Conventional Design and Simulation of an Urban Hybrid Bus

A. Khanipour, K. M. Ebrahimi, and W. J. Seale

Abstract—Due to heightened concerns over environmental and economic issues, the growing importance of air pollution, and the importance of conserving fossil fuel resources, the automotive industry is now forced to produce more fuel efficient, low emission vehicles and new drive system technologies. One of the most promising technologies to receive attention is the hybrid electric vehicle (HEV), which consists of two or more energy sources that supply energy to electric traction motors that in turn drive the wheels. This paper presents the various structures of HEV systems, the basic theoretical knowledge for describing their operation, and the general behavior of the HEV in acceleration, cruise, and deceleration phases. The conventional design and sizing of a series HEV is studied. A conventional bus and its series configuration are defined and evaluated using the ADVISOR. This section the simulation of a standard driving cycle and prediction of its fuel consumption and emissions of the HEV are discussed. Finally, the bus performance is investigated to establish whether it can satisfy the performance, fuel consumption and emissions requested. The validity of the simulation has been established by the close conformity between the fuel consumption of the conventional bus reported by the manufacturer to what has achieved from the simulation.

Keywords—Hybrid Electric Vehicle, Hybridization, LEV, HEV.

I. INTRODUCTION

The development of internal combustion engine (ICE) vehicles is one of the greatest achievements of modern technology. Conventional vehicles with ICE provide good performance and long operating range; however, they have caused and continue to cause serious problems for the poor fuel economy, environment pollution, and human life. Reducing fuel consumption and emissions is one of the most important goals of modern design. The Hybridization of a conventional combustion engine vehicle with an advanced electric motor drive may greatly enhance the overall efficiency and achieve higher fuel economy and reduced emissions [2]. Transit buses are considered to be the best candidates for hybrid application because they normally operate on predictable routes with frequent starts and stops. A hybrid propulsion system is better suited for transit buses than private cars because they operate at lower speed, limited acceleration, less road grades and ample space available for batteries [6].

II. HYBRID ELECTRIC VEHICLE CONCEPTS

A hybrid vehicle may be defined conveniently as a vehicle having two power sources for propulsion. Usually, one of these sources derives its power from fuel, whilst the other relies on stored energy which can be used for extra power at various stages during a journey. The stored energy may also be replenished by the fueled power source, or by recovering energy that would normally be lost in braking as shown in Figs. 1 and 2 [5]. This combination represents a cross between a conventional automobile and an electric vehicle. Normally, the target of this vehicle is to compete with the performance of the conventional and increased fuel efficiency and enhanced potential of reductions in emissions. Essentially, by using a hybrid system, a considerably smaller main engine can be used than in the corresponding conventional vehicle [5].

![Fig. 1 Ideal speed profile for stop/start cycle](image1)

![Fig. 2 Corresponding theoretical power demand by the propulsion](image2)
III. CLASSIFICATION OF HYBRID ELECTRIC VEHICLES

The architecture of a hybrid vehicle is loosely defined by routes of the power flow from the energy source to cars wheels. Traditionally two HEV configurations have been defined: series and parallel. In series hybrid drive train, the EM propels the vehicle while the ICE and generator generate electric power. In parallel structure, either the EM or ICE or even both can drive the vehicle. Note however in 2000, some newly introduced HEVs do not fill in to this classification. Therefore, HEVs are now classified into four kinds: series hybrid, parallel hybrid, series-parallel hybrid, and complex hybrid. The parallel hybrid is more efficient of satisfying high road power demands (high speed or acceleration), while series is more efficient for large energy demands. For public transportation purposes, where large weight is of more concern than high acceleration, the series propulsion strategy becomes more efficient and simpler [6]. Thus, in this research, the series configuration drive train has been preferred.

IV. GENERAL DESCRIPTION OF VEHICLE MOVEMENT

Designing and analyzing of each part of vehicle rely on some information about its performance and properties. According to Newton’s second law, vehicle acceleration can be written as:

\[
\frac{dV}{dt} = \frac{\sum F_t + \sum F_w}{M \delta}
\]  

(1)

Where \( \frac{dV}{dt} \) is vehicle acceleration, \( \sum F_t \) is the total tractive effort of the vehicle; \( \sum F_w \) is the total resistance, \( M \) is the total mass of the vehicle and \( \delta \) is the mass factor, which is an effect of rotating components in the power train. All of the vehicle resistances will be discussed in the following sections.

V. WHEEL ROLLING RESISTANCE

The rolling resistance of tyres on hard surfaces is primarily caused by hysteresis in the tyre materials. This is due to the deflection of the carcass while the tyre is rolling. On soft surfaces; the rolling resistance is primarily caused by deformation of the ground surface. The rolling resistance force can be written as:

\[
F_r = M \cdot g \cdot f_r \cdot \cos \alpha
\]  

(2)

where \( F_r \) is the rolling resistance force, \( M \) is Bus Mass, \( g \) is gravity acceleration, \( f_r \) is rolling resistance coefficient and \( \alpha \) is the road angle.

The power required to overcome the rolling resistance is:

\[
P_r = F_r \cdot V
\]  

(3)

VI. AERODYNAMIC DRAG

A vehicle travelling at a particular speed in air encounters a force resisting its motion. This force is referred to as aerodynamic drag. It mainly results from two components: shape drag and skin friction and is expressed as:

\[
F_w = \frac{1}{2} \rho A_f C_d V^2 (1 + C_u)
\]  

(4)

The power required to overcome aerodynamic drag force is:

\[
P_w = \frac{1}{2} \rho A_f C_d V^3 (1 + C_u)
\]  

(5)

where \( F_w \) is the aerodynamic drag force, \( C_w \) is the wind speed coefficient, \( \rho \) is the air density, \( A_f \) is the frontal area of the vehicle, \( C_d \) is the coefficient of air drag and \( V \) is velocity of the car.

VII. GRADING RESISTANCE

When a vehicle goes up or down a slope, its weight produces a component which is always directed to the downward direction. This component either opposes the forward motion (grade climbing) or helps the forward motion (grade descending). In vehicle performance analysis, only uphill operation is considered. This grading force is usually called grading resistance force and can be expressed as:

\[
F_g = M \cdot g \cdot \sin \alpha
\]  

(6)

The power required for climbing a hill inclined at an angle \( \alpha \) is:

\[
P_g = M \cdot g \cdot V \cdot \sin \alpha
\]  

(7)
where \( M \) is the total mass of the vehicle, \( V \) is the vehicle speed, \( g \) is the gravity acceleration and \( \alpha \) is the road angle.

The total vehicle resistance force and dynamic equation can be expressed as equations (8) and (9):

\[
F_r = F_f + F_w + F_g = M g (f_r \cos \alpha + \sin \alpha) + \frac{1}{2} \rho A f V^2 (1 + C_w) \tag{8}
\]

\[
M \frac{dv}{dt} = (F_f + F_r) - (F_g + F_w + F_f) \tag{9}
\]

where \( \frac{dv}{dt} \) is the linear acceleration of the vehicle, \( F_f \) and \( F_r \) are the rolling resistance of front and rear tyres respectively, \( F_w \) is the aerodynamic drag, \( F_g \) is the grading resistance and \( F_f, F_r \) are the tractive effort of the front and rear tyre respectively.

**VIII. COMPONENTS SIZING**

The major components in a series hybrid train include traction motor, engine/generator, and PPS (Peaking power source). The sizing of the power rating of these components is the first and most important step in the whole system design. The total tractive power (KW) for accelerating the vehicle from zero to speed \( V_f \) in \( t_a \) seconds can be obtained as:

\[
P_t = P_{wheel} = \frac{1}{1000} \left[ \frac{\delta M}{2 t_a} (V_f^2 + V_b^2) + \frac{2}{3} M g V_f (f_r \cos \alpha + \sin \alpha) + \frac{1}{5} \rho C_D A f V_f^3 \right] \tag{10}
\]

The power rating of electric motor (KW) in the flat road is:

\[
P_{EM} = \frac{1}{1000} \left[ \frac{\delta M}{2 t_a} (V_f^2 + V_b^2) + \frac{2}{3} M g V_f (f_r \cos \alpha + \sin \alpha) + \frac{1}{5} \rho C_D A f V_f^3 \right] \tag{11}
\]

The first term of above mentioned equations, represents the power used to accelerate the vehicle mass, and the second and third terms represent the average power for overcoming the tyre rolling resistance and aerodynamic drag.

The electric motor torque is:

\[
T_{EM} = \frac{P_{EM}}{\omega_{EM}} = \frac{60}{2\pi RPM_{EM}} P_{EM} = \frac{30 P_{EM}}{\pi RPM_{EM}} \tag{12}
\]

where \( M \) is the total mass of the vehicle (kg), \( g \) is the gravity acceleration (m/s²), \( \alpha \) is the road angle, \( \delta \) is the mass factor, \( t_a \) is the accelerating time (sec.), \( V_f \) is the final acceleration speed (m/s), \( V_b \) is the vehicle speed at EM’s base speed (m/s), \( \eta_t \) is the transmission efficiency, \( C_D \) Aerodynamic drag coefficient, \( \rho \) is the air density (kg/m³), \( RPM_{EM} \) is the electric motor speed (1/Min.), \( A_f \) is the Vehicle frontal area (m²) and \( f_r \) is the Rolling resistance coefficient.

Internal Combustion Engine and Generator in a series hybrid drive train are used to supply steady state power in order to prevent the PPS from being discharged completely. In the design of the engine/generator, two driving conditions should be considered: Driving for a long time with constant speed, such as highway driving between cities, and driving with a frequent stop-go driving pattern, such as driving in cities. At a constant speed, the power output (KW) from the engine/generator can be expressed:

\[
P_{e/g} = \frac{1}{1000} \eta_t \left[ \frac{2}{3} M g V_f (f_r \cos \alpha + \sin \alpha) + \frac{1}{5} \rho C_D A f V_f^3 \right] \tag{13}
\]

where \( \eta_t \) is the electric motor efficiency.

When the vehicle is driving in a stop and go pattern in urban areas, the power that the engine/generator produces should be equal to or slightly greater than the average load power in order to maintain balance PPS energy storage. The average load power can be expressed as:

\[
P_{ave} = \frac{1}{T} \int_0^T (M g f_r + \frac{1}{2} \rho C_D A f V^2) dt \tag{14}
\]

The first term in equation is the average power consumed to overcome the tyre rolling resistance and aerodynamic drag and the second term is the average power consumed in acceleration and deceleration.

In the design of an engine/generator system, the power capability should be greater than, or at least not less than, the power that is needed to support the vehicle driving at a constant speed (highway driving) and at average power when driving in urban areas. In actual design, a typical urban drive cycles may be used to predict the average power of the vehicle.

Battery sizing is based on an “energy management” approach. It is necessary to ensure that at any point on a journey cycle, the amount of energy in the storage device lies between its maximum and lower limits. It is obvious that by more generated energy from batteries, the vehicle can operate more in fully electric operation and the results are reduction of fuel consumption and air pollution, so it is necessary to select the batteries in the best state of engine performance and to reduce the engine work duration.

The battery must be capable of delivering sufficient power to the traction motor at any time. At the same time; it must store sufficient energy to avoid failure of power delivery due
to too deep discharging. To fully utilize the electric motor power capacity, the total power of the engine/generator and battery should be greater than or at least equal to the rated maximum power of the electric motor. Thus the power capacity of the battery (KW) can be expressed as:

$$P_{PPS} \geq \frac{P_{EM,Max}}{\eta_{Em}} - P_{e/g} \eta_{G}$$  \hspace{1cm} (15)

The energy capacity of the battery pack is determined by the length of time that the vehicle is required operate as pure electric in a specific driving. Having calculated the power, the designer must decide on the amount of pack voltage and thus from which the required amperage from the battery pack is obtained by the following equation:

$$I_{Batt} = \frac{P_{Batt}}{V_{Batt}}$$  \hspace{1cm} (16)

The amperage and multiplying it by the amount of pure electric mode time (hr), the energy capacity of the battery pack is evaluated as:

$$Q_{Batt} = I_{Batt} t_{PEM}$$  \hspace{1cm} (17)

where $P_{EM,MAX}$ is the maximum EM power (KW), $\eta_{Em}$ is the EM efficiency, $P_{e/g}$ is the engine/generator power (KW), $\eta_{G}$ is the generator efficiency, $P_{Batt}$ is the battery pack power (W), $P_{PPS}$ is the power capacity of the battery (KW), $V_{Batt}$ is the battery pack voltage (V), $I_{Batt}$ is the battery pack amperage (A) and $t_{PEM}$ is the vehicle pure electric mode duration (hr).

Table I presents some technical specification which has been used for the components sizing and conventional design of the bus.

| TABLE I |
| TECHNICAL SPECIFICATIONS |

| Drag coefficient | $C_D = 0.79$ |
| Wind speed coefficient | $C_W = 0.2$ |
| Rolling resistance coefficient | $f = 0.01$ |
| Frontal area (m$^2$) | $A_f = 6.75$ |
| Acceleration Time (sec.) | $t_a = 60$ |
| Transmission efficiency | $\eta_t = 0.85$ |
| Electric motor efficiency | $\eta_{Em} = 0.90$ |
| Generator efficiency | $\eta_g = 0.90$ |
| Bus total mass (kg) | $M = 18000$ |
| Mass factor | $\delta = 1.035$ |
| Air density (kg/m$^3$) | $\rho = 1.3$ |
| Maximum Speed (Km/h) | $V_{Max} = 80$ |
| Final acceleration speed (Km/h) | $V_f = 80$ |

Figs. 3 to 6 present electric motor, internal combustion engine and battery specification versus vehicle speed on the different slopes.

Fig. 3 shows the maximum EM power in level surface for achieves to 80 km/h is 144.1 kW and also for achieve to 20 km/h on slope=14% is 120 kW.

Fig. 4 shows that the maximum EM torque in level surface for achieve to 80 km/h is 189.4 N.M and also for achieve to 20 km/h on slope=14% for is 615 N.M.

Fig. 5 shows that 53.9 kW of engine power can be able of supporting the bus at 80 Km/h on a flat road, 27 Km/h on 4% slope, 17 Km/h on 7% slope and 8 Km/h on 14% slope.

Fig. 6 shows the maximum battery power in level surface for achieves to 80 km/h is 111.5 kW and also for achieve to 20 km/h on slope=14% is 20 kW.
IX. EFFECT OF DIFFERENT COMPONENTS ON BUS PERFORMANCE

Effect of Bus Weight

Table II shows the tractive effort that the bus need to achieve to a demand speed is tightly depend on the bus weight. For instance, in M=15000 kg, the bus need 15500N tractive effort, it increases to 18000 N when the bus weight is 18000 kg and 22000 N for M=21000 kg on the slope 14%. In continuous operating mode to achieve to 80 km/h on a flat road it needs 4400 N for M=15000 kg and 5500 N for M=18000 kg and 63000 N for M=180000 kg.

Table II present the summary results of parameters in different weight and slopes.

Table II shows, the bus tractive effort is strongly depend to road slope. It's clear that for achieve to 80 km/h it need 5500 N on the flat road, 10200 N on the 4% slope, 13700 N on the 7% slope and 21800 N on 14% slope. It obvious that the tractive effort increases about 400% when the slope increases from 0% to 14%.

The Most Critical Condition

The most critical condition appears when the batteries can no longer supply the EM and only the engine/generator should feed the EM to propel. Table II shows to achieve to speed 20 km/h on slope 14%, 120 kw and to achieve 80 km/h on the flat road, 54 kw ICE power is needed, if suppose the ICE fixed power around 120 kw and a total efficiency between engine and EM equal to 90 %, the effective power on the EM input shaft is about 108 kW. It means that when the batteries are out of work, the engine / generator supply 108 kW power at the EM input shaft.

As it can be seen in Fig. 7, this power can move the bus at 18, 32, 43, and 68 km/h on 14%, 7%, 4%, and level surfaces respectively.

These results are valid for the worst condition when the bus is fully loaded. It means the components are chosen properly and can satisfy all bus requirements to have suitable performance in all possible conditions.
The final structure that design for controller, electrical and mechanical parts is shown in Fig. 8. By referring to mentioned figure, for generating the acceleration force for the bus, two EM are used and each motor have their own inverters and controllers that are controlled by central control unit. These two motors are joined to the differential axle and to the wheels by a coupling gearbox. For batteries, a charger has performed which can charge the batteries by city electricity power during the night. According to this information, each part has their own controller that all of them are controlled by central control unit.

XI. MODELLING OF HYBRID SYSTEM IN ADVISOR

The Advanced Vehicle Simulator (ADVISOR) was designed as an analysis tool to assist the US Department of Energy (DOE) in developing technologies for hybrid electric vehicles through Hybrid Electric Vehicle Propulsion System contracts with Ford, General Motors, and Daimler Chrysler. Its primary role is to highlight the system-level interactions of hybrid and electric vehicle components and their impacts on the vehicle performance and fuel economy. ADVISOR was created in the Matlab/Simulink environment. Matlab provides an easy-to-use matrix-based programming environment for performing calculations while Simulink can be used to represent complex systems graphically using block diagrams [10].

- Model and Code used in Simulink

Each component has a MATLAB file containing its specifications in ADVISOR. In this section the assumption for series hybrid bus is performed. The simulation of AC motor is performed by two 1PV5138-4WS24-W12 Siemens motor. A 1FV51139WS28 Siemens generator is used as the generator. For ICE an OM 906 LA diesel motor with 205 kW power is simulated and Maxxima DC 900 batteries is used as the battery packs. The ON-OFF (Thermostatic) control strategy controls the engine and for other hybrid electric parts the available information in ADVISOR is used.

- Drive Cycle

A drive cycle is needed to investigate the performance of each component of the hybrid electric bus. The combination of two CBD14 drive cycle has been used for simulation which this cycle is repeated two times.

- Simulation Results

Figs. 9 and 10 show the results of the components simulation in the mentioned drive cycle with assumption that the bus travels on the level surface. Fig. 9 shows that the bus is capable to pass the drive cycle. Fig. 10 shows that the bus travels more than half of the path in pure electric mode and it is so effective for emission and fuel consumption reduction and also the generator is capable to keep the SOC of the battery pack over the 40%.
The emission and fuel consumption of the hybrid electric bus has been presented and the results are compared with the same parameters of the conventional diesel bus (Table III).

<table>
<thead>
<tr>
<th>Bus type &amp; Test conditions</th>
<th>Emission (grams/km)</th>
<th>Fuel Consumption (lit/100km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC</td>
<td>CO</td>
</tr>
<tr>
<td>Conventional</td>
<td>8.51</td>
<td>2.06</td>
</tr>
<tr>
<td>Hybrid</td>
<td>0.16</td>
<td>0.59</td>
</tr>
</tbody>
</table>

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