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## **Personal EV to answer the transportation challenges of mega-cities - Paper for the EVS30 Symposium**

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### **Summary**

This paper describes the ongoing activity of Project Hagar to develop an innovative type of vehicle and its derived technology. The project is a *demonstration* of Afeka Academic College of Engineering's vision of the ultimate solution of a clean energy vehicle for the ever-expanding mega-metropolis. The goal is to develop a personal *light vehicle* having the traffic and parking signature and the dynamics of a large *scooter* while providing the highway attributes of an M1 passenger *car* such as an *air-conditioned*, closed environment and "car like", familiar driver controls.

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### **1 Research Goals**

The development process aims to present a new type of L5e category vehicle with M1 category attributes. The project involves students, academic staff and industry. The main goal is to develop and build a whole vehicle demonstrating Afeka's vision. Good engineering practice with a high level of teamwork and coordination are required to integrate all systems and components into such a small vehicle. Four main topics of research and development are needed to meet the goals. The first is crashworthiness, while the second is "car like", familiar controls, i.e. the use of a steering wheel and brake and accelerator pedals. The third requirement is an autonomy range appropriate for a mega-metropolis (i.e., at least 200km) and the fourth is the comfort of a passenger car - in particular, by having a fully closed, air-conditioned body. In addition to the abovementioned specific research topics, there is the holistic automotive product engineering approach, which governs the direction of the solutions to ensure that they will be engineering viable and will meet user acceptability and European homologation.

By focusing the research on viable solutions, we increase the potential of the outcome to demonstrate ways of shifting commuters from their five-seat passenger cars to an L5e two-seat narrow track vehicle. This is expected to reduce general energy consumption, traffic congestion, parking search time and parking-related real estate and to allow for better use of personal time for business or leisure.

L-category narrow-track leaning vehicles capable of highway speeds are as old as any motor vehicle; yet they do not provide an acceptable solution for the majority of daily commuters because of their low safety level, the lack of comfort compared with passenger vehicles and the skills required to operate them. The research goals focus on tackling these obstacles to convert M1 category drivers to an acceptable L5e vehicle.

## 2 Research activities

### 2.1 Driver's controls

A fundamental assumption of this project is that in order to get an L5e vehicle to be accepted by drivers of passenger cars, the vehicle needs to have all the familiar controls of a passenger car, namely a steering wheel that is rotated in the direction of desired trajectory at all speeds, and brake and accelerator pedals in the same arrangement and geometry as in a passenger car.

The dynamics of a leaning two or three-wheel L5e vehicle at speeds higher than a threshold of approximately 15 km/h require the driver to apply small-angle steering input on the handle bar in the opposite direction to the required direction of turn. This in turn creates a side force that leans the vehicle and causes it to turn in the desired direction. In addition, the gyroscopic moment applied by the front wheel when steered assists in leaning the vehicle in the same direction. This phenomenon is known as “counter steer”. Once the vehicle reaches the required lean angle and turning radius, the steer angle returns to almost zero. At speeds lower than the threshold speed, the handle bar is operated by pointing it in the desired direction.

The steer-by-wire control strategy involves using the steering angle input of the driver along with the vehicle's forward traveling speed to calculate the desired trajectory radius of turn using two-wheel leaning vehicle equations of motion. The outputs of the calculation are the steer angle of the front wheels and the required angle of body lean. The actuation of motion is performed with a single electric motor that rotates the steering shaft. To ensure a quick and accurate steering motion response, an actuator encoder and steer angle sensor provide feedback to the controller. At the time of writing this paper, the first mule of the vehicle has been installed with the sensors and actuators and a successful simulation run has been performed, but the steer-by-wire control needs further in-lab testing before track testing can be carried out.

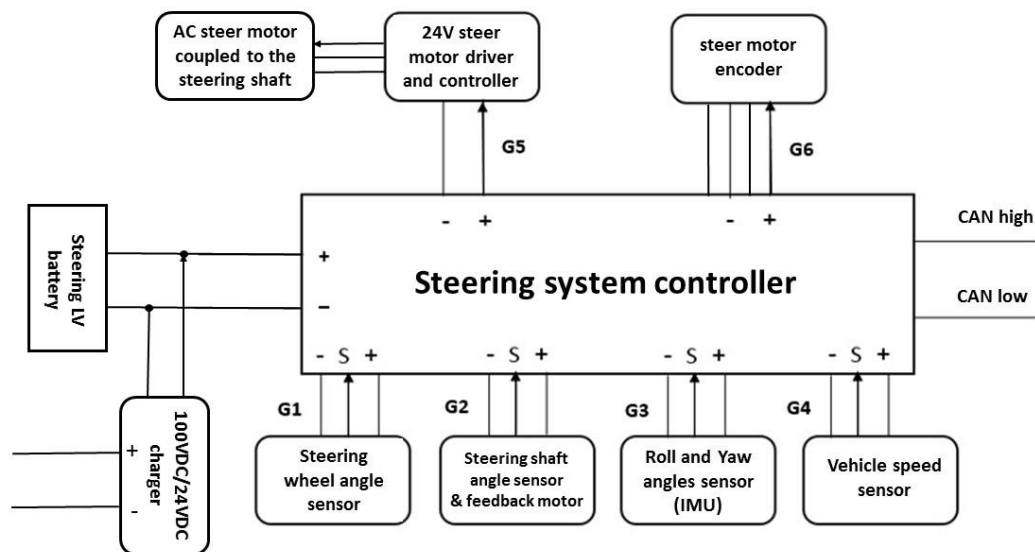


Figure 1: Block diagram of the control system

#### 2.1.1 Functional safety

The steer-by-wire system presents the most significant functional safety challenge of the vehicle, as the other systems are not electronic, except for the drive system. Due to the changing nature of the transmission function between the steering wheel angle input and the steering shaft angle output, a mechanical component to be used when the controlled steering system fails, as would occur for a power assisted steering system, is not feasible. Thus, we treat the functional safety of the steer system as we would for a steering system in an autonomous vehicle. The hardware has redundancy wherever it is needed and possible. The steering wheel



## 2.3 Aerodynamics

This activity focuses on reducing energy consumption and increasing vehicle stability and active safety. A narrow track vehicle having a maximum width of 850 mm has a low frontal area contributing to a low total drag resistance. The small length and large height combined with exposed front wheels, raises a challenge to creating a low drag coefficient. Furthermore, the tall and narrow shape is sensitive to side forces created by side winds. Therefore, an additional research activity was performed to optimize the downforce without compromising drag resistance. This was undertaken using both computational fluid dynamics (CFD) analysis and wind tunnel testing.

The development of the aerodynamics was performed jointly with the designer. That is to say, the aerodynamics team gave the geometrical constraints to the designer, and in return, the designer provided a revised body geometry. The revised body was tested and analysed again to verify that it reached the desired goals.

The final drag coefficient achieved was  $C_D = 0.34$ , with a downforce coefficient  $C_L = 0.21$ . Sensitivity to side wind was reduced dramatically by moving the side area centre behind the vehicle centre of gravity so that the vehicle will have a balancing yaw moment pointing the front wheels into the wind. The side force calculated and measured was significantly lower than the weight of the vehicle, thus implying a low impact on stability.



Figure 3: Initial scaled-down model used for wind tunnel testing

## 3 Electric drive unit and HVAC layout and performance

The drive and HVAC (heating, ventilation and air conditioning) systems are the main energy consumers that determine the potential range and performance of the vehicle. Since the vehicle is intended for full highway use, it needs considerable power and torque to keep up with traffic. The performance goals that set the top performance of the drive system are: continuous speed of 110 km/h on a 3° upwards slope; maximum continuous speed of 120 km/h; and maximum peak slope of 30°. At the current stage of development, the range goal is 170 km between full charges. The above goals result in a minimum required drivetrain performance, at the wheel, characterized by a top continuous power of 30 kW and a top continuous torque of 400 Nm.

### 3.1 Drivetrain layout and performance

A motor capable of meeting the power and torque performance goals outlined above with a single small rear driven wheel cannot be integrated into the wheel hub. Thus, the motor was positioned separately from the drive wheel, transmitting power to the wheel via a motorcycle drive chain. Due to the academic nature of the project, in contrast to an industrial project, the choice of motor was based on availability and cost rather than on the criterion of being the most suitable motor available. Thus, the drive unit was taken from an electric Zero motorcycle. The AC synchronous

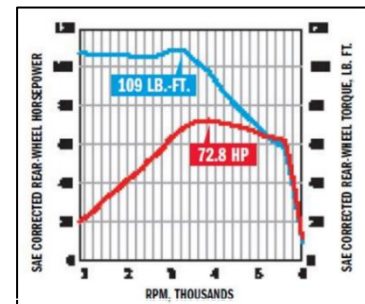


Figure 4: drive motor performance

motor is capable of a maximum power of 53kW @ 4000 rpm and a maximum torque of 148 Nm @ 3300 rpm. The optimal chain transmission ratio is 1:5.

Based on the vehicle drive loads at the set performance and the gross vehicle weight (GVW), frontal area, coefficient of drag, driven wheel rolling radius, and efficiencies of various components, we conducted a simulation to predict the performance of the vehicle.

The predicted energy consumption of the drive system measured at the battery, calculated according to the NEDC (New European Drive Cycle) profile, is 1.6 kWh per hour of drive, i.e., an average energy consumption of 34.4 Wh/km. The predicted energy consumption when driving continuously at 90 km/hr is 67.5 Wh/km.

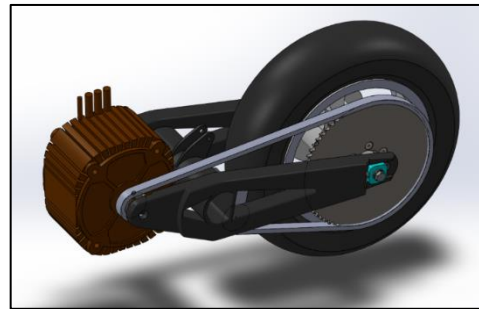


Figure 5: Drive system layout

### 3.2 Air conditioning layout and performance

The air conditioning system is based on the familiar vapor compression cycle, as it has higher coefficient of performance (COP) than alternative solutions, i.e., a COP of 3 according to the proposed design.

The general layout is similar to that of a passenger car, where the main HVAC package is positioned under the dashboard and comprises the evaporator, electric heater, blower, ducts and shutters, as seen in Fig. 6.

The battery's high (96) volt circuit drives the heater and the compressor. A DC inverter controller regulates the compressor work speed so that the compressor power consumption is optimized to the momentary load. The 12V circuit drives the AC controller, blower, fan, and so on.

The required power and energy consumption were calculated considering a steady-state heat load in mid-June at 12.00h with clear skies for three locations around the globe. The heat load considered the following: the metabolic load of the driver, the direct radiation load, the diffuse radiation load, the ambient load and the ventilation load. The final results are shown in table 1.

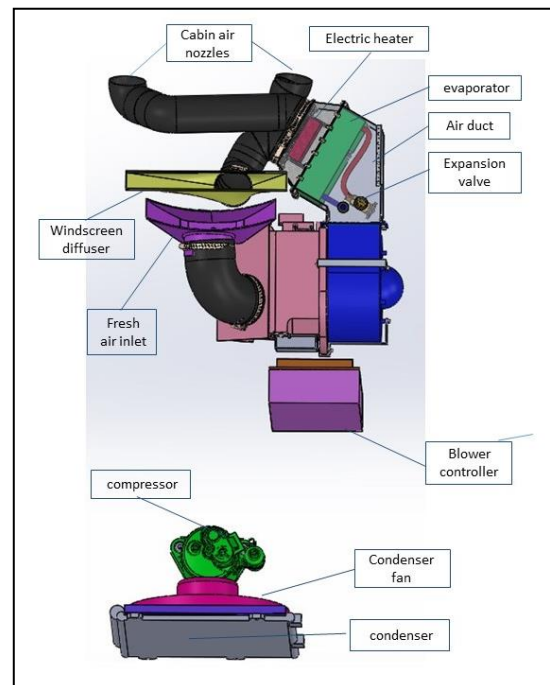


Figure 6: HVAC system layout

The system is capable of a maximum power of 2.1 kW. This maximum system power output would allow the vehicle atmosphere to be cooled to 24°C within 20 minutes of being parked for a long period in an ambient temperature of 35°C.

Table1: Power consumption for mid-day in June with a clear sky

Location	Required power (W)
Stuttgart	737
Singapore	858
Tel Aviv	1146

### 3.3 Expected overall performance

The total predicted energy consumption measured at the battery, considering the combined load of the drive and the AC systems, was simulated according to the NEDC profile. The results are presented in Fig. 7 and table 2.

Table 2: Power consumption and range prediction @ NEDC for mid-day in June, clear sky

Location and/or condition	Average energy consumption (Wh/km)	Range (km)
Without AC	34.4	306
Stuttgart w. AC	56.4	187
Singapore w. AC	60.0	176
Tel Aviv w. AC	68.6	154
90 km/h wo. AC	67.5	216

When calculating the range we assume that 85% of the rated battery capacity is being utilized. NEDC range predictions are considered optimistic rather than realistic. Based on the results in the table above, we can say that the vehicle is able to meet the required autonomy goal of 170km when the conditions are less demanding.

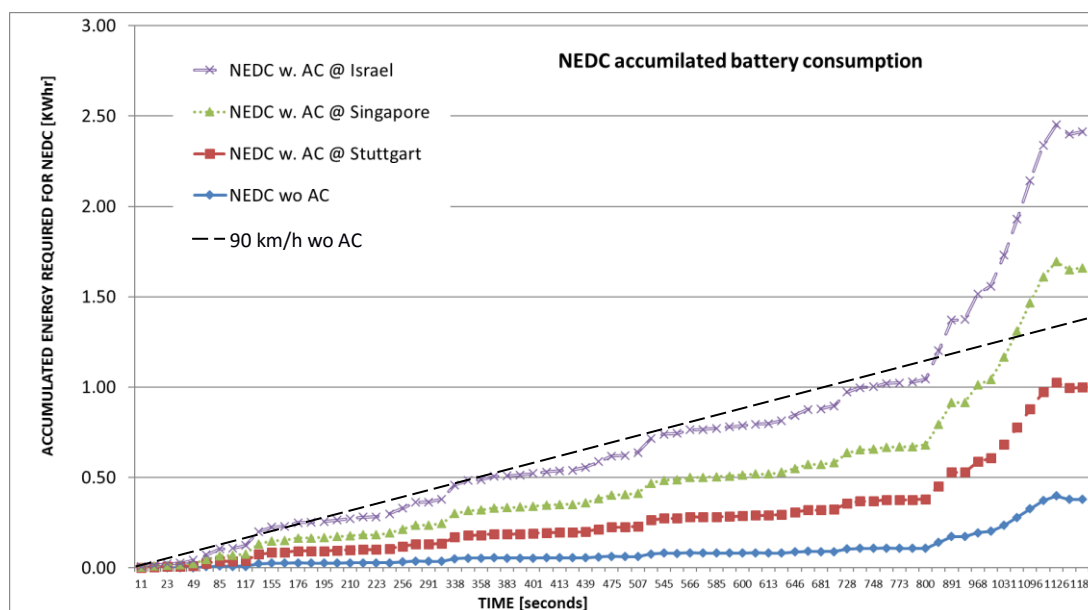


Figure 7: Predicted energy consumption

### 3.4 Battery and high voltage (HV) system

The battery pack is comprised of four parallel Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO<sub>2</sub>) batteries at a nominal voltage of 102V made by Farasis. Each unit is monitored separately with its own BMS to balance the 28-inline cells. The total battery capacity is 14.6 kWh. The battery is also the energy source to the 12V components of the vehicle and to the 24V steering controller. The HV diagram is shown in Fig. 8.

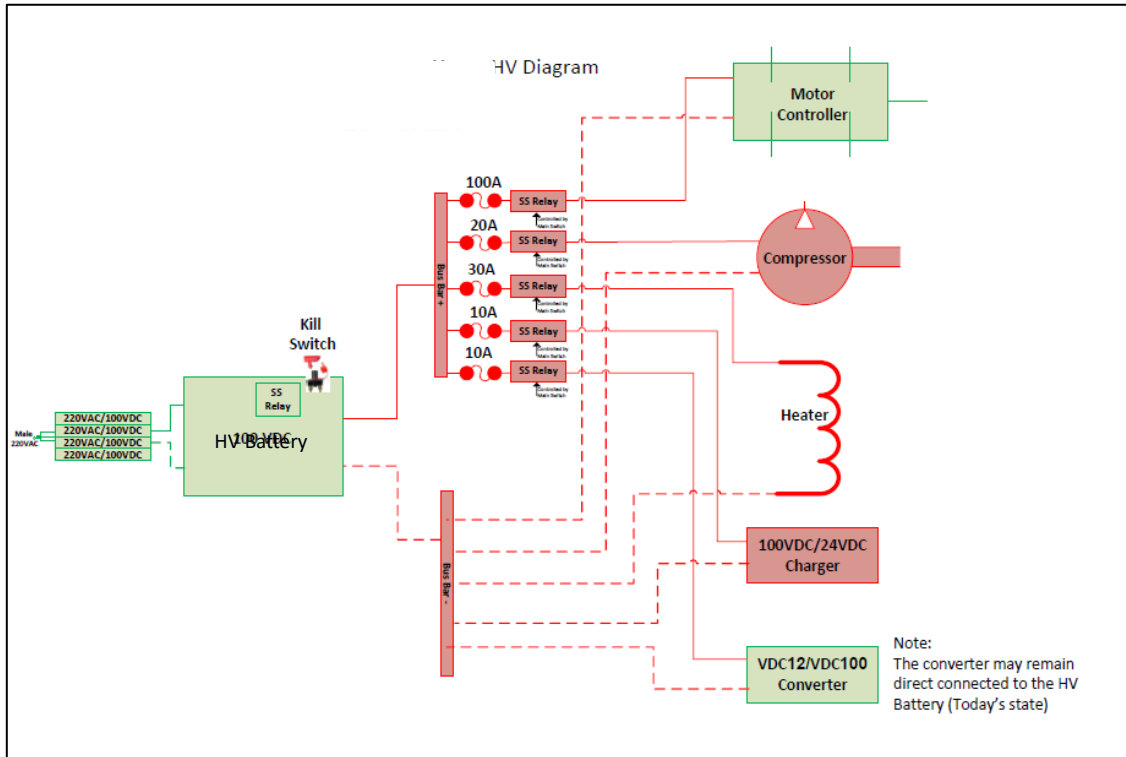


Figure 8: HV circuit layout

## 4 Product development activities

In order for the entire suggested approach to be accepted and attractive, and as part of automotive engineering studies and practical study activities, students replicated industry project integration and management processes. All the individual component systems and system sub-assemblies were combined into a single shared CAD assembly to ensure efficient packaging, good ergonomics and low weight. Many team meetings took place whereby teams in charge of different fields discussed the trade-offs to reach the optimum result for the vehicle.

### 4.1 Layout and arrangement

The vehicle is built around two occupants, with the passenger seated behind the driver. The batteries are located under the driver seat. A rear single wheel drives the vehicle, with the electric motor positioned in line with the hinge of the rear suspension. A male with 95 percentile height can drive the vehicle with comfort. The space for the passengers is compromised to reduce the overall height of the vehicle and achieve the aerodynamics goals.

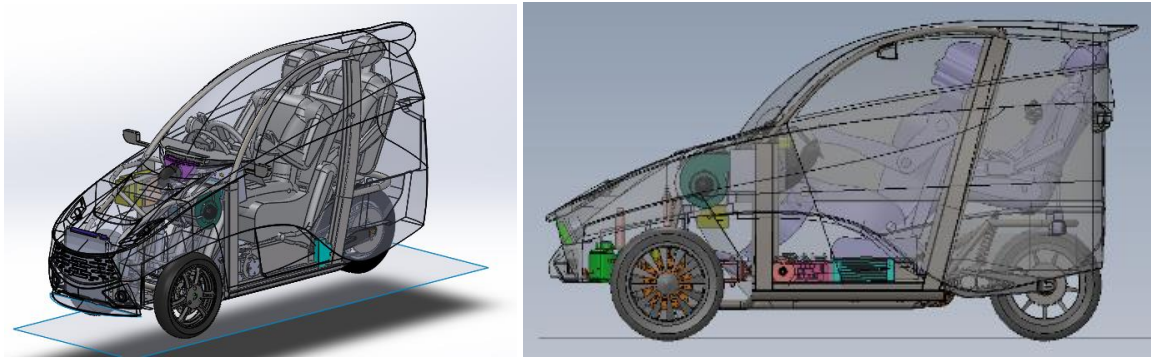


Figure 9: General view of the main CAD assembly

## 4.2 Vehicle design and enclosure

The goal of the design is to create the impression and feel of a passengers' car rather than a scooter. The body at this stage of activity is built as a full enclosure on top of the structural chassis. In the future, an integrated composite body will be designed and will lay on top of a lower aluminium chassis.



Figure 10: Designers' computerized model illustration based on aerodynamics inputs and all other design considerations

## 4.3 Regulative strategy

By meeting the regulatory requirements of L5e category vehicles, we ensure the possibility of having a road legal low weight, small vehicle meeting the product goals, while voluntarily fulfilling the down scaled safety requirements of an M1 vehicle. As such, an L5e vehicle with the designed safety level will be a novelty in the market. Furthermore, the steer-by-wire control without mechanical linkage does not contradict L5e requirements, while it does, contradict M1 current regulations.

## Acknowledgments

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