PHILIPPINE ENGINEERING JOURNAL
PEJ 2011; Vol. 32, No. 1: 15-26

DEVELOPMENT OF AN URBAN CONCEPT HYBRID VEHICLE

Gerald Jo C. Denoga, Juvy A. Balbarona, Tito N. Eusebio Jr [1]

[1] Mechanical Engineering Department, College of Engineering
University of the Philippines Diliman, Quezon City 1101
Email: up.mechanical.engineering@gmail.com

ABSTRACT

The research is about the development of a diesel hybrid vehicle. A small concept car was prototyped aimed at achieving high fuel mileage while still satisfying other consumer needs like speed, aesthetics, safety, usability and comfort. The design is comprehensive, including lightweight chassis design, aerodynamic shell design, calculated passenger safety, and optimized power generation. Aerodynamic design was done to provide input to the power requirements. The drive train is based on a series hybrid system, using a single cylinder diesel engine, an electric DC generator, a motor and a super capacitor. The key feature of the drive train is the control system that ensures a fixed power draw from the engine corresponding to the load and speed of the diesel engine at optimum brake specific fuel consumption..

Key words: diesel hybrid, aerodynamic design, engine map, series hybrid

1. INTRODUCTION

In light of increasing fuel prices and environmental issues associated with transportation, research into improving the fuel usage of the transportation sector is made more relevant. While some alternative energy technologies such as fuel cells are available, the cost of adopting such technologies are currently too high compared to fossil fuel technologies. As such, there is still relevance in developing more fuel-efficient vehicles. One technology that has been commercially accepted is the hybrid vehicle. Unfortunately, current models of hybrid vehicles have shown only marginal improvement on mileage compared to conventional automobiles.

2. BACKGROUND

The concept of hybrid vehicles is not new. Numerous studies has been done on this field leading up to the commercialization of various hybrid technologies. A hybrid vehicle, by its broadest definition, is a vehicle whose drive train is comprised of an internal combustion engine and an electric motor. Several configurations have been developed, based on either a parallel drive train, or a series drive train, or variants thereof. The parallel configuration involves the simultaneous contribution of mechanical power by the engine and the motor to the wheels. The series configuration involves the engine being dedicated to providing electrical power to the motor, which subsequently provides the mechanical power to the wheels.

Correspondence to: Department of Mechanical Engineering, University of the Philippines, Diliman

Received: August 15, 2011
Accepted: March 15, 2012

Commercial designs have been made available for both public and private modes of transportation. However, in the context of availability of hybrids in the Philippine landscape, the only ones seen as of this writing are passenger sedans sold by Toyota and Lexus, as well as diesel electric locomotives. While it may be speculated that hybrid vehicles have not yet made a significant presence in the local landscape because of economic reasons and un-ideal marketability, it is hypothesized that these reasons are brought about by the unfulfilled promise of superlative fuel economy.

The intended high fuel economy of hybrid vehicles are anticipated on the premise that an optimized combination of an internal combustion engine (ICE) and electric motor will consume less fuel in urban driving scenarios. It is established that for highway driving, a pure ICE powered vehicle will already yield excellent mileage while a hybrid configuration will not yield any, if at all, significant improvement. In contrast, for urban driving cycles, the typical hybrid vehicle capitalizes on its ability to reduce wasted engine capacity when the vehicle is idle, cruising, decelerating or at times of low demand. Depending on the configuration, the engine may be turned off, or be used to charge electrical storage devices.

The desire to implement hybrid technology into public or private transportation will yield different expectations. For public transportation, buses are expected to follow urban driving cycles characterized by slower average speeds and stop-and-go motion. Several studies have been done to optimize the drive train components such as engine, motor, energy storage and gear ratios, for popular standard drive cycles. For public transportation, given the proper matching of hybrid technology with the actual operating parameters, a high fuel economy can be achieved. Hence, the expectations for hybrid buses are often met when operated only as designed.

For private transportation, however, the performance and mileage expectations are often at odds with each other. Driving a hybrid sedan optimized for urban driving would often fall short on performance in highway driving. Using larger engines to achieve satisfactory highway driving performance would tend to suffer low urban driving mileage. As such, if consumer expectations are made to match the design conditions of the hybrid vehicle, the appreciation and marketability of hybrid technology would improve.

The research presented in this paper is the development of an urban concept hybrid vehicle. As presented above, the expectations for performance and fuel economy is for urban driving scenarios. While the design approach of the drive train may be applied to public transportation as well, this paper presents the vehicle development to include not just the power train, but the aerodynamics, chassis design, and passenger comfort and safety requirements, catered for private transportation. The urban concept focuses on small single/dual passenger cars similar to sub-compact vehicles in the market. This capacity reflects the average number of riders seen in privately driven cars during an urban commute. The performance is based on speed limits around the metropolitan. Safety and comfort requirements incorporate the needs of typical commuters.

3. DESIGN PARAMETERS

The goal was to develop a four wheeled vehicle prototype that provides the essential features found in current commercially available automobiles while achieving high fuel efficiency in urban driving situations. Although there may be argument as to what is essential, at the very least, the design team had to incorporate the following features: passenger safety and comfort, drivability and performance, provisions for storage and accessibility, fuel efficiency, aesthetics.

Because these required features still allowed a lot of leeway into the design, the dimensions of typical compact cars were first used as a basis for overall size of the chassis. This specified the ground clearance, width, height, length, wheel track and wheel base.

Table 1 Dimensional limits

Vehicle Length	220~350cm
Vehicle Width	120~130cm
Vehicle Height	100~130cm
Ground clearance	>10cm
Wheel Track	>100cm
Wheel Base	>120cm

A tubular chassis was then designed around these dimensions. Although aerodynamic design would lean toward a shorter height and narrower width, concern for safety was raised on the car being less visible to other cars on the road. Hence, the final dimensions of the car approached the upper design limit.

To emphasize fuel efficiency as well as recognizing the market trend toward single passenger commuter automobiles, only one seat was installed along the centerline of the car. To minimize the weight of the vehicle, a rear wheel drive configuration was used, and the engine and power train were also located behind the passenger cabin. This eliminated the need for CV joints for the front wheels, and a propeller shaft running the length of the car.

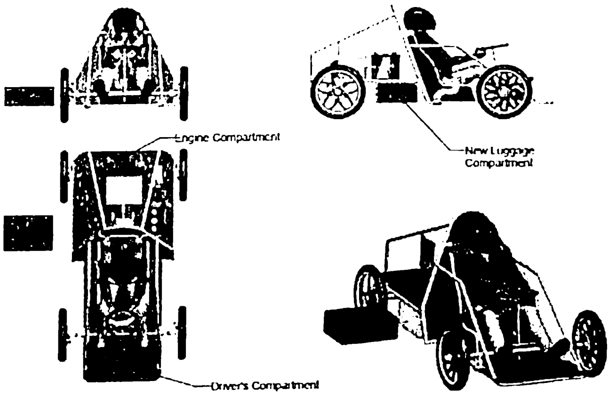

Fig. 1 Chassis Design

To ensure passenger safety and comfort, the driver was made to sit in an upright position. Provisions were made to ensure at least 180 degrees of visibility. As the rear engine configuration limited visibility from the back, side mirrors were relied upon.

A direct-current powered air conditioner system was also developed for the vehicle. However, because this was not considered a necessity, the system was not installed as its weight and electrical power draw would significantly reduce fuel efficiency.

Provisions were also made for storage and accessibility. A luggage compartment was placed behind the driver compartment that could accommodate small suitcases up to 50x40x20cm. As the car could only seat one person, only one passenger door was installed, opening sideward for easy access. Separate hatchways were installed for the engine compartment, auxiliary systems and luggage compartment.

With regard to drivability, a minimum turning radius of 6 meters was specified. A heads-up-display was installed for instrumentation. All controls including turn signals and lights were incorporated into the steering wheel for ergonomic reasons.

With regard to performance, the vehicle was targeted to achieve at least fifty kilometers per hour. The projected gross vehicle weight was only about 200kgs. Nonetheless, chassis design incorporated proper selection of wheels and tires to accommodate the dynamic load and speed, as well as braking power. Once the structural and mechanical systems were drafted, the design of the aerodynamics and drive train followed.

4. AERODYNAMICS

Initial aerodynamic design of the body began with analysis of known vehicle designs with low drag. It was noted that there were substantial differences in designs for high speed vehicles compared to small commuter cars. Instead of typical sports car designs with sharp noses, focus was placed on the tear drop shape. Hence, the front of the car tended to be blunt, while a long trailing edge was implemented. The 3-d design was then edited to incorporate the chassis dimensions and wheel placements.

After initial body shapes were drafted, the models were then simulated using finite element analysis software. The primary goal was to reduce the aerodynamic drag. The main constraint was the fixed frontal area. While efforts were made to minimize the frontal area of the top section, the width was constrained by the passenger's head and torso dimensions plus allowance for safety. Shown below are seven of the iterations made. Included are images of the velocity streamlines as well as the pressure contours along the vehicle. These simulations showed locations with higher tendencies for flow separation and turbulence. Each iteration was targeted at removing these trouble spots.

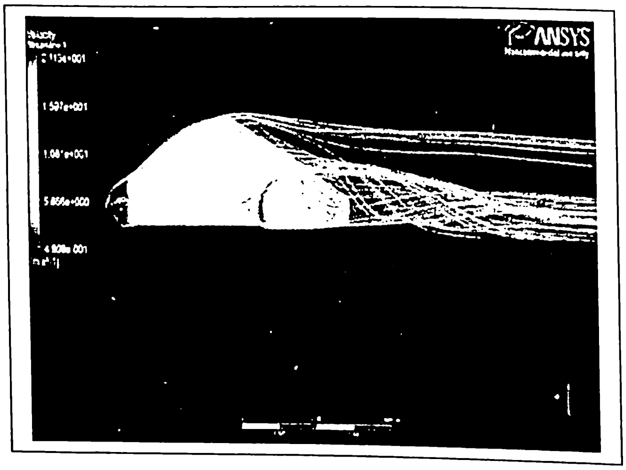

Fig. 2a Initial Design

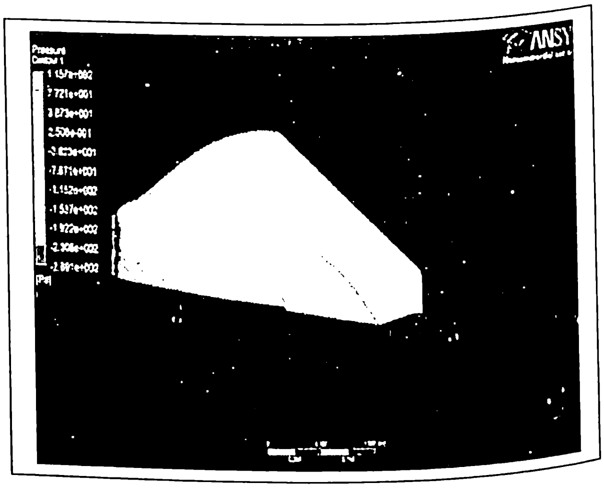

Fig. 2b Initial Design

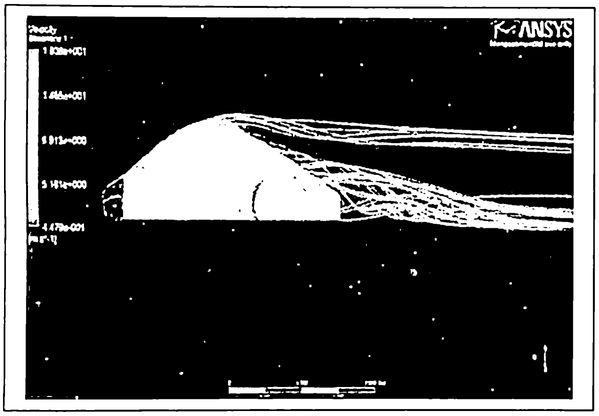

Fig. 3a Rear wheel cowling modified into an airfoil shape

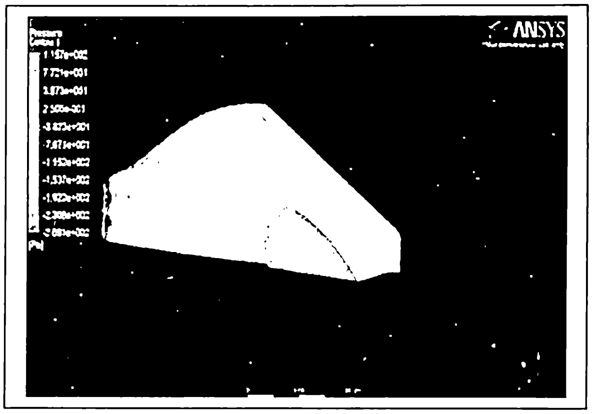

Fig. 3b Rear wheel cowling modified into an airfoil shape

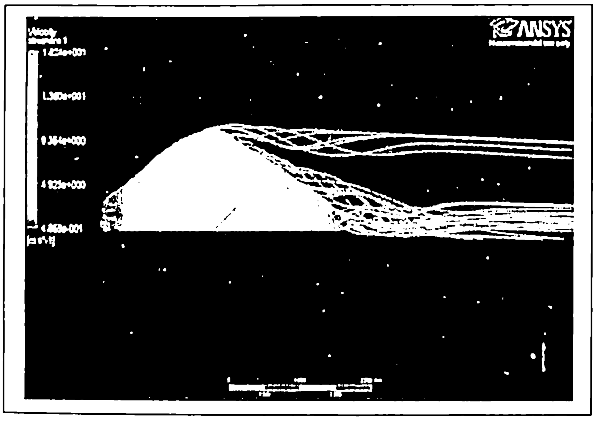

Fig. 4a: Modification of rear cowling

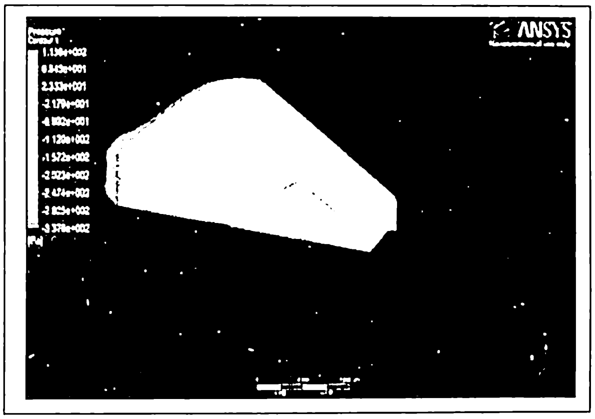

Fig. 4b: Modification of rear cowling

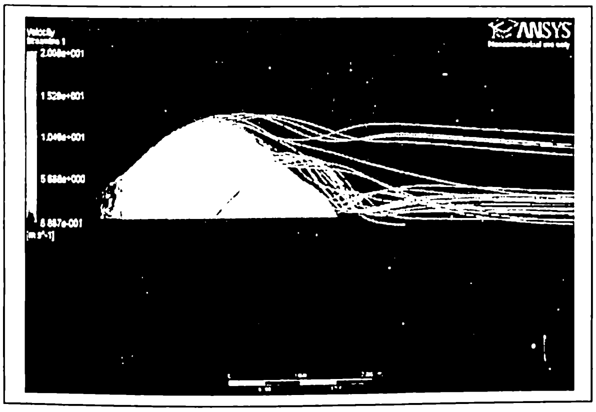

Fig. 5a: Integration of rear cowling with trailing edge of trunk

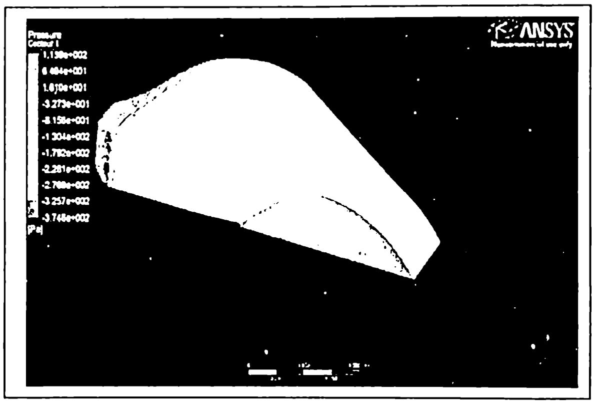

Fig. 5b: Integration of rear cowling with trailing edge of trunk

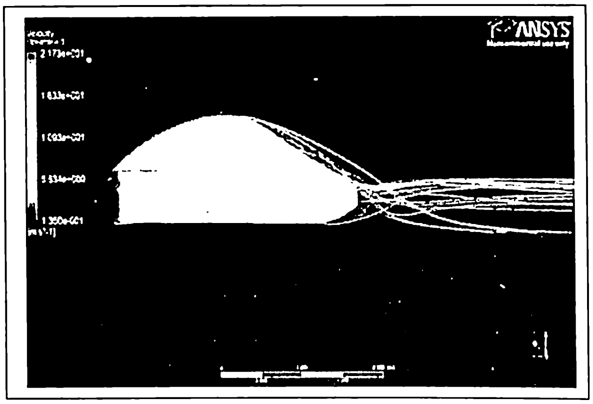

Fig. 6a Integration of side panel with rear cowling, and raising of rear bottom surface

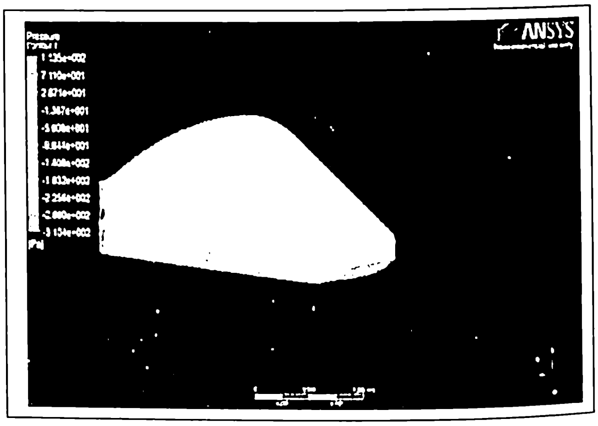

Fig. 6b: Integration of side panel with rear cowling, and raising of rear bottom surface

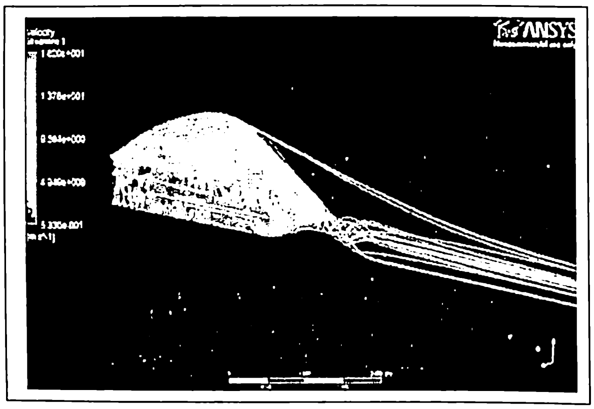

Fig. 7a: Raising of rear cowling above side shoulders

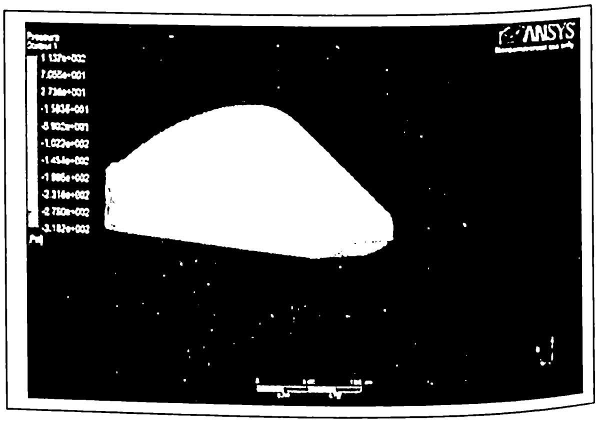

Fig. 7b: Raising of rear cowling above side shoulders

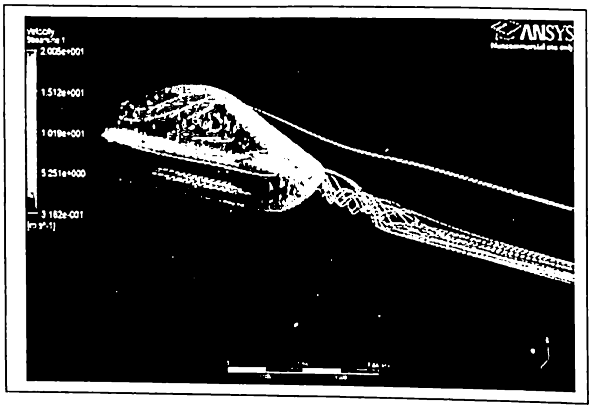

Fig. 8a: Narrowing of width toward rear

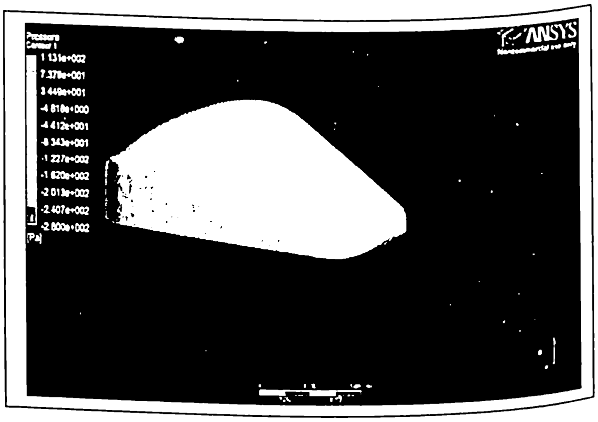

Fig.8b: Narrowing of width toward rear

One notable transition among designs was the lengthening of the car. Flow separation was most noticeable just beyond the apex of the car. This is expected from airfoil designs. The common solution was to reduce the aspect ratio (height to length) of the car. Because the driver position could only be adjusted by so much, attempts were made to adjust the overall length to allow for a gentler slope along the back. However, these attempts led to an exaggerated rear end extending almost a meter behind the rear wheels.

The FEA simulations resulted in the following values for drag force. These values were based on a simulated vehicle speed of 50 kilometers per hour. It is notable that variations in design theoretically led to a 33% reduction in drag. The 27-Newton drag force relates to about 1.35kW of aerodynamic losses. Although the simulated drag forces are small compared to the engine power of most cars today, it should be mentioned that the engine to be used for this prototype was rated only at 2.5kW.

Table 2 Drag Forces from Simulated Designs

Design	Drag (N)
1	-40.06
2	-39.67
3	-39.65
4	-45.48
5	-30.86
6	-31.41
7	-27.05

Once the design of the upper body was finalized, new refined simulations were made to consider the drag from the exposed wheels, as well as for other vehicle speeds. Shown below are the results of the simulation for coefficient of drag (Cd) and drag force (Fd).

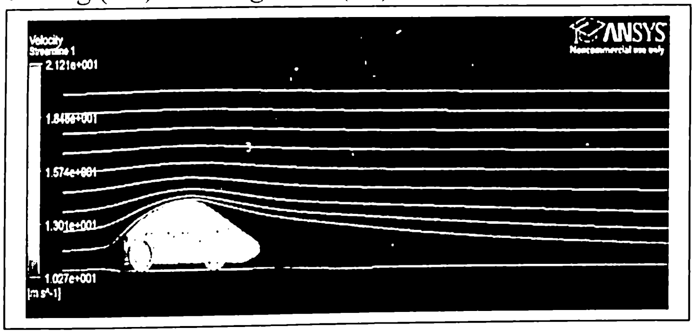

Fig.9: Velocity profile of the final design

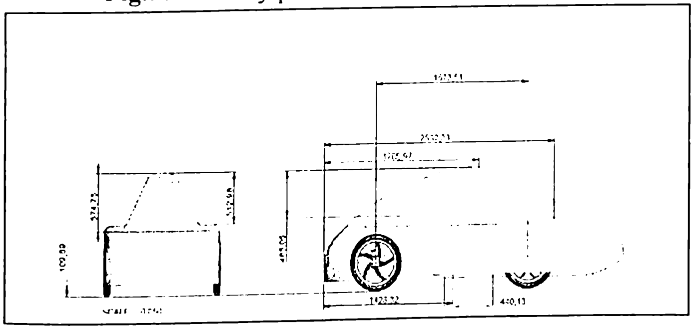

Fig.10: Final design showing driver position

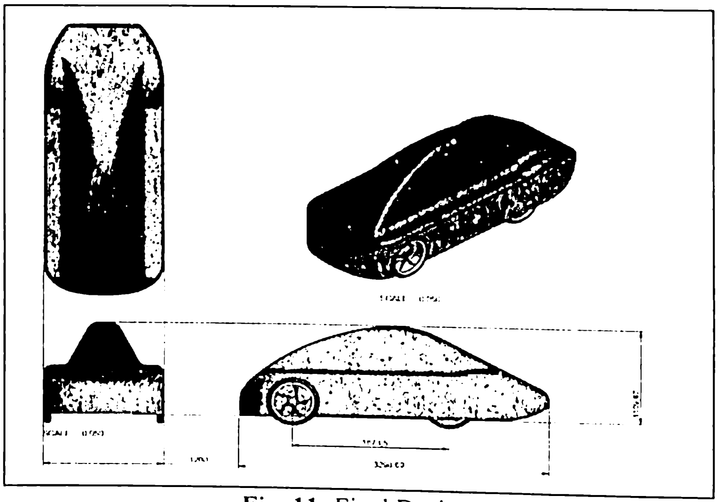

Fig. 11: Final Design

Table 3 Drag Data for Various Speeds

Speed (km/hr)	Cd	Fd (Newtons)
20	0.3067	5.7426
30	0.3026	12.718
40	0.2991	22.356
50	0.2963	34.626
60	0.2935	49.544

5. ROAD LOAD ESTIMATION

The aerodynamic design was necessary for the estimation of the total road load. Recall that this load is the sum of rolling resistance and drag force.

$$Rolling\ resistance = Cr \times g \times m$$

where Cr is the coefficient of rolling resistance approximated to 0.15, and m is the gross weight of the vehicle estimated at 200kg plus a 70kg driver

$$Drag\ force = \frac{1}{2} \times \rho \times Cd \times A \times V^2$$

where ρ is the density of air, Cd is the coefficient of drag, and A is the frontal area the vehicle.

The mechanical power applied by the motor to the wheels are then consumed by the load from the rolling resistance, drag force and the power needed to accelerate the vehicle, and mechanical losses.

$$\begin{aligned}&\mathit{Motor\ Power} - \mathit{Losses}\\&\quad= (\mathit{Rolling\ Resistance} + \mathit{Drag\ Force} + \mathit{mass} \times \mathit{acceleration}) \times \mathit{Speed}\end{aligned}$$

The losses indicated are mostly mechanical losses in the bearings, transmission and brakes. Initially, these losses were just estimated to be about 500watts.

The previous equation was used to estimate the necessary motor power to achieve 50kph. The main assumption in simulating the motion profile was that the electric motor could supply constant power to the wheels. As such, it would provide a very high torque at startup, and then decrease linearly with speed. Hence, at constant motor power, initial acceleration is high, but decays exponentially, allowing for an exponential velocity profile as well.

By requiring a minimum top vehicle speed of 50kph, the corresponding required brake power is approximately 1.5kW.

6. HYBRID DRIVETRAIN

The heart of this hybrid vehicle is in its drive train. The prototype is a series-type of hybrid vehicle such that the main energy source is an internal combustion single-cylinder Diesel engine directly coupled to an electric DC generator. The generated power is then used to power a DC motor that directly drives the wheels.

The highlight of the hybrid design is the controls of the engine parameters. Specifically, the drive train is designed to maintain the engine at a constant load and speed. This particular operating point is where the engine is at its best brake specific fuel consumption (BSFC). By maintaining the engine at this optimum operating point, we eliminate the inefficient operations at idle, or during acceleration, or at transient conditions such as slopes. Instead, it is the electric motor that is operated at various speeds, yet operating under constant power.

All this is done with two sets of controls. The first is the rack position of the engine governor. This maintains the speed of the engine by modulating the fuel flow accordingly. At a fixed engine speed, the generator can then produce electricity at a constant voltage. The second stage is an electronic motor controller that monitors the current draw by the motor. Recall that the generated voltage is kept constant. This time, the motor controller has a current limiter, which, when combined with constant voltage is a constant electrical power.

Even though power and voltage and current are fixed, the motor can provide variable torque and speed. This allows for fuel efficient cruising of the vehicle. At level roads, the motor allows it to achieve its maximum speed. However, at rising slopes, the torque requirement for the motor increases. The motor speed will slow down proportionally as the product of the two is the constant power.

The advantage of the above setup is that it does not allow the engine to operate above a particular load. However, another measure is needed to prevent the engine from operating below the designated optimum load. When the driver intentionally slows down, the road load is less. Relative to the designated optimum load, there is now excess power.

The surplus generated power is absorbed through the charging of a super capacitor. Another electronic controller senses that the current draw by the motor is less than optimum. The controller then charges the super capacitor with this balance of current. Hence, the overall current draw by both the motor and the super capacitor is constant.

Note that this engine management strategy is only useful while the super capacitor is not yet full. Once full, the engine is shut down, and the super capacitor is used to power the motor. Hence, the engine is either operating at its best BSFC or turned off. This hybrid setup would allow for good mileage for both urban stop-and-go traffic and highway driving.

Note that the straight-run mileage should not be significantly affected by the presence of the super capacitor. Its benefit would be seen in stop-and-go traffic. Evaluations of such driving scenarios are dependent on particular driving cycles. The vehicle was evaluated using straight distance running over various slopes.

7. ENGINE CHARACTERIZATION

According to the road load estimate, motor power of approximately 1.5kw is needed, assuming mechanical losses of 500watts. Based on manufacturer's ratings, the motor and generator efficiencies are 0.88 and 0.83 respectively. This would make the required generator and engine outputs to be 1.7kW and 2.0kW respectively. The next task was then to confirm if available engines can operate optimally at such an output.

The smallest Diesel engine locally available was a Kama KM170F single cylinder diesel engine. Diesel engines were chosen due to their higher efficiencies over gasoline engines. Although the rated output power was 2.5kW, it was anticipated that its best BSFC would occur below the rated power. This theory was verified via engine mapping.

An engine map was developed by testing the engine at various loads and speeds. This engine was directly coupled to the generator and loaded by electronic loads. From the graph below, the circular region in the middle indicates the best settings of which to run the engine. Fortunately, the generator output corresponding to 1.7kW at 3230rpm was in this region, making this engine suitable for our needs. The BSFC at this point was 355mL/kWh.

Given that the engine is operating at constant load, it became possible to estimate the mileage. The mileage was computed from

$$mileage = distance \div (BSFC \times brake\ power \times time)$$

Table 4 Engine Specifications

Engine Model	Kama KM170F
Bore x Stroke	70x55mm
Displacement	211cc
Rated Engine Speed	3000rpm
Compression Ratio	20:1
Rated Output Power	2.5kW

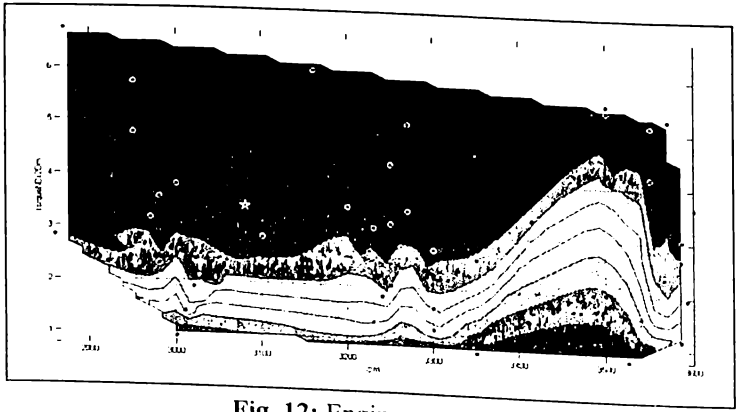

Fig. 12: Engine map

8. EXPERIMENTAL RESULTS AND PERFORMANCE

The vehicle was prototyped based on the above aerodynamic and power train design. It was then tested on various tracks to confirm speed and mileage. The initial results showed big discrepancies with theoretical values. Upon further testing using a chassis dynamometer, it was determined that the actual mechanical losses reached 860W. Recalibrated simulations show that the theoretical models match the actual experimental values.

Table 5 Theoretical vs. Actual Values

Assumed Losses	500 W
Theoretical Max Speed	49 kph
Theoretical Mileage @2.8km	68 km/L

Assumed Losses	900 W
Theoretical Max Speed	38 kph
Theoretical Mileage @2.8km	48 km/L

Measured Losses	860 W
Actual Max Speed	38 kph
Actual Mileage @ 3.3km	47 km/L

9. CONCLUSIONS

The research and development showed that simulations could provide reasonable estimates of vehicle performance with regard to aerodynamics and performance. Although falling below target, the vehicle performance is encouraging compared to conventional vehicles. With respect to the improvements, measures must be done to reduce the mechanical losses. Notwithstanding, different engines can be used in the future to compensate for the greater losses in order to achieve the desired top speed.

ACKNOWLEDGMENT

This research is supported by the Professorial Chair Award given by Emerson. The authors would like to thank Mr. Manuel V. Pangilinan of Meralco and Mr. Heng Dong Lim of Super Trade Enterprises for assisting with the fabrication of the prototypes.

REFERENCES

1. J. Y. Wong, Theory of Ground Vehicles, 4th ed., John Wiley & Sons, Inc., 2008.
2. N. E. Ahmad, E. Abo-Serie, A. Gaylard, Mesh Optimization for Ground Vehicle Aerodynamics, ISSR Journals, Vol. 2(1), March 2010.
3. S. Jindal, B. Khalighi, G. Iaccarino, Numerical Investigation of Road Vehicle Aerodynamics Using Immersed Boundary RANS Approach, SAE International 05B-419, 2005.
4. Manan Desai, S. A. Channiwala, H. J. Nagarsheth, Experimental and Computational Aerodynamic Investigations of a Car, WSEAS Transactions on Fluid Mechanics, Issue 4 Volume 3, October 2008, ISSN: 1790-5087.
5. G. Le Good, K. Garry, On the Use of Reference Models in Automotive Aerodynamics, SAE Technical Paper, 2004-01-1308.
6. B. Suh, A. Frank, Y. J. Chung, E. Y. Lee, Y. H. Chang, S. B. Han. "Powertrain system optimization for a heavy-duty hybrid electric bus." *International Journal of Automotive Technology* 12, no. 1 (2011): 131-139.
7. Delphine sinoquet, Gregory Rousseau, Yohan Milhau. "Design optimization and optimal control for hybrid vehicles." *Optim Eng*, 2011: 199-213.