Transforming A Lecture-Oriented Course On Design Of Automotive Systems Into A Unique Design Experience

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Abstract *¾ An automobile is amongst the foremost of products ever designed contributing greatly to the progress of mankind. Although an automobile, in essence, is a collection of mechanical, structural, electrical and electronic sub-systems, it is judged by its user by its attributes including styling. As designing a modern vehicle encompasses vast areas of technological details, it is important to learn about the design of automotive systems, initially at least, from a systems engineering perspective gathering a bird's eye-view of automotive product development processes and tools, as well as physical sub-systems or modules. For assimilation of concepts, detailed understanding of specific areas, and development of inter-personal skills, an instructional course in this area can be supplemented with a design project that evokes the interest and enthusiasm of students.*

Index Terms ¾ Automotive, Design, Systems, Technology

INTRODUCTION

A course entitled Design of Automotive Systems was recently introduced by the author in the M.Des. (Master of Design) program in the institute of his affiliation. Instead of the piecemeal approach adopted in courses in automotive engineering, the present course assumes a holistic and systems engineering-based approach, and provides a comprehensive perspective of automotive product development [1] with the customer as the primary design driver. The viewpoint adopted about an automobile is that it is one comprising physical sub-systems and attributes. Processes prevalent in vehicle development programs in the industry, as well as tools and technologies involved are covered. An important feature of the course is that the students are required to complete a common design project by applying some of the concepts which are taught in class. This helps in assimilation of ideas and development of interpersonal skills while simultaneously encouraging creativity in design. The feedback received from past students who have taken the course reveals that they found it exciting to work in the assigned projects in which the author had consciously aimed at mimicking real-life vehicle product development. In one offering of the course, the students were asked to design a small four-wheeler for the Indian market which would be cheaper than the existing vehicles and would draw users of relatively risky and unhealthy modes of transportation such as two- and three-wheelers currently flooding the Indian cities and suburbs. The class in this case was divided into four teams (by taking into account individual preferences) with an overall objective of carrying out the initial design of a small car as already mentioned. The groups formed would be responsible for Product Planning and Marketing, Body Engineering, Powertrain Engineering, and, Steering and Suspension System Design. The current paper will enumerate in some detail the outcome of the project in terms of design methodologies adopted and tools developed leading to a preliminary design. It may be pointed out that the study described actually laid the groundwork for a more detailed and collaborative on-going design project with the final goal of prototype fabrication. Based on the response received from the students who took the course, it can be concluded that the course turned out to be an exciting design experience for them.

COURSE CONTENTS

The topics [2,3] that are dealt with in the Design of Automotive Systems course are as follows: classification of automotive systems; interfacing of marketing, design and manufacturing; converting customer's needs into engineering targets; automotive product development milestones; trade-off analysis for conflict resolution; manufacturing cost and economic feasibility analysis; design tools such as reverse engineering, rapid prototyping, computer-aided design and engineering, Taguchi methods, etc.; a review of vehicle attributes (styling, ergonomics and packaging, aerodynamics, vehicle dynamics, crashworthiness, etc.); and, an overview of automotive technology (body, powertrain, ignition, cooling and exhaust systems, etc.)

DESIGN PROJECT

The class was given the task of designing a small car for the domestic market that would be an improvement compared to the existing ones. In urban areas across India, one comes across three-wheeled commuter taxis called "autorickshaws". The most common variety (Figure 3) is made by Bajaj Auto Ltd. These have been primarily powered by two-stroke petrol engines causing a great degree of pollution in the cities. The vehicles are also noisy and would be potentially unsafe from crashworthiness and vehicle dynamics perspectives. However, the autorickshaws are inexpensive and were seen as a means of providing

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livelihood to many a jobless youth. The autorickshaws also provided an alternative mode of transportation compared to city buses and a cost-effective alternative in comparison with four-wheeled cabs. These are never used as a personal vehicle. The next most economic petrol-based small car that has been sold in very large numbers across India is the four-seater Maruti 800 (Figure 5) designed originally by Suzuki Motor Corporation. Recently, a battery-powered mini electric car called Reva (Figure 6) that can accommodate two adults and two children has been introduced. While the prices of Maruti 800 and Reva are comparable, the autorickshaw, in comparison, would cost only about one-fourth. It should be mentioned that there a few other higher-priced modern hatch-backs (such as Tata Indica, Hyundai Santro, Maruti Alto, Fiat Palio, etc.) available in the market.

The main objectives set for the course design project then are as follows:

- Design a small car platform that is somewhere in between an autorickshaw and a Maruti 800 (both with respect to size and cost.)
- The platform to be designed should take into account international standards of crash safety.
- The platform should be package protected for transmission alternatives (such as front or rear wheel drive) and engine types (such as conventional IC engine or electric motor.)

In order to design the proposed "CPDM Car", the vehicle product development team comprising the class of thirteen M.Des. students was split into four groups as shown in Figure 1 below:

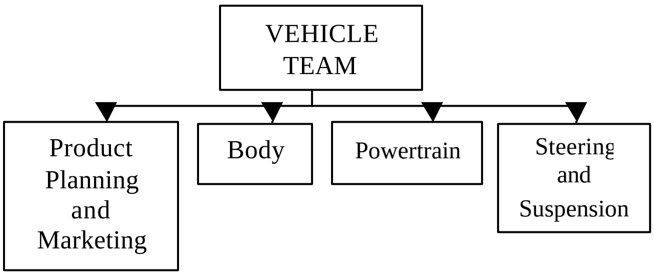

FIGURE. 1
COMPOSITION OF THE PRODUCT DEVELOPMENT TEAM

PRODUCT PLANNING AND MARKETING

The Product Planning and Marketing Group would be at the top of the hierarchy of the four groups and its main responsibilities would be to carry out market research, customer survey and setting vehicle-level design targets.

Exploring the target market

As part of market research, the present group determined the market share of various types of vehicles in the Indian market for a recent fiscal year as shown in Figure 2 below. The group concluded that a significant market opportunity existed in terms of designing an attractive but cost-effective small car that a chunk of the large number of two- and three-wheeler users can upgrade to.

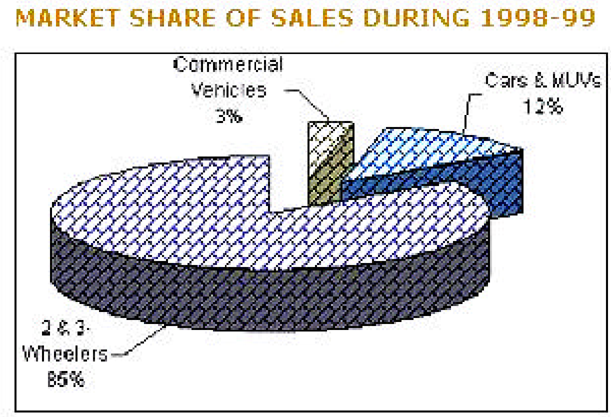

FIGURE. 2
COMPOSITION OF THE PRODUCT
(Source: http://www.aiacanada.com/en/downloads/AutoReportCHC.pdf)

Based on a questionnaire survey, the following appeared to be the needs of the autorickshaw drivers:

- More space and comfortable seating
- Lockable space for keeping valuable items
- Increased fuel economy
- Roof lamp for money transaction at night
- Lockable engine compartment

The following were the primary requirements of autorickshaw riders:

- More comfortable ride
- Greater leg and shoulder room
- Provision for luggage space

Competitive Vehicle Benchmarking and Target Setting

The Product Planning Group was instrumental in setting the initial targets of global design parameters. In order to achieve their objectives, the group embarked on a process called as Competitive Vehicle Benchmarking. According to this approach, specifications for vehicles falling in the same overall category of the CPDM concept car were compared and accordingly, targets were set such that the customer wants could be met and superiority over the nearest competing vehicles could be ensured. The group tried to kick-start the design process by collecting data on the following variables and setting numerical targets for these by taking into account consumers' needs and marketing strategy: overall length, maximum body width, wheel base, sill height, ground clearance, turning radius, roof height, weight-to-power ratio, kerb weight, tire size, powertrain specifications, fuel economy, cost, and number of occupants.

For ease of interpretation of data, graphical representation was employed as much as possible (see Figures 7 and 8 as illustrations.) The overall length and body weight were chosen to be higher than those of the nearest small vehicles, namely the Bajaj Autorickshaw and Reva shown in Figures 3 and 5 respectively. The values of these parameters are still less than those for Maruti 800 shown in Figure 6. The envisioned CPDM car thus finds a place between the ubiquitous three-wheeler commuter taxi i.e. the autorickshaw and the highest sold small retail car i.e. the Maruti 800. Where data was not readily available, relevant dimensions were physically measured as in the case of the autorickshaw (Figure 4).

FIGURE. 3
THE MOST COMMON "AUTORICKSHAW"

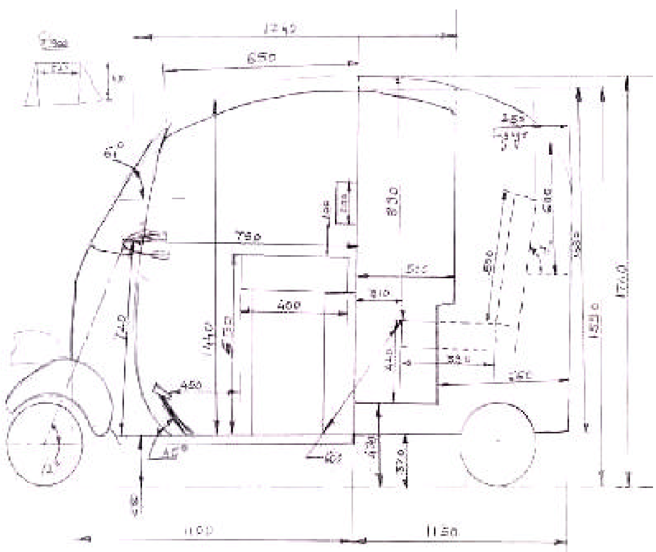

FIGURE. 4
MEASURED INTERIOR AND EXTERIOR DIMENSIONS (IN mm)

FIGURE. 5
THE MOST COMMON SMALL CAR IN INDIA
(Source: http://auto.indiamart.com/cars/maruti800/)

FIGURE. 6
REVA: A RECENTLY-INTRODUCED MINI ELECTRIC CAR
(Source: http://www.revaindia.com/decsrip.htm)

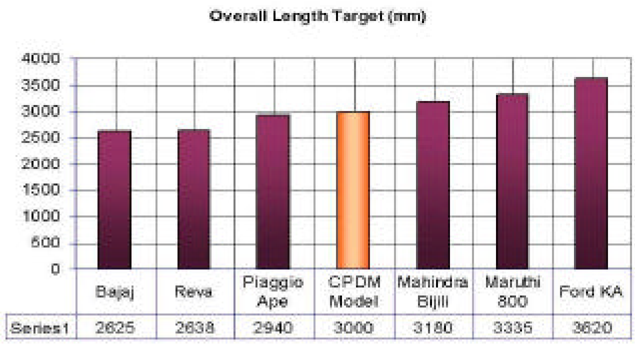

FIGURE. 7
POSITION OF THE CPDM CAR IN TERMS OF LENGTH

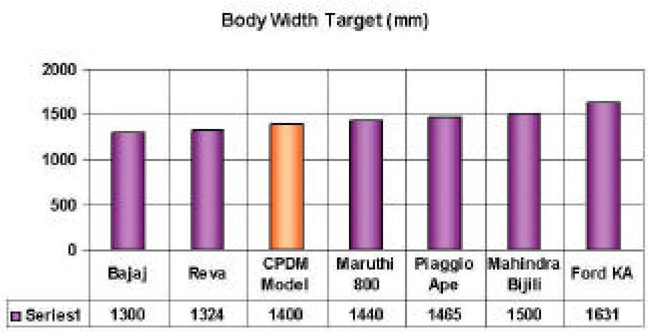

FIGURE. 8
POSITION OF THE CPDM CAR IN TERMS OF BODY WIDTH

It is worth mentioning that the current group did try to justify values of crucial target variables such as weight which are initially comprised of a large number of unknowns. Thus, the target unloaded (kerb) weight of the vehicle was broken down in terms of weights of various sub-systems as given in Table I.

TABLE I
WEIGHT ESTIMATION

ITEM	WEIGHT (kg)
Engine	70
Gear box and clutch	35
Differential	20
Chassis	70
Body shell and seats	75
Steering and suspension	30
Tires and wheels	60
Axles	40
Miscellaneous	50
TOTAL	450

After considering the prices of available four-wheelers in the Indian market and responses received from potential buyers, the retail price of the CPDM car was set aggressively at INR (Indian Rupees) 1, 25,000 (USD 2550).

The remaining groups were kept informed about the progress in target setting by the current group. Due to limitations of time, all groups worked on their product development responsibilities in tandem by displaying team spirit and communication skills.

The Product Planning Group also accomplished the following tasks:

- Documented regulations and standards to be met by cars in India
- Documented prospective suppliers of material and parts
- Monitored weight and cost targets as design progressed

BODY ENGINEERING

The Body Engineering Group would have the broad responsibility of designing the exterior vehicle form and underlying structure with due attention paid to various functional attributes including ergonomics and packaging.

Body attribute targets

The Body Design Group started by setting some basic targets for body attributes as given below:

- Aerodynamics: Co-efficient of aerodynamic drag should be between 0.28 to 0.3.
- NVH (Noise, Vibration and Harshness): The minimum natural frequency of body-in-white (i.e. body and chassis only) should be 20 Hz.
- Crashworthiness: The platform should have good occupant safety performance in front and side impact star rating tests (NCAP and LINCAP) conducted by NHTSA (National Highway Traffic Safety Administration) in the USA.
- Durability: Key body joints should have a life expectancy of at least 10 years.
- Vehicle dynamics: The design should provide for the minimum turning radius target, and packaging for desirable suspension system.

Additionally, important considerations for the present group included aesthetic exterior styling (Figure 9), ergonomics (favorable ingress and egress, seating comfort, exterior visibility, ease of operating control knobs/switches, etc.; see Figure 10) and room for packaging of mechanical and electrical hardware/sub-systems.

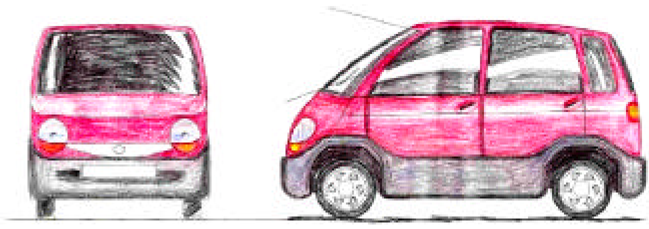

FIGURE. 9
PROPOSED STYLING CONCEPT

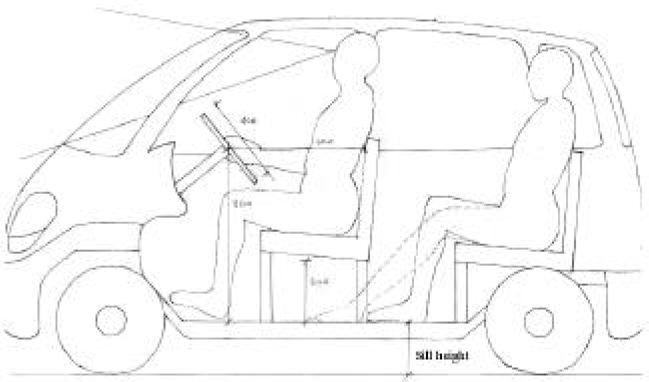

FIGURE. 10
EXTERIOR VSIBILITY AND INTERIOR PACKAGING IN SIDE VIEW

Opting for light-weight aluminum body

The market survey revealed that fuel economy was a very important preference for potential customers. If available technology is used for propulsion system (conventional IC engine or battery-powered electric motor), it was realized that the weight of the proposed vehicle should be as low as possible. The Body Group therefore decided to explore the usage of aluminum in body construction. This would undoubtedly have a negative impact on cost; nevertheless, the team thought it might be possible to meet the cost objective by using extruded members, optimizing design by using computer-aided engineering, and minimizing expenses related to manufacturing by choosing an appropriate body configuration. The group also considered the advantages of using aluminum from a re-cycling standpoint.

Use of CAD and CAE in body design

The Body Design Group explored various body design concepts: notably, body mounted on frame-type chassis, space frame-based body, and spot-welded/riveted sheet metal-based uni-body constructions. For reasons of economy of manufacturing and low initial investment on dies, it was decided that the structural body would be body-on-frame type and made from extruded aluminum members with secondary operations like bending to suit desired exterior styling. The skin could be made of light-weight materials like reinforced plastics. A preliminary design of the complete framed body and chassis developed using CAD (Computer-Aided Design) tools is shown in Figure 11. In order to meet some of the body attribute targets outlined earlier, finite element analysis-based CAE (Computer-Aided Engineering) was used. Feedback from the Powertrain Engineering Group revealed (Figure 14) that there was barely enough space in the front for packaging engine, and crush space during a frontal collision would also be quite limited. Also, the windshield would be unduly large in the concept in Figure 11. Hence, the design was somewhat modified in the front as depicted in Figure 12.

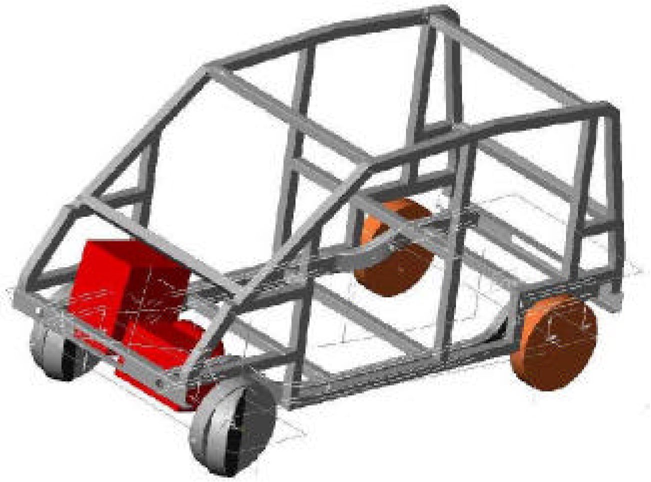

FIGURE. 11
CAD MODEL OF AN INITIAL BODY-ON-FRAME CONCEPT

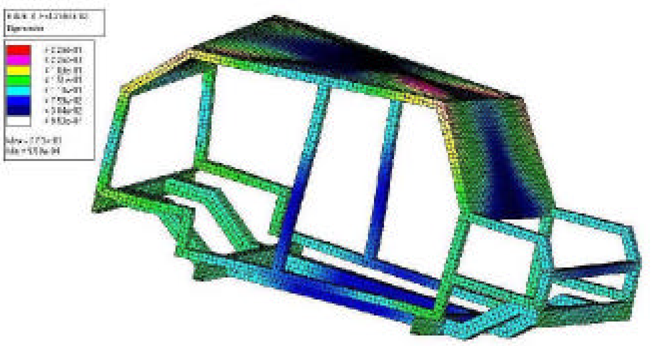

FIGURE. 12
FIRST TORSIONAL MODE OF THE BODY WITH A MODIFIED FRONT END (FREQUENCY = 42 Hz)

A finite element model was built using the Hypermesh software and free vibration analysis was carried out using the OptiStruct solver. Aluminum of grade AA 6060 (T4) and a uniform thickness of 2.5 mm were assumed for the extruded members of the frame. The lowest natural frequency obtained was 38 Hz corresponding to an overall bending mode. The next higher mode was for body torsion (Figure 12) and had a frequency of 42 Hz. Thus the NVH targets laid out earlier were met. A frontal crash simulation of the same design was carried out with the aid of the explicit nonlinear dynamic analysis code LSDYNA. Deformation of the body at 20 ms, shown in Figure 13, indicated unacceptable distortion of the front occupant cage implying that further improvements were needed in design.

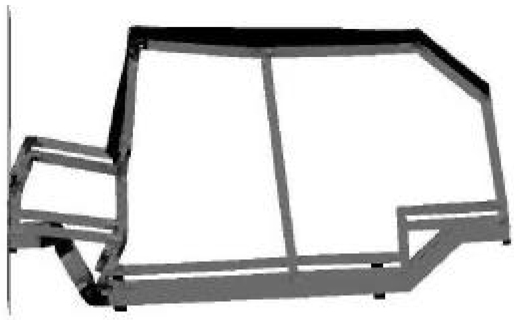

FIGURE. 13
DEFORMED BODY AND CHASSIS AT 20 ms FROM A FRONT CRASH SIMULATION AGAINST A RIGID WALL WITH AN INITIAL VELOCITY OF 35 mph (56 kph)

POWERTRAIN ENGINEERING

The Powertrain Group studied various reciprocating engine configurations such as spark ignition, compression ignition, and rotary engines. Along with fossil fuels currently in use, data on a number of alternative renewable energy sources (such as ethanol) was collected. Battery-powered electric motor-based powertrain was considered. Additionally, serial and parallel hybrid powertrains with a combination of combustion engine and electric motor were investigated. The present group also determined the engine and transmission envelopes using dimensions of powertrain of existing vehicles and examined the adequacy of the current design from a viewpoint of packaging. Both front and rear wheel drive transmission systems with transverse and longitudinal combustion engine lay-outs were considered. The side view of a package drawing for a rear wheel drive system with engine, gear box, drive shaft and differential is given in Figure 14. The space in the front of the preliminary design in Figure 11 was found to be barely adequate for packaging the engine and other accessories including the cooling system. The group also investigated a suitable exhaust system and space for fuel tank under the chassis.

The present group calculated the required engine and electric motor specifications for the target weight of the vehicle. For the case of combustion engine, the gear box specifications were also determined.

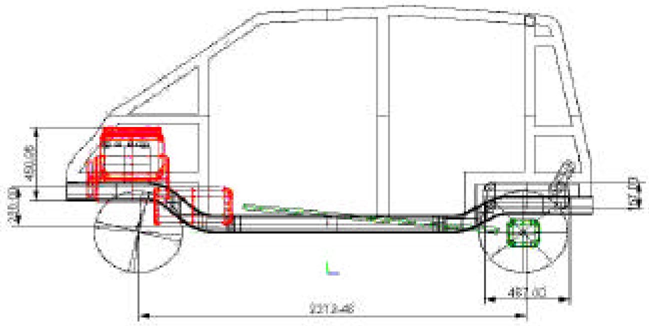

FIGURE. 14
POWERTRAIN PACKAGING WITH A LONGITUDINAL IC ENGINE AND REAR WHEEL DRIVE TRANSMISSION

Combustion engine targets through regression analysis

A new approach was followed in arriving at engine ratings such as power, torque and volume. As enough time was not available to perform detailed design of a combustion engine, market-based data of existing vehicles was used and regression analyses were performed using the MINITAB statistical analysis package. It was found, for example, that a strong correlation existed between desired maximum engine BHP (Brake Horse Power) and vehicle weight (kg). Vehicles with spark ignition engine and MPFI (Multi-Port Fuel Injection) system were considered in the analysis. The fitted prediction in Figure 15 had an R^2 value of 87% and a similar value for adjusted R^2 as well. The regression-based quadratic relation is given below:

$$P = 12.08 + 0.0198*Weight + 0.000051*Weight^2 \quad (1)$$

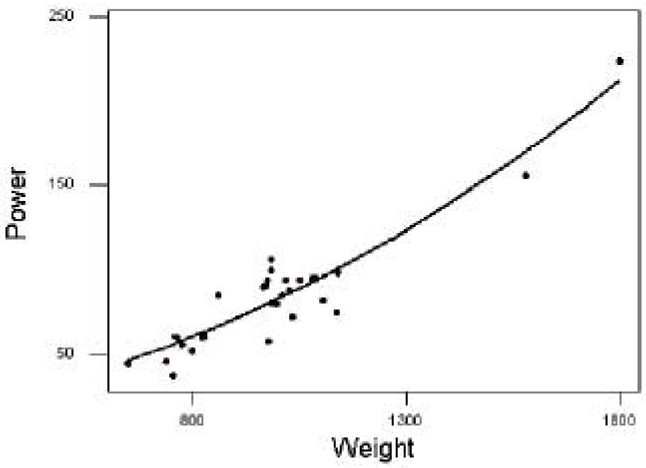

FIGURE. 15
POWER VS. WEIGHT VARIATION FOR A NUMBER OF VEHICLES SOLD IN THE INDIAN MARKET

Based on (1), target maximum engine power turns out to be 31.3 HP for a vehicle weight of 450 kg. Similar significant correlations were also observed for engine volume and torque (maximum) with respect to power (maximum). These relations helped in determining the target engine size and torque to be delivered.

STEERING AND SUSPENSION DESIGN

The Steering and Suspension System Design Group initially surveyed prevalent steering mechanisms, and, suspension and braking systems. Recommendations were made for tire dimensions as well as suspension-related parameters such as camber, caster, king pin inclination, and toe in or out. For the chosen dimensions of the vehicle and geometry of the steering knuckle, the minimum turning radius with Ackerman steering concept was determined as 4.3 m which is comparable to those for small cars. For this minimum turning radius, the toppling speed of the vehicle was found to be reasonably high. Forces acting on the vehicle during cornering were also computed. Basic dimensions of a rack-and-pinion steering system were also derived for design purposes. The present group recommended McPherson-type suspension system at the front and leaf springs combined with shock absorbers at the rear.

CONCLUSIONS

It was possible to complete the stated contents of the semester-length course. To the author's best knowledge, Design of Automotive Systems is a unique course that embodies both automotive product development and technology. The course evaluation feedback received indicated that the students found the project involving real-life automotive design procedures as highly beneficial.

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