions of the disc. The stress and strains of the disc can then be determined from the elastic material constitutive equations such as Equation 2 and Equation 8. In the design, the values of displacement, stress and strains are checked against the benchmark or accepted values. An example of the circumferential stress for the rotating FGM hollow disc is shown in Figure 8 [44]. It can be seen that the distribution is not uniform and has maximum values towards the inner surface. The result is applicable to components such as turbine rotors and the flywheel of automotive engines. Hence, it is an appropriate stage to introduce and present research work on automotive vehicle development.

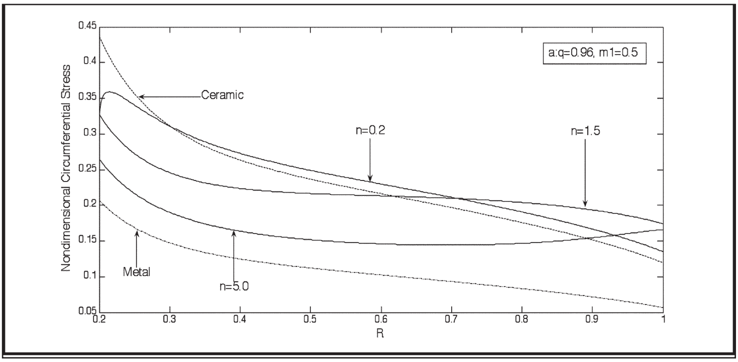


Figure 8 Distribution of normalised circumferential stress σ_θ for free-free hollow rotating FGM disc.[44]

ENERGY SCENARIO

Studies on energy demand in the 21st century has been conducted by the World Energy Council and many researchers [49, 50, 51, 52] and a summary of energy availability is shown in Figure 9 [49]. From Figure 9, it can be seen that during the period 2005 to 2050, the use of oil is less as compared to the use of Natural Gas (NG). Further, the use of oil during this period, is seen to be decreasing whereas usage of NG remains almost constant. Hence, NG is the fuel of choice for at least the next 50 years.

The oil and gas consumption and production for Malaysia is shown in Figure 10 [53]. For oil, the trend for production is reducing and consumption is increasing. It could be projected that in the years after 2015, consumption will be greater than production. This means that oil may have to be imported to meet consumption. For gas, however, production is still higher than consumption for the years after 2015. Hence, gas is a viable, if not the only immediate alternative fuel when oil needs to be imported. Therefore technology to harness the use of gas, especially for automotive use, needs to be developed immediately so that it is ready off the shelf when the need arises. Malaysia currently produces 39.8 million tonnes oil equivalent (mtoe) of NG and consumes only 19.5 mtoe. Hence, there is plenty of NG available for automotive use.

To utilise NG for automotives, a number of issues need to be addressed, technological, economic and political. This section focuses on only the technology aspect. The main concern in using NG for automotives is the safety, storage and refuelling infrastructure. NGV also has lower emission levels as set out by the EURO 3 and EURO 4 requirements. Table 1 shows the results of tests on two types of fuels compared to the standards requirement as reported by Middleton and Neumann [54]. It can be seen that NGV complies with all the requirements of the standards. Other alternative fuels are electric, hydrogen, propane, alcohol, bio-based, fuel cell and nuclear. However, these alternative fuels are still being researched.

Table 1 Comparison of emission levels against standards (Units: grams/kilowatt hour) [54].

	CO	**NMHC**	**CH_4**	**NO_X**	**PM**
EURO 3 limit	5.45	0.78	1.6	5.0	0.16
EURO 4.1 limit	4.0	0.55	1.1	3.5	0.03
NGV test results G20 gas	0.131	0.011	0.156	3.09	0.006
NGV test results G25 gas	0.134	0.020	0.459	2.88	0.007

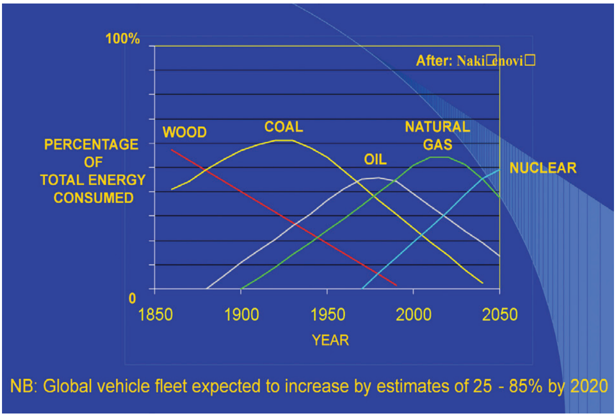


Figure 9 The availability of fuel and usage [49]

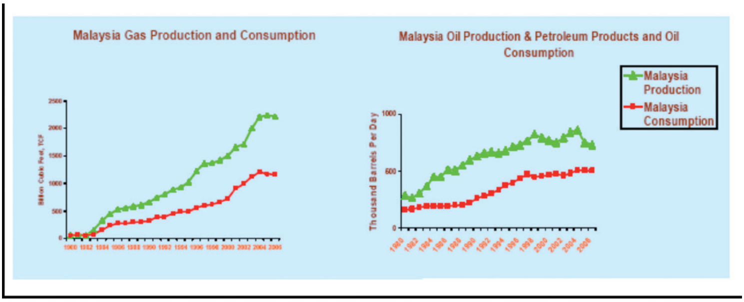


Figure 10 Gas and oil consumption and production in Malaysia [53]

RESEARCH AND DEVELOPMENT WORK ON COMPRESSED NATURAL GAS DIRECT INJECTION (CNGDI) VEHICLES

Earlier research work on automotive concentrated on tailgate stress and vibration [55,56,57] and on deformation of wheels [58]. Based on these works, it was found that automotive research and development (R and D) has always been influenced by fuel availability and its form. We have seen changes in car designs from the era of horses and cows, coal and liquid petrol. The present work was first motivated by the energy scenario as described in previous Section [59,60]. As was observed, oil reserves are reducing. This will affect automotive design, research and development activities, particularly, alternative fuels, engine and transmission, fuel storage and vehicle body. For passenger cars, the solution is to either seek an alternative fuel to be fully utilised and/or new fuels need to be developed. In either case, technological research and development on the engine, transmission, fuel storage and the vehicle body need to be carried out extensively.

The focus areas of automotive R and D differ from country to country, from region to region (such as EU, ASEAN) and from one economic grouping to another (such as AFTA). The choice of focus mostly depends on national interests, regional interests and sometimes also on the technical consultants and advisors of the government. For the automotive sector, international regulations related to the environment (such as EURO 3 and EURO 4) and guidelines related to passenger safety (such as NCAP) have very much influenced the research focus. This section provides an overview of automotive research, particularly the focus areas, mechanisms and management of research activities, challenges faced and issues related to public sector automotive R and D.

The second motivation is industrial support. In this case, Proton has given full support in terms of base body, engine, research expertise and information. Industrial support and commitment are very important for research success.

The third motivation is market potential. Table 2 shows the population of NGV in some selected countries. In Asia-Pacific countries, Pakistan ranks the top as far as number of vehicles are concerned with 1.7 million vehicles followed by Iran and India. The number of NGV in Malaysia is still very low at only 32,325 units. Hence there is great market potential for the use of NGV. Given the high price of gasoline, NGV offers a cheaper fuel alternative.

Table 2 Number of NGV and refuelling stations in selected countries [53].

ANGVA

3.55 MILLIONS NATURAL GAS VEHICLES AND 4500 REFUELLING STATIONS IN ASIA PACIFIC

	Country	No. of Vehicles	No. of Stations	Remarks
1	Pakistan	1,700,000	1,974	Apr '08
2	Iran	748,903	413	May '08
3	India	523,074	402	Apr '08
4	China	200,873	486	Jan '08
5	Bangladesh	150,000	200	Dec '07
6	Thailand	71,014	185	Apr '08
7	Uzbekistan	47,000	43	Dec '07
8	Japan	32,691	324	Sept '07
9	Malaysia	32,325	75	Apr '08
10	Republic of Korea	14,323	121	Oct '07
11	Myanmar	10,900	20	Dec '06
12	Tajikistan	10,600	53	Dec '07
13	Kyrgyzstan	6,000	6	Dec '07
14	Indonesia	3,079	8	Apr '08
15	Australia	2,453	146	Mar '07
16	Singapore	370	3	Apr '08
17	United Arab Emirates	305	2	Mar '07
18	New Zealand	283	14	Mar '07
19	Philippines	36	1	Feb '06
20	Taiwan*	4	1	Apr '05
	Total	3,554,233	4,477	

With regard to the mono-fuel passenger vehicle, UPM, UM, UKM, PRSS, UTM, UiTM, UTP and PROTON carried out a joint program to develop the Compressed Natural Gas vehicle (CNGV) sponsored by (MOSTI) under the Intensification of Research in Priority Areas (IRPA) mechanism. The program covers natural gas storage (UPM), fuel system and injectors (UKM, UM), combustion and ignition (UKM, UPM, UTP), electronic control unit and diagnostic kit (UPM), performance and emission (UM, UiTM), vehicle body architecture (UPM) and refuelling technology (PRSS, UTM, UTP). PROTON was involved in each of these projects. It was a collaborative effort between the Universities, Research Institutes and Industry with strong funding [60].

The program used the 1.6 liter CAMPRO as the base engine, as shown in Figure 11, and the Proton Waja vehicle platform, as shown in Figure 12, as the base platform. The research methodology is shown Figure 13. The development includes the vehicle platform, fuel storage tank, fuel system, ignition system, cylinder head, exhaust, electronic control unit, fuel injectors and the refuelling equipment; compressor and dispenser. Other related aspects investigated are the drive shafts [61,62], suspension springs [63], rigidity [64] and transmission matching [65].

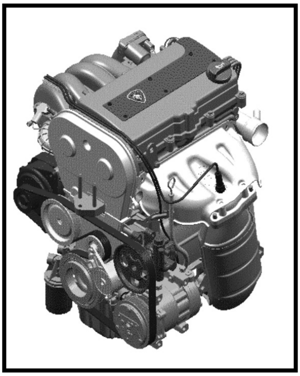


Figure 11 Campro gasoline engine

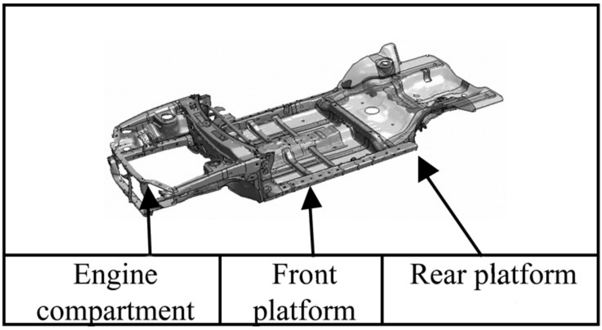


Figure 12 Proton Waja vehicle platform

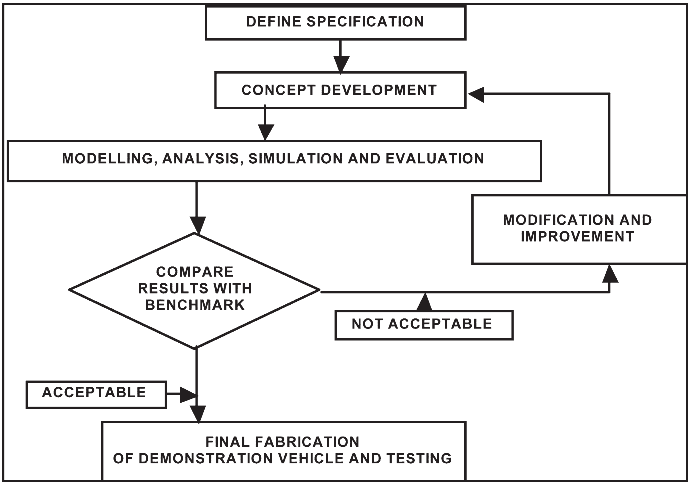


Figure 13 The research methodology

The fuel storage is a cylindrical tank with an aluminium liner wound with carbon fibre. The pressure capacity is 200.0 bar. Three tanks are fitted to provide a predicted range of 300.0 km. A new cylinder head was designed to fit the injectors and fuel rail to the CAMPRO engine block. To achieve good combustion characteristics, a longer spark plug is used. The arrangement of tank, fuel systems and injector and fuel systems configurations is shown in Figure 14. An Electronic Control Unit (ECU) which included the hardware, software and diagnostic kit was designed and calibrated. The program also took into account the exhaust emissions, in particular NO_x. To achieve this, a catalytic converter was designed [66]. The vehicle platform was developed to adapt the CNG tanks with the main considerations being safety, tank size, number and weight, mileage and refuelling time. An important design criterion was platform structural safety during crash and these were simulated using various designs of structural reinforcements, weights and tank mountings. For refuelling work, the compressor and dispenser are also being designed. In view of the high pressures involved, rigorous analysis such as mode shape and stress analyses were performed on the components to ensure safety. A prototype refuelling station was constructed. The CNG/DI prototype vehicle is as shown in Figure 15. The details for the platform analysis will be presented in the following sections.

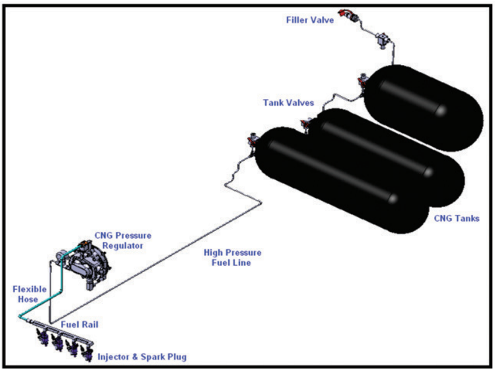


Figure 14 The arrangement of tank, fuel systems and injector and fuel systems configurations.

Figure 15 The CNG/DI prototype vehicle.

Challenges and Difficulties Faced

In executing the program, a number of difficulties were faced which can be divided into three categories: technical, institutional and industrial support.

The technical part of the program requires major design, analysis, fabrication and testing. Highly skilled manpower is required for a specified period and such expertise is difficult to acquire as most prefer jobs on a permanent basis. For the CNGDI project, this was made possible through collaborations with a number of institutions. Another difficulty was in the fabrication of the prototypes. Rapid prototyping is usually needed. For epoxy type, it can be done either in-house or by a third party within the country. However, for more delicate and complex components and metal rapid prototyping, usually a third party from outside Malaysia is required. It costs more and takes longer. Researchers also have to be aware of intellectual property rights and the disclosure of technical information that could jeopardize patent filing. On the supply side, technically competent suppliers providing technical information, equipment, software, testing and fabrication works, raw materials, electronic components and specialist consumables should be readily available. Provision of good support from suppliers is crucial to the success of the research.

The second challenge is support from research institutions, particularly, during the kick off and early stage. This includes administrative functions and suitable space. Timeliness in personnel recruitment, procurement of equipment and materials is crucial. In this regard, a suitable procurement procedure conducive for research works that will reduce if not eliminate unnecessary delay is needed.

The support from the automotive industry is as important as that from the institutions. This could be in kind such as base vehicle, base engine, information or data, expertise, fabrication and testing standards, procedures and services. For the CNGDI program, industry support was obtained from Proton.

COMPRESSED NATURAL GAS DIRECT INJECTION (CNGDI) VEHICLE BODY

The automotive body is a complex structure, made up of upper body and platform. The platform usually forms the basic size. Various cars of different makes and models can share the same platform and, therefore, are also able to share many of the same drive trains such as, engine, transmission, and final drive components, suspension and steering components. The platform can be divided into three different parts; namely, engine compartment, front platform and rear platform as shown in Figure 12. The engine compartment refers to the part covering the engine up to the firewall, while the front refers to the part from the firewall up to the rear passenger seat excluding the firewall. Finally the rear platform is identified as the structure from the rear passenger seat up to the rear end. The detailed description and development of the rear and front platforms are given in the following sections.

The work on the vehicle body concentrated on the development of the platform to accommodate cylindrical CNG tanks underneath the vehicle [67,68,69,70,71,72,73,74]. Three types of platform were developed depending on the number of tanks; namely 3-tank platform, 4-tank platform and 5 tank platform. The 3-tank platform carries 3 CNG tanks underneath the rear platform. The 4-tank design carries 3 tanks underneath the rear platform and one tank underneath the front platform and the 5-tank design carries 3 tanks in the rear and 2 tanks in the front. The design concept for these platforms is shown in Figure 16. It is worth noting that the 4-tank platform and 5-tank platform share the same rear platform. The following sections present the results of the platform analysis.

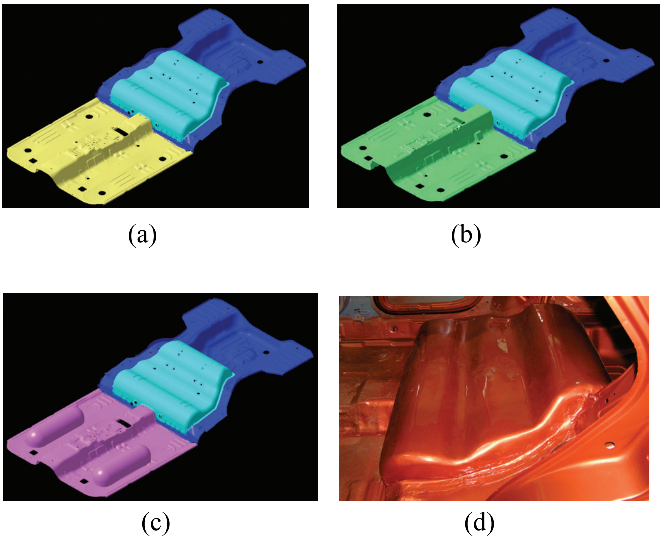


Figure 16 The design concepts for CNGDI platform (a) 3-tank platform, (b) 4-tank platform and (c) 5 tank platform (d) fabricated rear platform.

Since the work involved crash analysis, a brief theoretical background on crash analysis in automotive applications is described in this section. For automotive crash analysis, the component is hit by a rigid wall of mass m of 950 kg travelling at prescribed speed v. For frontal crash, v is 90 km/h and for rear crash, 60 km/h. The main parameters used in the evaluation of crashworthiness of a structure are kinetic energy (KE), internal strain energy (IE) and hourglass energy (HE). Kinetic energy for a rigid mass, m, moving at a speed v is given by:-

Equation 12 $$KE = \frac{1}{2}mv^2$$

During crash event, this KE will be transferred into internal strain energy (IE). At the beginning of impact, elastic deformation occurs. The stress distribution is often non uniform, especially for complex structures like car platforms, and pockets of highly stressed areas may occur. As the crash proceeds, more kinetic energy is released (results in reduction of v) and this causes plastic deformation starting from the high stressed regions. As the crash proceeds further, v will reduce further over time and increase structural deformation and distortion. To account for distortion without change of volume, hourglass energy, HE is used. In most cases, the value of HE is small and negligible while some parts of the structure may fail plastically. The total energy (TE) in the system becomes:-

Equation 13 $$TE = KE + IE$$

During crash, total energy is conserved and hence:-

Equation 14 $$\frac{1}{2}mv^2 = \frac{1}{2}k_e y_e^2 + k_p y_p^2 + HE$$

where k_e and k_p are the elastic and plastic stiffness of the structure respectively, and y_e and y_p are the elastic and plastic displacements respectively. The y_p only occurs when the yield criteria of the material is satisfied. For von Mises yield criteria, yield occurs when:-

Equation 15 $$\sigma_{eq} = \sqrt{\frac{3}{2}S_{ij}S_{ij}} = \sigma_y$$

where σ_{eq} and σ_y are the equivalent and yield stress respectively and $S_{ij,}$ the deviatoric stress. The plastic strain resulting from material yielding is determined from the Prandtl Reuss flow rule, that is, Equation 16 $$d\varepsilon_{ij}^{p} = \frac{3}{2}\frac{d\varepsilon_{p}}{\sigma_{eq}}S_{ij}$$

and,

Equation 17 $$d\varepsilon_{p} = \sqrt{\frac{2}{3}d\varepsilon_{ij}^{p}d\varepsilon_{ij}^{p}}$$

where ε_{ij}^{p} and $d\varepsilon_{ij}^{p}$, are plastic strain and increment of plastic strains respectively and $d\varepsilon_p$ is equivalent plastic strain increment. For analysis involving crash, as in the present case, the elastic displacement y_e is very small compared with plastic displacement y_p. Also, in the present analysis, a 'good' mesh is developed that resulted in very small HE. Hence, neglecting elastic energy and HE, the internal energy expression reduces to:-

Equation 18 $$IE = k_p y^2_p$$

In integral form, Equation 18, can be written as

Equation 19 $$IE = \int k_p y_p dy = \int F dy_p$$

where F is the crush force which is given by

Equation 20 $$F = k_p y_p$$

Hence, from Equation 19, it can be seen that the internal energy can be obtained from the area under the graph of crash force, F, versus plastic displacement, y_p. From Equation 18, it can be seen that IE is very much dependent on y_p. The crashworthiness of a structure is often represented by a graph of IE versus displacement as will be presented in a later section.

CNGDI VEHICLE REAR PLATFORM

The model for the rear platform is shown in Figure 17. The rear platform is constructed of mild steel plate and is contoured to accommodate 3 different sizes of tanks [72]. This is to optimise the space available so that maximum volume of gas can be carried and at the same time keep the interior of the vehicle in conformity with ergonomic requirements of passenger space such as the head clearance. At the same time also, the clearance between the tanks allows ease of assembly and disassembly of the tanks both during manufacturing and maintenance. The rear platform was analysed for lateral impact and the deformed shape during crash shown in Figure 18. It can be seen that, the tank compartment deformed slightly at the end of the crash event. The internal energy versus time for the rear platform is shown in Figure 19. The internal energy for the CNG platform with reinforcement (denoted as platform A) has high internal energy of 14 kJ and this is comparable with that of gasoline origin and hence considered acceptable.

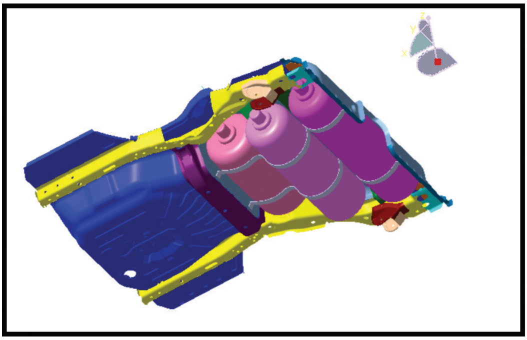


Figure 17 CNGDI vehicle rear platform with tanks mounted

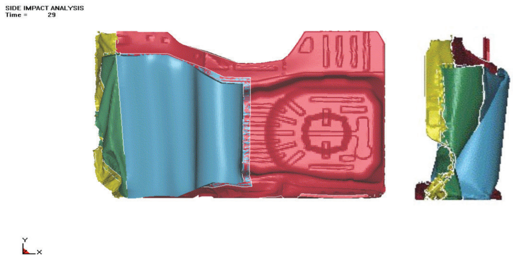


Figure 18 Deformed shape of rear platform

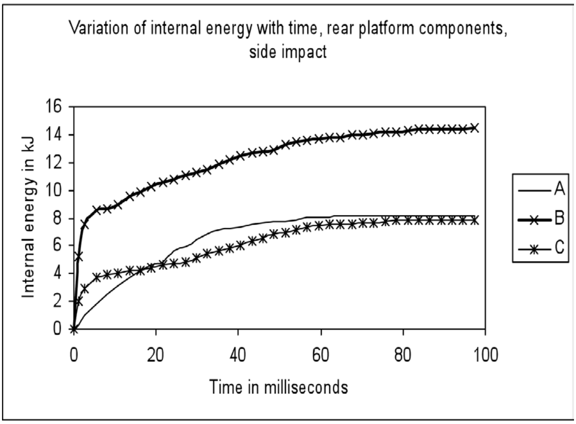


Figure 19 Internal energy versus time for rear platform [72].

CNGDI Vehicle 4-Tank Front Platform

In this section, the behaviour of a compressed natural gas vehicle (CNGV) front platform assembly subjected to lateral crash was studied [67,69,71,73]. The work consists of two main parts. First, to determine the optimum number of ribs for the backbone, three types of backbone are analyzed. Second, using the optimum backbone configurations obtained from the first part, the behaviour of the assembly is analyzed. For the second part, the effect of tank mounting structure is determined. The final results obtained provided the optimum backbone structure as well as tank mounting structure for the front platform. Altair Hypermesh software was used to develop the FE model. Crash analysis was carried out using LS-DYNA software. Since the front platform is not in the crumple zone for the frontal and rear crash, only lateral crash is considered. In the analysis, a rigid barrier of mass 200.0 kg moving at a speed of 5.0 m/s in the y-direction crashed into the front floor assembly. The results of the crash in terms of crash mode, displacements and energy absorption were obtained and compared to that of the gasoline base platform model.

Finite Element Model, Materials and Boundary Conditions

The basic construction of the front platform (without Compressed Natural Gas (CNG) tank) is quite complex as shown in Figure 20 [67]. The component focused on in the present study is the backbone. In the analysis, all components are made of mild steel with properties as given in Table 3.

Table 3 Material properties

Young's Modulus (Gpa)	Poisson's ratio	Range Elongation at Break (%)	Ultimate Tensile Stress (UTS) (MPa)	Yield Stress (MPa)
209.0	0.3	26 to 54	280 to 674	129 to 424

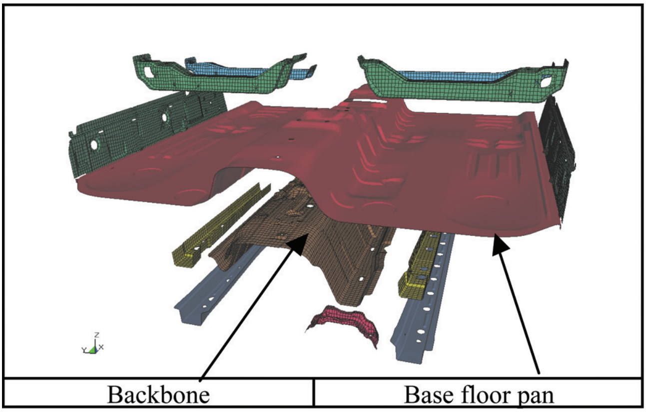


Figure 20 Exploded view of a typical front platform [67]

The platform of Figure 20 is called the base platform (platform A) which is to be modified to accommodate one CNG tank. This is done by raising the centre portion of the floor pan, and extending the height of the backbone. The size of the backbone, namely height and width is determined by the tank size to be used. For the present study, a tank of diameter 200 mm is to be used. The platform is subjected to lateral impact against a rigid wall of mass of 200.0 kg moving at a speed of 5m/s. In the present study, the dimension and shape of the tank support structure is varied such that the crashworthiness characteristics of the front platform under lateral impact is comparable with the base design. The parameters considered are energy absorption, and lateral displacement. The purpose is to determine the most suitable height of the support structure and the need for additional side reinforcement in order to achieve desired crashworthiness characteristics. The number of cases studied is given in Table 4.

Table 4 Types of platforms studied

Platform Types	Characteristics	Tank mounting structure height (h)	Maximum displacement (mm)	Energy Absorbed J
Platform A	Gasoline platform, low backbone with centre member	None	90	1.75
Platform B	CNG platform with high backbone	None	160	1.25
Platform C	CNG platform with high backbone	0	210	1.8
Platform D	CNG platform with high backbone	9 mm	90	2.1

Crash Behaviour of Front Platform Assembly with Different Types of Backbone Reinforcement

In this section, the behaviour of front platform assembly with different types of backbone reinforcement without tank mounting structure is presented. The main objective of this study is to determine suitable design of platform backbone based on the highest energy absorbed and also the closest to the gasoline platform. The different types of backbone structure in the present study are shown in Figure 21. The deformed shape of platform with backbone A and backbone B for t=0 ms and t=30 ms is shown in Figure 22. It can be seen that deformation is greater for backbone B compared with backbone A. This is due to the weakening of the structure as a result of increase in backbone height without ribs to increase the stiffness. The crashworthiness performance of front floor assembly without tank mounting for platforms with backbones A, B and C, for crash events t=0 ms to t=100 ms is shown in Figure 23, for displacement, and Figure 24, for energy absorbed. It can be seen that platform with backbone A has the least displacement followed by platform with backbone C. The energy absorbed is highest for platform with backbone A followed by platform with backbone C. Further refinement of backbone C by adding ribs (denoted by platform D in Figure 23) improved the displacement but did not match that of platform with backbone A. Due to the complexity of the backbone structure with ribs as well as the requirement to accommodate the CNG cylindrical tank, further improvement in crashworthiness was carried out with the design of the tank mounting structure where the tank mounting structure is designed to absorb the remainder of the crash energy so that the net energy absorbed matches that of platform A. The analysis on the tank mounting structure is described in the proceeding section.

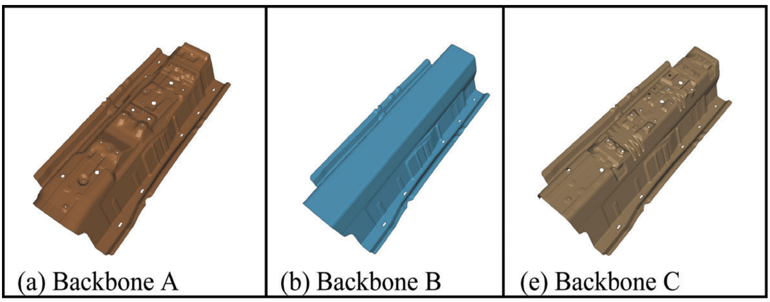


Figure 21 Types of backbone analyzed

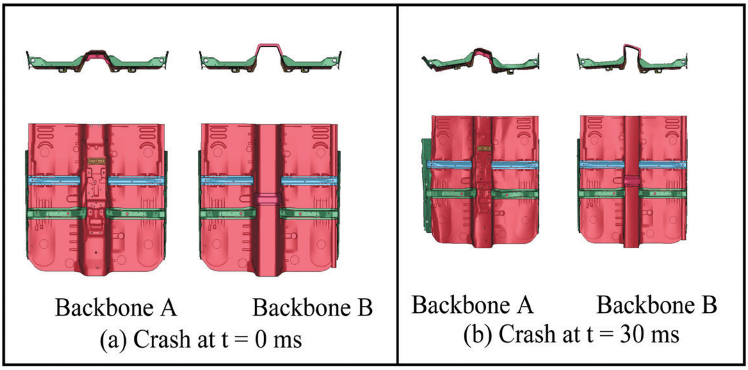


Figure 22 Crash behaviour for front floor assembly with Backbone A and Backbone B without tank mounting

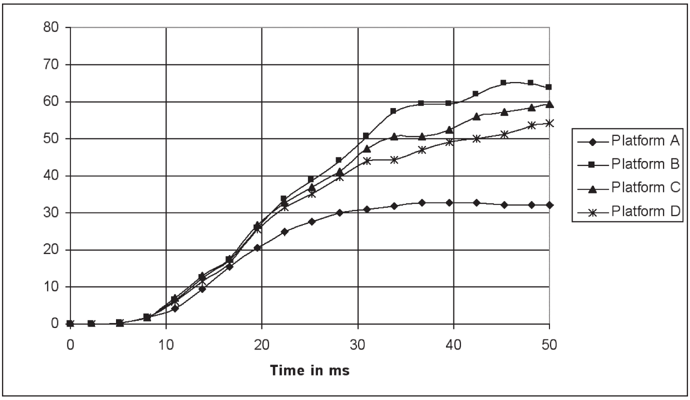


Figure 23 Crash displacement versus time for front floor assembly without tank mounting.

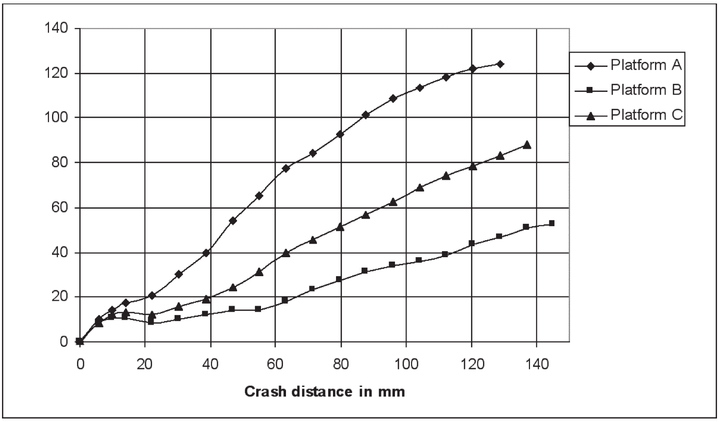


Figure 24 Crash displacement versus time for front floor assembly without tank mounting.

Crash Behaviour of CNG Front Floor Assembly with Tank Mounting Structure

In this section, the behaviour of front platform assembly fitted with improved backbone reinforcement C with tank mounting structure is presented. The main objective of this study is to determine the effect of the tank mounting structure on the crashworthiness of the platform. From the results, the most suitable tank mounting structure geometry will be selected.

The geometry and dimension of the tank mounting structure is shown in Figure 25. The structure is an inverted U channel of length 250 mm, width 25 mm, thickness 4 mm and height h mm. In the present paper the value of h=0 mm and h=9 mm is investigated. The assembly of front platform is shown in Figure 26 whereas Figure 27 shows the platform with a cylindrical tank fitted. The crash analysis was carried out without the tank. The deformed shape of platform with backbone A and backbone B for t=0 ms and t=100 ms is shown in Figure 28. It can be seen that, the tank compartment size is reduced as a result of crash. It is greatest for platform B without mounting structure. For platform C (h=0 mm) there is severe bending of the mounting structure. The bending direction is such that it does not intrude into the tank compartment. For platforms D (h= 9 mm), the mounting structure remains straight. The variation of displacement with time for platforms A, B, C and D is shown in Figure 29. From Figure 29, it can be seen that the displacement increases from the start of impact (time = 0 ms). The crash event is completed within 100 ms. From 0 to 5 ms, there is hardly any displacement due to the time travelled to reach the platform. There is a gap between the rigid wall and platform. For 5 to 30 ms, the displacement is linear with time. During these times, elastic deformation occurs. Thereafter, the deformation is non linear and saturates upon completion of the crash to certain values depending on the design. During these times, plastic deformation occurs whereby some parts collapse and crumple. The maximum displacement provides some measure of safety to the tank and passenger. However, in this work, our objective is to design a CNG platform that matches the base design (platform A of Figure 29). In Figure 29, platform D is shown to meet the requirement completion of crash.

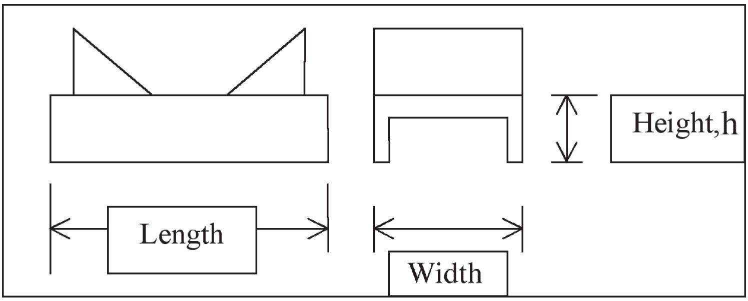


Figure 25 Shape and dimension of tank mounting structure

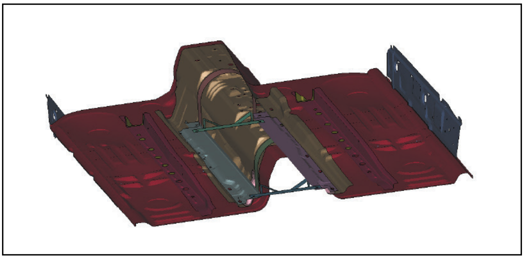
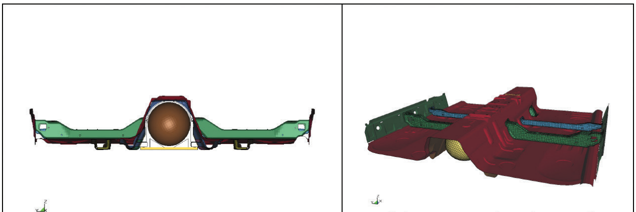


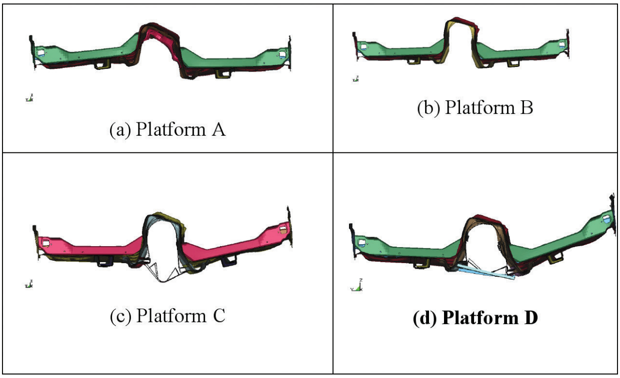
Figure 26 Under floor view of platform B without tank.



(a) Front view of platform D with tank

(b) Isometric view of platform D with tank

Figure 27 Front floor assembly with Backbone C and mounting structure C with CNG tank



(a) Platform A

(b) Platform B

(c) Platform C

(d) Platform D

Figure 28 Deformed shape of front floor platform assembly as given in Table 4.

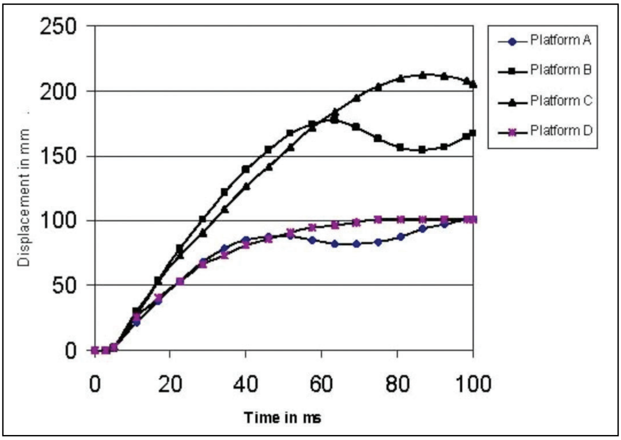


Figure 29 Crashworthiness characteristics (displacement) of front floor platform assembly as given in Table 4.

The variation of energy absorbed with crash distance is shown in Figure 30. It started with a small elastic energy (for crash distance up to 25 mm for most platforms) followed by large elastic energy absorbtion. The value of the energy absorbed depends on the stiffness of the platform. Again for the present work, platform characteristics similar to or better than that of the base design are sought. From Figure 30 platform D is shown to be superior compared to the other platforms in terms of energy absorbed. The summary of the results are given in Table 2. Based on crashworthiness characteristics such as crash distance and energy absorbed, the performance of platform D is suitable with maximum displacement of 91 mm and energy absorbtion of 2.1 J.

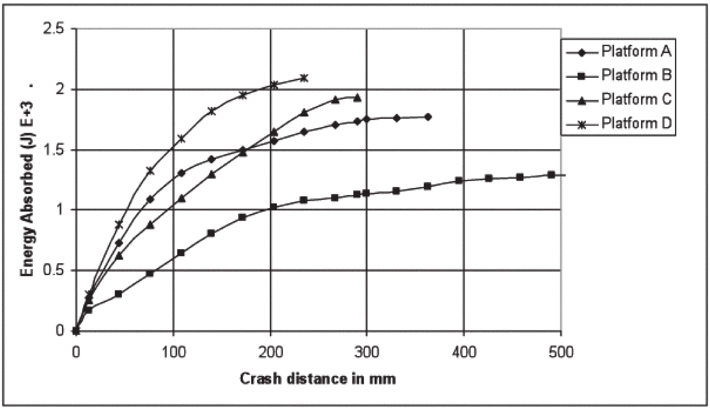


Figure 30 Crashworthiness characteristics (energy absorption) of front floor platform assembly as given in Table 4.

Conclusions

The behaviour of Compressed Natural Gas Vehicle front floor assembly subjected to lateral crash load has been carried out. The results showed that the backbone without ribs (backbone B) gave lower crashworthiness characteristics as compared with the backbone with ribs (backbone C). Therefore the crashworthiness of platform backbone depends on the geometry. To meet the desired design crashworthiness characteristics of the front floor assembly, suitable shape and size of the tank mounting structure is needed. From the present work, the U channel of width 25.0 mm, height 9.0 mm, 4.0 mm thick with added reinforcement is suitable for the purpose. Comparison with base platform A showed that platform D is acceptable. Therefore, mounting structure with h = 9 mm and additional reinforcement is sufficient to provide the necessary strength and crashworthiness characteristics of the platform. For these dimensions, a maximum displacement of 91 mm and energy absorbtion of 2.1 J are obtained.

CNGDI Vehicle 5-Tank Front Platform

In the present section, the finite element is used for the crash analysis. In the present work, the parameters being studied are the bulge length (L), bulge height (H) and bulge diameter (D) [68]. Only lateral impact will be analysed for all these platforms. The platform with H = 0.0 represents the base design, that is, platform without bulge, and forms the basis for comparison. The characteristics of the platform without bulge have already been accepted. For this reason, the objective of the work is to achieve the characteristics of the bulged platform close to that without bulge. In the present work, the bulged platform is considered acceptable when it has similar or better characteristics as compared to the platform without bulge.

Finite element modelling, materials and boundary conditions

The shape of the front platform under investigation is as shown in Figure 31. The overall length of the platform is 1.394 m and width is 1.335 m. The notation used to describe the bulge geometry is shown in Figure 31. A typical finite element mesh is shown in Figure 32. The platform is made of mild steel with the properties given in Table 3. The boundary conditions used in the present analysis is that the side PR is fully restraint while the side QS is subjected to a rigid wall impact. The mass of the rigid wall is 950 kg and its initial velocity is 50 km/h (13.9 m/s) in the y direction (y is in the direction RS shown in Figure 31, for the notation and direction). For all cases, the analyses were carried out for a maximum period of 100.0 ms. This is to ensure that all the kinetic energy has been completely dissipated.

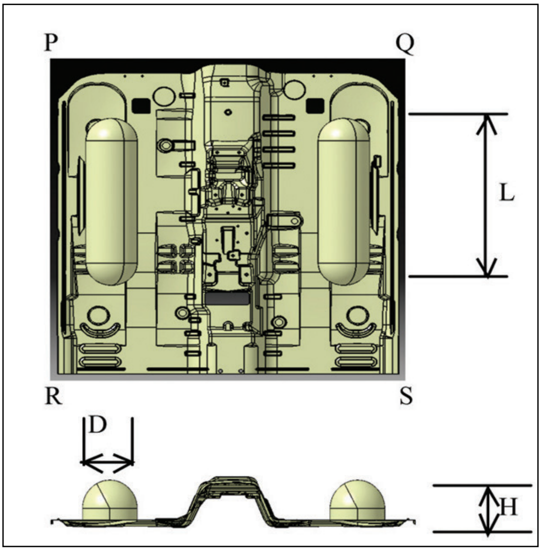


Figure 31 Bulge geometry and notation (bulge length, L, height, H and diameter, D)

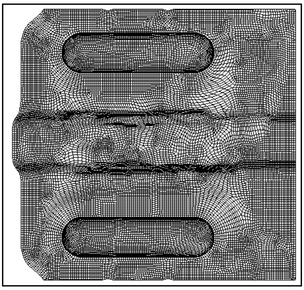
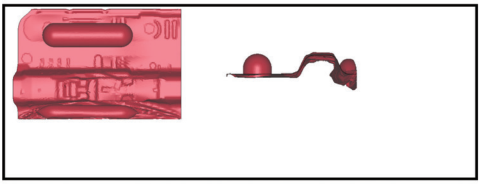


Figure 32 Finite element mesh for the bulged platform

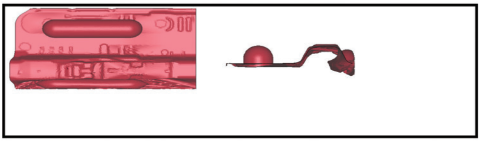
Crash Behaviour

The crash behaviour is best described by looking at the shape of platform deformation at various time intervals from t = 0 ms to t = 200.0 ms at time intervals of 50 ms. For platform with H = 140.0

mm, a typical shape of deformation is shown as in Figure 33. It can be seen that crash initiated at the impact side with the platform crumpled in the direction of velocity. There is no displacement normal to the plane of the platform suggesting that crumpling occurs on the same plane as the platform and no intrusion to the passenger compartment as a result of the crash.



t = 50 ms



t = 100 ms

Figure 33 Deformation of front platform.

The y displacement versus time curve for platform with H = 140 mm and different values of L (ranging from 200 mm to 1350 mm) is shown in Figure 34. It can be seen that initially, overall displacement increases linearly with time for the first 10 ms and after that displacement saturates to a maximum value. The maximum crash displacement is reached after 60.0 ms. Maximum numerical value depends on the bulge length.

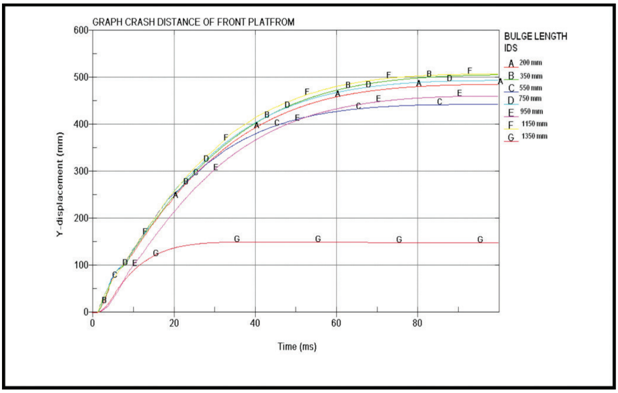


Figure 34 Displacement against time for different L at H = 140 mm.

The y displacement versus time curve for the platform with L=750mm and different values of H (ranging from 0 to 140 mm is shown in Figure 35). It can be seen that a similar trend as that of **Figure 34** is obtained. For constant L, the values depend on the bulge height, H. The maximum crash displacement is also reached after 60.0 ms.

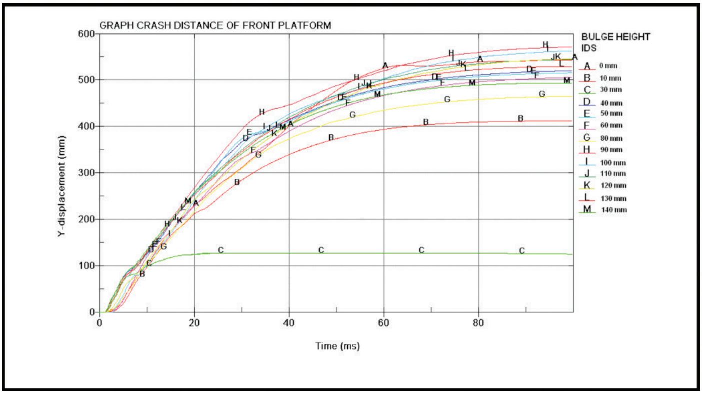


Figure 35 Crash distance against time for different bulge heights with L = 750 mm.

Crashworthiness Characteristics

The crashworthiness of a structure can be assessed by its ability to absorb the kinetic energy of the impact (KE) and dissipate it as Internal Energy, IE. There are a number of criteria that can be used; namely, the maximum value of IE achieved after the crash completes and/or the shortest time for completion of crash. For the purpose of the present paper, maximum IE is used. For bulge front platform, the variation of IE with respect to time is shown in Figure 36 (H = 140mm and L varies) and Figure 37 (L = 750mm and H varies) for all the cases studied. It can be seen from Figure 36 and Figure 37 that the values of IE is zero at t = 0 and increases to maximum values at a time that depends on L or H. For all cases, maximum IE is achieved after 60 ms.

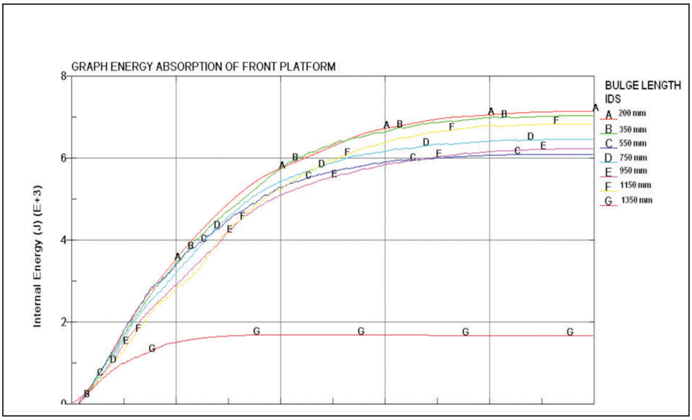


Figure 36 Crash energy absorbed against time for different bulge lengths for H = 140 mm.

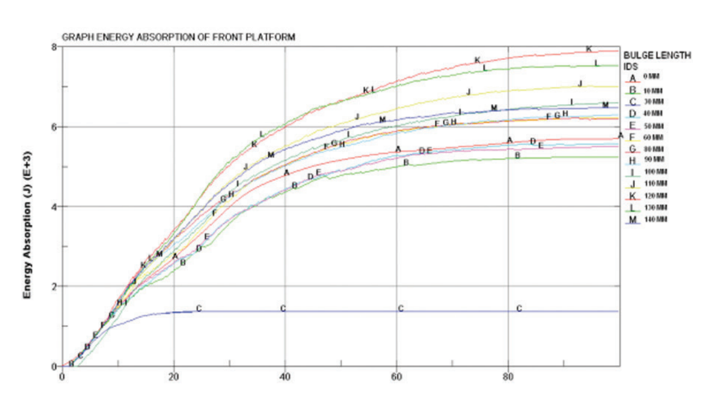


Figure 37 Crash energy absorbed against time for different L at H = 140 mm.

Effect of L and H on Crashworthiness

The variation of maximum IE with L (for H=140) and variation with H (for L=750) are shown in Figure 38 and Figure 39 respectively. From the results (see Figure 38), it can be seen that maximum IE increases slightly as L increases from 0 to 400mm and thereafter, reduces slightly up to 1200mm. For L greater than 1200, energy reduces abruptly. For design purposes, for L in the range 200 to 1200 mm, the energy absorbed can be considered to be constant within the range 6000 to 7000 J. Hence, in this range, L does not affect energy absorption. Figure 39 shows the variation of maximum IE with H for L = 750.0 mm. It can be seen that energy absorbed reduces for H = 0 to H = 30mm (IE is minimum at H = 30mm) and increases again from H = 40 to H = 120 mm before it reduces again at H above 130 mm. Highest value of 7914 J is obtained for H = 120mm. Figure 39 shows that H has higher influence on energy absorption compared with L. From Figure 39 we can conclude that H = 120 mm is the suitable bulge height.

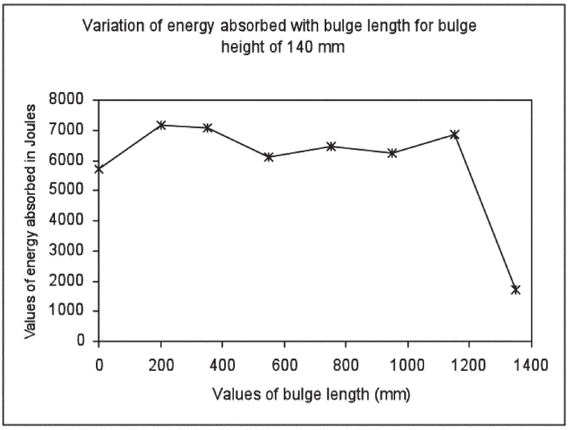


Figure 38 Crash energy absorbed against bulge length L for H = 140 mm

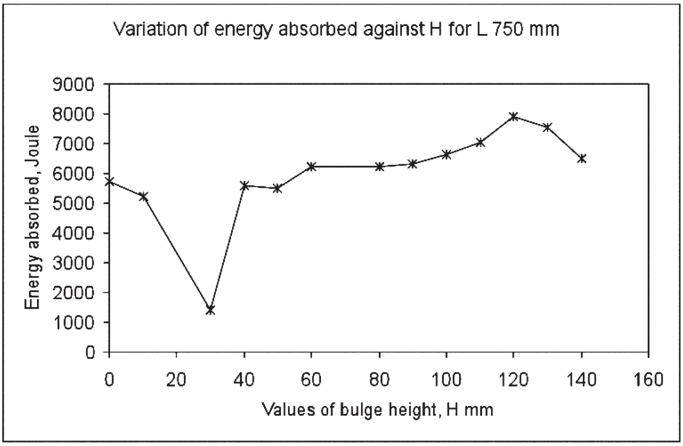


Figure 39 Crash energy absorbed against bulge height H for L = 750 mm

Conclusions

The crash behaviour of bulged front platform for compressed natural gas vehicle has been carried out. From the results obtained, it can be concluded that, bulge length L and height H affect the values of maximum IE of the platform. The optimum bulge height of 120.0mm is obtained for highest IE. For the optimised bulge height the IE values of the front platform subjected to lateral impact is 7914 J. The IE for platform without bulge (H = 0 mm) is found to be 5726.2 J. Hence, the platform with bulge height of 120.0 mm is considered safe to be used in CNG vehicles.

MANAGEMENT OF MULTI-INSTITUTIONAL COLLABORATIVE RESEARCH PROJECTS

Management is not the core expertise of the author. However, during the course of doing research, the author experienced proposing and managing collaborative research involving many institutions [59,60]. Hence it is the intention of the author, to share this experience in this section. This section is devoted to collaborative research.

From the author's experience, collaborative research can be divided into different types; namely, single or multi projects and/or single or many institutions. The different types are as shown in Table 5. For collaborative projects, generally more than two institutions are involved. For research that has many projects, it is usually referred to as a program. For a program that has many projects, it can be further characterised into either "program with many coordinated projects" or "program with many integrated projects". These characteristics are illustrated in Figure 40 and Figure 41 respectively. It can be seen that the coordinated program has projects that are independent of each other whereas, the integrated program has projects that are dependent on each other. Programs with integrated projects are usually preferable and when managed properly, more likely to succeed. We will focus on integrated projects where the important characteristics are as follows:-

1. The output of each project will directly affect the success of other projects.
2. The output of one project may become the input of another.
3. The success of the program is determined by the success of all the projects.
4. All projects need to be completed simultaneously.
5. There is an element of integration between project outputs.

Table 5 Types of research projects

Types	Program	Project	Number of Researchers	Number of Institutions
Single		1	1	1
Single		1	2 and more	1
Multi		1	2 and more	2 and more
Single	1	2 and more	2 and more	1
Multi	1	2 and more	2 and more	2 and more
"Institutions" – An Institution Legally Established Under The Act				

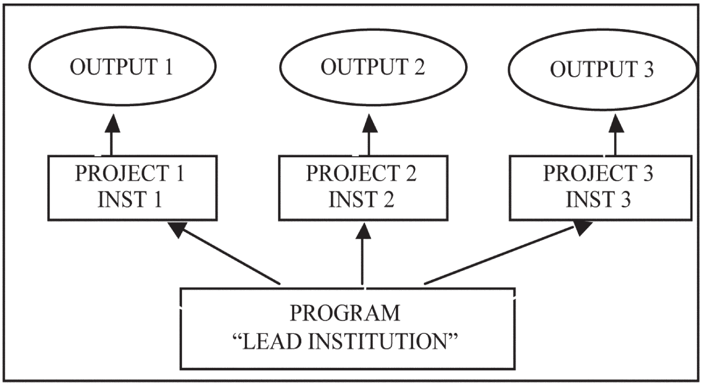


Figure 40 Program with many coordinated projects

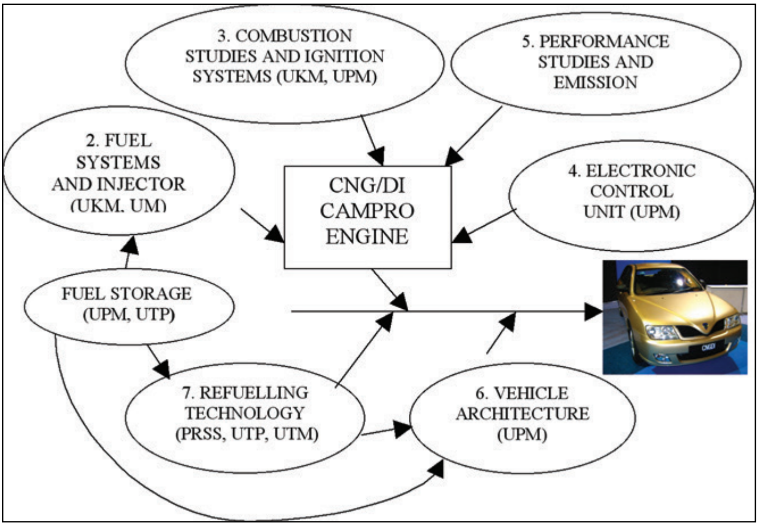


Figure 41 Program with many integrated projects

Based on the above characteristics, to manage such a program requires a slightly different philosophical approach. First and foremost, the initial intention for conducting the research has to be correct. If the initial intention is not clear, most probably the program may fail, or start for the wrong reason or it may not even start. Secondly, success is highly dependent on the sincerity of the researchers, including the project heads. Thirdly, everyone involved in the research should place the importance of the program above their personal interests and bear in mind that they need each other to succeed, and finally emphasis is put on planning to carry out the program. If we fail to plan, then we actually plan to fail.

An important aspect of collaborative research is that it usually involves many researchers. Hence it is important to select the researchers properly. They should be dedicated to the program, committed to do the work, have passion for the project, and be honest and sincere. They should also be fully interested and not merely riders on the project. The head of project and head of program shall be elected from among the researchers and have the same personal qualities and be able to motivate the team. For programs involving the industry, it is always necessary to have industry representatives in each of the projects.

The process of doing collaborative research is similar to that of non-collaborative projects except that there should be an element of integration. It usually begins with forming the team, preparing and submitting the proposal, project implementation, progress monitoring and integration and finally concluding the results. During implementation, funds need to be disbursed on time, planning for procurement, appointment of research assistance, training of researchers and submission of progress reports as scheduled. The heads of projects should meet regularly and as frequently as possible to discuss the results and problems related to the project output.

Another important aspect during implementation and monitoring of integrated programs is integration activities. Integration activities may take the form of meetings but a retreat or workshop is preferable because free flow of criticisms and ideas is needed. The purposes of integration are to:-

1. Streamline outputs, milestones, time frame and budget.
2. Identify and accommodate constraints of other projects that have direct impact on our own.
3. Find ways to make it work and proof of concept
4. Have input from the grant provider and if applicable input from the industry collaborator
5. Assist the other projects when required and
6. Solve problems jointly and not a place to blame on each other.

With careful manoeuvring and clarity of intentions, integration activities usually yield fruitful and desired results. The program and project heads play a very important role in the integration exercise. Each member of the program needs to play their role. The lead institution, particularly, has the role of overall responsibilities including fund disbursement, coordination of progress and reports, contact with grant provider and industry, and important decisions related to the program. The collaborative institutions, on the other hand, have to execute the project, submit the required reports to the lead institutions as scheduled and attend the regular monitoring meetings and integration activities. The members from the collaborative institutions also represent the institutions with respect to the program. Other issues that need to be resolved when embarking on a collaborative program include intellectual properties, non disclosure agreement, mechanisms of usage of facilities, collaborative agreement, exhibition and publicity. The CNGDI Engine and Transmission research program as described in previous Section is a success. The program has submitted 16 inventions for patent filing [79, 80, 81, 82, 83, 84, 85, 86,87,88,89,90,91,92,93,94]. Hence it can be concluded that multi-institutional research programs can be carried out successfully.

CONCLUSION

In conclusion, we can say that,

1. Verified predictive method is a useful research philosophy for engineering.
2. Research in materials is important for the betterment of human living standards especially in increasing safety. Elasto-plastic materials, material ratchetting and functionally graded materials have been identified as characteristics that affect component behaviour and stress distribution.
3. Energy has always been an important and critical commodity that warrants special attention in terms of its alternative sources as well as preparing the technology for its proper and efficient utilisation such as in automotive application.
4. Research in automotive areas should focus on utilising materials and alternative energy sources such as Natural Gas to meet the requirements of crashworthiness characteristics, emission and energy efficiency.
5. Integrated research projects can be successful in a multi-institutional collaborative environment provided that key issues and challenges are addressed properly as shown in the management of the Development of CNGDI vehicle program.

BIOGRAPHY

Barkawi Bin Sahari was born on 25th October 1957, in Kampung Sahari, Simpang Rengam, Johor, a village named after his father. However, he was brought up in Kampung Seri Paya in Kulai.

Barkawi obtained a First Class Honours Degree, Bachelor of Science in Mechanical Engineering, 1981 and Ph.D in Mechanical Engineering, 1984, both from the University of Nottingham, United Kingdom. Beefore that he went to various schools prior to his tertiary education; namely, Sekolah Kebangsaan Kulai (1964-1967), Sekolah Kebangsaan Polis Kem, Kulai (1968-1969), Sekolah Sultan Ibrahim Kulai (1970-1975), Maktab Sultan Abu Bakar Johor Baru (1976) and West Bridgford College of Further Education, Nottingham, UK (1976-1978) before entering Nottingham University, UK in 1978. Barkawi then joined Universiti Putra Malaysia (UPM), then called Universiti Pertanian Malaysia, in 1981 as a Tutor. He was offered an SERC studentship to do his Ph.D at Nottingham University but turned it down as he also received a scholarship from the Malaysian Government. He then pursued his studies for a Ph.D degree in 1981, also at the University of Nottingham, UK. He completed the Ph.D program within 3 years and earned his Ph.D in Mechanical Engineering in December 1984. His thesis was entitled "Finite Element Investigation of Incremental Deformation of Components". Barkawi's current fields of interest include Stress Analysis, Material Engineering, Finite Element Method, Automotive Engineering and Engineering Design. Four papers were published based on his Ph.D thesis.

Dr. Barkawi returned to UPM in 1985 and was appointed as a lecturer in the newly formed Department of Mechanical and Systems Engineering, Faculty of Engineering. The Department began offering the B.E. (Mechanical/Systems) degree in 1985 with the first intake in July. The total number of academic staff in 1985 was five. Dr. Barkawi's main job functions at the time were teaching and student assessment. From 1988 to 1993, Dr. Barkawi was appointed as Head of the Department during which time his additional duties included the development of curriculum for accreditation by the Board of Engineers, Public Services Department, Malaysia and Institution of Engineers Malaysia (the B.E. program was accredited in 1989), planning for the laboratory development, assisting in the recruitment of new academic as well as technical staff, planning for staff development, especially for lecturers to further their studies at Ph.D level, setting up academic linkages with University of Bradford, United Kingdom to assist in curriculum development, assisting in the appointment of External Examiners and External Assessors, application and management of the government development budget (the department was given RM 5 million for development in 1985), successful application of the staff development grant under the Asian Development Bank, successful application of the fund for the Committee for International Cooperation in Higher Education (CICHE), planning and implementation of postgraduate programs in Manufacturing Systems Engineering, organizing departmental as well as National Seminars, planning and implementation of staff teaching duties, chairing departmental meetings, development of new courses, participating in the running of Continued Professional Development Courses with Motorola and managing the day to day running of the department.

Over the past 24 years, Dr. Barkawi has taught subjects for Diploma in Engineering; Strength of materials and Workshop Technology, for Bachelor's degree Degree; Fluid Dynamics and Machine, Energy in Agriculture, Strength of Materials, Engineering

Design I and Engineering Design II and for the M.S. Degree; Finite Elements in Computer Aided Engineering and Advanced Fracture Mechanics. Based on the teaching assessment survey conducted by the faculty, Dr. Barkawi's teaching quality was rated high, normally no less than 3.5 out of 5. He was thus awarded "An Excellence Service Award" by UPM in 1993.

Since completion of his Ph.D, Dr. Barkawi has been actively involved in research. In 1986, he was a member of a research group which managed to secure a research grant amounting to RM 500,000.00 from the Ministry of Science Technology and Environment, Malaysia (MOSTE) under the Intensification of Research in Priority Areas (IRPA) mechanism. The title of the program was "Automation and Computer Application in Industry (2-07-05-03) (1986 – 1990). The program was successfully carried out and was completed in 1990 with 11 publications. In 1991, Dr. Barkawi headed a 3-member research group and proposed an IRPA research program entitled "Finite Element Analysis for Stress, Thermofluids and Vibrations" also under the IRPA mechanism. The program was approved in 1991 (number 2-07-05-015) with a grant amounting to RM 550,000.00. The program has been successfully carried out and ended in 1995 with 12 publications. Following that, in 1997, Dr. Barkawi acquired a research grant entitled "Finite Element Prediction and failure analysis on Integral Elastomeric Spigot and Socket Joints for Steel Pipes (03-02-04-0064)". The project began in 1998 and was completed in 2002. The grant amount for the project was RM120,500.00 and it resulted in 5 publications being produced. In addition to that, he also carried out five projects under the UPM short term mechanism. The projects were: (i) "Crash behaviour of carbon/epoxy, glass/epoxy and 'sabut'/epoxy cones under axial load" in 2000 amounting to RM10,000.00; (ii) Finite element and experimental investigation of composite cones under axial loads in 1998 amounting to RM 1000.00; (iii) “Carbonisation and graphitization of cellulosic natural plant fibre” in 1998 amounting to RM10,000.00; (iv) “Finite element analysis of energy absorption capacity of conical composite component” in 1997 amounting RM10,000.00; and (v) “Filament wound ‘mengkuang’ fibre composite materials” in 1997 amounting to RM15,000.00. Twenty five publications were produced related to these projects.

Dr. Barkawi was also the head of a team that implemented a research Program classified as National Prioritised Research (PR) under the IRPA mechanism. The title of the program was “Compressed Natural Gas (CNG)/Direct Injection (DI) Engine and Transmission”. The program was approved by the Malaysian Government with a grant amounting to RM28,836,318.00. The program began in July 2002 and ended in 2007. The program was a multi-institutional research project involving UPM, UKM, UM, PRSS, PROTON, UTP, UTM, UiTM with a total of 89 researchers and 63 research assistants. The program managed to file 16 inventions for patenting. The program output won the Gold Medal and Henry Goh Special Awards for Innovation for Environment at the ITEX 2006, Kuala Lumpur and Gold Medal with Special Mention and Special Award from The Association of Polish Inventions at the EUREKA 2006 in Belgium.

Dr. Barkawi has successfully supervised 4 Ph.D students and 15 M.S. students and on average 4 B.E. (Mechanical) students per year over the past 20 years. Currently he is supervising 3 Ph.D students and 4 M.S students.

Dr. Barkawi’s expertise is known nationally as well as internationally. He was appointed the Deputy Chairman, International Conference and Exhibition on Composite Materials and nano Structures (IC2MS08) 2008, External Examiner for M.S. degree in Universiti Sains Malaysia in 2008 (1 candidate), External Examiner for M.S. and Ph.D degree in Universiti Teknologi Malaysia in 1997 (1 MS), 1998 (2 MS), 2000 (1 MS) and 2008 (1 MS, 1 Ph.D) and examiner in UPM 1997 (2 candidates for M.S.), 1999 (1 for Ph.D), 2000 (1 for Ph.D and 1 for M.S) and 2001 (1 for M.S). In addition to that, he was a referee for the "World Engineering Congress 2002 – Mechanical Engineering, "International Conference on Advanced Materials and Processing, AMPT, 1998, Journal, Institution of Engineers, Malaysia, 1986, Asean Journal of Science and Technology for developments, SIRIM, 1993, Referee for Professor and Associate Professor applications, Universiti Teknologi Malaysia, 2001, Referee for Associate Professor applications, International Islamic University Malaysia, 2001, Mentor for Institution of Engineers Malaysia professional training, Member, National Accreditation Board for Private Colleges (LAN), 1998, 1999, 2000 and 2001 and Member, Organising Committee for "International Conference on Advanced Materials and Processing, AMPT, 1998.

Additionally Dr. Barkawi was a Member, of the Board of Governors for the International Conference on Mechanical Behaviour of Material 7 (ICM7) for the period 1991-1996. He was also a Member of the National Committee on Standards (2002 – 2007), Committee Member for Developing Malaysian Standards on Natural Gas Vehicle (2008 to date), panel evaluation for National Awards "Anugerah Inovasi Penyelidikan Sektor Awam Bersama Swasta (AIPB)", MOSTI (2002 to date) and Panel member for Malaysian Qualification Agency (MQA). Dr. Barkawi has been a Corporate Member of The Institution of Engineers, Malaysia since 1990 and a registered Professional Engineer (Mechanical) with The Board of Engineers, Malaysia since 1990.

Dr.Barkawi was invited to deliver a position paper at the International Forum on Advanced Technologies (IATF), Concorde

Hotel, Shah Alam, 7-8 November 2000 entitled "Position Paper on Numerical Modelling" and also to present a paper on "Some Application of Finite Element Method to the Design of Machine Components" at the International conference on Expert Systems and Information Technology in Agriculture held at the Shangri La Hotel, Kuala Lumpur, May, 1994. In 2001, he was consulted by the Malaysian Technology Development Corporation (MTDC) for Technical Assistance Fund (ITAF) applications and by the Ministry of Science, Technology and Environment for Industry Grant Scheme Applications.

Dr. Barkawi has also been invited as visiting research scholar under the CICHE program to the University of Bradford, UK in 1987, to the University of Wales and University College of Swansea under the Asian Development Bank in 1996 and to University of Kyoto and Institute of Precision Engineering, Yokohama, Japan under the Japan Society for the Promotion of Science (JSPS) in 1991.

Dr. Barkawi was appointed as the Deputy Dean (Research) from January 1999 to September 2002. As Deputy Dean (Research), he was in charge of matters related to the research activities of the faculty members which include management of application of research grants, evaluation and recommendation of research proposals. Dr.Barkawi chairs the Faculty's research committee meetings and represents the faculty during UPM's research committee meetings. In addition to that, he is also in charge of graduate studies for the faculty including management of graduate applications, evaluation of graduate student progress reports, participating in graduate studies promotion programs and managing the fields as well as the resources for graduate studies. He chairs the Faculty's graduate studies meetings and represents the faculty at UPM's graduate studies committee meetings.

Dr. Barkawi's was promoted to the post of Associate Professor in 1993 and to the post of Professor in 2002. He was appointed as the Head, Advanced Automotive Technology Laboratory, Institute of Advanced Technology (ITMA), Universiti Putra Malaysia from 1st November 2002 to 31 October 2005 and appointed as Director, Institute of Advanced Technology (ITMA), Universiti Putra Malaysia from 4 September 2006 to 3 September 2009. He is currently a Professor in the Department of Mechanical and Manufacturing, Faculty of Engineering, UPM.

Professor Ir. Dr. Barkawi is married to Pn. Zurina Binti Che Med and they are blessed with six children, Ashraff, Firdaus, Aida, Anis, Anas and Aisyah.

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5. All individuals and organisations that have supported me throughout my career.

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73. Norfaizah Mohd Arsad, Barkawi Sahari, Abdul Majid Hamouda, Wong Shaw Voon, "Crashworthiness assessment of platform backbone in auto body considering the design and the fabrication histories", Conference on Advanced Materials, Advanced Technology Congress 2005, Putrajaya, Malaysia, 6-8 December 2005.

74. Siti Marhainis Abu Mansor, Barkawi Sahari, Wong Shaw Voon, Abdul Majid Hamouda, "Static stiffness and stress distribution under torsion loads of gasoline and natural gas vehicle", Conference on Advanced Materials, Advanced Technology Congress 2005, Putrajaya, Malaysia, 6-8 December 2005.

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76. El Sadig Mehdi Ahmad, "Crash characteristics of glass fibre/epoxy and carbon fibre/epoxy conical shells", 2001.

77. Saad A. Mutasher, "Evaluation of mechanical properties of hybrid aluminium/fibre-reinforced composites", 2006.

78. Mehdi Bayat, "Analysis of functionally graded materials (FGM) axially symmetrical rotating discs", 2009.

Inventions from CNGDI Research Program with Inventors from UPM, UKM, UM, UiTM, UTM, UTP, PRSS and PROTON.

79. PI20053410 Test Method and Optimization of Ignition System Parameter Inside CNG/DI.
80. PI20055456 Wobble Plate Compressor.
81. PI20053472 Body Structure for Natural Gas Vehicles
82. PI20053653 Front Floor NGV Platforms Structure.
83. PI20053656 Front Tank Mounting Bracket.
84. PI20053472 Backbone structure of Front Vehicle.
85. PI20054276 Method and System for Calibration of Mass Flow Measurement for Volumetric Flow Measurement Device.
86. PI20055361 Radio Frequency Coaxial Resonant Cavity for Compressed Natural Gas Ignition.
87. PI20054808 Method for Controlling Multiple-Injection of Gaseous Fuel In a Direct Injection Engine.
88. PI20053655 Front Tank Mounting Structure.
89. PI20053654 Rear Floor NGV Platform.
90. PI20062343 Led-Based Schlieren Mirror System.
91. PI20062344 Nozzle And Seat Geometry for Direct Injection.
92. PI20062342 Fuel Rail For Direct Injection Gaseous Engine.
93. PI20062452 Compressed Natural Gas Fuel Injection System And Method.
94. PI20086155 Direct injection of gaseous fuel internal combustion reciprocating piston engine.

LIST OF INAUGURAL LECTURES

1. Prof. Dr. Sulaiman M. Yassin
   The Challenge to Communication Research in Extension
   22 July 1989

2. Prof. Ir. Abang Abdullah Abang Ali
   Indigenous Materials and Technology for Low Cost Housing
   30 August 1990

3. Prof. Dr. Abdul Rahman Abdul Razak
   Plant Parasitic Nematodes, Lesser Known Pests of Agricultural Crops
   30 January 1993

4. Prof. Dr. Mohamed Suleiman
   Numerical Solution of Ordinary Differential Equations: A Historical Perspective
   11 December 1993

5. Prof. Dr. Mohd. Ariff Hussein
   Changing Roles of Agricultural Economics
   5 March 1994

6. Prof. Dr. Mohd. Ismail Ahmad
   Marketing Management: Prospects and Challenges for Agriculture
   6 April 1994

7. Prof. Dr. Mohamed Mahyuddin Mohd. Dahan
   The Changing Demand for Livestock Products
   20 April 1994

8. Prof. Dr. Ruth Kiew
   Plant Taxonomy, Biodiversity and Conservation
   11 May 1994

9. Prof. Ir. Dr. Mohd. Zohadie Bardaie
   Engineering Technological Developments Propelling Agriculture into the 21st Century
   28 May 1994

10. Prof. Dr. Shamsuddin Jusop
    Rock, Mineral and Soil
    18 June 1994

11. Prof. Dr. Abdul Salam Abdullah
Natural Toxicants Affecting Animal Health and Production
29 June 1994

12. Prof. Dr. Mohd. Yusof Hussein
Pest Control: A Challenge in Applied Ecology
9 July 1994

13. Prof. Dr. Kapt. Mohd. Ibrahim Haji Mohamed
Managing Challenges in Fisheries Development through Science and Technology
23 July 1994

14. Prof. Dr. Hj. Amat Juhari Moain
Sejarah Keagungan Bahasa Melayu
6 Ogos 1994

15. Prof. Dr. Law Ah Theem
Oil Pollution in the Malaysian Seas
24 September 1994

16. Prof. Dr. Md. Nordin Hj. Lajis
Fine Chemicals from Biological Resources: The Wealth from Nature
21 January 1995

17. Prof. Dr. Sheikh Omar Abdul Rahman
Health, Disease and Death in Creatures Great and Small
25 February 1995

18. Prof. Dr. Mohamed Shariff Mohamed Din
Fish Health: An Odyssey through the Asia - Pacific Region
25 March 1995

19. Prof. Dr. Tengku Azmi Tengku Ibrahim
Chromosome Distribution and Production Performance of Water Buffaloes
6 May 1995

20. Prof. Dr. Abdul Hamid Mahmood
Bahasa Melayu sebagai Bahasa Ilmu- Cabaran dan Harapan
10 Jun 1995

21. Prof. Dr. Rahim Md. Sail
Extension Education for Industrialising Malaysia: Trends, Priorities and Emerging Issues
22 July 1995

22. Prof. Dr. Nik Muhammad Nik Abd. Majid
The Diminishing Tropical Rain Forest: Causes, Symptoms and Cure
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23. Prof. Dr. Ang Kok Jee
The Evolution of an Environmentally Friendly Hatchery Technology for Udang Galah, the King of Freshwater Prawns and a Glimpse into the Future of Aquaculture in the 21st Century
14 October 1995

24. Prof. Dr. Sharifuddin Haji Abdul Hamid
Management of Highly Weathered Acid Soils for Sustainable Crop Production
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Fish Processing and Preservation: Recent Advances and Future Directions
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Pesticide Usage: Concern and Options
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Microbial Fermentation and Utilization of Agricultural Bioresources and Wastes in Malaysia
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28. Prof. Dr. Wan Sulaiman Wan Harun
Soil Physics: From Glass Beads to Precision Agriculture
16 March 1996

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Sustained Growth and Sustainable Development: Is there a Trade-Off 1 or Malaysia
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30. Prof. Dr. Chew Tek Ann
Sharecropping in Perfectly Competitive Markets: A Contradiction in Terms
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Back to the Future with the Sun
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The Fascinating Numbers
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Fungi: Friends or Foes
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35. Prof. Dr. Tan Soon Guan
Genetic Diversity of Some Southeast Asian Animals: Of Buffaloes and Goats and Fishes Too
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Leptospirosis-A Model for Epidemiology, Diagnosis and Control of Infectious Diseases
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Plant Biotechnology - Strategies for Commercialization
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Market Relationships in the Malaysian Fish Trade: Theory and Application
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Food and Its Healing Power
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Materials, Energy and CNGDI Vehicle Engineering

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Analisis Pemasaran Pertanian di Malaysia: Keperluan Agenda Pembaharuan
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Penjagaan Kesihatan Primer di Malaysia: Cabaran Prospek dan Implikasi dalam Latihan dan Penyelidikan Perubatan serta Sains Kesihatan di Universiti Putra Malaysia
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