

Design and Optimisation of the Propulsion Control Strategy for a Pneumatic Hybrid City Bus

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ABSTRACT

A control strategy has been designed for a city bus equipped with a pneumatic hybrid propulsion system. The control system design is based on the precise management of energy flows during both energy storage and regeneration. Energy recovered from the braking process is stored in the form of compressed air that is redeployed for engine start and to supplement the engine air supply during vehicle acceleration. Operation modes are changed dynamically and the energy distribution is controlled to realize three principal functions: Stop-Start, Boost and Regenerative Braking. A forward facing simulation model facilitates an analysis of the vehicle dynamic performance, engine transient response, fuel economy and energy usage. To identify respectively (1) the maximum overall fuel economy, (2) the maximum amount of air and energy recovered during the braking and (3) the minimum loss of available energy during acceleration, a number of variables in the control strategy are selected in an optimisation process. Three optimisation algorithms are compared in different aspects of the control strategy: (1) using the Pattern Search to optimise the initial air tank pressure for every stop-start event in order to maximize the pressure increment in the air tanks; (2) conducting the Genetic Algorithm optimisation to find out the best gear change strategy during braking in order to maximize the energy recovery to the air tanks; and (3) implementing the multiobjective optimisation to simultaneously minimize the fuel consumption and the loss of available energy in the air flow during acceleration. The rationale for the choice of optimisation methods is explained and recommendations made for the development of energy management strategies in which a variety of different vehicle functions contribute to an overall fuel economy benefit.

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INTRODUCTION

After comparing the three principal hybrid vehicle control strategies, respectively rule-based, global optimisation and real-time optimisation, an energy control strategy based on the use of thresholds in the degree of energy storage and regeneration (a "logic threshold" methodology) for a pneumatic hybrid city bus has been designed. By employing the control strategy, the operating modes of the bus can be changed dynamically to realize the three principal functions of the pneumatic hybrid system, respectively Stop-Start, Boost, and Regenerative Braking.

A forward facing simulation model of the bus which includes the detailed engine model has been developed in GT-POWER with MATLAB/Simulink co-simulation support. The pneumatic hybrid city bus dynamic performance, engine transient response, fuel economy and energy usage can be analysed from this model.

To obtain the best overall fuel economy a number of variables in the control strategy were selected using an optimisation process. Three global optimisation algorithms, Pattern Search (PS), Genetic Algorithm (GA) and multi-objective Non-dominated Sorting Genetic Algorithm II (NSGA-II), are compared and employed for the optimisation of the control strategy considered at three levels:

1. Using the PS to optimize the initial air tank pressure for every stop-start event to maximize the pressure increment in the air tanks.
2. Conducting the GA optimisation to find out the best gear change strategy during braking to maximize the energy recovery to the air tanks.
3. Implementing the multi-objective optimisation to simultaneously minimize a) the fuel consumption and b) the loss of available energy in the air flow during a vehicle acceleration (Using the NSGA-II).

PNEUMATIC HYBRID CITY BUS CONTROL STRATEGY

Unlike the Hybrid Electric Vehicle (HEV), the pneumatic hybrid city bus cannot be driven by pneumatic energy alone. But pneumatic hybrid technology has the potential to be a low-cost alternative to the electric motor based micro hybrid technology by converting kinetic energy to pneumatic energy during braking, re-using the stored energy to power an air starter to realize a stop-start operation [1, 2]. Normally the micro hybrid system is the integration of starter and alternator in the conventional Internal Combustion (IC) engine vehicle, in which the starter should also function as a generator motor. These components tend to add both cost and weight to the vehicle.

[3]. As mentioned in [4], the pneumatic hybrid system also has another advantage which can improve the engine performance by injecting compressed air into the inlet manifold to build-up engine torque more rapidly compared with the unassisted engine. So the control strategy implements three functions:

1. Stop-Start: when the vehicle starts, the air starter cranks the engine; when the vehicle is stopped, the IC engine is switched off to save the idle fuel consumption if stop conditions are satisfied.
2. Boost: during the acceleration, the Boost Function is switched ON to eliminate the turbo-lag and improve the engine transient response.
3. Regenerative Braking: During deceleration, the Regenerative Braking Function is engaged..

Overview the Control Strategy of Hybrid Vehicles

The control strategy of a hybrid vehicle is defined as an algorithm which regulates the operation of the vehicle powertrain [5]. It is usually implemented in the hybrid vehicle controller which has a supervisory role in regard to the operation of the vehicle. The main objectives of the control strategy are to continuously monitor the driver's demand, vehicle status, current traffic information, and even the information provided by the global positioning system to determine the proper vehicle operating state for optimal fuel economy, minimum overall energy use, and vehicle performance [5, 6, 7]. Hybrid vehicle control strategies can be divided into three categories: ruled-based, numerical optimisation-based and real-time optimisation [8]. All the main solutions are classified according to Figure 1.

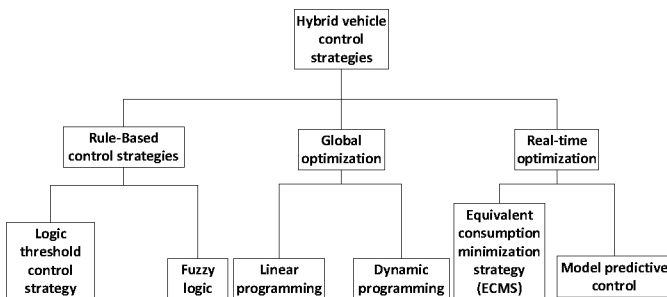


Figure 1. Classification of hybrid vehicle control strategies

Rule-Based Control Strategies

The rule-based control strategies are designed without *a priori* knowledge of the driving cycle. Therefore, they are effective in the real-time supervisory control of the power flow in the hybrid powertrain. The objective of rule-based control strategies is often “load-levelling” which tends to shift the actual IC engine operating point as close as possible to the optimal point of the efficiency, fuel consumption, or emissions at a particular engine speed. The rules can be obtained by using heuristics, intuition, human expertise, and even mathematical models [5]. Two typical rule-based control strategies are introduced here: respectively (1) the logic threshold control strategy and (2) the fuzzy logic control strategy.

The logic threshold control strategy is widely used because of its speed and simplicity [9]. It is based on analysis of power flow in a hybrid powertrain, efficiency/fuel or emission maps of an IC engine, and human experience is utilized to design deterministic rules to split the requested power between power converters [5]. The fuzzy logic control strategy is an extension of the conventional rule-based control strategy typified by a logic threshold control strategy [5]. The fuzzy logic control strategy uses the decision-making property instead of using deterministic rules. As a result, it can be adopted to realize a real-time though possibly suboptimal power split. The main advantages of the fuzzy logic control strategy are robustness and the potential for adaptive behaviour [5]. Although the rule-based control approaches can offer an improvement in energy efficiency, it is clear that they do not guarantee an optimal result in all conditions [8].

Global Optimisation

The global optimisation approach can find the global optimum solution by performing the optimisation over a prescribed driving cycle. It is non-causal in nature and requires *a priori* knowledge of the driving cycle information and could not be used directly for real-time hybrid vehicle control strategy. However, the result of the global optimisation can be considered as the benchmark for designing rules for online implementation or comparison for evaluating the quality of other control strategies. The most common global optimisation approach is the Dynamic Programming (DP).

DP calculates every possible combination energy output of the IC engine and another power source in the hybrid powertrain such as motor power at each step, ensuring that the global optimum can be reached. DP seems to be a reasonable approach for optimal power split in hybrid vehicles. It is a powerful tool to save general dynamic optimisation problems, easily handling the constraints and nonlinearity of the problem while obtaining a globally optimal solution [5]. Although DP can find the global optimum, it is an offline algorithm. DP will supply a benchmark which can be compared with the rule-based control strategy's result.

Real-Time Optimisation

In the context of electric hybrid vehicles, in order to develop a cost function to be used in a real-time optimisation process, the rate of fuel consumption must be available as a measurement. Variations of the stored electrical energy should also be taken into account to guarantee electrical self-sustainability [5]. The most well-known approach of the real-time optimisation is the Equivalent Consumption Minimization Strategy (ECMS).

The “equivalent fuel consumption” of the ECMS is the electrical energy flow cost according how much it will cost in fuel terms to restore that energy. Application of the ECMS method includes an assessment of the relative value derived from a drive cycle of electricity and fuel. The process includes the notion of the “free” energy that is derived from regenerative braking [8]. Although the solution of the ECMS is not globally optimal, it is particularly suited to real-time implementation and is reported to be close to optimal in practice [10].

The control modes which govern the vehicle during this process are now described in more detail: (Each mode is referred to the Stages shown in Figure 3)

1. Cranking mode (1-2)

Based on the input signals and the pressure in the two air tanks, the control strategy assigns one air tank to start the engine by opening the valve of this air tank.

2. Full acceleration mode (2-3, 5-6)

In this mode, the driver demands full (100%) acceleration. The mode can be either part of an acceleration event like stage 2-3 or a full acceleration event such as stage 5-6. The control strategy chooses one air tank to realize the boost function by opening the valves. Additional fuel is then metered according to the additional air supplied to improve cylinder MEP. Based on the findings of previous research, the air tank with the lower pressure can recover more braking energy during the deceleration. As a result, the control strategy chooses the air tank with lower pressure to implement the boost function.

3. Acceleration mode (3-4)

Acceleration mode is selected when the driver demand is less than 100%. The vehicle operation modes can transfer between the fully acceleration mode and the acceleration mode depending on the driver demand.

4. Cruise mode (4-5)

In this mode, the vehicle has a fixed speed.

5. Acceleration mode (5-6)

The vehicle accelerates with boost assistance from one of the air tanks when full acceleration is requested by the driver.

6. Deceleration mode (6-7)

Based on the pneumatic hybrid system condition, the control strategy controls the vehicle to operate between three states: a) Regeneration to air tank 1, b) Regeneration to air tank 2 and c) Regeneration braking off.

7. Stop mode (7-8)

Based on the condition in the pneumatic hybrid system, the control strategy turns the engine on or off during the vehicle stop period.

Stateflow is an environment for modelling and simulating combinatorial and sequential decision logic based on state machines and flow charts [9]. The principal reason however for using Stateflow is that the function of the pneumatic hybrid city bus naturally consists of a number of states. Based on different state transition conditions, the model will transfer from one state to another. In complex circumstances, secondary models manage a state transition within

high level states. Figure 4 shows the state diagram of the control strategy for the pneumatic hybrid city bus and its implementation in Stateflow is shown in Figure 5.

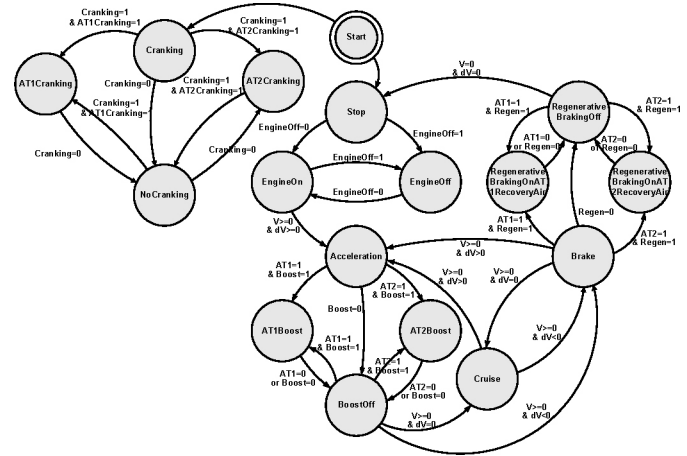


Figure 4. State diagram of control strategy for the pneumatic hybrid city bus

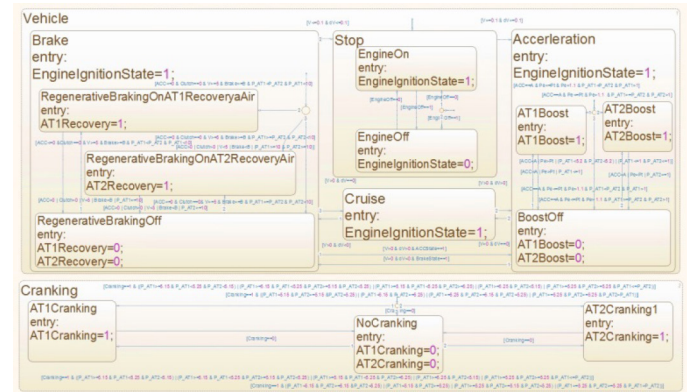


Figure 5. Stateflow diagram of control strategy for the pneumatic hybrid city bus

PNEUMATIC HYBRID CITY BUS SIMULATION MODEL

The vehicle simulation model has been built using GT-POWER and MATLAB/Simulink. The GT-POWER signals can be passed to or from Simulink via “SimulinkHarness” component. Its function is to couple GT-POWER to MATLAB/Simulink and to enable the cosimulation process. This is a common practice in the industry where the engine, powertrain, and vehicle physics are modelled in GTPOWER, and electronic controllers are modelled in Simulink [11].

In this research, the forward facing model is utilised for control strategy optimisation to produce more precise results than would be the case with a backward facing model [12]. These two models in GT-POWER and Simulink are combined to form a forward facing simulation model which includes a driver model that must follow the target speed. Compared with the backward facing simulation model, there are several benefits such as (1) the forward facing model gives insight into the driveability of the vehicle and provides better understanding of the dynamic and physical limits of the powertrain [13]; and (2) the forward facing simulation model can simulate the transient performance of the vehicle especially the internal combustion engine transient response. By contrast, the backward facing simulation model normally determines the performance of the engine based on the efficiency models or maps. A disadvantage of the forward facing model is a relatively smaller time step when compared to the backward facing model, resulting in very much longer simulation time. For example, the longest time step value for continuous simulation in the GT-POWER is 0.001 s [14].

Engine and Pneumatic Regenerative System Model

The engine and pneumatic regenerative system model demonstrated in these results is developed from the pneumatic hybrid engine concept mentioned in [1] and two air tanks pneumatic hybrid engine backward facing model in [2]. It is based on the engine with the pneumatic intake port boost system model used in [4] and with an added air tank. The pneumatic regenerative system and the engine main technical parameters are summarized in Table 2.

Vehicle Model

In this research, the main objective is to study the relationship between the vehicle performance, the engine fuel consumption and the energy recovery efficiency. The schematic representation of the forces acting on the city bus is presented in Figure 6.

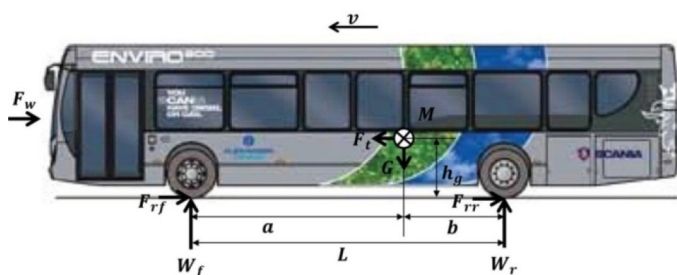


Figure 6. Forces acting on the city bus

Table 2. Main technical parameters of the engine and pneumatic system

Displacement (l)	7.25
Electronic control system	High pressure & common rail
No. of Cylinders (-)	6
Bore (mm)	108
Stroke (mm)	132
Compression ratio (-)	17.5:1
Intake way	Turbo-charging & inter-cooling
Rated power/speed (kW/rpm)	177/2300
Max. torque/speed (Nm/rpm)	900/1400~1600
Intake valve (-)	2
Diameter (mm)	32.5
Opening point (normal)	61°BTDC
Closing point (normal)	91°ABDC
Exhaust valve (-)	2
Diameter (mm)	29.5
Opening point (normal)	105°BBDC
Closing point (normal)	67°ATDC
Air tank volume (l)	151
No. of Air tank (-)	2
Gear ratios, 1-5	6.9, 4.13, 2.45, 1.49, 1
Final drive ratio	5.125
Additional mass of air starter (kg)	15
Additional mass of air tank (kg)	100

The elementary equation that describes the longitudinal dynamics of a road vehicle is (1):

$$M \frac{d}{dt} v = F_t - (F_w + F_r + F_g) \quad (1)$$

Where,

F_w = aerodynamic friction

F_r = rolling friction

F_g = force caused by gravity when driving on non-horizontal roads

F_t = traction force

M = vehicle mass

v = vehicle speed.

The aerodynamic friction F_w can be expressed (2),

$$F_w = \frac{1}{2} \rho_a A_f c_d v^2 \quad (2)$$

Where,

v = vehicle speed

ρ_a = density of the ambient air

c_d = aerodynamic drag coefficient

A_f = frontal area of the vehicle.

The rolling friction F_r is modelled as

$$F_r = F_{rf} + F_{rr} = c_r M g \cos \alpha \quad (3)$$

Where,

M = vehicle mass

g = acceleration due to gravity

c_r = coefficient of the rolling resistance

F_{rf} = rolling friction on the front axle

F_{rr} = rolling friction on the rear axle

The term $\cos \alpha$ models the influence of a non-horizontal road. For this research, only the horizontal road is considered ($\alpha = 0$).

The uphill driving force F_g is modelled,

$$F_g = M g \sin \alpha \quad (4)$$

The traction force F_t for a rear-wheel-drive vehicle,

$$F_t = \frac{\mu M g \cos \alpha [L - c_r(h_g - r_d)] / L}{1 - \mu h_g / L} \quad (5)$$

Where, μ = the friction coefficient.

The vehicle subsystem model in GT-POWER transmits a vehicle load (including vehicle's inertia load) back to the engine model as a torque. The speed of the engine and the vehicle drivetrain (which are geared together by the transmission) is then calculated by the engine model. This speed is calculated taking the engine's brake torque and subtracting from it the load torque applied by the vehicle (as well as any auxiliary torque applied to the engine model), and then using any

remaining "positive" torque to accelerate the powertrain. As a result, the simulation includes the transient response of the engine facilitating the investigation of the control of both the engine and its subsystems.

Driver Model

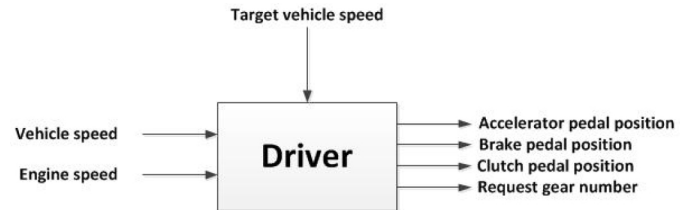


Figure 7. Input and output of the driver model

The driver model controls accelerator position, brake pedal position, transmission gear number, clutch pedal position. It is primarily used for controlling vehicles with manual transmissions as it contains the necessary functions for vehicle launch (*driveaway* event) and gear shifting. The input and output of the driver model are shown in [Figure 7](#).

Driving Cycles Model

The drive cycle may be generated via several options, including constant, equation, or imposed time series. This template can also be used to generate a signal of the current time, angle, or cycle at each time step.

Air Tanks Energy Recovery Model

The air tank has been modelled as a control volume, which exchanges air mass only with the pipes connecting the air tank. The air tanks have a fixed volume V_{AT} . It is assumed the storage and discharge of air is at constant temperature. The mean-value model of the air tank's state is calculated using the following [Equations \(6 and 7\)](#).

$$pV_{AT} = mRT \quad (6)$$

Where,

p = air tank pressure

m = air mass in the air tank

R = gas constant

T = air tank temperature.

$$\Delta E = \Delta m c_v T \quad (7)$$