Activity Report, year 2010

1. Didactic Activity
   As all the 18 mandatory credits were acquired in the first year itself, there was no further didactic activity.

2. Research Activity
   Research in the second year was carried out on the following two projects:
   a. Bredamenerinibus project: The University of Pisa is helping Bredamenerinibus (BMB), an Italian manufacturer of urban, suburban and intercity buses, develop hybrid buses.

   The work involved:
   a) Creating models of the three bus platforms (existing buses);
   b) Simulating the models of the conventional bus on the standard test cycle (SORT1) and city specific cycles (Milano and Bologna); and comparing the results with the actual test results provided by BMB;
   c) After gaining confidence in the quality of modelling, upgrading the models to incorporate series hybrid transmission;
   d) Sizing the critical parameters for the three platforms of the (proposed) hybrid buses;
   e) Simulating these upgraded models on the standard test cycle and city specific cycles, and comparing the results with those of the existing buses.

   LMS.Imagine AMESim® was the modelling and simulation software used. Special efforts were made to model realistic sub-systems to reflect real-life machines, building in parameters for efficiencies. The PMM was programmed to determine the most optimal way to meet the driver’s requirements for power while utilizing the two energy sources of the vehicle.

   TABLE I. CURRENT FLEET OF BMB VEHICLES MODELLLED

<table>
<thead>
<tr>
<th>Bus Models</th>
<th>Vivacity M</th>
<th>Avancity L</th>
<th>Avancity S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>9 meters</td>
<td>12 meters</td>
<td>18 meters</td>
</tr>
<tr>
<td>Weight (trial)</td>
<td>9.67 tonnes</td>
<td>14.35 tonnes</td>
<td>20.99 tonnes</td>
</tr>
<tr>
<td>Weight (full)</td>
<td>13.29 tonnes</td>
<td>17.08 tonnes</td>
<td>25.06 tonnes</td>
</tr>
<tr>
<td>Engine</td>
<td>Deutz</td>
<td>Deutz</td>
<td>MAN</td>
</tr>
<tr>
<td>Capacity</td>
<td>4.8 litres</td>
<td>7.2 litres</td>
<td>10.6 litres</td>
</tr>
<tr>
<td>Max Power</td>
<td>158 kW</td>
<td>213 kW</td>
<td>235 kW</td>
</tr>
<tr>
<td>Torque</td>
<td>800 Nm</td>
<td>1200 Nm</td>
<td>1600 Nm</td>
</tr>
<tr>
<td>Consumption</td>
<td>44.65 litres/100 km</td>
<td>49.66 litres/100 km</td>
<td>63.49 litres/100 km</td>
</tr>
</tbody>
</table>

   Fig. 1: A Bredamenerinini bus

   Fig. 2: the series-hybrid vehicle drive-train scheme

   If, $P_{ED}(t) = P_{E_{GS}}(t) + P_{RESS}(t)$  \[1\]
   where,

   $P_{ED}(t)$ is determined by the driver’s commands;
   $P_{E_{GS}}(t)$ is determined by the PMM; then
   $P_{RESS}(t)$ is automatically determined by the difference.

   If the $P_{ED}(t)$ is imagined to be the sum of an average value and a ripple, the equation modifies to:

   $P_{ED}(t) = P_{EDa}(t) + r(t)$  \[2\]

   where, it is possible to control the system such that the quantity $r(t)$ is completely delivered by $P_{RESS}(t)$, and does not form part of the primary converter:

   $P_{RESS}(t) = r(t), \quad \therefore P_{E_{GS}}(t) = P_{EDa}(t)$  \[3\]
Hence, the ICE delivers only the average power requested by propulsion, leaving the RESS to deliver the rest.

This strategy requires an approximate prior knowledge of the future system load $P_{ED}(t)$, which is a function of the driver’s request for torque and the vehicle duty cycle. This could be obtained by multiplying the past history of $P_{ED}(t)$ with a simple filter, e.g: $P_{EGS}(t)$ is the output of a filter having as input $P_{ED}(t)$ and as a transfer function $1/(1+s\tau)$.

$$P_{EGS}(t) = \frac{1}{T} \int_{0}^{T} P_{ED}(\tau) d\tau \quad (4)$$

In both cases a suitable value for $\tau$ needs to be chosen.

The propulsion system sizing was in accordance with the following boundary conditions:

1. **Level road**
   - Max speed: 80 km/h
   - Max speed without discharging the RESS: 50 km/h
   - Programmed ON/OFF

2. **Road with 16% gradient**
   - Max speed: 10 km/h (range 0.5 km)
   - Start-up acceleration: 0.3 m/s²

Conditions 2a) and 2b) identified the max tractive power and the max (starting) tractive effort for the propulsion system: therefore they completely defined characteristics for the electric drive. The RESS was sized in accordance with condition 1c) (pure electric mode on level gradient), according to the specified range and maximum current limits for the Li-ion battery, evaluated in the real urban cycle and in the SORT1 cycle. The sizing of the ICE could be evaluated with reference to the maximum power, (the max power needed by the ICE), or the efficient power (power at which the engine efficiency is highest).

The main characteristics of the considered sizing are listed in Table II.

### TABLE II. SIZING OF THE CONSIDERED HYBRID BUSES

<table>
<thead>
<tr>
<th>Bus Models</th>
<th>Vivacity M</th>
<th>Avancity L</th>
<th>Avancity S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>9 meters</td>
<td>12 meters</td>
<td>18 meters</td>
</tr>
<tr>
<td>Weight (full load)</td>
<td>13.95 tonnes</td>
<td>17.96 tonnes</td>
<td>26.67 tonnes</td>
</tr>
<tr>
<td>Weight (partial load)</td>
<td>11.3 tonnes</td>
<td>14.3 tonnes</td>
<td>21.1 tonnes</td>
</tr>
<tr>
<td>Auxiliaries</td>
<td>6 kW</td>
<td>9 kW</td>
<td>12 kW</td>
</tr>
<tr>
<td>ICE max power</td>
<td>48 kW</td>
<td>61 kW</td>
<td>84 kW</td>
</tr>
<tr>
<td>ICE efficient power</td>
<td>36 kW</td>
<td>48 kW</td>
<td>69 kW</td>
</tr>
<tr>
<td>RESS Energy</td>
<td>31.1 kWh</td>
<td>38.9 kWh</td>
<td>51.8 kWh</td>
</tr>
</tbody>
</table>

From the main results it was interesting to note that the size of the ICE needed, reduced significantly from the one in the conventional bus.

### TABLE III. FUEL CONSUMPTION

<table>
<thead>
<tr>
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<th>Vivacity M</th>
<th>Avancity L</th>
<th>Avancity S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>9 meters</td>
<td>12 meters</td>
<td>18 meters</td>
</tr>
<tr>
<td>HEV (full load)</td>
<td>43.57 litres/100km</td>
<td>57.89 litres/100km</td>
<td>83.68 litres/100km</td>
</tr>
<tr>
<td>SORT1 cycle</td>
<td>55.98 litres/100km</td>
<td>75.89 litres/100km</td>
<td>111.71 litres/100km</td>
</tr>
<tr>
<td>Conv.(full load)</td>
<td>43.57 litres/100km</td>
<td>57.89 litres/100km</td>
<td>83.68 litres/100km</td>
</tr>
<tr>
<td>SORT1 cycle</td>
<td>55.98 litres/100km</td>
<td>75.89 litres/100km</td>
<td>111.71 litres/100km</td>
</tr>
</tbody>
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The simulation results showed a significant reduction of over 20% in fuel consumption of the series-hybrid driveline compared to the conventional one, besides a reduction in the primary converter size. The technology is also saves fuel during traffic congestions and unscheduled stops. The ON-OFF strategy results in an additional fuel saving between 1 to 2%. This confirms that series–hybrid technology is well-suited to the variable load requirements of urban buses.
b. **Hybrid Commercial Vehicle (HCV) Project:**
The HCV project (under EU’s 7th Framework Programme), aims to develop and demonstrate hybrid electric urban buses and delivery vehicles. The University of Pisa is entrusted with development of the Li-battery based RESS for the HEV. An accurate estimate of the battery degradation is needed to maintain its performance over the designed lifetime and obtain the estimated reduction in fuel consumption. Currently, no proven technique for online monitoring of key RESS parameters on a vehicle exists. The task includes:

- literature review of existing models and strategies to determine SOC and SOH of Li-ion batteries;
- proposing a mathematical model and technique to determine SOC and SOH of Li-ion batteries;
- defining a complete set of test matrices to validate the model and control strategy; and
- testing the Li cells extensively to evaluate the effectiveness of the model and technique proposed.

The SOC could be defined as:

\[
SOC = 1 - \frac{Q}{C_{SOC}} \quad (5)
\]

where, \( Q \int_{0}^{t} i_{m} \, dt \) is the extracted charge and \( C_{SOC} \) the capacity of the battery considered. The SOC strongly depends upon the discharge rate and the battery temperature. Since lithium batteries exhibit columbic efficiencies of near unity, the parasitic effects are not relevant. Striking a balance between complexity of the model and practicality, the model shown in fig. 5 was proposed.

\[
\begin{align*}
L_{c} & \quad C_{c} \quad R_{0} \\
& \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad
surrounding the battery, 
$s$ is the Laplace transform. 
$P_e$ is the power generated inside the battery (appears as heat); 
and those correlating discharge processes with SOC (5). In general, the determination of the structure of functions of the type of (7) can be made by means of comparison between the actual and modelled behaviour in a selected number of tests, determining functions and parameters, and the subsequent evaluation of the model’s performance in cases different from those that have determined it. In general, the process of model synthesis and parameter evaluations requires minimising an error function such as:

$$\text{err}(X_s(t), X_m(t, p)) = \min$$

where $X_s = (V_s, \theta_s)$ and $X_m = (V_m, \theta_m)$ are actual and model quantities respectively, and the error function $\text{err}$ can be of many kinds, such as, for instance:

$$\text{err}(x(t), y(t)) = \frac{1}{T} \int_{t_1}^{t_2} (x(t) - y(t))^2 \, dt$$

Simply measuring the battery current $I(t)$ and numerically integrating it could compute $Q_e$, to determine the SOC. However, this evaluation is subject to error accumulation with time which needs to be periodically corrected. The multiple-step test shown in figure 6 provides a method to correct the errors in the online evaluation of SOC on-board a vehicle, periodically (say, when the vehicle is stopped for more than 20 minutes at a time, or at night when the vehicle is stationary. This technique, cannot be used on olivine based lithium batteries (like LiFePO₄) that show a significant hysteresis phenomena. The multiple-step test can also be used to determine the model parameters.

The multiple-step test: The test cell is first fully charged (or discharged) and then subjected to partial-discharge – rest (or partial-charge-rest) phase cycles. At the end of each rest phase the voltage is independent of the previous battery current, and is a good indication of battery OCV and SOC. The experiment determines the impulse-response of the battery, providing a mechanism to evaluate the parameters for the battery model (experimental results shown in fig. 6). From the knowledge of the current drawn from the battery at each step and the value of the corresponding rest voltage, a correlation curve between OCV and SOC shown in fig. 7 was derived.

Next year, the partners should deliver Li batteries for tests. Tests shall be performed to validate and develop this model and SOC estimation technique, and expanded to estimate SOH.

3. Publications
- T. Huria, “Rail Traction: The economics of transiting towards Hybrid & Hydrail”, 6th International Hydrail Conference, Istanbul (Turkey), July 1-2, 2010

4. Workshops, Conferences & Meetings